MODELLING STREAMFLOW FROM FORESTED WATERSHEDS ON THE CANADIAN BOREAL SHIELD USING THE SOIL AND WATER ASSESSMENT TOOL (SWAT)

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University of Saskatchewan
Saskatoon

By

BIJAYA GAUTAM

PERMISSION TO USE

Head of the Department of Civil and Geological Engineering
University of Saskatchewan
Saskatoon, Saskatchewan, Canada (S7N 5A9)

ABSTRACT

The Forest Watershed and Riparian Disturbance (FORWARD) Project was initiated in 2001 in Canada. The main objective of the project is to investigate the effects of tree harvesting upon streamflow and nutrient export from forested watersheds, and to develop hydrologic and water quality modelling tools to predict these effects. For this purpose, the FORWARD Project has been adapting the Soil and Water Assessment Tool (SWAT) model for boreal forest watersheds. The SWAT model was originally developed for the management of agricultural watersheds in the USA. Therefore, the FORWARD project researchers modified the SWAT model to make it more suitable for simulating hydrological processes occurring in boreal forest watersheds. The modified model is called SWAT_{BF}.

SWAT_{BF} was successfully tested on the western Boreal Plain where the soil mantel is thick. However, the model must be tested before applying it on eastern Boreal Shield watersheds where the soil layer is thin. Therefore, the focus of this study was to investigate the applicability of SWAT_{BF} for Boreal Shield watersheds and to investigate differences in calibration parameters and their values, and model set-up for hydrological simulation between Boreal Shield and Boreal Plain watersheds.

Initial set-up and testing of the model showed that a simplified version of SWAT_{BF} provided acceptable performance in Boreal Shield watersheds. Hence the simplified version of the SWAT_{BF} model was used in this modelling investigation. The simplified SWAT_{BF} omitted the Boreal Plain litter layer and wetland representations.

Two types of tests were conducted to verify the applicability of the SWAT_{BF} model: (1) split-sample test; and (2) proxy-basin test. In total, six case studies were performed from the two different tests. In general the simplified $\mathrm{SWAT}_{\mathrm{BF}}$ model was able to predict the pattern of monthly and daily streamflow in all six case studies. The performance of the model was much better for simulation of monthly runoff compared to daily runoff. However, it was found that the model underestimated the many of the daily peak flows in all case studies. Potential sources of model error are discussed.

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LIST OF ABBREVIATIONS

Ae = Soil horizon according to the Canadian System of Soil Classification. Ae is a mineral horizon that forms at or near the soil surface which is characterized by the eluviations of minerals and/or organic matter.

aniso = anisotropic factor

ArcSWAT = ArcSWAT using ArcGIS version 9.1

AVSWAT = ArcView-SWAT

AVSWAT-X = AVSWAT interface tool was further modified to

Case I = Chief Peter (Calibration: 2006-2007; Validation: 2008-2009)

Case II = Chief Peter (Calibration: 2008-2009; Validation: 2006-2007)

Case III = Entwash (Calibration: 2006-2007; Validation: 2008-2009)

Case IV = Entwash (Calibration: 2008-2009; Validation: 2006-2007)

Case V = Calibrated on Chief Peter and Validated on Entwash

Case VI = Calibrated on Entwash and validated on Chief Peter

cc = Cubic centimetre

CSSC = Canadian System of Soil Classification

DEM = Digital Elevation Model

Dfb = Koppen-Geiger climate classification system (D: temperature of warmest month greater than or equal to 10 degrees Celsius, and temperature of coldest month –3 degrees Celsius or lower; f: precipitation more evenly distributed throughout year; and b: temperature of each of four warmest months 10 degrees Celsius or above but warmest month less than 22 degrees Celsius)

DRMF = Dog River-Matawin Forest

D_v = deviation of runoff volume

e_a = actual evapotranspiration (mm),

ea = amount of evapotranspiration on day i (mm)

e_L = evapotranspiration from the litter layer (mm),

e_o = potential evapotranspiration (mm)

FORWARD = Forest Watershed and Riparian Disturbance

g = gram

GIS = Geographical Information System

HRU = Hydrologic Response Unit

K_{sat} = Vertical saturated hydraulic conductivity (mm/h),

$K_{sat,bd}$ = Vertical saturated hydraulic conductivity of the bedrock underlying the soil profile

$K_{sat,l}$ = Vertical saturated hydraulic conductivity of the soil layer (mm/h)

$K_{sat,l+1}$ = Vertical saturated hydraulic conductivity of the underlying soil Layer

$K_{sat,l=n}$ = Vertical saturated hydraulic conductivity of the lowest layer ,n, in the soil profile (mm/h)

$K_{sat,max}$ = Vertical maximum saturated hydraulic conductivity of the soil layer (mm/h)

LAI = Leaf Area Index

LFSS = Legacy Forest Small Streams

L_h = length of the hill slope (m),

L_{max} = maximum quantity of water that can be held in the litter layer (mm)

NSE = Nash-Sutcliffe efficiency

NTS = National topography survey

NWW = Northwest west

OMNR = Ontario Ministry of Natural Resources

Q_{gw} = amount of return flow on day i (mm)

Q_{l} = lateral flow (mm),

Q_{mean} = mean observed runoff (mm)

Q_{obs} = observed runoff (mm),

Q_{pred} = predicted runoff (mm),

Q_{sur} = amount of surface runoff on day i (mm)

Q_{sur} = surface runoff (mm),

R_{C} = amount of precipitation after canopy interception has been removed (mm)

R_{day} = amount of precipitation on day i (mm)

$R_{L(F)}$ = final amount of water held in the litter layer (mm)

$R_{L(i)}$ = initial amount of water held in the litter layer (mm)

RMSE = root mean square error

R_{S} = amount of water that reaches the soil surface (mm)

RSR = RMSE- observations standard deviation ratio

S = slope (mm/mm)

$Sat_{l=1}$ = amount of water in the top soil layer at saturation (mm)

SSE = South south east

$STDEV_{obs}$ = standard deviation of the observed data

SWAT = Soil and Water Assessment Tool

$SWAT_{BF}$ = modified version of SWAT for boreal forest conditions

SW_{d} = drainable volume of water in the soil layer (mm)

SW_{f} = final soil water content (mm)

SW_{f} = final soil water content (mm)

SW_i = initial soil water content (mm)

SW_i = initial soil water content on day i (mm)

$SW_{l=1}$ = drainable volume of water in the top layer (mm)

t = time (days)

T_{lag} = lateral flow time (days)

V_{obs} = measured runoff volume

V_{pred} = predicted runoff volume

$w^*_{p,l}$ = amount of percolation calculated using the storage routing technique (mm)

$w^*_{p,l=n}$ = amount of percolation from the lowest layer, n, in the soil profile calculated using the storage routing technique (mm)

WLR = Global water-level recorder

$w_{p,l}$ = amount of water percolating to the underlying soil layer (mm)

$w_{p,l=n}$ = amount of water percolating out of the lowest layer ,n, in the soil profile (mm)

wtlfr = factor to represent some portion of lateral flow and baseflow from upland HRUs to be diverted towards the lowland land wetlands

α_l = recession constants for lateral flow

β_l = recession constants for lateral flow

ϕ_d = drainable porosity of the soil layer (mm/mm)

% = percentage

CHAPTER 1
INTRODUCTION

1.1 Background

Harvesting of trees in the Canadian boreal forest is a matter of concern to environmentalists and forest managers in Canada because it can cause changes in hydrological processes in watersheds. The removal of vegetation from watersheds, either through natural processes (e.g. weather, wildfire, and diseases) or by human activities (e.g. harvesting and thinning) decreases the rate of evapotranspiration from the landscape (Vertessy 2000). As a consequence of this, surface runoff increases and is responsible for transporting additional nutrient and sediment load from the disturbed forested stands towards the downstream receiving waters. It is well known that the stream environment, fed by the upstream watersheds, is an important aquatic habitat. Additionally, the downstream receiving water may be used by humans for different purposes such as recreation, water supply and agriculture (Putz et al. 2003). Therefore, the management of forest dominated watersheds is important to maintain natural hydrological processes, and stream water quality (Putz et al. 2003).

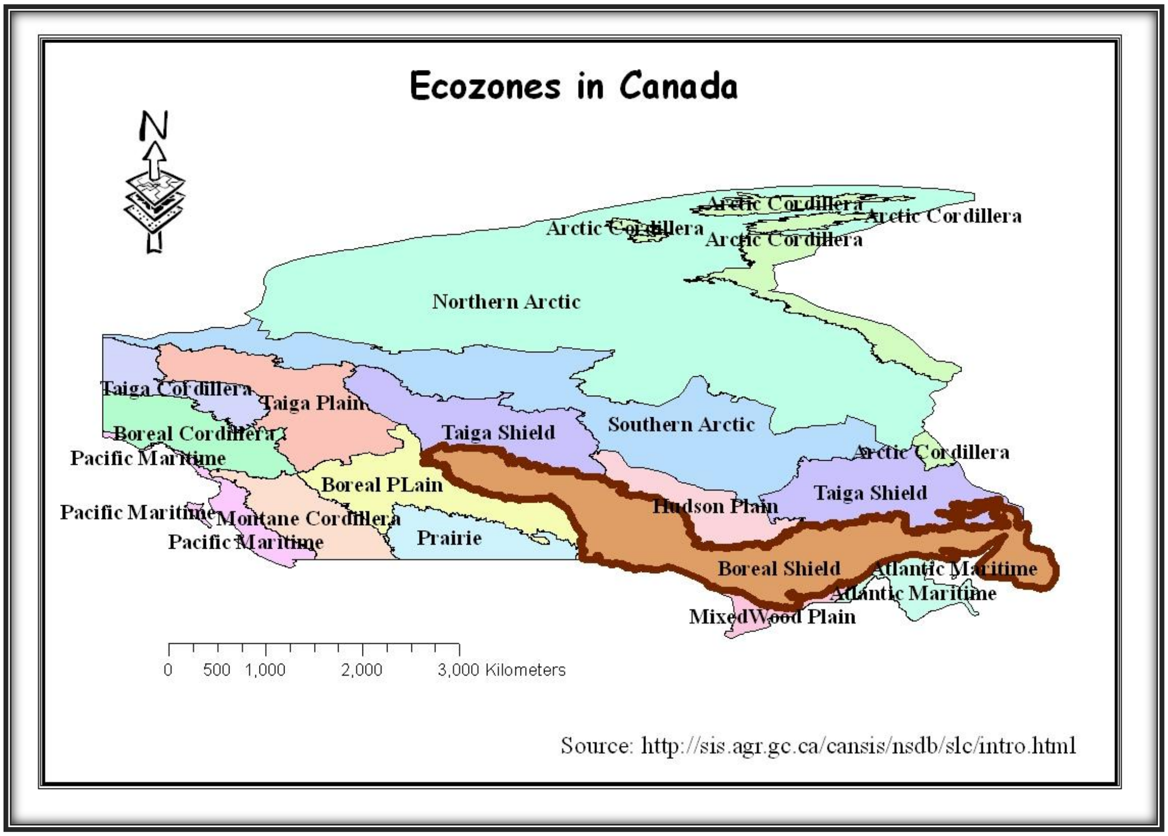
The Forest Watershed and Riparian Disturbance (FORWARD) project was initiated in 2001 in order to investigate the effects of watershed disturbance in the western sub region (Boreal Plain) of the Canadian boreal forest (Smith et al. 2003). The project is responsible for investigating the effects of watershed disturbances on water quality and quantity, and to develop hydrological and ecological models, which can be utilized as planning tools for forest managers and policy makers (Prepas et al. 2006).

Different management practices and strategies can be assessed utilizing these modelling tools in order to minimize the adverse effects to the environment caused by harvesting operations.

Since the FORWARD project was originated on the western Boreal Plain ecozone of the Canadian boreal forest, its modelling approaches and hydrological monitoring of disturbed and forested watersheds have concentrated on this region. Although the project is also collecting data from forest dominant watersheds located on the Boreal Shield of north-western Ontario in Canada, the data have not as yet been used for hydrological modelling.

1.2 Problem Definition

According to Environment Canada (2010a), the Boreal Shield (Figure 1.1) is one of the largest ecozones of Canada, which covers almost 20% of the country's landmass. The Boreal Shield extends 3,800 kilometres from Northern Saskatchewan to Newfoundland and Labrador, passing north of Lake Winnipeg, the Great lakes and the St. Lawrence River (Canadian Forest Service 2010). Its myriad rivers and lakes account for 22% of Canada's freshwater surface area. The statistics of Environment Canada (2010a) show that the Boreal Shield ecozone contains 43% of Canada's commercial forestland. Further, it is known that 400,000 hectares of forest is being harvested every year on the Boreal Shield (Canadian Geographic 2010). Considering the significant amount of forestry activities occurring within this ecozone, there is an urgent need for forest managers to be able to predict the volume and quality of the streamflow coming from disturbed and undisturbed forested watersheds, which ultimately affects downstream water use. To fulfill this need, the forest managers require a hydrological model that can be used as a basis for planning and decision making to prevent or minimize adverse impacts to the environment.



Source: http://sis.agr.gc.ca/cansis/nsdb/slc/intro.html

Figure 1.1 Boreal Shield ecozone.

As a basis of modelling, the FORWARD project in Canada has been using the Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998) for hydrologic simulation in the western forested watersheds on the Boreal Plain ecozone of Canada. However, Fohrer et al. (2001) and Govender and Everson (2005) argued that the SWAT model has relatively few applications where forest was the dominant land cover, as it was originally developed for the management of agricultural watersheds in the USA (Gassman et al. 2007). Furthermore, one of the constraints of the original SWAT model found by Watson et al. (2005) and Kirby and Durrans (2007), is its inability to simulate forest growth accurately. Nonetheless, over the last decade, the SWAT model has been modified by several researchers to make it more suitable for different types of forested watersheds around the world (Watson et al. 2005; Kirby et al. 2007). Different researchers in Canada (McKeown et al. 2003, McKeown et al. 2005, and MacDonald et al. 2005) have attempted to modify the SWAT model to better simulate the hydrological processes occurring in the boreal forests of Canada. Considering the positive results obtained from these studies, Watson et al. (2008) reported that the modified SWAT model can be utilized to test different management scenarios in forested watersheds.

As a part of the FORWARD project, to better represent the hydrological processes occurring in the western forested watersheds on the Boreal Plain, Watson et al. (2008) further refined the SWAT model and named the modified version SWAT_{BF}. The SWAT_{BF} model was successfully tested on the western Boreal Plain, where the soil profile is well-developed and glacial till is also thick. However, the model must first be tested before using it in the eastern forested watersheds on the Boreal Shield, where the soil mantle is thin and the soil profile is poorly developed.

1.3 Research Objectives

This research project serves as a starting point for modelling streamflow in forested watersheds on the Boreal Shield using SWAT_{BF}. The main objective of this research project is to investigate the general applicability of the SWAT_{BF} model beyond the Boreal Plain. The specific objectives of the project are stipulated below:

1. Attempt to simulate the streamflow occurring from forest dominant watersheds on the Boreal Shield of Canada using the $SWAT_{BF}$ model in its current form.
2. Assess the suitability of the $SWAT_{BF}$ model for simulation of streamflow in Boreal Shield watersheds in comparison to Boreal Plain watersheds.
3. Identify differences in key parameters and parameter values for simulations on the Boreal Shield in comparison to the Boreal Plain, and
4. Identify process representation problems, if any, in simulating streamflow on the Boreal Shield using the $SWAT_{BF}$ model and incorporate corrective measures to improve the model.

1.4 Scope of the research program

The scope of the modelling investigation was to calibrate and validate the $SWAT_{BF}$ model for forested watersheds located in north-western Ontario within the Boreal Shield sub region of Canada. The research project has focused only on the simulation of hydrological processes related to streamflow. It has not included the water quality issues within the watersheds. The model has been calibrated and validated for small-scale watersheds monitored by the FORWARD project in the Boreal Shield. Therefore, the application of the modelling results may be limited to predict hydrological phenomenon occurring in small-scale forested watersheds on the eastern Canadian Boreal Shield that possess similar soil and land use characteristics to those investigated in this research.

1.5 Methodology

The $SWAT_{BF}$ model, a modified version of Soil and Water Assessment Tool (SWAT), was used to conduct the hydrological modelling. The input data that are required to run the model are Geographical Information System (GIS) data and meteorological data. The GIS data include: Digital Elevation Model (DEM), land use map and soils map. The required climate data are: (1) precipitation, (2) maximum and minimum air temperature, (3) relative humidity, (4) solar radiation, and (5) wind speed. The GIS data was obtained from the AbitibiBowater ArcView GIS database, and the meteorological variables were acquired from the FORWARD project database of field measurements and from Environment Canada weather stations. The streamflow data that are required to calibrate and validate the models were acquired from the FORWARD flow monitoring sites. The parameters that were used to calibrate and validate the model were adopted based upon the Boreal Plain calibration parameters, and from the knowledge gained through a literature review of characteristics of the eastern Canadian boreal shield.

Initially, the Chief Peter watershed, one of the watersheds monitored by the FORWARD project within the Legacy Forest Small Streams (LFSS) study area on the eastern Boreal Shield, was calibrated and validated following the split-sample test procedure described by Klemes (1986). Thereafter, the general applicability of the model was investigated by performing a proxy-basin validation test as described by Klemes (1986) on the Chief Peter watershed and Entwash watershed (located adjacent to the Chief Peter watershed).

1.6 Synopsis of the thesis

The thesis document is organized in the following pattern: Chapter 2 provides a description of different types of hydrological models and a literature review on the SWAT model and the $SWAT_{BF}$ model. A description of the study area is provided in Chapter 3. Procedures followed to formulate the model and the assumptions that were made are explained in Chapter 4. The results, analysis and discussion are included in Chapter 5. Finally, Chapter 6 presents a summary of the research conducted, the conclusions reached, and possible areas for future research work.

CHAPTER 2
LITERATURE REVIEW

This Chapter provides an overview of several types of hydrological models that are available in water resources engineering. Further, it provides information about the SWAT model and the modifications that are made in the $\mathrm{SWAT_{BF}}$ model. In addition, applications of the SWAT model are also described in this chapter.

2.1 Watershed Modelling

Watershed modelling provides insight into the field of hydrological sciences. Watershed models actually represent the natural hydrological processes in a simplified way. According to Beven (2000), watershed models are designed to understand the hydrological processes occurring in the watersheds and to investigate their interaction with each other. Basically, watershed models are divided into three different categories: (1) lumped models, (2) distributed models, and (3) semi-distributed models (Singh 1995).

In lumped models, the whole watershed is considered as a single unit (Beven, 2000). Hence, the watershed characteristics and input data are represented by averaging values for the entire catchment. Therefore, these models do not account for the spatial variations of the processes or the boundary conditions. HEC-1 (Hydrologic Engineering Center, 1981) and Hydrologic Model-HYMO (Williams and Hann, 1972) are examples of lumped models. According to Putz et al. (2003), the act of averaging parameters and input data may lead to false representation of the hydrological processes.

Contrary to the lumped models, distributed models take explicit account of spatial variations in the processes representation, input data, and boundary conditions. Examples of distributed models include SHE model (Systeme Hydrologique Europeen) (Abbott et al. 1986) and IHDM model (Institute of Hydrology Distributed Model) (Calver and Wood. 1995). In distributed models, watersheds are represented as a spatial grid or a pattern of elements (Chanasky and Verschuren 1983a). Hence, in this type of model, it is required to input variables and physical characteristics to each grid point, which account for the spatial variation in the watershed representation. However, in many cases, detailed data on watershed characteristics and input parameters are not available. Therefore, it is required to interpolate or average some of the parameters to assign values to each of the grid elements. This deficiency of distributed models has given rise to semi-distributed models, which are a gradation between lumped and distributed models.

In semi-distributed models, watersheds are represented as a number of sub-catchments. The semi-distributed model can be created either from a lumped model, which can subdivide the watershed into different numbers of sub-catchments, or from a distributed model in which some processes, inputs, and boundary conditions are lumped (Putz et al. 2003). One example of a semi-distributed model is SWAT (Arnold et al. 1998).

According to Singh (1995), considering the spatial scale of the catchment, watershed models can be classified as: (1) small scale models (area $\leq$ 100 km^2); (2) medium scale models (100 km^2 $\leq$ area$\leq$ 1000 km^2); and (3) large scale models (area $\geq$ 1000 km^2). Watershed models are also categorized based upon the simulation period (continuous time series covering multiple events or single event based) and simulation time increment (hourly, daily, monthly, or yearly increments) (Diskin and Simon 1979). Likewise, depending upon the description of the hydrological processes and the methods of solution used, a model can be classified as deterministic, stochastic or a mixed model (Abbott and Refsgarrd 1996). In a deterministic model, the parameters are considered free from random variation while a stochastic model accounts for random variables in its modelling approach. A mixed model is the combination of deterministic and stochastic models.

Abbott and Refsgarrd (1996) further categorized the hydrologic models as empirical, physically-based, and conceptual. An empirical model is a type of model that does not consider the physical processes occurring in a watershed in its modelling approach. However, a physically-based model uses a set of scientific principles and basic mathematical formulation to represent the natural system at an appropriate scale. According to Abbott and Refsgarrd (1996), practically, a physically-based model has to be fully distributed. However, due to the complexity of this type of model, some of the process descriptions of the natural system are simplified and often empirical components are incorporated into it (Putz et al. 2003). A model including these types of simplifications and empirical components is called a conceptual model.

In a conceptual model, important hydrological processes such as evapotranspiration, surface storage, percolation, snowmelt, baseflow, and surface runoff are computed by using simple mathematical equations rather than solving governing partial differential equations. In order to replace the partial differential equations with simple statements, different model calibration parameters are incorporated into the model. Hence, the main advantage of this type of model is that it is much simpler from the mathematical point of view (Beven 2000).

The FORWARD project in Canada has adapted a semi-distributed conceptual hydrologic model- SWAT (Arnold et al. 1998) to predict the impact of forest disturbances on runoff quantity and quality in forest dominant watersheds located on the western Boreal Plain. Before selecting SWAT as a modelling tool for the FORWARD project, Putz et al. (2003) reviewed four different hydrologic models: (1) TOPMODEL (Beven et al. 1997); (2) DHSVM (Wigmosta et al. 1994); (3) HSPF (Donigian et al. 1995); and (4) SWAT (Arnold et al. 1998). Eleven key factors were established to investigate the most suitable model in simulating the disturbance and recovery effects in the western Boreal Plain forests of Canada. After a thorough analysis, it was concluded that the SWAT model fulfilled more criteria than other models. Therefore, the FORWARD project adopted the SWAT model as a hydrological modelling tool for further adaption and development to address its objectives.

2.2 Description of SWAT

The Soil and Water Assessment Tool (SWAT) is a watershed scale conceptual model that operates on a daily time step (Arnold et al. 1998). It is a physically based model (Gassman et al. 2007) that can simulate long term water yield and water quality (sediment, nutrients and pesticides) from watersheds with varying soils and land management practices. The SWAT model is applicable for hydrological prediction in both large and small scale watersheds. For example Gassman et al. (2007) has cited 100 published studies in which the SWAT model was applied to simulate water yield and water quality from watersheds less than 1 km^2 to greater than 1000 km^2. Out of those 100 modelling studies, 14 were for watersheds less than 5 km^2 that were calibrated and validated using continuous streamflow data varying from one year to six years duration.

The comprehensive SWAT model is capable of simulating different hydrological components such as climate, hydrology, soil temperature, plant growth, erosion, nutrient transport, pesticide transport, and land management practices (Arnold et al. 1998; Neitsch et al. 2005). The model accounts for spatial details and is a better predictor of long term yields rather than a single flood event (Arnold et al. 1998). In the SWAT model, a watershed can be partitioned into smaller units on the basis of two-levels of discretisation. First, a watershed can be divided into any number of smaller spatial units called sub-watersheds. Thereafter, the sub-watersheds are further subdivided into non-spatial groupings called hydrologic response units (HRUs) on the basis of the identical soil and land use characteristics. Hence, the SWAT model can preserve the spatially distributed parameters of the entire basin (Srinivasan et al. 1998).

The SWAT model is based upon the water balance equation, and takes into account important hydrological processes such as precipitation, evapotranspiration, overland flow, lateral flow, baseflow, and soil water storage as shown in the Figure 2.1. In the SWAT model, the water balance for the soil component of each HRU (assuming a single layer) is represented by the following equation:

$$SW_f = SW_i + \sum_{i=1}^{n}\left(R_{day} - ET_a - Q_{sur} - Q_{\mathrm{l}} - w_p + CR\right) \qquad [2.1]$$

where, SW_f is the final soil water content of the soil layer (mm), SW_i is the initial soil water content of the soil layer on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), ET_a is the amount of evapotranspiration on day i (mm), Q_{sur} is the amount of surface runoff on day i (mm), Q_l is the lateral flow on day i (mm), w_p is the amount of water percolating to the underlying soil layer on day i (mm), and *CR* is the upward movement of water from the shallow aquifer on day i (mm). SWAT has the capability to represent multiple soil layers in the HRU water balance if increased complexity is required.

The contribution to streamflow from each HRU (assuming a single soil layer) can be represented by the subsequent equation:

$$\mathrm{Q} = R_{day} - ET_a - Q_{sur} - Q_{\mathrm{l}} - w_p + CR + Q_{gws} - Q_{gwd} \qquad [2.2]$$

where, Q is the runoff leaving the HRU on day i (mm), Q_{gws} is the base flow from the shallow aquifer on day i (mm), Q_{gwd} is groundwater flow lost to the deep aquifer on day i (mm) and all other parameters have been described previously. The total streamflow from the watershed is the summation of the Q contributions from each HRU.

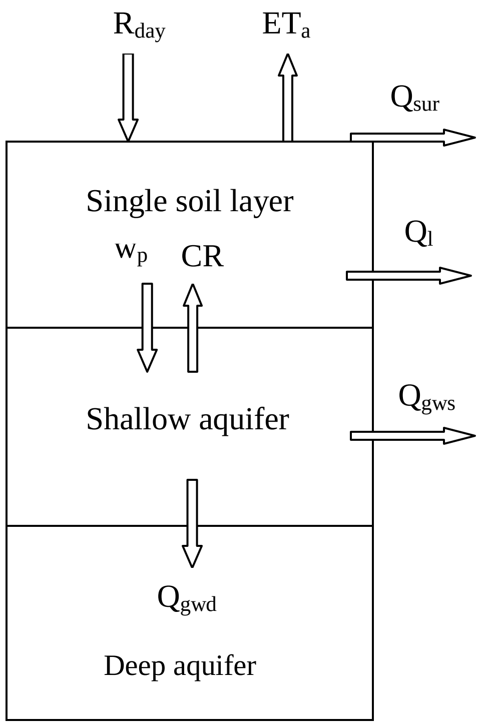


Figure 2.1 Schematic representation of the water balance for a single soil layer HRU represented in SWAT.

2.2.1 Precipitation

Precipitation, either in the form of rainfall or snow, is the main input component of watershed modelling. The reliable output of the model highly depends upon accurate input. Therefore, precipitation is the key input component of watershed modelling. In humid regions, rainfall is the main source of precipitation whereas in cold regions, snow often becomes the main contributor of precipitation, which explicitly defines the surface and subsurface hydrological cycle (Faria et al. 2000).

Precipitation can be categorized either as rain or snow by considering the average daily temperature. In the SWAT model, the critical temperature that is used to catagorize precipitation as snow or rain is defined by the user (Neitch et al. 2008). If the average daily air temperature is less than the critical temperature, then the precipitation is classified as snow. The snowfall is accumulated at the ground surface in the form of snow pack. The amount of water stored in the snow pack is calculated as snow water equivalent. The snow pack will increase with additional snowfall or decrease with snow melt or sublimation.

The snow cover routine incorporated into the SWAT model can account for the non-uniform distribution of snow at the ground surface due to drifting, shading, topography and land cover. The snow melt is calculated in the SWAT model by considering the air and snow pack temperature, a melting factor, and the snow cover. In the SWAT model, the melted snow (snow water equivalent) is added to the precipitation input in the calculation of surface runoff and percolation.

2.2.2 Evapotranspiration

Evapotranspiration is another important factor of watershed modelling. The water balance of arid and semi-arid regions largely depends upon this factor (Jutla, 2006). There are two components in evapotranspiration: evaporation and transpiration. Evaporation is the loss of water from the soil surface and water bodies whereas transpiration is consumptive use of water by plants. Due to evapotranspiration phenomenon, a large amount of water moves back to the atmosphere from land surfaces. Evapotranspiration is further categorized as potential evapotranspiration and actual evapotranspiration.

The SWAT model offers three methods for computing potential evapotranspiration. They are: (1) Penman-Monteith (Monteith 1965), (2) Priestley-Taylor (Priestley and Taylor 1972), and (3) Hargreaves (Hargreaves et al. 1985). In the SWAT model, evaporation from soil and plants are computed separately as stated by Ritchie (1972). Potential soil water evaporation is calculated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU) whereas actual soil water evaporation is estimated by using exponential functions of soil depth and water content (Arnold et al. 1998; Neitsch et al. 2005).

2.2.3 Surface runoff

Overland flow is categorized into two portions: infiltration excess overland flow and saturation excess overland flow (Beven 2000). Generally, when rainfall intensity exceeds the infiltration capacity of the soil, then infiltration excess runoff is generated. Saturation excess runoff mechanism may occur in either of the following situations: (1) on areas of high antecedent soil moisture conditions; (2) where there is a thin soil layer and the storage capacity of soil is limited; and (3) in areas of low permeability and low slope (Beven 2000). Hence, surface runoff depends upon the infiltration capacity and degree of saturation of underlying soil layers. It also depends upon the vegetation cover of the ground as well as in the degree of ground slope.

To compute surface runoff in the SWAT model, either the SCS curve number method (USDA 1972) or the Green and Ampt infiltration equation (Green and Ampt 1911) can be used. Before utilizing either method, the entire catchment basin is divided into a number of sub-basins. Thereafter, the overland flow for each sub-basin is predicted separately and routed through a channel system to calculate the total watershed surface runoff.

2.2.4 Infiltration

Infiltration refers to the entry of surface water into the underlying soil layers. The infiltration process plays an important role to supply water for plant growth and to recharge the ground water aquifers. The rate of infiltration depends upon the physical properties of the soil, vegetation cover on the ground, initial water content of the soil, soil temperature, and the intensity of rainfall or rate of snowmelt.

In the SWAT model, the amount of water infiltrating into the soil profile is calculated indirectly because the surface runoff is computed directly using either of the previously mentioned methods (Neitsch et al. 2005). Hence, the infiltrated water is calculated as a difference between the amount of rainfall and the amount of surface runoff.

2.2.5 Lateral subsurface flow

Lateral subsurface flow, or interflow, originates below the ground surface but above the zone where the soil and bedrock profile is saturated with water. The lateral subsurface flow contributes to the streamflow within the watershed. In the SWAT model, lateral subsurface flow is calculated using redistribution phenomenon. The redistribution process is defined by the continuous movement of water through soil profiles (Neitsch et al. 2005). The redistribution component is computed in SWAT by using a kinematic storage model developed by Sloan and Moore (1984). Since the redistribution phenomenon is affected by soil temperature, the SWAT model does not allow redistribution from the soil layer having temperature 0°C or below.

2.2.6 Return flow

A portion of the input precipitation ultimately recharges the groundwater aquifers after percolating through different soil layers. Return flow, or baseflow, is the water that originates from the groundwater and contributes to the streamflow. In the SWAT model, groundwater is partitioned into two aquifer systems: (1) shallow aquifer, and (2) deep aquifer. According to Arnold et al. (1993), a shallow aquifer is an unconfined aquifer that contributes to the baseflow of the stream within the watershed while a deep aquifer is a confined aquifer that contributes baseflow to the stream outside of the delineated watershed. Hence, water recharging the deep aquifer does not contribute to the streamflow within the delineated watershed.

To calculate the amount of water percolating through each soil layer, a storage routing mechanism combined with a crack-flow routine is used in the SWAT model.

With this estimation, the amount of water contributing to recharge either the shallow or deep aquifer is then determined.

2.3 ArcView Interface

The SWAT model is able to integrate topographic features, land use, soil type, and other digital data into the SWAT 2000 model using the Geographic Information System (GIS) data layers and the ArcView-SWAT (AVSWAT) interface tool developed by Di Luzio et al. (2004a, 2004b). The SWAT model can generate its data input by utilizing and sharing the same framework as ArcView 3.x GIS data layers.

The AVSWAT interface tool was further modified to AVSWAT-X to provide additional data input generation functionality for applications of the SWAT 2005 model (Di Luzio et al., 2005). In addition, there is a recent development in the SWAT interface that is compatible with ArcGIS version 9.1 (ArcSWAT). In this study, ArcView version 3.1 and the AVSWAT_X tool was utilized.

The SWAT model can be calibrated either manually or automatically, depending upon the choice of the users. The automatic calibration method was incorporated into the SWAT model by Van Griensven and Bauwens (2003). There are two objective functions that can be used in the automatic calibration of the SWAT model. The first one is the sum of the squares of the residuals (mean square error method), and the second one is the sum of the squares of the difference of the measured and simulated values after ranking. The automatic calibration method uses the shuffled complex evolution algorithm (SCE-UA) developed by Duan et al. (1992).

2.4 Application of SWAT in Canada

The SWAT model has been adopted by various sectors in Canada for different management scenarios. One of the applications performed with the SWAT model was in the hydrological analysis of riparian wetlands in Canada. Riparian wetlands are considered very important resources in Canada as they help to filter sediments and nutrients, attenuate flood control, and improve water quality. Hence, Singh et al. (2005) used the SWAT model by coupling it with the Riparian Ecological Management Model (REMM), to predict the benefits of wetlands in subbasins in terms of reducing surface runoff and filtering of sediments. They applied the model to the upper Canagagigue Creek Watershed of the Grand River Basin in Southern Ontario and the results obtained from the study were used to guide the design and implementation of effective wetland policy in agricultural watersheds in Ontario. In addition, Liu et al (2007) integrated the SWAT model (watershed-scale) and REMM model (field-scale) using a GIS interface to estimate water quality benefits of riparian buffers in the lower Canagagigue Creek agricultural watershed located in southern Ontario.

Michaud et al. (2007) used the SWAT model for quantifying the change in phosphorous mobility from an agricultural watershed, as a result of alteration in land use and cropping system in the Pike River basin of south-western Quebec. The results obtained from this study were then used as a decision making aid by the stakeholders involved in the sustainable development of the Pike River watershed.

Yang et al. (2008) performed a water quantity and quality assessment related to the conservation and restoration of wetlands in the Broughton’s Creek Watershed located in south-western Manitoba using SWAT. From this study, it was concluded that the SWAT model provided very good simulation performance. Furthermore, Yang et al.

(2010) utilized SWAT to examine the effect of wetland conservation and restoration on streamflow and sediment control in the Broughton’s Creek Watershed. The outcome of this study was helpful to design effective watershed restoration strategies in the Broughton’s Creek Watershed.

Additionally, Ahamad (2010) utilized the SWAT model as a hydrological modelling tool to examine the effect of nitrogen export on the Thomas Brook Watershed in Nova Scotia. The research result in this study revealed that the SWAT model can be used as a decision making tool for agricultural watershed management in Nova Scotia.

The SWAT model was also adopted by the Water and Climate Impacts Research Center, Environment Canada, Victoria for the study of impacts of climate variability in the hydrologic regime and nutrient transport to Lake Winnipeg from agricultural watersheds (Shrestha et al. 2009; Shrestha et al. 2011).

An additional application being developed for the SWAT model is within the forestry sector of Canada. The FORWARD project has been investigating the impacts of fire and harvesting disturbances on streamflow in forested watersheds situated on the Boreal Plain in Central Alberta. The project has been monitoring the streamflow and water quality from forested watersheds on the Boreal Plain since 2001. Later, in 2003, the FORWARD project initiated the Legacy Forest Small Streams (LFSS) study on the Boreal Shield of north-western Ontario. Currently, there are 20 experimental watersheds on the Boreal Plain and 9 experimental watersheds on the Boreal Shield. The main purpose of this project is to gather a comprehensive database of pre- and post-disturbance conditions, for scientific analysis, and to help in the development of streamflow and water quality modelling tools for boreal forest watersheds (Smith et al. 2003). The analytical results obtained from the research are being used by the forest industry in forest management, planning, and operations.

2.5 Development of SWAT$_{BF}$ model within the forestry sector in Canada

In order to better represent the hydrological processes occurring in forested watersheds on the Boreal Plains in Canada, Watson et al. (2008) introduced a modified version of the SWAT 2005 model, which is called the SWAT$_{BF}$ model. The main purpose of this modification was to develop a hydrologic and water quality modelling tool to build upon to investigate the effects of tree harvesting upon streamflow and nutrient export from forested watersheds. The SWAT$_{BF}$ model was first applied to the Willow Creek watershed located on the Boreal Plain in north central Alberta, Canada. The modifications that were implemented in the SWAT$_{BF}$ model are described in the following sections.

2.5.1 Solar radiation

The amount of incoming solar radiation can be heavily influenced by latitude and the orientation (slope and aspect) of the hill slopes (Watson et al. 2008). Considering the importance of topography on the incoming solar radiation, Watson et al. (2008) incorporated an algorithm into the SWAT$_{BF}$ model to account for the effects of slope and aspect on the amount of solar radiation reaching the ground surface. For this purpose, an algorithm developed by Swift (1976) was used.

The algorithm helps to predict the daily total potential solar radiation on any sloping surface at any latitude. Using this algorithm, the actual solar radiation on a sloping surface can be computed utilizing the measured solar radiation from a nearby horizontal surface. The correction factors that are applied on the measured solar radiation are computed from the potential solar radiation. The model also makes some adjustments to the estimated actual solar radiation for map area[*] because the map area for mountain slopes is less than surface area.

The data inputs that are required to compute the actual solar radiation are the Julian day, latitude, inclination and aspect of the hill slopes. The Julian day is automatically updated by $\mathrm{SWAT_{BF}}$ and a separate algorithm was not included in the model to perform this task. The SWAT ArcView GIS interface determines the latitude and inclination of slope.

According to Watson et al. (2008), the main advantage of using the algorithm of Swift (1976) in $\mathrm{SWAT_{BF}}$ model is that the method is relatively simple. It was reported that this method does not depend on parameters that are site-specific and that require calibration using local data.

2.5.2 Litter layer

The litter layer found on the forest floor can store a significant volume of water as it acts as an energy absorbing macro-porous material (Wattenbach et al. 2005). Moreover, Peltoniemi et al. (2007) found that the litter layer that exists in the boreal forest is thick and has the potential to store a substantial amount of water. However, the SWAT model does not account for the litter layer. Considering the important role of the litter layer in the overall water balance of forest dominant watersheds on the Boreal Plain, Watson et al. (2008) incorporated a litter layer model in $\mathrm{SWAT_{BF}}$ to act as a simple storage compartment that functions in an identical manner to the canopy storage compartment.

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[*] Map area = the horizontal projection of a sloping surface

This approach was initially used by Wattenbach et al. (2005) in the Soil and Water Integrated Model (SWIM) (Krysanova et al. 1998).

It is found that the precipitation falling from the canopy is trapped by the litter layer and is stored in it. The water stored in the litter layer is available to move back to the atmosphere by evaporation. Therefore, to represent the hydrological processes occurring in the litter layer, Watson et al. (2008) implemented four different conditions in the SWAT$_{BF}$ model. These conditions are as follows:

- If the amount of precipitation falling from the canopy is less than the available storage capacity of the litter layer then

  $$\mathrm{R_{L(F)}} = \mathrm{R_{L(i)}} + \mathrm{R_C} \text{ and } \mathrm{R_S} = 0 \text{ if } \mathrm{R_C} \le \mathrm{L_{max}} - \mathrm{R_{L(i)}} \qquad [2.3]$$

  where, $R_{L(F)}$ is the final amount of water held in the litter layer (mm), $R_{L(i)}$ is the initial amount of water held in the litter layer (mm), R_C is the amount of precipitation after canopy interception has been removed (mm), R_S is the amount of water that reaches the soil surface (mm), and L_{max} is the maximum quantity of water that can be held in the litter layer (mm).

- If the amount of precipitation falling from the canopy is greater than the storage capacity of the litter layer then

  $$\mathrm{R_{L(F)}} = \mathrm{L_{max}} \text{ and } \mathrm{R_S} = \mathrm{R_C} - \left(\mathrm{L_{max}} - \mathrm{R_{L(i)}}\right) \text{ if } \mathrm{R_C} > \mathrm{L_{max}} - \mathrm{R_{L(i)}} \qquad [2.4]$$

  where all the variables have been defined previously.

- If the potential evaporation is less than the amount of water stored in the litter layer then

  $$e_a = e_L = e_o \qquad [2.5]$$

  $$R_{L(F)} = R_{L(i)} - e_L \qquad [2.6]$$

where e_a is the actual evaporation (mm), e_L is the evaporation from the litter layer (mm), e_o is the potential evaporation (mm) and all other variables are according to the previously defined symbols.

- If the potential evaporation is greater than the amount of water held in the litter layer then

$$e_L = R_{L(i)} \qquad [2.7]$$

$$R_{L(F)} = 0 \qquad [2.8]$$

where all the variables have been defined previously.

The main advantage of this litter layer model as stated by Wattenbach et al. (2005) is that only one parameter needs to be assigned. This parameter is the maximum storage capacity of the litter layer.

2.5.3 Anisotropy

The SWAT model considers the soil layers as isotropic soils, where the saturated hydraulic conductivity of each soil layer is same in the horizontal and vertical directions. However, Dun et al. (2009) reported that in forested watersheds, the horizontal saturated hydraulic conductivity is greater than the vertical hydraulic conductivity. This shows that the forested soils follow anisotropic behaviour. Furthermore, after carrying out experiments on the soils in two locations of the Boreal Plain in Alberta, Whitson et al. (2003) reported that the horizontal saturated conductivity of the Ae soil horizon exceeds the vertical saturated hydraulic conductivity by ratios between 1.75 and 12.8. Given that the soils found on the Boreal Plain follow anisotropic behaviour, Watson et al. (2008)

incorporated an anisotropic factor (aniso) into the SWAT_{BF} model. The anisotropy factor was previously used by Eckhardt et al. (2002) in SWAT-G.

The SWAT_{BF} model uses the kinematic storage model to calculate lateral flow, in which the aniso factor was incorporated. This kinematic storage model is represented by the following equation.

$$Q_l = 0.024\left(\frac{2SW_d \times K_{sat} \times \text{aniso} \times S}{\phi_d \times L_h}\right) \qquad [2.9]$$

where Q_l is the lateral flow (mm), SW_d is the drainable volume of water in the soil layer (mm), K_{sat} is the saturated hydraulic conductivity (mm/h), aniso is the anisotropic factor, S is the slope (mm/mm), ϕ_d is the drainable porosity of the soil layer (mm/mm), L_h is length of the hill slope (m), and 0.024 is a conversion factor.

The aniso parameter was also incorporated in the equation used to calculate the lateral flow time as shown below:

$$T_{lag} = 10.4\left(\frac{L_h}{K_{sat,max} \times \text{aniso}}\right) \qquad [2.10]$$

where T_{lag} is the lateral flow time (days), $K_{sat,max}$ is the maximum saturated hydraulic conductivity of the soil layer in the soil profile (mm/h), 10.4 is a conversion factor and all other variables have been defined previously.

The value of the aniso factor can be obtained either from field measurements or through calibration.

2.5.4 Percolation

The percolation component used by the SWAT model was slightly modified by Watson et al. (2008) in the SWAT_{BF} model. For this purpose, they used the equations that were previously utilized by the Soil Water Balance Capacity Model (SWBCM) (Evans et al. 1999) and the Catchment Resources and Soil Hydrology (CRASH) model (Marechal and Holman 2005). Additionally, an approach followed in the Soil Moisture Routing (SMR) model (Frankenberger et al. 1999) was also included into the SWAT_{BF} model, which helps to limit the rate of water outflow from the soil profile. The equations that are implemented in the SWAT_{BF} model are the following:

- To limit the rate of percolation based on the saturated hydraulic conductivity

  $$w_{p,l} = min\left(24K_{sat,l},\ 24K_{sat,l+1},\ w^{*}{}_{p,l}\right) \qquad [2.11]$$

  where $w_{p,l}$ is the amount of water percolating to the underlying soil layer (mm), $K_{sat,l}$ is the vertical saturated hydraulic conductivity of the soil layer (mm/h), $K_{sat,l+1}$ is the vertical saturated hydraulic conductivity of the underlying soil layer, $w*_{p,l}$ is the amount of percolation calculated using the storage routing technique (mm), and 24 is a factor to convert hourly percolation to daily percolation.

- To limit the rate of percolation from the bottom soil layer into the underlying bedrock

  $$w_{p,l=n} = min\left(24K_{sat,l=n},\ 24K_{sat,bd},\ w^{*}{}_{p,l=n}\right) \qquad [2.12]$$

  where $w_{p,l=n}$ is the amount of water percolating out of the lowest layer ,n, in the soil profile (mm), $K_{sat,l=n}$ is the vertical saturated hydraulic conductivity of the lowest layer ,n, in the soil profile (mm/h), $K_{sat,bd}$ is the vertical saturated hydraulic conductivity of the bedrock underlying the soil profile, and $w^*_{p,l=n}$ is the amount of percolation from the lowest layer, n, in the soil profile calculated using the storage routing technique (mm).

The value of $K_{sat,bd}$ can be obtained either from field measurements or through calibration.

2.5.5 Groundwater

Watson et al. (2008) reported that the SWAT model contributes a significant amount of baseflow to the stream during winter. They figured out that this case is not true for small watersheds that experience long periods of subzero temperature. According to the field observations carried out on the Willow Creek watershed in Alberta, it was found that only small quantities of baseflow seep out of the ground during the winter period however the water freezes in the channel shortly afterwards. As a result, the water frozen in the channel gradually assembles over time. However, Watson et al. (2008) outlined that the SWAT model does not consider the simulation of the assembled ice in the channel. Therefore, to overcome this limitation, they incorporated a simple modification into the $SWAT_{BF}$ model. They added the baseflow seeping out of the aquifer to the snow pack in the case of average air temperature being less than 0°C. This modification caused the baseflow that seeps out of the shallow aquifer in winter to be stored in the snow pack until spring, when all ice in the channel starts melting.

2.5.6 Wetlands

The SWAT model has a wetland submodel. However, Watson et al. (2008) reported that this wetland submodel has many limitations: (1) wetlands are not treated as HRUs, (2) hydrological processes such as surface runoff, percolation, lateral flow, baseflow, and vegetation growth are not simulated, and (3) wetlands are treated as open-water bodies. To overcome these limitations, Watson et al. (2008) incorporated a bucket model approach into the $SWAT_{BF}$ model. They found this approach to be useful in simulating bog and fen wetlands, which are the dominant types of wetlands on the Boreal Plains (Prepas et al. 2003). The bucket model approach was earlier used by Hormann et al. (2007) to simulate wetland processes in a watershed in Germany.

The wetland submodel implemented in $SWAT_{BF}$ considers two layers in the soil profiles. They are the upper organic layer and lower organic layer. The equations that are incorporated into $SWAT_{BF}$ in the wetland model are given below:

- The overall water balance for the wetlands per unit area is simulated as

  $$SW_f = SW_i + R_s - ET_a - Q_{sur} - Q_l - w_p + CR \qquad [2.13]$$

  where ,SW_f is the final soil water content (mm), SW_i is the initial soil water content (mm), R_s is the amount of water that reaches the soil surface (mm), ET_a is the amount of evapotranspiration (mm), Q_{sur} is the amount of surface runoff (mm), Q_l is the lateral flow (mm), w_p is the amount of water percolating to the underlying soil layer (mm), and CR is the upward movement of water from the shallow aquifer (mm).

- Surface runoff that is generated per unit area in wetlands are represented as

$$Q_{sur} = SW_{l=1} - Sat_{l=1} \quad if\ SW_{l=1} > Sat_{l=1} \qquad [2.14]$$

$$Q_{sur} = 0 \qquad if \quad SW_{l=1} < Sat_{l=1} \qquad [2.15]$$

where $SW_{l=1}$ is the drainable volume of water in the top layer (mm), $Sat_{l=1}$ is the amount of water in the top soil layer at saturation (mm) and all other parameters have been defined earlier.

- To calculate the lateral flow from the upper and the lower layers of the wetlands, a nonlinear function developed by Farmer et al. (2003) was used. It is given by the subsequent equation:

$$Q_l = \alpha_l (SW_l)^{\beta_l} \qquad [2.16]$$

where α_l and β_l are the recession constants for lateral flow and all other parameters have been defined previously.

The other hydrological processes that are included in the wetland submodel within $SWAT_{BF}$ include the following: evapotranspiration, canopy and litter interception, and baseflow. However, the wetland submodel does not simulate the interaction between surface water and groundwater.

Wetlands in the $SWAT_{BF}$ model are categorized as upland and lowland wetlands. The wetlands that are found in the upper reaches of the sub watersheds are considered as upland wetlands whereas the ones that are located next to the stream channels are called lowland wetlands. These wetlands categories are defined as HRUs in the $SWAT_{BF}$ model. Therefore, they are formed during the HRU delineation process using the SWAT ArcView GIS interface. However, the parameters required by the wetland model have to be input manually by the users in the ArcView GIS interface. Additionally, though it is possible to define multiple upland wetlands within the model, only one lowland wetland may be designated for any given sub watershed.

2.5.7 Hydrological Connectivity between HRUs

It was found that the earlier version of SWAT had no spatial relationship between HRUs. However, Watson et al. (2008) reported that there should be some level of hydrological connectivity between the HRUs. They determined that certain HRUs have greater hydrologic importance than others regarding their position in the landscape. For example, lowland wetlands were found to be a very important hydrologic component as they help to absorb the peak flows during the flooding period and release the water to the stream during dry spells. Given that finding, Watson et al. (2008) created a hydrological connectivity between upland HRUs and lowland wetlands in the $SWAT_{BF}$ model. They allowed a portion of lateral flow and baseflow from upland HRUs to be diverted through the lowland wetland. For this purpose, a wetland factor named “wtlfr” was used in the model. They added the lateral flow from the upland HRUs to the soil profile of the lowland wetlands. The baseflow from the upland HRUs was added to recharge the shallow aquifer of lowland wetlands.

2.5.8 Simplified snowmelt routine

Watson et al. (2008) used the snow accumulation and snowmelt routine from the original SWAT model while simulating the hydrological phenomenon occurring in the Willow Creek watershed located on the Boreal Plain in north central Alberta. However, Watson and Putz (2012) incorporated a further modification to $SWAT_{BF}$ by substituting a simplified snow accumulation and melt routine based upon the LIARDFLOW model developed by Vander Linden and Woo (2003).

In the original SWAT model, 5 input parameters are required to simulate snow accumulation and melt; however, the simplified routine utilized by Watson and Putz (2012) requires only 2 input parameters to simulate the snow accumulation and melt component. These parameters are: (1) melt factor for snow (SMFCN), and (2) threshold temperature for snowfall and snowmelt (SFMTMP).

2.6 Global Application of SWAT in forested watersheds

The SWAT model was primarily developed for agricultural watersheds. Hence, relatively few studies have been conducted in different countries regarding the utilization of the SWAT model in forested watersheds. To apply SWAT in a forested region, Watson et al. (2005) incorporated the forest growth model 3-PG into SWAT and applied it to pine and eucalyptus forest plantations located in southern Australia. Watson et al. (2005) found that the modified SWAT/3-PG tool could better simulate the leaf area index (LAI) of forest plantations and could be used as a decision making tool in the management of the catchments where forests occupy a large proportion of the land use.

In the United States, Ahl et al. (2008) used the SWAT model to simulate the streamflow of Tenderfoot Creek, which was fed by snow-dominated, forested, mountainous watersheds situated in central Montana. The research demonstrated that the SWAT model performed well in the aforementioned forested region; however, they recommended some of the parameters be refined to better represent hydrological processes in the snow-dominated watersheds. Similarly, Kirby and Durrans (2007) studied the combined effects of forests and agriculture on water availability in the heterogeneous watersheds of the south-eastern USA, using the PnET-II3SL/SWAT model.

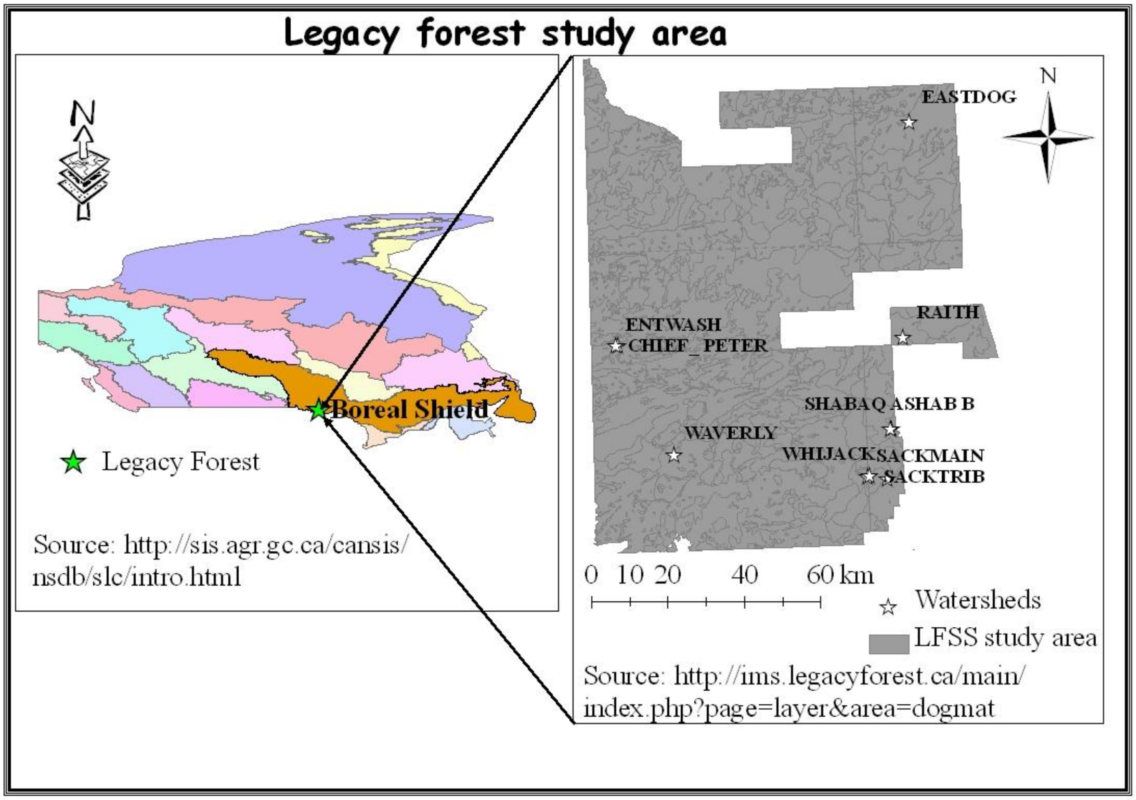
In order to investigate the environmental and economic impacts to society as consequences of deforestation, reforestation, live barriers, and agro forestry on two Andean watersheds (Moyobamba, Peru, and Pimampiro, Ecuador), the SWAT model was used in combination with a socioeconomic optimization model (ECOSAUT). From this study, Quintero et al. (2009) found that the efficiency of SWAT simulations in the Andes depend mostly on the watershed area. In the watersheds having area greater than 10,000 ha and which have a large number of meteorological stations, the SWAT model showed good results in predicting the changes in the hydrological regime of the deforested watersheds. However, it was found that the SWAT calibration was a challenging task in the case of the watersheds having smaller area, few meteorological stations, and other complex conditions like large slopes, heavy rainfall intensities, and short dry season.

CHAPTER 3
DESCRIPTION OF THE STUDY AREA AND FIELD DATA

3.1 Introduction

The FORWARD project is currently monitoring nine watersheds within the Legacy Forest Small Streams (LFSS) study area (Figure 3.1) on the Boreal Shield of north-western Ontario, Canada. Out of these nine watersheds, initially, the Chief Peter watershed was chosen to commence this modelling investigation. Thereafter, Entwash watershed was selected to perform further investigation. The main reason the Chief Peter and Entwash watersheds were selected amongst the nine available was that a local FORWARD weather station had been established in close proximity and the two had the longest period of local meteorological monitoring data available within the LFSS. Moreover, the Chief Peter and Entwash watersheds are located adjacent to each other and have similar soil type and land use.

The LFSS study area lies within the 14,000 km^2 experimental Legacy Forest. The LFSS was inaugurated in 2002 by Lakehead University, the Ontario and Federal Governments, and industries working in north-western Ontario (Legacy Forest 2007). It incorporates the Quetico Provincial Park (a wilderness preserve) and the Dog River-Matawin Forest (DRMF) Management Area, which is being managed by the Ontario Ministry of Natural Resources (OMNR). The area covered by DRMF is 9,450 km^2 and its rolling terrain is typical of the Boreal Shield ecozone (OMNR 2005). The boundary of the LFSS study area is located within a 75 km radius inside the DRMF. The topography of the DRMF is defined as a landscape having low to moderate relief; including thin layers of Podzol/Spodosol soils over discontinuous till and that incorporates a substantial amount of inorganic sediment (aeolian deposits) with numerous projections of igneous bedrock and myriad lakes and streams (Canadian Forest Service 2010; OMNR 2005; Singer et al. 2002). According to the Ontario Ministry of Northern Development and Mines (2003), the bedrock geology of the DRMF is Precambrian Shield of the Quetico, Wabigoon and Wawa subprovinces.


Legacy forest study area

Source: http://sis.agr.gc.ca/cansis/nsdb/slc/intro.html

Source: http://ims.legacyforest.ca/main/index.php?page=layer&area=dogmat

Figure 3.1 Legacy Forest Small Streams (LFSS) study area.

According to the Koppen-Geiger climate classification system, the climate of the Boreal Shield ecozone is categorised as Dfb[*] having long cold winters and short warm summers. However, the Laurentian Great Lakes have a moderating effect on the climate of bordering regions, warming them in winter and cooling them in summer (Canadian Forest Service 2010). Data acquired from published climate normals (1971 to 2000) from a weather station at Atikokan (AUT) (Environment Canada 2010b), which is approximately 58 km away from the Chief Peter watershed, indicate that the mean monthly temperature of the region in January is -18.1 °C while in July it is 17.7 °C. Likewise, the mean annual precipitation for the region over the past 30 years has been documented as 740 mm (Environment Canada 2010b). Out of this mean annual precipitation, 172 mm of the precipitation is recorded as annual snow water equivalents. Moreover, the mean April rain (from 1971- 2000) has been documented as 27.1 mm.

Additionally, the annual runoff (from 2005 - 2008) obtained from the DRMF hydrometric station located at Whitefish River, Nolalu (FORWARD database) shows that the mean annual runoff and the spring runoff from the Whitefish River are 334.4 mm and 249.3 mm, respectively. It can be observed that the proportion of spring runoff to the annual runoff is 0.75. Moreover, the runoff proportion (ratio of annual runoff in mm to annual precipitation in mm) is 0.45.

3.2 Chief Peter Watershed

3.2.1 Location

The Chief Peter watershed (Figure 3.2) has been monitored by the FORWARD project since 2004 to obtain water quality and streamflow data. The watershed is located

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[*] See explanation in the List of Abbreviations

approximately 120 km northwest west (NWW) of Thunder Bay, Ontario. Chief Peter watershed has a surface drainage area of 1.81 km^2 with forest being the dominant vegetation type.

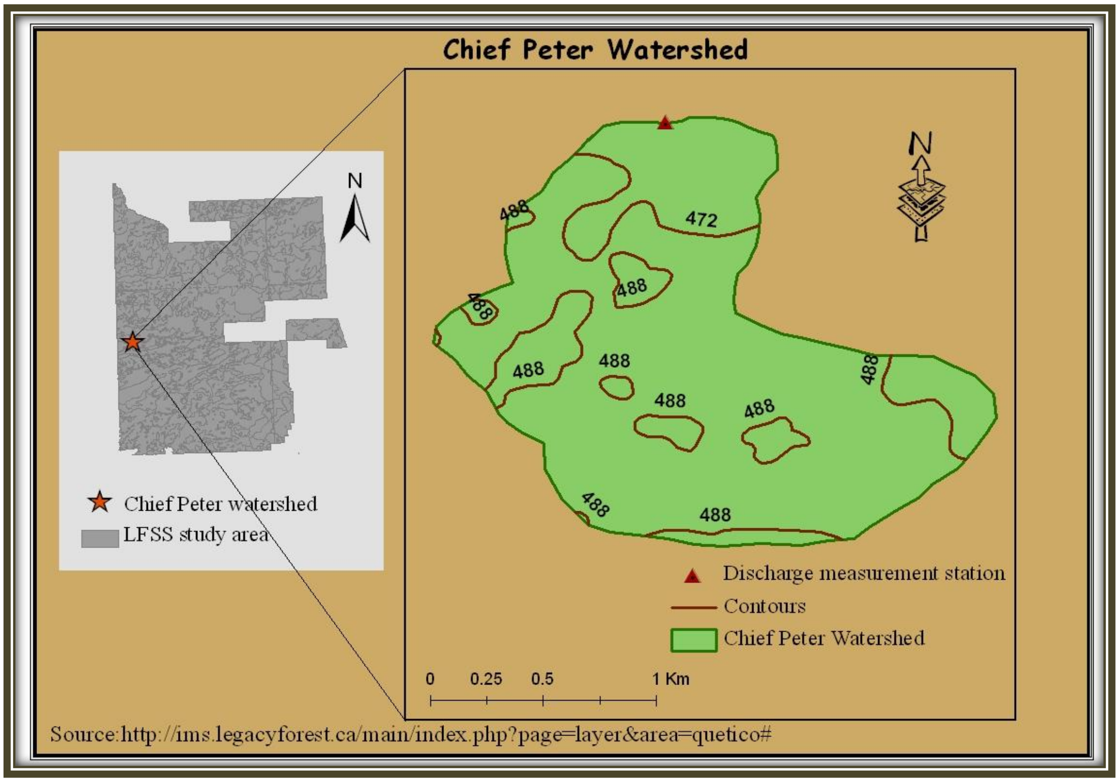


Figure 3.2 Chief Peter Watershed.

3.2.2 Climate and Hydrology

The streamflow monitoring site of the Chief Peter watershed is located at 48° 46’ 49.65” latitude north and 90° 51’ 58.05” longitude west (Figure 3.3). The streamflow data obtained from the FORWARD Project database for the Chief Peter watershed reveals that measurements were available during the open water period from May to October for four years, 2006-2009 (Table 5.1). However, for 2009 it was reported that there was an error in the observed data from July to September due to leakage in the Chief Peter watershed weir. Therefore, the measured streamflow data from May through

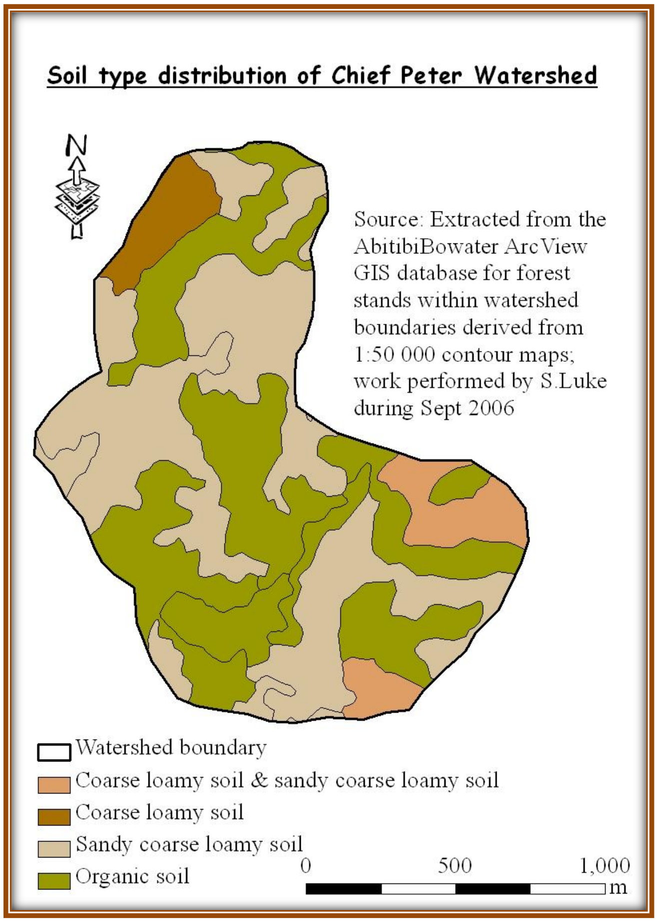
October for 2006 to 2008 shows that the average runoff for the observation period from the Chief Peter watershed is 193.2 mm. The channel length of the watershed is 1.4 km with 1.6% average channel slope. There are wetlands and open areas within the watershed. According to the FORWARD project database, the wetlands only cover approximately 1% of the total watershed area.

Figure 3.3 Flow monitoring site at the Chief Peter Watershed

3.2.3 Topography and soil

The topography of the Chief Peter watershed can be characterized as gently sloping as it has approximately 30 meters only of elevation difference from head to toe of the watershed (460 m at the gauging station and 490 m at the highest point of the watershed). The uppermost part of the watershed is almost flat with a gentle slope in the mid-region.

The soil order of the Chief Peter watershed is Dystric Brunisol (Agriculture and Agri-Food Canada, 2010). The soil texture of the watershed is classified into three different categories: organic soil, sandy-coarse loamy soil, and coarse loamy soil (Figure 3.4). Out of these three soil textures, the watershed is mainly dominated by organic soil and sandy-coarse loamy soil. Each of these soils covers approximately a 0.8 km^2 area of the watershed. In the context of soil thickness, it was found that approximately 0.38 km^2 area of the watershed has a soil depth less than 100 cm.

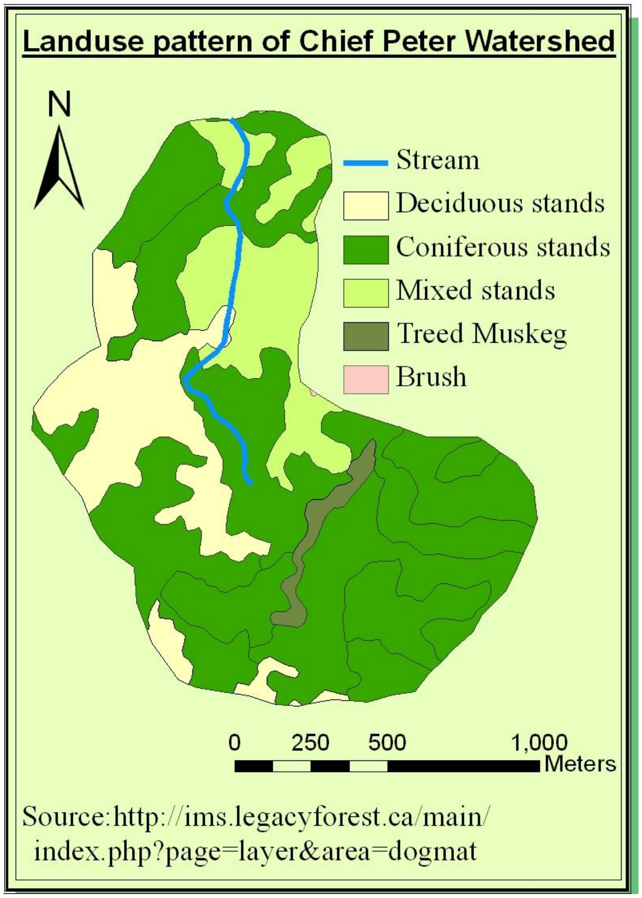


Source: Extracted from the AbitibiBowater ArcView GIS database for forest stands within watershed boundaries derived from 1:50 000 contour maps; work performed by S.Luke during Sept 2006

Figure 3.4 Soil texture of Chief Peter Watershed.

3.2.4 Vegetation

The data obtained from the FORWARD project data repository shows that 98% of the Chief Peter watershed is covered with forest. Out of this forested area, coniferous dominant stands cover 68.1% of the watershed while deciduous dominant stands cover 29.9% of the watershed (Figure 3.5).



Landuse pattern of Chief Peter Watershed

Source:http://ims.legacyforest.ca/main/index.php?page=layer&area=dogmat

Figure 3.5 Land use pattern of Chief Peter Watershed.

Predominant species are black spruce (Picea mariana; 45.6% of the total watershed area), white birch (Betula papyrifera; 19.7%), eastern white cedar (Thuja occidentalis; 12.9%), balsam fir (Abies balsamea, 4.8%) white spruce (Picea glauca; 2.4%), tamarack (Larix laricina; 2.4%). The remaining 2% of the land use includes roads, bedrock outcrops and other vegetation species. According to the FORWARD project data, approximately 7% of the watershed area has been harvested recently.

3.2.5 Instrumentation and field measurements

The meteorological data that are required to run the $\mathrm{SWAT}_{\mathrm{BF}}$ model were obtained from the FORWARD project Brule Creek Meteorological Station (Figure 3.6). The Brule Creek weather station is located approximately 9.5 km SSE (south southeast) from the Chief Peter watershed. It was installed by the FORWARD project in 2006 and operates year round. It is an automated meteorological station that records all the climatic variables such as precipitation, air temperature, relative humidity, solar radiation, and wind speed.

Figure 3.6 Brule Creek Meteorological Station.

There is an additional rain gauge installed at a distance of approximately 200 m downstream of the streamflow monitoring site of the Chief Peter watershed. The precipitation data obtained from this additional rain gauge are used for comparison with the data obtained from the Brule Creek Meteorological Station.

Table 3.1 shows the total annual and the May to October precipitation measured in 2006 to 2009. The mean annual precipitation recorded from 2006 to 2009 at the Brule Creek Meteorological Station (Table 3.1) was 671.5 mm, whereas the average May through October precipitation is 515.3 mm. Comparing the four years of precipitation data available from the Brule Creek station, it can be observed that 2007 was the wettest year and 2009 was the driest year.

Table 3.1 Precipitation data obtained from the Brule Creek Meteorological Station.

Years	**Total annual precipitation (mm)**	**May to October precipitation (mm)**	**No. of events (May to October)**
2006	682.8	443.4	12
2007	764.8	641.1	30
2008	709.9	552.2	23
2009	528.6	424.4	19

To measure the snowfall water equivalent during winter period, the rain gauge is converted to winter operation. For this purpose, a snowfall conversion adaptor is installed in the precipitation gauge. This equipment consists of a catch tube, antifreeze reservoir, and overflow tube (Campbell Scientific 2012). The snow that is captured in the snow tube dissolves into the antifreeze and starts melting. The melted snow increases the level of water and antifreeze solution ultimately causing the mixture to pass through the overflow tube and into the tipping bucket. Thereafter, the mixture is measured by using the tipping bucket mechanism.

The snow that is accumulated at the ground during the winter months produces a snowpack. In many hydrologic studies a snow survey is conducted to measure the water equivalent of the snowpack. To measure the depth of the snowpack at a point on the ground, a snow tube consisting of a coring tube is vertically inserted into the snowpack surface and the depth reading is recorded (Dingman 2002). Thereafter, the tube is further pushed a few centimetres into the soil and twisted to get the snow core into the snow tube. This snow tube containing snowpack core is then taken to the laboratory to measure the water equivalent of the snowpack. However, for this study, measured snowpack data were not available.

For the measurement of the streamflow, a permanent V- notch weir (Figure 3.3) was constructed at the outlet of the Chief Peter Watershed. The stilling pond created upstream of the weir is instrumented with a Global water-level recorder (WLR) that is programmed to record water depth at 10 minute intervals. To cross check the data collected from the automatic water level recorder, there is a staff gauge installed within the stilling pond and its reading is noted during every site visit. Additionally, the streamflow is measured using a current meter instrument during every site visit approximately from late April to mid November. Utilizing a current meter, stream velocity is measured at the 60% depth (measured from the water surface) for each segment along a transect perpendicular to the flow and the water depth for the respective segment is noted (P. Dinsmore, Lakehead University, personal communication 2010). The streamflow discharge is sometimes verified at the weir using the bucket method (i.e. timed volume collection method). A summary of the instrumentation installed or used at the study site and the data obtained are depicted in Table 3.2.

Table 3.2 Summary of the data obtained from field measurements.

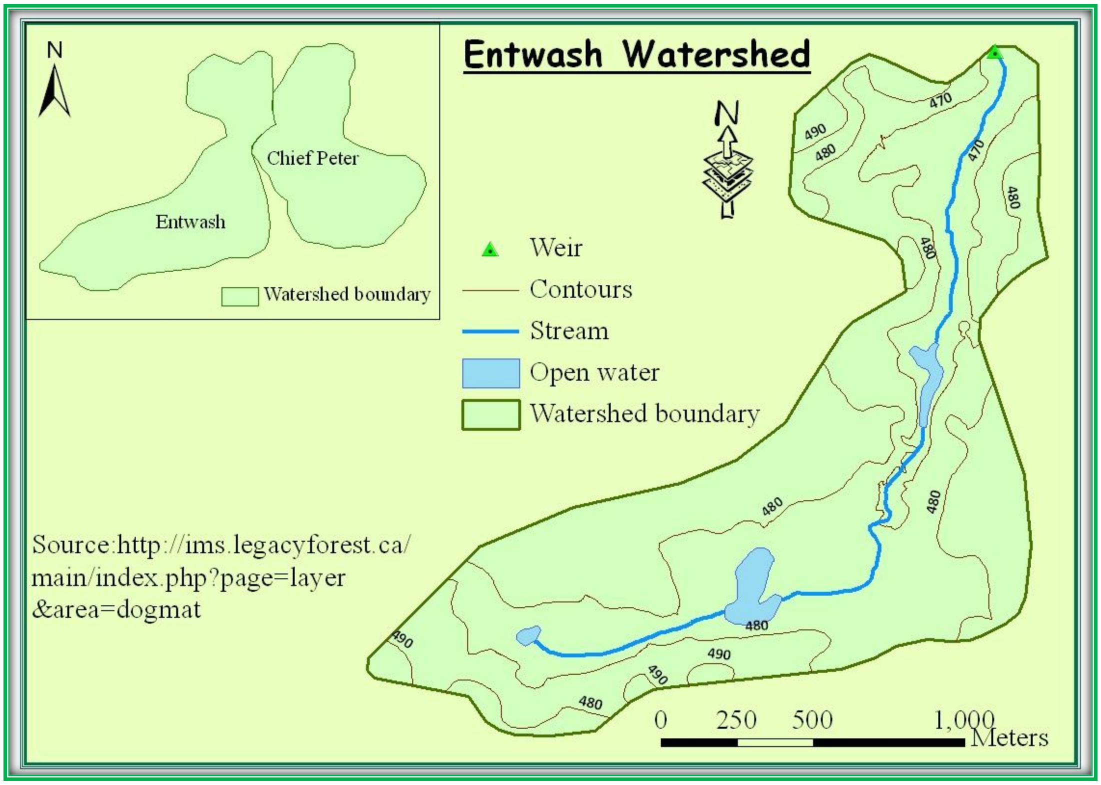
Instrumentation	Location of measurements	Frequency of measurements	Observations recorded
Brule Creek Road Meteorological Station	Nearly 9.5 km SSE of the Chief Peter Watershed	Hourly	Precipitation (mm), Max., Min. and average: Air Temperature (°C), Relative Humidity (%), Solar Radiation (kW/m^2), and Wind Speed (m/s)
Global Water Instruments: W15 and W16 water-level recorders	In the stilling pool behind V-Notch weir at the toe of the watershed	Ten minute intervals	Water level (m)
Staff gauges (Generic)	In the stilling pool behind V-Notch weir at the toe of the watershed	Manually approximately every one week	Water Level (m)
Bucket and stop watch	Measured at the weir outflow	Manually approximately every one week	Discharge (m^3/s)
Gurley 625D Pygmy Current Meter	Measured in the stream channel upstream of the weir	Manually approximately every one week	Velocity (m/s), and Stream depth (m)
Rain gauge (Generic)	Approximately 200 m away from the Chief Peter watershed	Manually approximately every one week	Precipitation (mm)

The data acquired from the current meter reading are used to calculate discharge using the velocity area method. Thereafter, a graph of discharge versus water level reading is plotted. The relationship obtained from this graph is then used to calculate the discharge at ten minutes intervals using the WLR readings.

3.3 Entwash watershed

3.3.1 Location

The Entwash watershed is located adjacent to the Chief Peter watershed. Entwash has been monitored by the FORWARD project since 2006 to obtain water quality and streamflow data. The Entwash watershed (Figure 3.7) has a surface drainage area of 2.15 km^2. The landuse of the watershed is also dominated by forest.



Source:http://ims.legacyforest.ca/main/index.php?page=layer&area=dogmat

Figure 3.7 Entwash watershed.

3.3.2 Climate and Hydrology

The climate of the Entwash watershed is the same as the Chief Peter watershed due to its close proximity. The streamflow monitoring site of the Entwash watershed is approximately one kilometre away from the Chief Peter flow monitoring site. Both of the watersheds drain to a common lake that lies in between them. The flow monitoring site of the Entwash watershed is located at 48°46’50.21” latitude north and 90°52’26.26” longitude west (Figure 3.8).

Similar to the Chief Peter watershed the streamflow monitoring period within the Entwash watershed was intended to be May to October corresponding to open water conditions. Technical difficulties caused delays with set-up of the monitoring station in 2006, 2008 and 2009 reducing the streamflow monitoring period to July to October, June to October, and July to October, respectively. The streamflow data were collected from May to October in 2007.

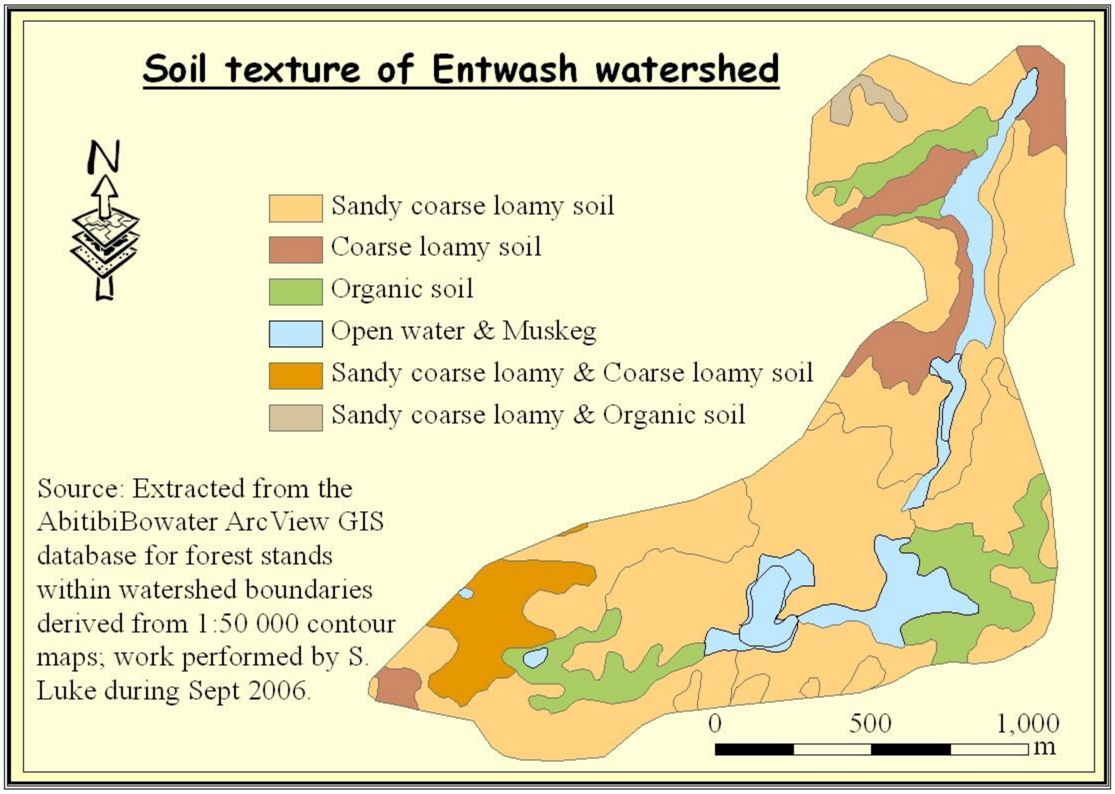
The channel length of the Entwash watershed is 3.3 km with 1.2 % average channel slope. There are open water and wetlands in the Entwash watershed. According to the FORWARD project data, open water is approximately 2.1% of the total watershed area and treeless wetlands constitute approximately 13.5% of the watershed area.

Figure 3.8	Flow monitoring site at the Entwash watershed.

3.3.3 Topography and soil

The Entwash watershed has a terraced topography sloping towards the flow monitoring site; however, the middle portion of the watershed is comparatively flat. The topography of the Entwash watershed can also be characterized as gently sloping as it has approximately 30 meters only of elevation difference from head to outlet of the watershed (460 m at the gauging station and 490 m at the highest point of the watershed).

According to Agriculture and Agri-Food Canada (2010), the soil order of the Entwash watershed is Dystric Brunisol. The soil texture of the watershed is classified into three different categories: organic soil, sandy-coarse loamy soil, and coarse loamy soil. Out of these three soil textures, the watershed is mainly dominated by sandy-coarse loamy soil (Figure 3.9).



Source: Extracted from the AbitibiBowater ArcView GIS database for forest stands within watershed boundaries derived from 1:50 000 contour maps; work performed by S. Luke during Sept 2006.

Figure 3.9 Soil texture of Entwash Watershed.

3.3.4 Vegetation

The data obtained from the FORWARD project data repository shows that the landuse pattern of the Entwash watershed is dominated by forest (Figure 3.10). Contrary to the Chief Peter watershed, the Entwash watershed is dominated by mixed stands of coniferous and deciduous trees. Predominant species of the Entwash watershed are black spruce, white birch, eastern white cedar, balsam fir, white spruce and tamarack which are similar to the Chief Peter watershed. The other land use categories of the Entwash watershed include roads, bedrock outcrops, open water, wetlands and other vegetation species. According to the FORWARD project database, the Entwash watershed has not been harvested for the past 20 years.

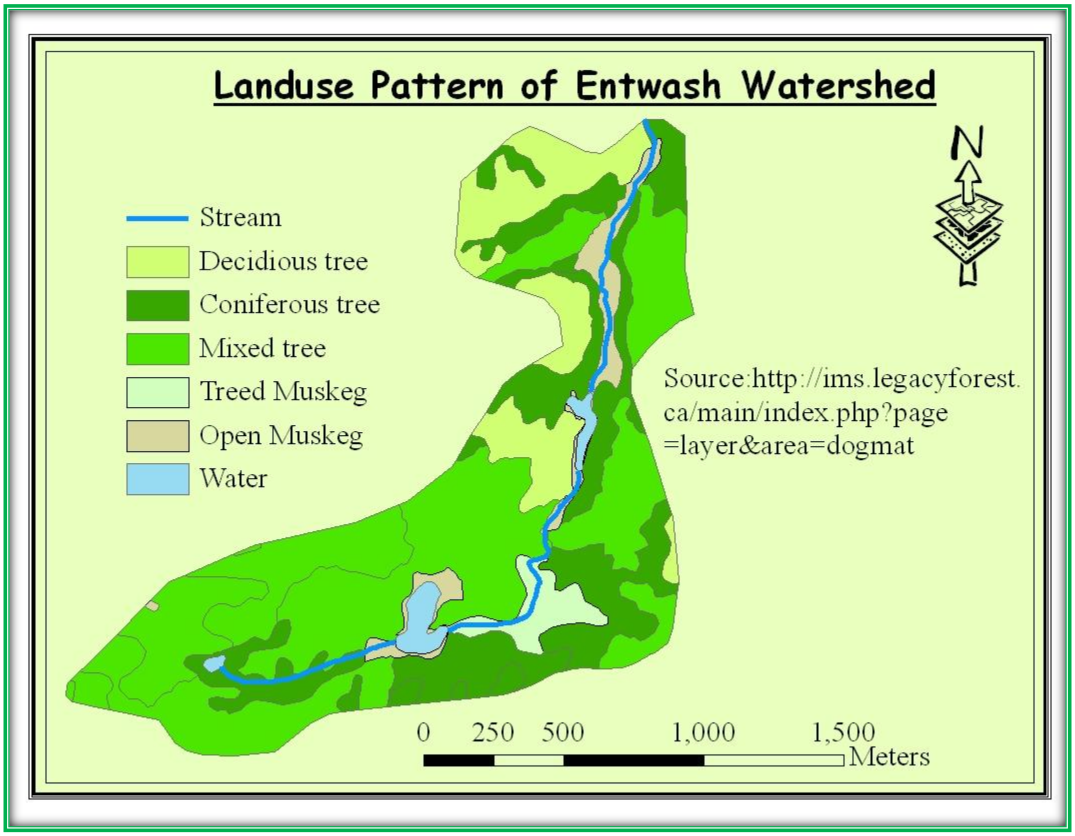


Figure 3.10 Land use pattern of Entwash watershed.

3.3.5 Instrumentation and field measurements

The meteorological data that are required to run the $\mathrm{SWAT_{BF}}$ model were obtained from the FORWARD project Brule Creek Meteorological Station, which is the same meteorological station as mentioned previously. This weather station is approximately 10.6 km SSE (south south east) from the Entwash watershed. The same meteorological data as used in the Chief Peter model were utilized to run the Entwash model. The procedure followed to measure the Entwash streamflow is same as applied in the Chief Peter watershed. Likewise, the instruments installed in the field to collect the streamflow data are also similar to that of the Chief Peter watershed.

CHAPTER 4
MODELLING METHODOLOGY

This chapter describes the overall procedures that have been followed to set up the $SWAT_{BF}$ model. In addition, the chapter gives information about the input data that are required to run the model and the sources from where the data have been obtained.

4.1 Input data and model setup

The entire working procedures that have been followed in this research project have been subdivided into five major sections as described below.

4.1.1 Collection of input and comparison data

The GIS data that are required to run the $SWAT_{BF}$ model are the Digital Elevation Model (DEM), stream network, land use map, and soil map. The meteorological data that are essential to run the model include precipitation, maximum and minimum air temperature, relative humidity, solar radiation, and wind speed. These meteorological data are required on a daily basis. To conduct this research, the climate data were obtained from the FORWARD weather station (Brule Creek Meteorological Station) and the Environment Canada weather stations (Atikokan (AUT) & Atikokan (Marmion) databases). Likewise, the streamflow data that are required to calibrate the model were obtained from the FORWARD streamflow monitoring sites database. Similarly, the different model calibration parameters and the range of values for those parameters have been selected based upon the literature review on hydrological modelling in the Boreal

Plain and the Boreal Shield of Canada, field observations in the FORWARD database, and analysis of GIS data for the Boreal Shield in northwestern Ontario, Canada.

In order to delineate a watershed boundary and to divide the watershed into a number of subwatersheds, a DEM is normally required. The DEM data is also essential to calculate the slope length and the aspect of the slope. In this research, the DEM topography data were acquired from the FORWARD project database repository. The grid resolution of the DEM was 25 m × 25 m.

The land use map of the Legacy Forest study area was acquired from the FORWARD database. The FORWARD project had adopted this map from the AbitibiBowater ArcView GIS database developed for forest stands within the Legacy Forest watershed boundaries. The same map contained soils data. Hence, utilizing these soils data and comparing with the Forest Resource Inventory Description (1996) for DRMF, the soils coverage map required for this project was developed. The GIS stream network was downloaded from the Dog River - Matawin forest website.

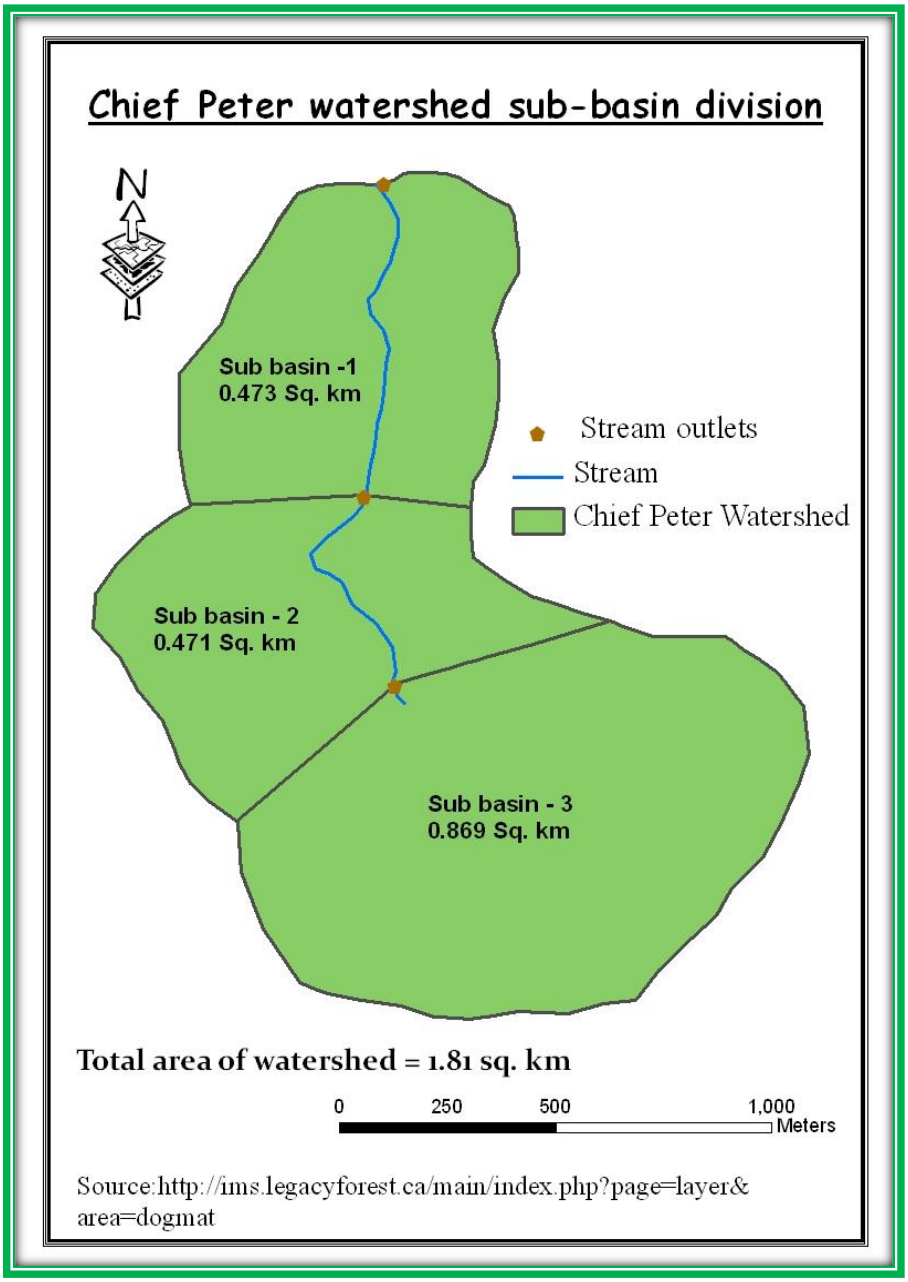
4.1.2 Initial setup of $SWAT_{BF}$ model for the Chief Peter watershed

In this research the Chief Peter watershed was manually delineated without using the DEM. Unfortunately the available DEM could not define the watershed boundary accurately as it produced an unrealistic shape of the watershed with sharp boundaries. There may be several reasons for this issue as discussed in Moore et al (1991): (1) error in mapping elevation (interpolated from coarse grid, no ground truthing for that area), and (2) the watershed is relatively flat and resolution of the available DEM is not sufficient to produce an accurate watershed boundary. Technicians within the FORWARD project had delineated the boundaries of the FORWARD watersheds in

Ontario based on 1:25,000 contour lines. Hence, this manually delineated watershed boundary was used to setup $SWAT_{BF}$ for the Chief Peter watershed.

To begin with, the Chief Peter watershed was subdivided into three subbasins (Figure 4.1) considering the topography as defined by NTS mapping and the heterogeneity associated with the land use pattern of the watershed. It was found that the Chief Peter watershed is mainly dominated by organic soil and sandy coarse loamy soil. However, due to the lack of detailed information about the organic soil, the entire watershed was treated as a single soil unit consisting of a single soil layer of sandy coarse loamy soil. Other researchers using the SWAT model for hydrological predictions have also used a single soil layer and single soil type. For example studies conducted by Sulis et al. (2003); Badas et al. (2003); and Jirayoot and Trung (2005) each considered a single soil type for an entire catchment area greater than 50 km^2 in the absence of detailed soil data. Similarly, Francos et al. (2001) had used a single soil layer of one meter depth for hydrological and water quality modelling in a medium-sized coastal basin due to the absence of detailed soil data.

In general, the DEM, soil map, and land use map are used to delineate HRUs in the SWAT modelling approach. However, due to the aforementioned problems in the available DEM, the HRUs were established manually for each subbasin considering the heterogeneity associated with the land use pattern and single soil type. The watershed has mainly three types of forest dominant land uses: coniferous stands, deciduous stands and mixed stands. Therefore, subbasin- 1 and -2 were segmented into three HRUs each based upon the percentage of area of each dominant landuse. Since subbasin-3 is mainly dominated by coniferous stands, it was treated as one HRU. Consequently, the overall procedure resulted in the creation of 7 HRUs for the Chief Peter Watershed.



Source:http://ims.legacyforest.ca/main/index.php?page=layer&area=dogmat

Figure 4.1 Subbasin discretisation of the Chief Peter Watershed.

The soil order of Chief Peter watershed was found to be Dystric Brunisol (Agriculture and Agri-Food Canada, 2010). The total soil thickness for the Chief Peter watershed was chosen as 500 mm based upon information in the AbitibiBowater ArcView GIS database. Soil properties were estimated based upon the following: (1) Canadian System of Soil Classification (CSSC) for Dystric Brunisol; (2) reconnaissance survey conducted on north-western, Ontario (Hills and Morwick 1944); (3) Canadian soil texture triangle (Juma 2011) for sandy loamy soil; (4) literature review done for Dystric Brunisol on Canadian Boreal Shield (Smith et al. 2011); (5) saturated hydraulic conductivity and bulk density calculation equations provided by Balland et al. (2008) for Canadian soil, and (6) a range of saturated hydraulic conductivity data for eastern Canadian Boreal Shield obtained from a ground water assessment study conducted by Singer and Cheng (2002). The following Table 4.1 shows the estimated soil properties for the single soil layer.

Table 4.1 Estimated soil properties for Chief peter watershed.

Soil properties	**Base value**
Depth (mm)	500
Available water capacity (mm/mm)	0.20
Saturated hydraulic conductivity (mm/h)	2.00
Bulk Density (g/cm^3)	1.50
Organic Carbon (weight %)	0.45
Clay (weight %)	12.50
Silt (weight %)	22.25
Sand (weight %)	65.25

In this research project, the Penman-Monteith method was used to calculate potential evapotranspiration because the data required for computing the potential evapotranspiration by using this formula was available. Additionally, it was found that many SWAT users recommended using Penman-Monteith method to calculate potential evapotranspiration for different hydrological predictions.

According to Bonell (1993), infiltration excess (Hortonian) overland flow rarely occurs in forested catchments. Furthermore, it was mentioned that Hortonian overland flow is restricted to the areas where the natural soils have undergone disturbance (for example soil compaction during logging). Additionally, Beven (2000) stated that infiltration excess (Hortonian) overland flow does not occur in the forested catchments but occurs in locations like the badlands in the southern United States. Furthermore, Gasman et al. (2007) mentioned that there are very few examples of SWAT application in which SWAT users have used the Green and Ampt infiltration option. Given that, the SCS curve number approach was used in this study to calculate surface runoff rather than the Green and Ampt equation.

Moreover, according to Boughton (1989) the SCS curve number method was originally developed for small ungauged watersheds. Additional researchers such as Fennessey et al. (2001), and Tedela (2009) have more recently shown that the SCS curve number method is applicable for estimating runoff from small-scale watersheds. The Soil Conservation Service Engineering Division (1986) provides SCS curve numbers for calculating runoff in forested watersheds. In addition, the studies conducted by Ahl et al. (2008), and Stratton et al. (2009) using the SWAT model are examples of the application of the SCS curve number method in forested watersheds.

The SCS curve number is a function of antecedent soil moisture condition, soil permeability, and land use (Neitsch et al. 2005). The Soil Conservation Service Engineering Division (1986) developed equations to assign curve number values for various land cover and soil types, within three categories of antecedent soil moisture condition[*]. To initiate the modelling process an initial input value of curve number is selected based upon land use, soil type, and antecedent soil moisture condition.

The variable storage routing method of Williams (1969) was utilized to route the streamflow. The model was calibrated using the complex shuffle auto calibration routine and the procedure that was applied to calibrate the model was the sum of the squares of the residuals.

4.1.3 Parameter sensitivity analysis and model calibration for Chief Peter

In order to calibrate and validate the $SWAT_{BF}$ model, the split-sample test procedure described by Klemes (1986) was applied in the Chief Peter Watershed. The model was "warmed up" using five years of daily meteorological data (2001-2005) that was available from the previously mentioned Environment Canada weather station located at Atikokan. The initial soil water content and other initial model input parameters that are required to run the $SWAT_{BF}$ model were set based upon the Boreal Plain's model setup and literature review performed for the Boreal Shield watersheds. The "warm up" period allows the model parameters, such as soil water content and curve number, to adjust to the time series of antecedent meteorological conditions before beginning the calibration procedure.

The streamflow data obtained from the FORWARD project database for the Chief peter watershed reveals that streamflow measurements were recorded from May to October for three years (2006-2008). However, for 2009 it was reported that there was an error in the observed data from July to September due to leakage in the Chief Peter

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[*] SCS curve number method defines three antecedent soil moisture conditions: I – dry (wilting point), II – average moisture, and III – wet (field capacity).

watershed's weir. Therefore, to judge the performance of the $SWAT_{BF}$ model for the Chief Peter watershed, only measured data from May to October for (2006-2008); and measured data from May to June for 2009 were used.

Initially, the Chief Peter watershed was calibrated from 2006-2007 and validated from 2008-2009 using the measured streamflow data. Although, the model conducts a continuous simulation that predicts the streamflow for the entire year in both the calibration and the validation periods, only measured versus predicted streamflow data (for the previously mentioned measurement periods) were used to judge the model performance for the monthly and daily simulations. The monthly streamflow data were computed by integrating the daily flows. The Chief Peter watershed could be calibrated and validated using evapotranspiration and soil water content data if there were evapotranspiration and soil moisture data available.

The literature review performed by Watson and Putz (2008a) reported that there are no consistent recommendations given by researchers for the length of the data period required to calibrate a rainfall-runoff model. For example, Sorooshian et al. (1983) recommended using at least one year of data for calibrating rainfall-runoff models. In contrast, Xu and Vandewiele (1994) mentioned that in order to achieve satisfactory results in calibrating monthly water balance models in humid watersheds, approximately 10 years of data are required. However, Perrin et al. (2007) have shown that a model can produce acceptable results even using less than one year of data for the calibration period. Moreover, it was found that researchers such as Arabi et al. (2006), Bracmort et al. (2006), and Kang et al. (2006) have successfully calibrated and validated a rainfall-runoff model using two years of data each for the calibration and validation periods.

The SWAT_{BF} model was calibrated using 11 different parameters. The parameters that were adjusted during the calibration period are shown in Table 4.1. These parameters were adopted based upon the sensitivity analysis performed for the most significant Boreal Plain calibration parameters and the literature review done on the eastern Canadian Boreal Shield (Watson et al. 2008; Samuel et al. 2011). With the knowledge gained from the literature review regarding the hydrological phenomenon occurring on the shallow - soil forested watersheds on the eastern Canadian Boreal Shield, it was found that the subsurface flow moving laterally through the shallow groundwater layer was the major contributor to the streamflow (Buttle et al. 2001; Buttle et al. 2004; Peter et al. 1995; Renzetti et al. 1992). In order to incorporate this phenomenon in the model calibration, the saturated hydraulic conductivity of the shallow groundwater layer and the anisotropy factors were adjusted.

Table 4.2 Calibrated parameters and their units

Parameter	**Description**	**Units**
ALPHA_BF	Baseflow alpha factor	days
CN_2	SCS runoff curve number	-
SOL_K	Saturated hydraulic conductivity	mm/h
SOL_Z	Soil depth	mm
SOL_AWC	Available water capacity	mm/mm
ANISO	Anisotropy factor	-
SOL_KBED	Saturated hydraulic conductivity of shallow groundwater layer	mm/h
ESCO	Soil evaporation compensation factor	-
SURLAG	Surface runoff lag coefficient	days
SMFCN	Melt factor for snow	mm $°C^{-1}$ d^{-1}
SFMTMP	Threshold temperature for snowfall and snowmelt.	°C

The litter layer routine of the SWAT_{BF} model was initially used in the model set-up for the Chief Peter watershed. However, using this routine the model could not produce a substantial volume of streamflow for the observation period and the Nash Sutcliffe efficiency acquired for the daily validation period was less than 0.30, which is not a satisfactory result according to Van Liew et al. (2005). Thereafter, the Chief Peter watershed was modelled without using the litter layer routine. Without the litter layer representation it was found that there was a substantial increase in the total water yield of the model and the NSE value was approximately 0.45 for the daily validation period.

Furthermore, it was found that the litter layer is very shallow on the eastern Canadian Boreal Shield. The thickness of the litter layer is approximately 2 cm under coniferous stands, and less than 10 cm under deciduous stands (P. Dinsmore, Lakehead University, personal communication 2012). Moreover, it the Chief Peter watershed is mainly dominated by coniferous stands. Also, the wetland factor used in the Boreal Plain watershed was not utilized in this study because the Chief Peter watershed consists of very small coverage area of wetland (approximately 1% of total watershed area). Additionally, Refsgaard et al. (2010) stated that it is better to reduce the number of calibration parameters so that the model can more easily be applied with other data sets. Given that, the litter layer routine and the wetland factor was not utilized in this study.

4.1.3.1 Model evaluation

To evaluate the performance of the model, two approaches were applied: (1) visual methods, and (2) statistical methods. As a means of visual comparison, hydrographs and scatter plots were used. A streamflow hydrograph is a plot of stream discharge versus time. It helps to compare the timing and magnitude of the predicted streamflow to the observed streamflow. Additionally, the peak flows and the shape of the recession curves of the predicted and observed streamflow helps to visualize the goodness-of-fit of the simulated runoff. In this study, monthly and daily streamflow hydrographs were plotted for the calibration and validation periods.

A scatter plot helps to examine the relationship between two variables. In addition, it is easier to view the outlier data with the help of a scatter diagram. In this research, scatter plots of monthly and daily flows showing the observed versus simulated runoff volumes were plotted.

Statistical methods provide a quantitative measure of the goodness-of-fit of the predicted streamflow to the observed streamflow. ASCE (1993) provided a guideline for selection of model evaluation criteria for continuous hydrographs. Following this guideline, Nash-Sutcliffe efficiency (NSE) and deviation of runoff volume (D_v) were used in this research to judge the outcomes of the model. A brief discussion for each of these indicators is presented below.

The Nash-Sutcliffe efficiency (NSE) is given by

$$\mathrm{NSE} = 1 - \frac{\Sigma\left(Q_{obs} - Q_{pred}\right)^2}{\Sigma\left(Q_{obs} - Q_{mean}\right)^2} \qquad [4.1]$$

where, Q_{obs} is the observed streamflow, Q_{pred} is the predicted streamflow, and Q_{mean} is the mean observed streamflow) for the simulated period. Nash and Sutcliffe (1970) mentioned that NSE factor is a normalized statistic that determines the ratio of the variance of the simulated data to the measured data. The range of NSE lies between -∞ to 1, with 1 being the optimal value indicating a perfect fit between the observed and simulated data (Moriasi et al. 2007). In this study, the Nash-Sutcliffe efficiency was computed on a daily and monthly basis.

Van Liew et al. (2005) established criterion for the evaluation of the results obtained from two watersheds in the USA by utilizing the SWAT model. On the basis of this criteria, NSE greater than 0.75 indicates a good performance of the model; values of NSE between 0.75 to 0.36 shows the predicted streamflow is satisfactory; and NSE less than 0.36 reveals a poor performance of the model. However, different researchers such as Moriasi et al. (2007), Saleh et al. (2000), and Santhi et al. (2001) have established alternate performance rating for the acquired value of NSE (Table 4.3).

Table 4.3 Reported performance rating for Nash - Sutcliffe Efficiency (NSE).

NSE Value	**Performance Rating**	**References**
> 0.75	Very good	Van Liew et al. (2005)
0.36 to 0.75	Satisfactory	
> 0.65	Very good	Saleh et al. (2000)
0.54 to 0.65	Adequate	
> 0.50	Satisfactory	Santhi et al. (2001)
$0.75 < NSE \leq 1.00$	Very good	Moriasi et al. (2007)
$0.65 < NSE \leq 0.75$	Good	
$0.50 < NSE \leq 0.65$	Satisfactory	
$NSE \leq 0.50$	Unsatisfactory	

The deviation of runoff volume is given by the following equation:

$$D_v\,(\%) = \frac{\sum\left(V_{pred}\text{-}V_{obs}\right)}{\sum\left(V_{obs}\right)} \times 100 \qquad [4.2]$$

where, V_{obs} is the measured runoff; and V_{pred} is the predicted runoff. According to ASCE (1993), the deviation of runoff volume (D_v) provides a measure of model performance based on continuous hydrographs. The smaller the magnitude of D_v , the better the performance of the model (ASCE, 1993).

Andersen et al. (2001) established criteria to rate model performance for a range of D_v values obtained. Similarly, Van Liew et al. (2003) produced another guideline stating that D_v values obtained within ±20% indicate satisfactory performance of the model. Since many researchers using the SWAT model refer to the Van Liew et al. (2003) paper to judge the model performance using D_v statistics, the same guideline was chosen to evaluate the model performance in this study.

4.1.4 Model validation for Chief Peter watershed

The calibrated model for the Chief Peter watershed was validated by performing a split-sample test as mentioned previously. Goodness-of-fit to the measured streamflow data was determined using the previously mentioned visual and statistical methods. Moreover, goodness-of-fit was assessed relative to success of other model investigations reported in the literature as mentioned previously.

4.1.5 Application to other Boreal Shield watersheds

From this study, it was found that the model fit for the Chief Peter watershed is representative. Therefore, the model was applied to another Boreal Shield watershed monitored by the FORWARD Project. For this purpose, the Entwash watershed was selected.

The applicability of the Chief Peter calibration parameter sets and values to another Boreal Shield watershed was investigated by performing the proxy-basin validation test as recommended by Klemes (1986). Before doing this test, a split-sample test was also carried out on the Entwash watershed. Thereafter, to validate the model following the proxy-basin test procedure, the calibrated parameters of the Chief Peter watershed were applied on the Entwash watershed and vice versa. To evaluate the outcome of the model performance, the same goodness-of- fit- criterion as mentioned previously was employed for the Entwash watershed.

CHAPTER 5
RESULTS, ANALYSIS, AND DISCUSSION

This chapter describes the outcome of the hydrological modelling in Boreal Shield watersheds. It includes an interpretation of the modelling results, and discusses the performance of the $SWAT_{BF}$ model. In this study, the performance of the $SWAT_{BF}$ model was investigated by conducting a split-sample test and a proxy-basin test. The split-sample test includes four different cases and the proxy- basin test includes two cases.

Visual observation and statistical measures were used to evaluate the performance of the model. As shown in Chapter 4, model performance criteria using NSE statistics differ amongst researchers. In this study, NSE vales were calculated and reported to provide an indication of model performance relative to other studies. Judgment of goodness-of-fit of the model was primarily based upon visual comparison of observed and predicted streamflow.

All streamflow modelling in this study was conducted on a continuous basis using a daily time step over multi-year calibration and validation periods. However, the model performance was judged based only upon comparison to measured streamflow data collected during the open water observation period (nominally May to October each year) for all six case studies. The results obtained from each of these tests are described in the following sections.

5.1 Split-sample test

If many years of record are available for a hydrological simulation then the data should be divided into two equal parts to conduct a split sample test (Klemes, 1986). One part should be used for calibration and the other part for validation. Thereafter, the goodness of fit results acquired from both cases should be compared. Klemes (1986) stated that a model can be considered as acceptable when the two cases produce similar results and the errors in both calibration and validation runs are within an acceptable margin.

In this study, the split sample procedure was used although the measured data available for comparison was limited to four open water observation periods occurring over four years. The split sample test was initially applied to the Chief Peter watershed and then applied to the Entwash watershed. The results obtained from both watersheds are categorized into four different cases as listed below.

1. Case I: Chief Peter (Calibration: 2006-2007; Validation: 2008-2009)
2. Case II: Chief Peter (Calibration: 2008-2009; Validation: 2006-2007)
3. Case III: Entwash (Calibration: 2006-2007; Validation: 2008-2009)
4. Case IV: Entwash (Calibration: 2008-2009; Validation: 2006-2007)

5.1.1 Chief Peter watershed (Split - sample test results)

Case I: Chief Peter (Calibration: 2006-2007; Validation: 2008-2009)

The observed and predicted monthly runoff for the calibration and validation periods is shown in Figure 5.1. The computed Nash-Sutcliffe efficiencies based upon monthly runoff for the calibration and validation periods are also presented in Figure 5.1. It is evident that the NSE value based on monthly runoff for the calibration period was greater than 0.75, however for the validation period the acquired value of NSE was slightly less than 0.75. It can be observed that the $\mathrm{SWAT_{BF}}$ model was able to predict the general monthly pattern of runoff for both the calibration and validation periods. The hydrograph of monthly runoffs shows that the model prediction for 2006 in the calibration was very good. However, the model greatly underestimated the June peak flow in 2007 during the calibration period. In addition, it is apparent that the model underestimated the May and overestimated September peak flows that occurred in 2008 for the validation period.

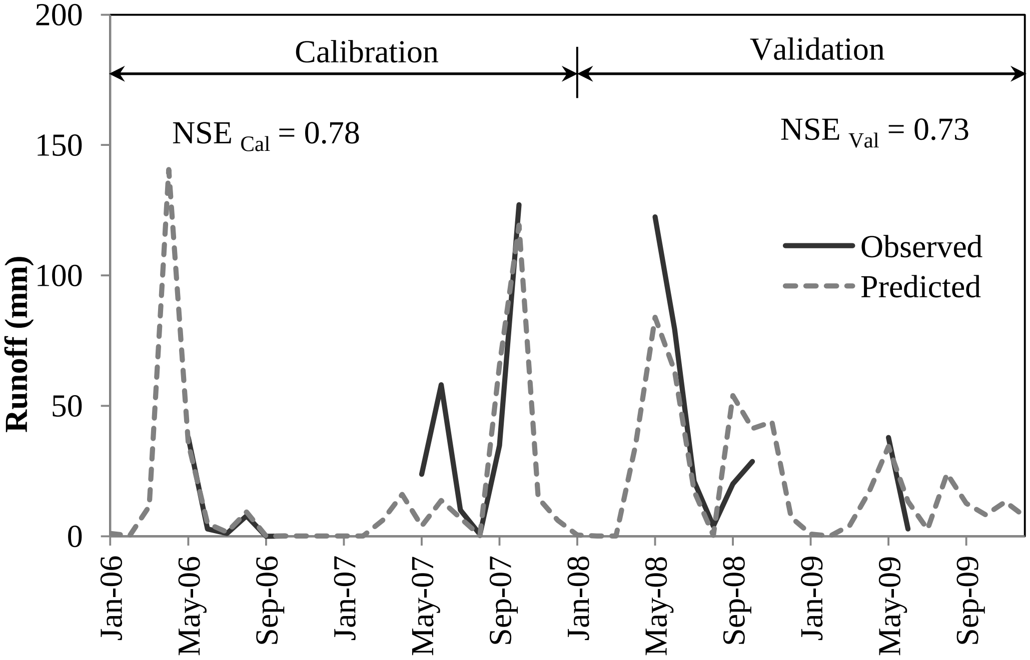


Figure 5.1 Chief Peter watershed observed and predicted monthly runoff for the Case I calibration and validation periods

The observed and predicted daily runoff for the calibration and validation periods is presented in Figure 5.2. Calculated NSE values for the prediction of daily runoff are also presented in Figure 5.2. This figure reveals that the $\mathrm{SWAT_{BF}}$ model generally predicts the observed pattern of daily runoff for both the calibration and validation period. However, the peak flows are generally underestimated. In particular the same problem occurs in representing the peak flows in 2007 and 2008 during the calibration and validation periods as was evident in the monthly runoff predictions. NSE values of 0.67and 0.50 were achieved for the prediction of daily runoff for the calibration and validation periods, respectively. The prediction of daily runoff was poorer in comparison to monthly runoff as indicated by the reduction in the magnitude of NSE values.

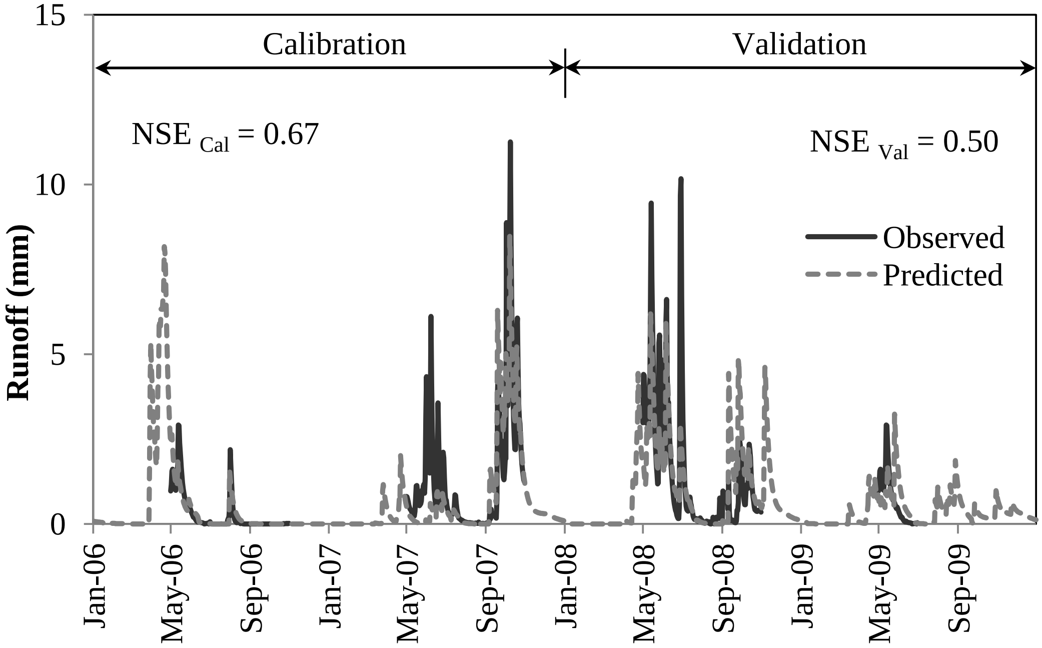


Figure 5.2 Chief Peter watershed observed and predicted daily runoff for the Case I calibration and validation periods.

The scatter diagrams of the observed-predicted data pairs for monthly and daily runoff for both the calibration and validation periods are presented in Figure 5.3 and Figure 5.4, respectively. The acquired coefficients of efficiency (R^2) indicate how well the plot of observed-predicted data pairs fits to the 1:1 line.. Inspection of Figure 5.3 reveals that the $SWAT_{BF}$ model highly underestimated one of the peak monthly flow events during the period of record. This finding supports the previous observation that the June 2007 streamflow could not be represented by the model.

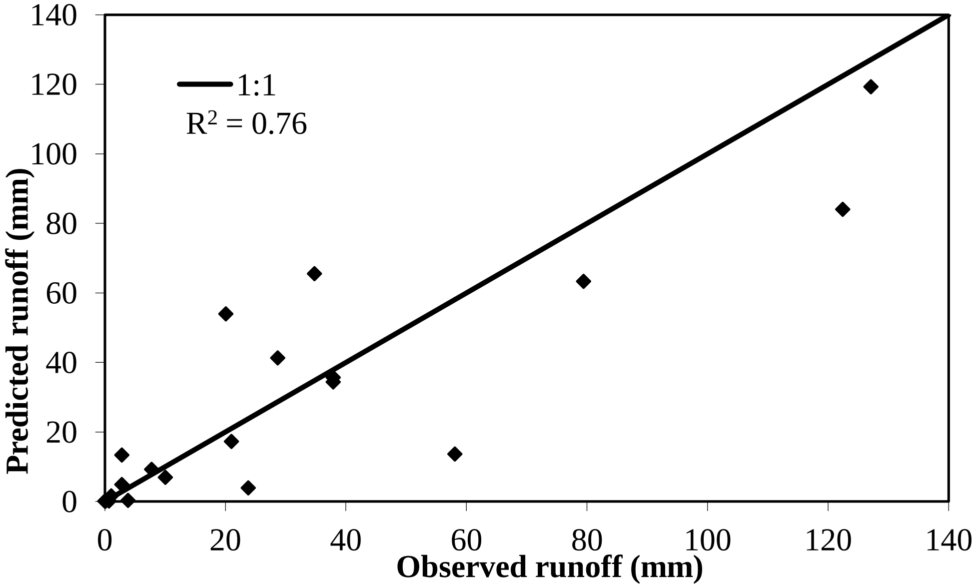


Figure 5.3 Scatter diagram of Chief Peter watershed observed and predicted monthly runoff for the Case I calibration and validation period.

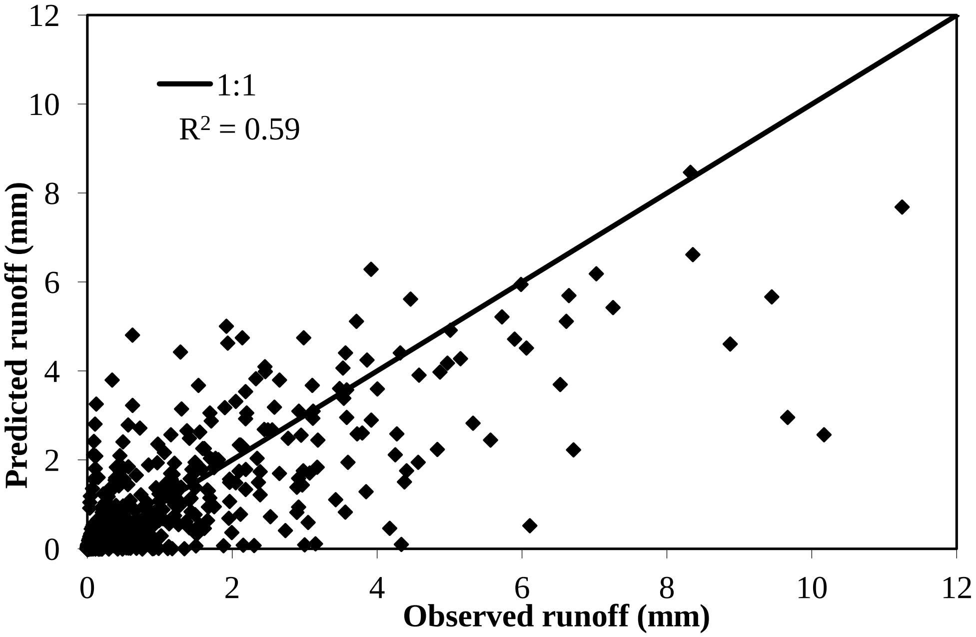


Figure 5.4 Scatter diagram of Chief Peter watershed observed and predicted daily runoff for the Case I calibration and validation period.

The observed and predicted runoff volume for each observation period, and the deviation between these volumes are listed in Table 5.1. It is apparent that the deviations of runoff volumes for individual observation periods vary within a range of ±20%. The accumulated deviation of runoff volume over the four observation periods for 2006 to 2009 was -8.3%. These results indicate that model predictions of runoff volume are much more variable for short term periods (e.g. individual observation periods) compared to longer term predictions (e.g. a multi-year simulation period).

Table 5.1 Chief Peter watershed observed and predicted runoff and deviation of runoff volume for Case I observation periods.

Observation period		**Observed runoff (mm)**	**Predicted runoff (mm)**	**Deviation of runoff volume (D_v) (%)**
Calibration Period	2006 (May - Oct)	49.6	51.5	3.8
	2007 (May - Oct)	254.5	209.4	-17.7
Validation Period	2008 (May - Oct)	275.5	260.1	-5.6
	2009 (May - June)	40.7	47.7	17.2

Note: The deviation of runoff volume (D_v) is calculated for each observation period using Equation 4.2.

The observed and predicted runoff volume for each observation period, and the deviation between these volumes are listed in Table 5.1. It is apparent that the deviations of runoff volumes for individual observation periods vary within a range of ±20%. The accumulated deviation of runoff volume over the four observation periods for 2006 to 2009 was -8.3%. These results indicate that model predictions of runoff volume are much more variable for short term periods (e.g. individual observation periods) compared to longer term predictions (e.g. a multi-year simulation period).

Case II: Chief Peter (Calibration: 2008-2009; Validation: 2006-2007)

The Case II calibration – and validation model runs were analysed following the same procedure as for Case I. The predicted hydrographs, scatter diagrams, NSE and D_v results for Case II are presented in Appendix A. A comparison of Case I and Case II results is presented below.

Comparison of Chief Peter Case I and Case II Results

Table 5.2 shows a summary of NSE values acquired from Case I and Case II for monthly and daily runoff simulations during the calibration and validation periods. Similarly, the subsequent Table 5.3 presents a summary of deviation of runoff volume results for Case I and Case II.

Table 5.2 Summary of NSE values for Chief Peter watershed in Case I and Case II.

Description		**Nash-Sutcliffe Efficiency (NSE)**	
		Monthly	Daily
Case I	Calibration Period (2006-2007)	0.78	0.67
	Validation Period (2008-2009)	0.73	0.50
Case II	Calibration Period (2008-2009)	0.78	0.53
	Validation period (2006-2007)	0.77	0.66

When comparing the NSE values shown in Table 5.2 for the Case I and Case II models, it was found that the values for monthly and daily runoff simulations were almost identical for both the cases in 2006-2007. However, the NSE values acquired for monthly and daily runoff simulations in 2008-2009 are greater in Case II compared to Case I. Nonetheless, the deviations of runoff volumes from subsequent Table 5.3 clearly show that Case I produced better results compared to the Case II as the deviation of runoff volumes were always less than for Case II and less than 20% for each observation period. From the aforementioned statistical analysis for Case I and Case II models, it was found that the Case I results are satisfactory considering the deviation of runoff volume model performance indicator. Additionally, it is apparent that the monthly hydrograph plotted for Case I is marginally better than Case II model. Therefore, the Case I model was selected for further investigation. The final calibration parameter values that were used in the Case I model are presented in Table 5.4.

Table 5.3 Summary of deviation of runoff volumes from Case I and Case II for the Chief Peter watershed.

Observation period	**D_v (%) from Case I**	**D_v (%) from Case II**
2006 (May - Oct)	3.8	27.4
2007 (May - Oct)	-17.7	-27.0
2008 (May - Oct)	-5.6	-7.0
2009 (May - June)	17.2	19.4

Note: D_v = Deviation of runoff volume

Table 5.4 Calibrated parameters in the Case I model and their upper and lower bounds and optimized value.

Parameter	**Description**	**Base Value**	**Lower bound**	**Upper bound**	**Optimized Value**
ALPHA_BF	Baseflow alpha factor (days)	0.0480	0.01	0.1	0.0448
CN_2	Initial SCS runoff curve number for moisture condition II (-)	77, 73†	-25%	25%	9.79% (84,80†)
SOL_K	Saturated hydraulic Conductivity (mm/h)	2.0	-50%	50%	-26.90% (1.46)
SOL_Z	Soil depth (mm)	500	-25%	25%	-0.39% (498)
SOL_AWC	Available water capacity (mm/mm)	0.20	-25%	25%	15.54% (0.23)
ANISO	Anisotropy factor (-)	3.0	1	8	1.00
SOL_KBED	Saturated hydraulic conductivity of shallow groundwater layer (mm/h)	0.10	0.001	1	0.01
ESCO	Soil evaporation compensation factor (-)	0.50	0.01	1	0.27
SURLAG	Surface runoff lag coefficient (days)	0.70	0.01	2	0.06
SMFCN	Melt factor for snow ($mm°C^{-1} d^{-1}$)	3.0	1	5	1.19
SFMTMP	Threshold temperature for snowfall and snowmelt (°C)	0.0	-2	2	1.94

Notes: † CN_2 = 77 is used for deciduous or coniferous dominant land use; CN_2 = 73 is used for mixed forest of deciduous & coniferous stands.

5.1.2 Entwash watershed (Split-sample test results)

Case III: Entwash (Calibration: 2006-2007; Validation: 2008-2009)

The hydrograph of monthly runoff plotted in Figure 5.5 shows that the $SWAT_{BF}$ model was generally able to predict the monthly runoff for the calibration and validation periods. However, the model again greatly underestimated the June peak flow in 2007 during the calibration period. The Nash-Sutcliffe efficiency obtained for the monthly runoff values during the calibration period was 0.84. However, the NSE value obtained for the monthly runoff values for the validation period dropped to 0.73.

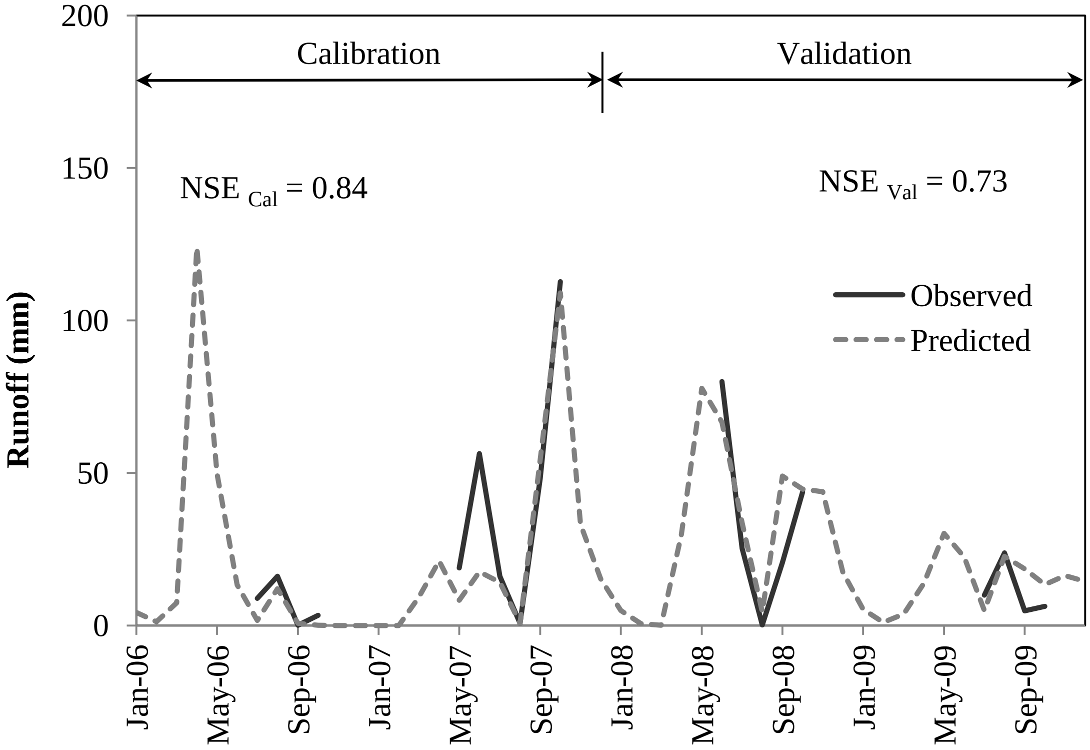


Figure 5.5 Entwash watershed observed and predicted monthly runoff for the Case III calibration and validation periods.

The hydrograph of daily runoff presented in Figure 5.6 reveals that the model could not predict many of the peak daily flows occurring during the calibration period. Likewise, it is apparent that the model could not simulate a peak flow that occurred in July 2008 during the validation period. The NSE values reported in Figure 5.6 for daily runoff for the calibration and validation periods are 0.64 and 0.54, respectively.

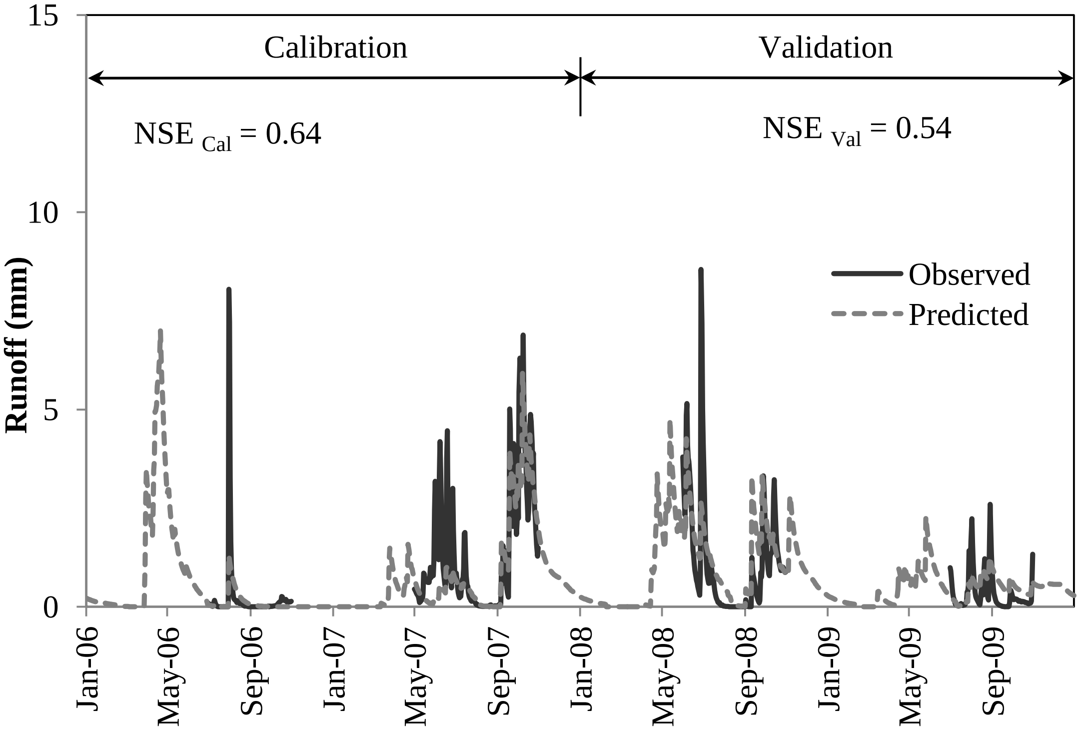


Figure 5.6 Entwash watershed observed and predicted daily runoff for the Case III calibration and validation periods.

The scatter diagrams of the observed-predicted data pairs for monthly and daily runoff for both the calibration and validation periods are presented in Figure 5.7 and Figure 5.8, respectively. The coefficients of efficiency (R^2) relative to the 1:1 line acquired from the monthly and daily runoff scatter plots are respectively 0.81 and 0.60.

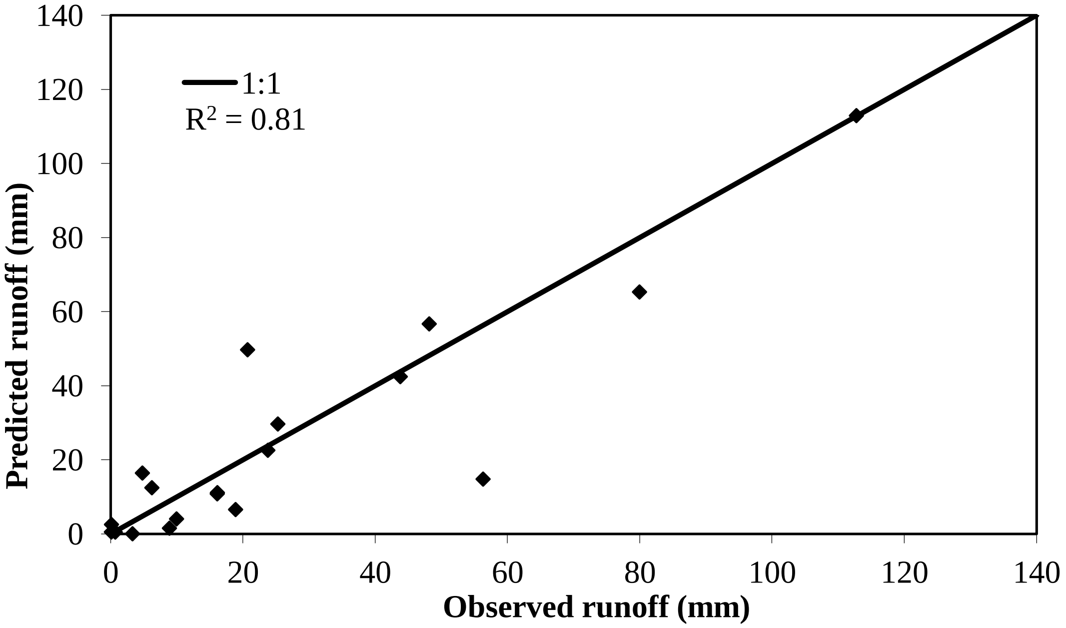


Figure 5.7 Scatter diagram of Entwash watershed observed and predicted monthly runoff for Case III calibration and validation periods.

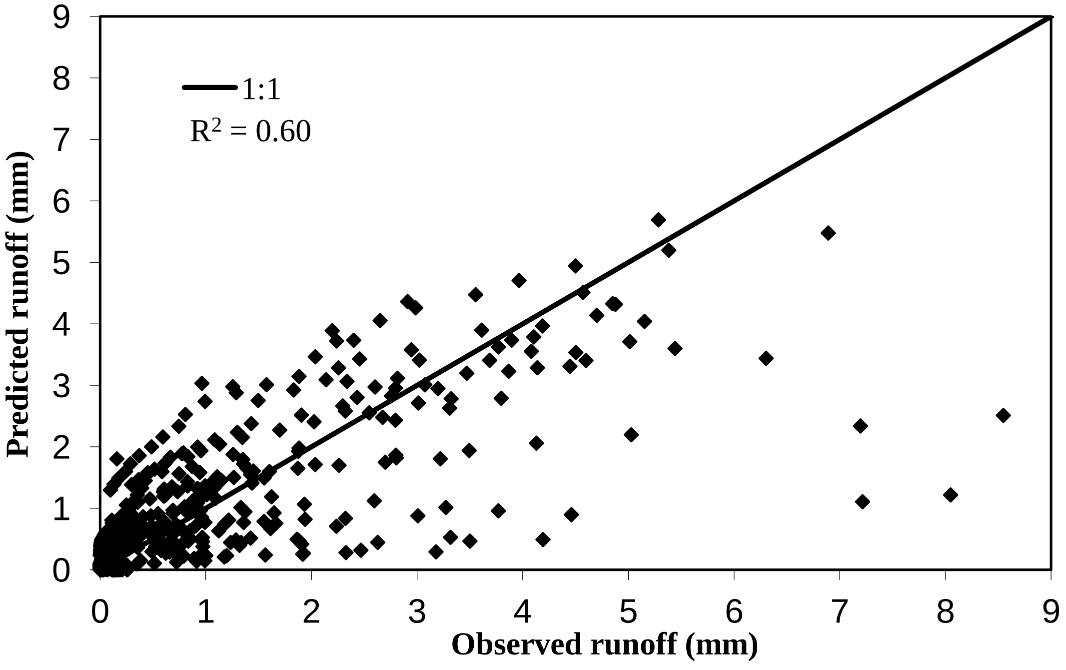


Figure 5.8 Scatter diagram of Entwash watershed observed and predicted daily runoff for Case III calibration and validation periods.

The following Table 5.5 shows the observed and predicted runoff volume of each observation period and the deviation between these volumes for Case III. It can be seen that the model underestimated the runoff volume for the calibration period by 49.2% and 19.3% for the 2006 and 2007 observation periods, respectively. The model overestimated the runoff volume for the 2008 observation period by 16.9% and for the 2009 observation period by 32.8%. Inspection of the deviation of streamflow volume for each observation period shows that the deviations of runoff volumes were much greater than ± 20% for some years. The accumulated deviation of runoff volume over the four observation periods for 2006 to 2009 was -4.0%. These results indicate that model predictions of runoff volume are much more variable for short term periods compared to longer term predictions.

Table 5.5 Entwash watershed observed and predicted runoff and deviation of runoff for Case III.

Observation period		**Observed runoff (mm)**	**Predicted runoff (mm)**	**Deviation of runoff volume (%)**
Calibration Period	2006 (July-Oct)	28.4	14.4	-49.2
	2007 (May-Oct)	253.0	204.1	-19.3
Validation Period	2008 (June-Oct)	169.9	198.5	16.9
	2009 (July-Oct)	44.8	59.4	32.8

Note: The deviation of runoff volume (D_v) is calculated for each observation period using Equation 4.2.

Case IV: Entwash (Calibration: 2008-2009; Validation: 2006-2007)

The Case IV calibration and validation model runs were analysed following the same procedure as for Case III. The predicted hydrographs, scatter diagrams, NSE and D_v results for Case IV are presented in Appendix A. A comparison of Case III and Case IV results is presented below.

Comparison of Entwash Case III and Case IV Results

Table 5.6 shows a summary of NSE values acquired for the Entwash watershed from Case III and Case IV for monthly and daily runoff simulations during the calibration and validation periods. Similarly, Table 5.7 shows a summary of deviation of runoff volume results for Case III and Case IV.

Table 5.6 Summary of NSE values for Entwash watershed in Case III and Case IV.

Description		**Nash-Sutcliffe Efficiency (NSE)**	
		Monthly	Daily
Case III	Calibration Period (2006-2007)	0.84	0.64
	Validation Period (2008-2009)	0.73	0.54
Case IV	Calibration Period (2008-2009)	0.80	0.58
	Validation period (2006-2007)	0.83	0.62

Table 5.7 Summary of deviation of runoff volumes for Case III and Case IV for the Entwash watershed.

Observation period	**D_v (%) from Case III**	**D_v (%) from Case IV**
2006 (July-Oct)	-49.2	-53.1
2007 (May-Oct)	-19.3	-17.1
2008 (June-Oct)	16.9	17.3
2009 (July-Oct)	32.8	19.6

Note: D_v = Deviation of runoff volume

Comparing the NSE values from the Table 5.6 for the Case III and Case IV models, it was found that the acquired values for monthly and daily simulations were similar for 2006-2007. However, in 2008-2009 the acquired values of NSE are larger for Case IV compared to Case III for both monthly and daily simulations. Additionally, it is apparent that the deviations of runoff volumes are better in Case IV compared to Case III. Visual comparison shows that the hydrograph of monthly runoff produced by the Case IV model is marginally better for 2009 compared to the hydrograph of monthly runoff produced by the Case III model. From both the visual and statistical comparisons, it was found that the Case IV model produced better results than the Case III model. Therefore, the Case IV calibration parameters were selected for further analysis. The final calibration parameter values used in the Case IV model are presented in Table 5.8.

Table 5.8 Calibrated parameters in the Case IV model and their upper and lower bounds and optimized value.

Parameter	**Description**	**Base Value**	**Lower bound**	**Upper bound**	**Optimized Value**
ALPHA_BF	Baseflow alpha factor (days)	0.0480	0.01	0.1	0.0100
CN_2	Initial SCS runoff curve number for moisture condition II (-)	77, 73†	-25%	25%	-16.01% (64.67,61.31†)
SOL_K	Saturated hydraulic Conductivity (mm/h)	2.0	-50%	50%	-20.67% (1.58)
SOL_Z	Soil depth (mm)	500	-25%	25%	-9.42% (452.9)
SOL_AWC	Available water capacity (mm/mm)	0.20	-25%	25%	0.60% (0.20)
ANISO	Anisotropy factor (-)	3.0	1	8	3.83
SOL_KBED	Saturated hydraulic conductivity of shallow groundwater layer (mm/h)	0.10	0.001	1	0.001
ESCO	Soil evaporation compensation factor (-)	0.50	0.01	1	0.66
SURLAG	Surface runoff lag coefficient (days)	0.70	0.01	2	0.04
SMFCN	Melt factor for snow ($mm°C^{-1} d^{-1}$)	3.0	1	5	1.00
SFMTMP	Threshold temperature for snowfall and snowmelt (°C)	0.0	-2	2	0.88

Notes: † $CN_2 = 77$ is used for deciduous or coniferous dominant land use; $CN_2 = 73$ is used for mixed forest of deciduous & coniferous stands.

5.2 Proxy-basin test

Klemes (1986) stated that a proxy-basin test gives an indication of the geographical transportability of a model within a particular region that has a similar climate. Following this test procedure, the $SWAT_{BF}$ model was calibrated on the Chief Peter watershed and then validated on the Entwash watershed and vice versa. The proxy basin test was segmented into two different cases as indicated below:

Case V: Calibrated on Chief Peter and validated on Entwash

Case VI: Calibrated on Entwash and validated on Chief Peter

5.2.1 Case V: Calibration on Chief Peter and validation on Entwash

In this case, the previously calibrated parameters for the Chief Peter watershed were applied on the Entwash watershed. The calibration parameter set and final values selected from the split-sample test of the Chief Peter watershed were presented in Table 5.4. The same parameter set and values were applied on the Entwash watershed to investigate their suitability in simulating the runoff from the Entwash watershed. In this case, the Entwash watershed was validated using four open water observation periods over the years 2006 to 2009.

Figure 5.9 shows the hydrographs of monthly runoff for the validation period. It is apparent that the predicted runoff representatively matches the observed monthly runoff during the observation periods with the exception of the June 2007 peak flow. The Nash-Sutcliffe efficiency for monthly runoff was found to be 0.74.

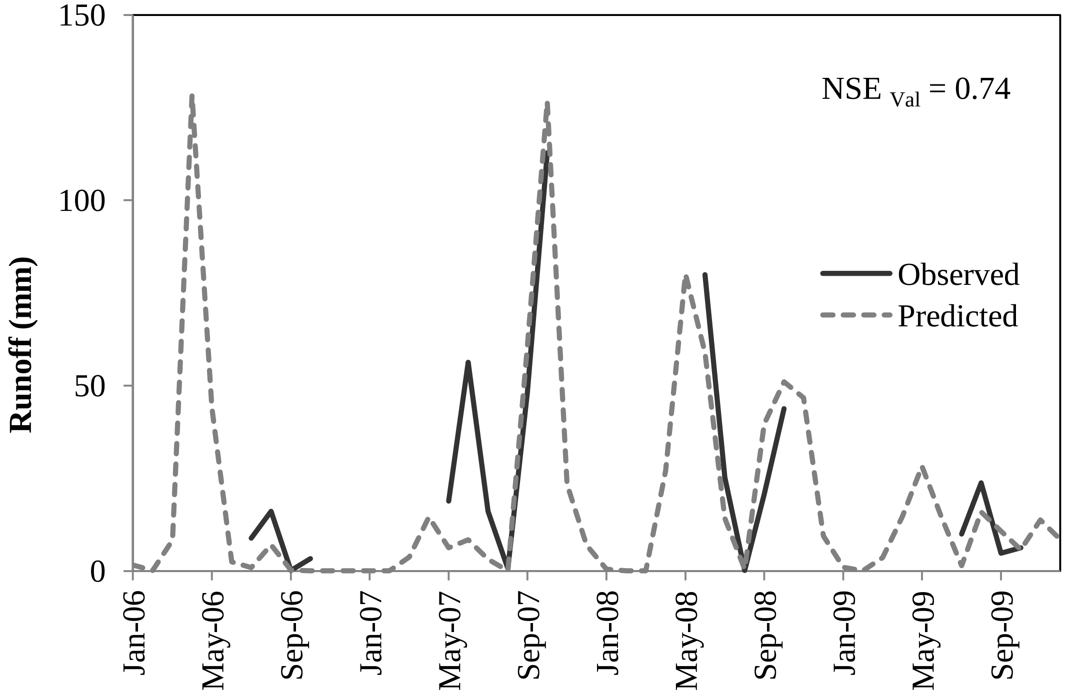


Figure 5.9 Entwash watershed observed and predicted monthly runoff for the Case V validation period.

The daily runoff hydrograph is presented in Figure 5.10 and reveals that the model was generally able to predict the observed pattern of runoff. As noted previously for the split sample test results for the Entwash watershed, the model was unable to simulate the many of the peak daily flows. The NSE value for daily runoff obtained from this analysis was 0.56. Therefore, it can be stated that the calibrated parameter set from the Chief Peter watershed produced less representative results for daily runoff compared to monthly for the Entwash watershed.

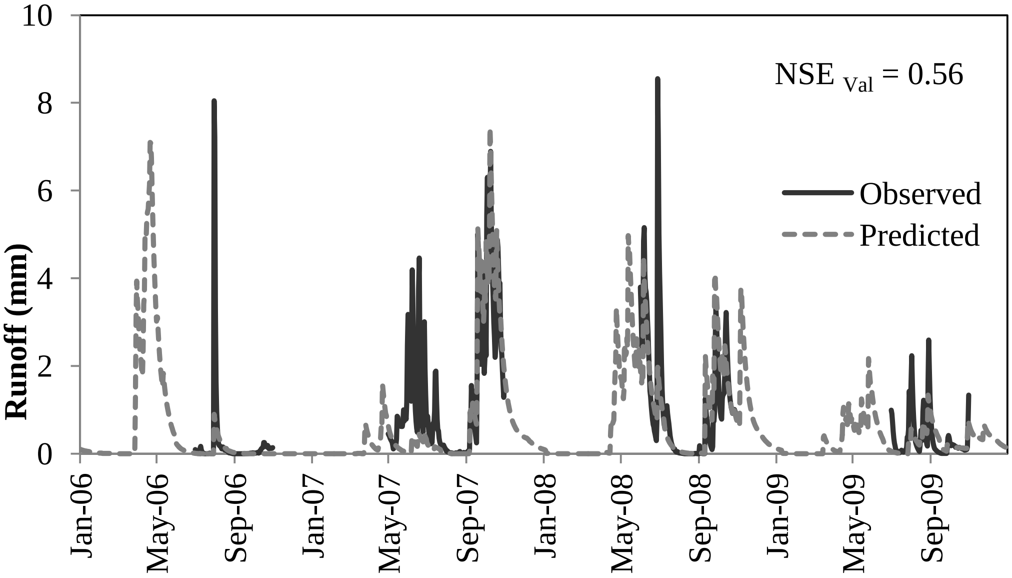


Figure 5.10 Entwash watershed observed and predicted daily runoff for the Case V validation period.

The scatter diagrams of the observed-predicted data pairs for monthly and daily runoff are presented in Figure 5.11 and Figure 5.12, respectively. Inspection of Figure 5.11 shows that the plot of observed-predicted monthly runoff data pairs has good correlation with the 1:1 line. Additionally, observing Figure 5.12, it can be stated that the relationship between observed-predicted daily runoff data pairs and the 1:1 line is poor in comparison to the monthly runoff correlation.

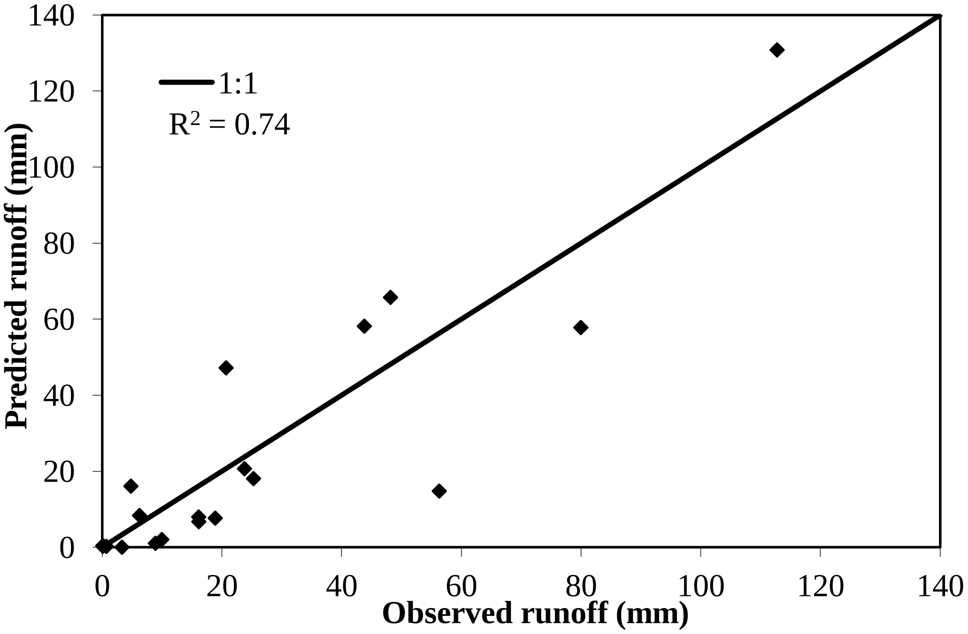


Figure 5.11 Scatter diagram of the Entwash watershed observed and predicted monthly runoff for the Case V validation period.

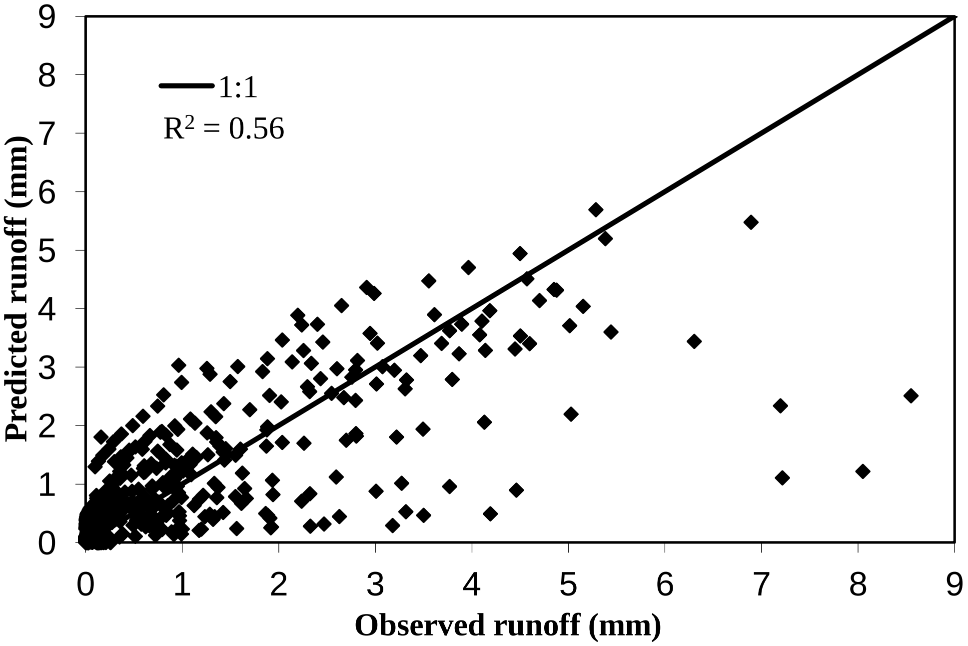


Figure 5.12 Scatter diagram of the Entwash watershed observed and predicted daily runoff for the Case V validation period

The observed and predicted runoff volume for each observation period, and the deviation between these volumes are presented in Table 5.9. It is apparent that the model underestimated the runoff during the observation period in 2006 and 2009 by 71.0% and 24.3%, respectively. For the observation periods during 2007 and 2008, the model prediction is within the range of ±20%.

From the previous analysis of the Case III and Case IV models of the split-sample test for the Entwash watershed, it is apparent that the model could not simulate many of the peak daily flows during the observation periods even though it was using the Entwash calibration parameter values for calibration and validation. Therefore, it is not surprising the same problem occurs in simulating the peak daily flows in this proxy-basin validation test using the Chief Peter parameter set. The overall results of the visual comparisons and statistical analysis demonstrates the calibration parameters of the Chief Peter watershed can produce representative streamflow results for the Entwash watershed for monthly runoff but the results for daily runoff are poor in comparison.

Table 5.9 Entwash watershed observed and predicted runoff and deviation of runoff volume for Case V.

Observation period	**Observed runoff (mm)**	**Predicted runoff (mm)**	**Deviation of runoff volume (%)**
2006 (July-Oct)	28.4	9.3	-71.0
2007 (May-Oct)	253.0	225.9	-18.9
2008 (June-Oct)	169.9	181.6	-3.3
2009 (July-Oct)	44.8	47.1	-24.3

Note: The deviation of runoff volume (D_v) is calculated for each observation period using Equation 4.2.

5.2.2 Case VI: Calibration on Entwash and validation on Chief Peter

This is the last test case in which the calibrated parameters of the Entwash watershed were applied to the Chief Peter watershed. Table 5.8 presents the calibration parameter set and final values used for the Entwash watershed. These parameter values were applied to the Chief Peter watershed for the proxy-basin validation test. Measured runoff data collected during the open water observation periods in 2006 to 2009 were used for this validation test.

Figure 5.13 shows the hydrographs of monthly runoff for the Chief Peter watershed for the validation period. These hydrographs reveal that the predicted runoff reasonably matches with the observed runoff except for underestimating the peak flows in 2007 and 2008. The Nash Sutcliffe efficiency produced by the model for the observation periods is 0.73.

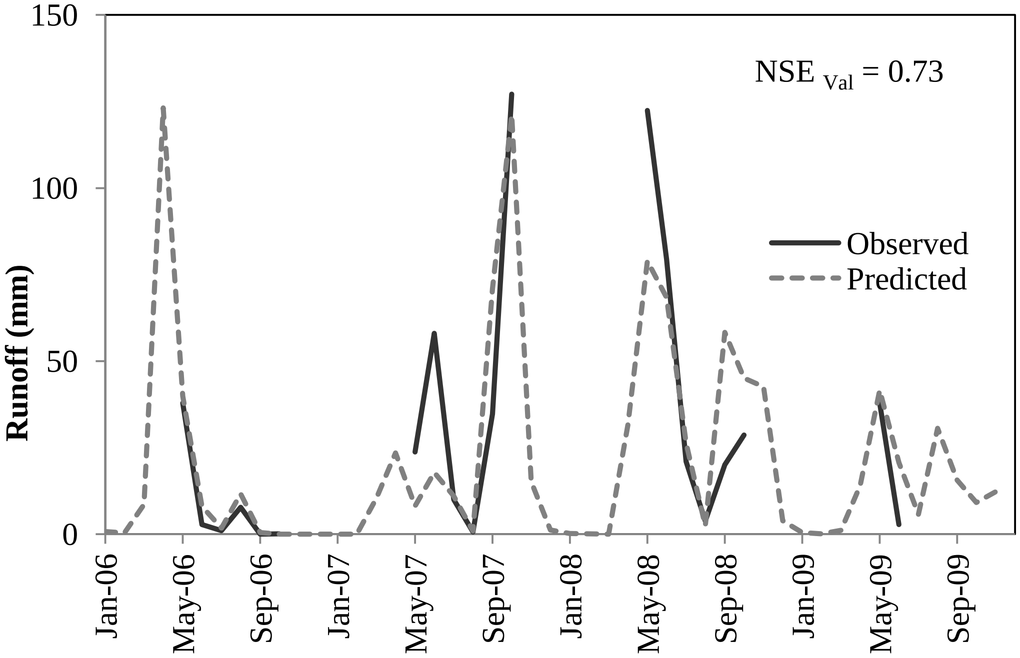


Figure 5.13 Chief Peter observed and predicted monthly runoff for the Case VI validation period.

The simulated hydrograph of daily runoff in Figure 5.14 reveals that the model was unable to consistently simulate the daily observed runoff. The major problem was the model could not simulate peak flows in 2007 and 2008. This problem was encountered previously when calibrating and validating the Chief Peter watershed in the split sample tests. The NSE value for daily runoff was computed as 0.55. Therefore, it can be stated that the calibrated parameter set from the Entwash watershed produced less representative results for daily runoff compared to monthly for the Chief Peter watershed.

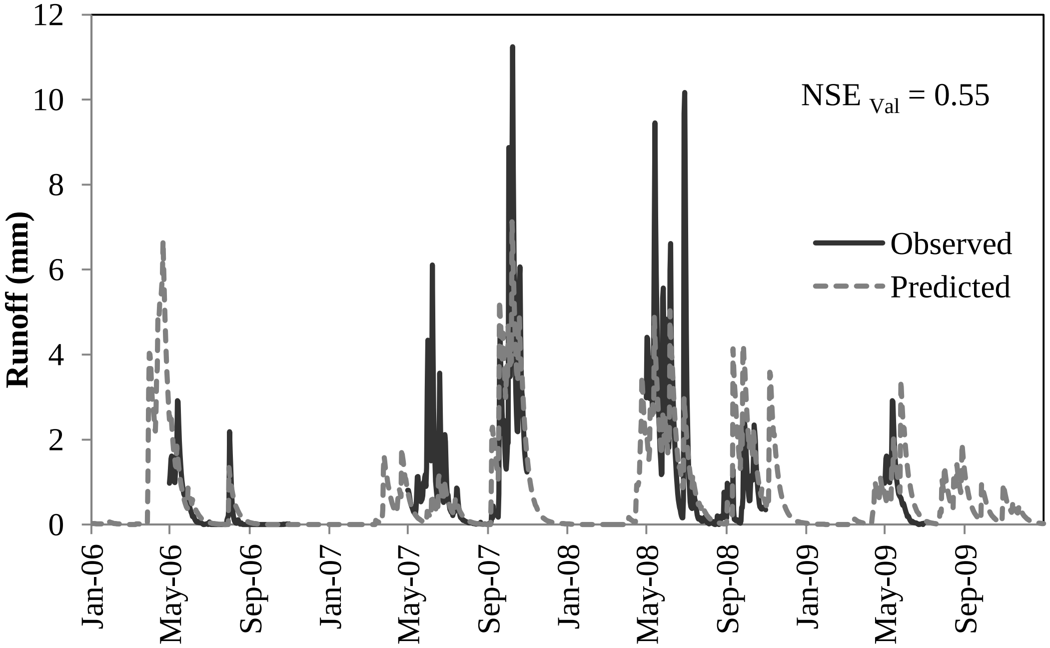


Figure 5.14 Chief Peter observed and predicted daily runoff for the Case VI validation period.

The scatter diagrams of the observed-predicted data pairs of monthly and daily runoff are presented in Figure 5.15 and Figure 5.16, respectively. These scatter plots show that the monthly and daily runoff volumes are generally underestimated by the model for the peak flows.

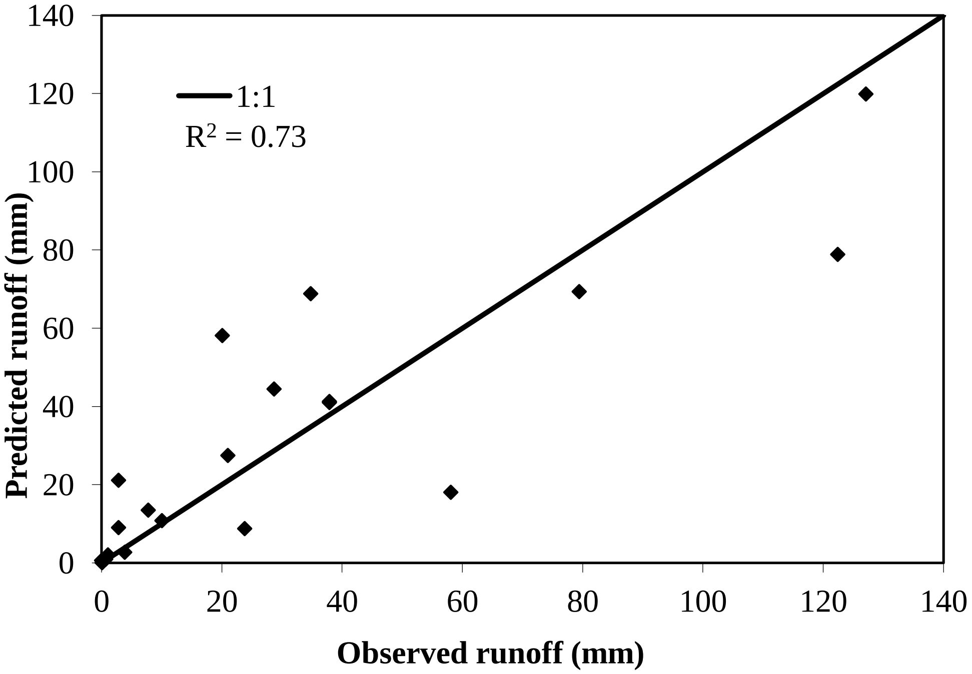


Figure 5.15 Scatter diagram of the Chief Peter watershed observed and predicted monthly runoff for the Case VI validation period.

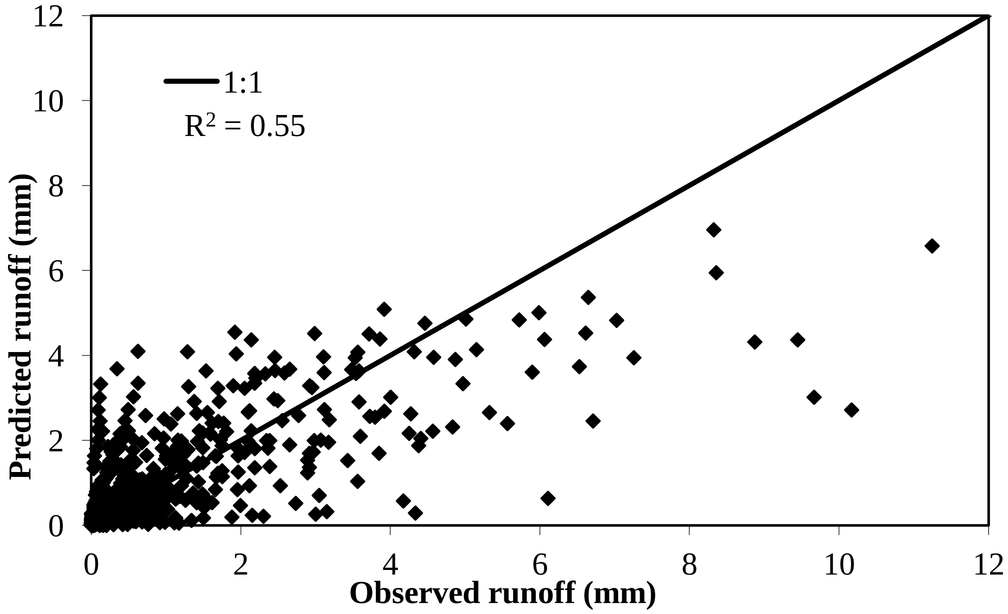


Figure 5.16 Scatter diagram of the Chief Peter watershed observed and predicted daily runoff for the Case VI validation period.

The observed and predicted runoff volume for each observation period and the deviation between these volumes are presented in Table 5.10. It can be observed that for 2007 and 2008 observation periods, the deviation of runoff volume is less than 15% which is a good result. However, the model overestimated the runoff by 33.4% and 53.2% during the observation periods in 2006 and 2009, respectively. The accumulated deviation of runoff volume over the four observation periods for 2006 to 2009 was 2.7%. These results indicate that model predictions of runoff volume are quite variable for short term periods (e.g. individual observation periods) compared to longer term predictions (e.g. a multi-year simulation).

Table 5.10 Chief Peter observed and predicted runoff and deviation of runoff volume for Case VI.

Observation period	**Observed runoff (mm)**	**Predicted runoff (mm)**	**Deviation of runoff volume (%)**
2006 (May-Oct)	49.6	66.2	33.4
2007 (May-Oct)	254.5	227.3	-10.7
2008 (May-Oct)	275.5	281.0	2.0
2009 (May-June)	40.7	62.4	53.2

Note: The deviation of runoff volume (D_v) is calculated for each observation period using Equation 4.2.

5.3 Discussion

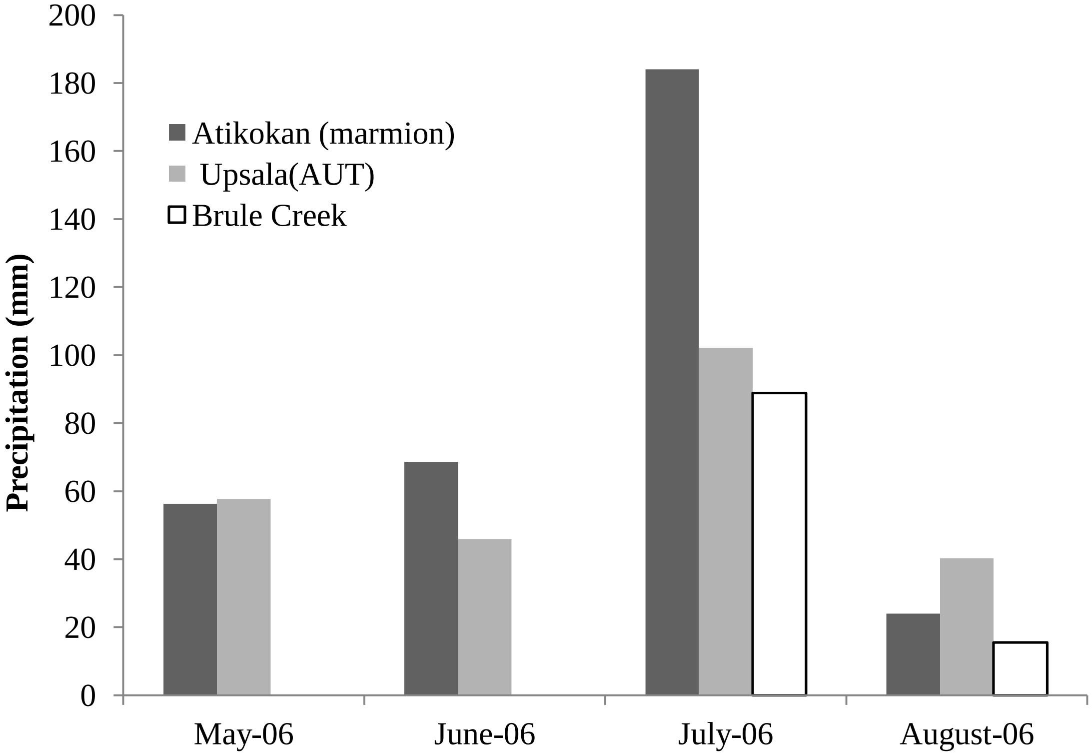
The results obtained from the previous analysis of the split-sample test and proxy-basin test show that the $SWAT_{BF}$ model was able to produce representative results for monthly runoff in all cases despite using a single soil layer and type in the Chief Peter and the Entwash watersheds.

It is evident that the NSE values for monthly runoff produced by the model were greater than 0.75 for the calibration period in all four cases of the split-sample test. Similarly, the NSE values obtained in Case II and Case IV for monthly runoff during the validation periods were also greater than 0.75. However, in Case I and Case III, NSE values produced by the models for monthly runoff during the validation periods were marginally less than 0.75. The NSE values for daily runoff acquired for the calibration and validation periods were between 0.67 and 0.50 in all four cases.

Similar results were obtained from the proxy-basin tests in which the models produced NSE values in the range of 0.73 to 0.74, and 0.55 to 0.56 for monthly and daily runoff simulations, respectively.

Inspections of the monthly and daily hydrographs in all six case studies show that the $SWAT_{BF}$ model was generally able to predict the pattern of runoff for both the calibration and validation periods. However, examination of monthly and daily hydrographs and scatter plots for the Chief Peter and Entwash watersheds revel that there is a large discrepancy between the observed and predicted runoff for many of the peak flows, particularly for daily runoff. It is apparent that, the model was not able to predict the peak flows in June, 2007 and spring/summer 2008 in the Chief Peter watershed, and peak flow that occurred in June 2007 in the Entwash watershed.

There may be several reasons for underestimating the June flows in 2007. It is likely that there is significant spatial variability of precipitation over the Chief Peter and Entwash watersheds in comparison to the Brule Creek Meteorological Station (established by the FORWARD project) as this weather station is approximately 9.5 km away from the Chief Peter watershed. To investigate this argument, precipitation data recorded from two different Environment Canada Meteorological Stations - Upsala (AUT) and Atikokan (marmion), situated near to the Chief Peter watershed, were compared with the data obtained from the Brule Creek Weather Station. Upsala (AUT) and Atikokan (marmion) Meteorological Stations are approximately 40 km North East and 50 km West of Chief Peter watershed respectively. In particular two years of data from 2006 to 2007 were compared as 2006 was a dry year and 2007 was a wet year.



Note: The Brule Creek Meteorological Station precipitation data was available only from 16th June, 2006. Therefore, this data is not included in the monthly precipitation bar chart.

Figure 5.17 Monthly precipitation recorded in 2006 at three meteorological stations close to Chief Peter and Entwash watersheds.

From Figure 5.17, it can be observed that there is variability in the amount of precipitation recorded among the three meteorological stations in 2006. Moreover, a very large amount of precipitation occurred at Atikokan in August 2006 in comparison to the two other stations. In addition, Figure 5.18 shows that there are differences in the precipitation among Brule Creek, Upsala (AUT) and Atikokan Marmion Meteorological Stations in the year 2007, especially from May to July. Moreover, it is known that in this modelling task, the $SWAT_{BF}$ model was underestimating the streamflow volume particularly from the end of May to mid July 2007 in each aforementioned case study. Therefore, from inspection of Figure 5.18, it is plausible there is an underestimation of the actual precipitation that occurred over the Chief Peter and Entwash watersheds compared to the precipitation data recorded at the Brule Creek Meteorological Station during this time period.

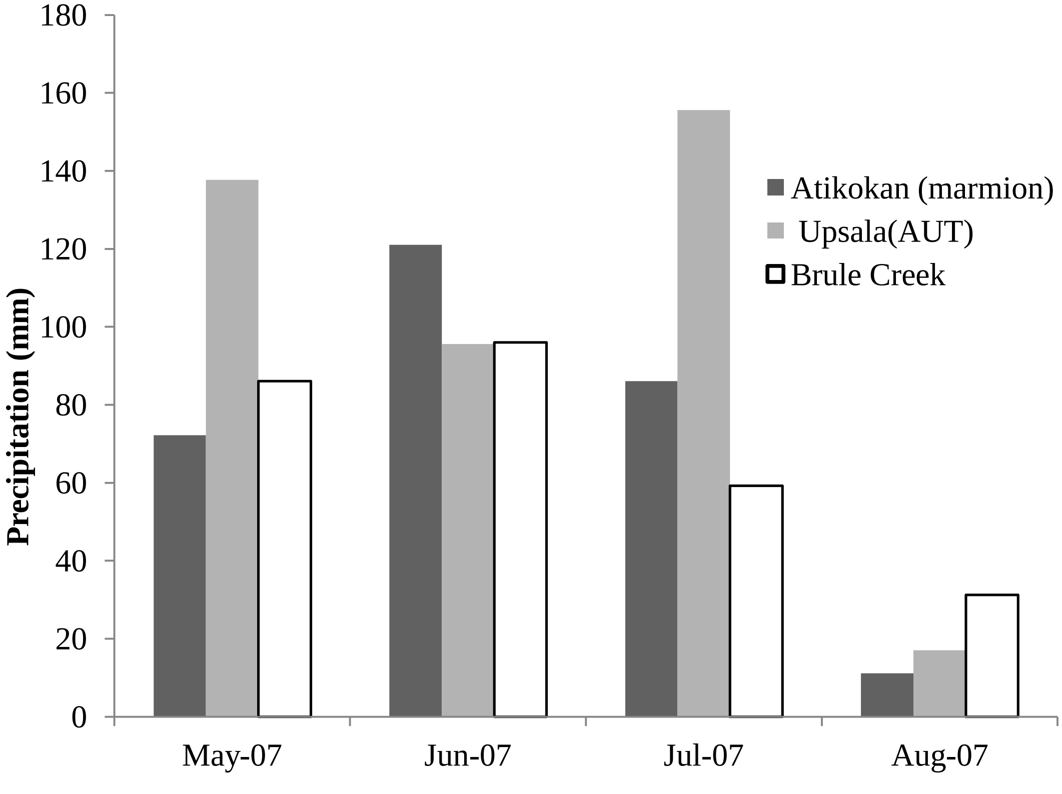


Figure 5.18 Monthly precipitation recorded in 2007at three meteorological stations close to Chief Peter and Entwash watersheds .

Another possible issue that may contribute to poor model performance during daily runoff simulation in May due to snowmelt are errors in calculating the accumulation of snow by the model during the winter months. The snow precipitation data used for this study was obtained only from the Brule Creek Meteorological Station. The station is converted to winter operation as described in Chapter 3 and records the water equivalent of the snow falling over the winter months. The model accumulates the water equivalent of the snowfall over the winter months until a threshold temperature occurs in the spring to initiate melting.

The discussion above illustrated there is variability in precipitation capture recorded among the three meteorological stations within the region. Hence, discrepancies are plausible between the snowfall water equivalent accumulated in the model (based upon the Brule Creek station records) and the snowfall that actually accumulated on the ground in the Chief Peter and Entwash watersheds. Moreover, the snow drifting that occurs during storms can produce large variation in the distribution of snow accumulation on the ground. Each of these potential sources of input error are plausible explanations for the model underestimating daily snowmelt flows in May for both the Chief Peter Entwash watersheds.

By inspection of the results obtained from applying two different sets of calibration parameter values (from Table 5.4 and Table 5.9) on the Chief Peter watershed and the Entwash watershed, it can be observed that both sets of parameter values produced satisfactory results for monthly runoff simulations in all cases. However, to select a particular set of parameter values for application in other Boreal Shield watersheds with similar soils characteristics, it is recommended the vegetation cover be used as a guiding criterion. Therefore, on coniferous dominated watersheds (as represented by Chief Peter) the parameter values from Table 5.4 are recommended. Whereas on watersheds dominated by mixed stands of coniferous and deciduous cover (as represented by Entwash) the parameter values from Table 5.9 should be used.

CHAPTER 6
SUMMARY AND RECOMMENDATIONS

6.1 Summary

The Forest Watershed and Riparian Disturbance (FORWARD) Project has been using a modified version of the Soil and Water Assessment Tool model ($SWAT_{BF}$) to predict the streamflow occurring from forested watersheds on the Boreal Plain in Canada. This model was successfully tested on the western Canadian Boreal Plain where the soil mantel is thick. To verify the applicability of this model in simulating streamflow from forest dominant watersheds on the eastern Canadian Boreal Shield, where the soil mantle is thin and bedrock is exposed, a modelling study was conducted. For this study, the Chief Peter and Entwash watersheds that are monitored by the FORWARD project within the Legacy Forest Small Streams (LFSS) study area on the Canadian Boreal Shield of north-western Ontario were selected. These two watersheds share a common boundary, have similar topography and have a common dominant soil type.

Two types of tests were conducted to verify the suitability of the $SWAT_{BF}$ model in simulating the streamflow from forest dominant watersheds on the eastern Canadian Boreal Shield: (1) Split- sample test; and (2) Proxy-basin test. The split-sample test included four different case studies and the proxy-basin test had two cases. In total, six different case studies were conducted in an attempt to make a reliable conclusion regarding the application of $SWAT_{BF}$ in Boreal Shield watersheds.

Test results acquired from all these cases were presented and discussed in Chapter 5. The following section presents conclusions based upon the modelling investigation conducted in this research. Some recommendations that are proposed for future studies are also presented in this chapter.

6.2 Conclusions

6.2.1 Split-sample test

There were four different cases in the split-sample test. Case I and Case II were related to calibrating and validating $SWAT_{BF}$ for the Chief Peter watershed while Case III and Case IV were related to calibrating and validating the model for the Entwash watershed. In Case I, the Chief Peter watershed was calibrated using open water observation periods in 2006 and 2007 and validated using open water observation periods in 2008 and 2009. In Case II the calibration and validation periods were switched. Case III and Case IV for the Entwash watershed followed the same procedure for calibration and validation as the Chief Peter watershed.

It was found that the $SWAT_{BF}$ model produced satisfactory results for monthly runoff in all the aforementioned cases according to criteria described in Chapter 4. The Nash-Sutcliffe efficiency acquired for monthly runoff was always greater than 0.75 for the calibration periods. Similarly, the NSE values obtained for monthly runoff for the validation periods were greater than 0.75 in Case II and Case IV and marginally less than 0.75 in Case I and Case III, indicating satisfactory performance of the model.

The model performance was poorer for simulation of daily runoff in all cases. The Nash-Sutcliffe efficiency values produced for daily runoff were in the range of 0.50 to 0.67 for the calibration and validation periods. The predicted runoff volume summed over the open water observation periods in 2006 to 2009 were within ±20% of the observed total for each case study; however, the discrepancy between the observed and predicted runoff volumes for individual observation periods were greater than ±20% in many instances in each of the case studies.

Visual examination of measured and predicted monthly and daily runoff hydrographs and scatter plots of predicted and measured runoff pairs showed that the model was frequently underestimating runoff peaks. In particular the daily and monthly runoff models were under estimating the peak flows occurring in June 2007 and spring/summer 2008 in the Chief Peter watershed and in June 2007 in the Entwash watershed. The daily runoff models also had trouble simulating the snowmelt runoff that occurs in early May.

A potential source of error contributing to underestimation of spring/summer peak flows resulting from rain events may be underestimation of the actual precipitation that occurred over the watersheds in comparison to input precipitation data measured at the Brule Creek Meteorological Station. An analysis of monthly rainfall, collected at three meteorological stations close to the Chief Peter and Entwash watersheds, demonstrated there is spatial variability in precipitation data and some evidence that the Brule Creek Station is capturing less rainfall than the other two stations. The difficulty in simulating snowmelt runoff in the daily runoff model may be due to errors in calculation of the snow accumulation at the Brule Creek station during the winter months or the Brule Creek snow accumulation data being unrepresentative of the snowpack distribution over the watersheds.

6.2.3 Proxy-basin test

In the proxy-basin test, calibration parameter values obtained from calibrating the Chief Peter watershed were applied on the Entwash watershed and vice versa. The first approach was presented as Case V and the other approach was presented as Case VI.

Visual inspection of the daily and monthly runoff hydrographs of Case V and Case VI showed that the calibration parameter valuess from either Chief Peter watershed or Entwash watershed were able to simulate the measured pattern of runoff. The NSE values acquired for monthly runoff simulations in Case V and Case VI were 0.74 and 0.73 respectively. The NSE value obtained for daily runoff simulations in Case V was 0.56 and in Case IV was 0.55. Similar to the split sample tests the predicted runoff volume summed over the open water observation periods in 2006 to 2009 were within ±20% of the observed total for each proxy-basin test; however, the discrepancy between the observed and predicted runoff volumes for individual observation periods were greater than ±20% in many instances for both tests.

Overall examination of the split-sample test and the proxy-basin test shows that the calibration parameter values for the Chief Peter watershed and for the Entwash watershed were able to produce reasonable results for monthly runoff simulations in all cases. Therefore, both of these parameter sets could be used in further modelling work on other Boreal Shield watersheds with similar soil and vegetation characteristics. Given that the majority of each watershed is covered by sandy-coarse loamy soil, if the watershed is dominated by coniferous stands then it is recommended to use the calibrated parameter set from the Chief Peter watershed or if the watershed is dominated by mixed stands of coniferous and deciduous trees then the parameter set from the Entwash watershed should be used.

In summary, the SWAT_{BF} model was able to representatively simulate monthly streamflow occurring from forest dominant watersheds on the eastern Boreal Shield of Canada. Simulation of daily streamflow had much poorer results. The model was able to match the general pattern of measured data but tended to underestimate many of the daily peak flows.

Comparing the results obtained from applying the SWAT_{BF} model on the western Boreal Plain in Alberta and on the eastern Boreal Shield in Ontario, it is reported that in the Boreal Plain the model was able to produce good results in the calibration period; however, the model prediction was not as good for the validation period (Watson et al. 2008). In this study the SWAT_{BF} model generated satisfactory results for both the calibration and validation periods when applying it on the eastern Boreal Shield watersheds. Additionally, it is apparent that on the Boreal Plain, the model was calibrated and validated on a single watershed following the procedure of split-sample test only. In this research the model was calibrated and validated on two watersheds following two different test procedures as mentioned previously. From both procedure validation tests, the model produced satisfactory results on Boreal Shield watersheds. Therefore, it can be stated that the SWAT_{BF} model has undergone a more rigorous test in this research.

Comparing the calibration parameter sets that were used on the Boreal Plain and Boreal Shield watersheds, it was found that there were 15 calibration parameters used on the Boreal Plain (Watson et al. 2008); however, only 11 calibration parameters were used on the Boreal Shield. The wetland factor used in the Boreal Plain watershed simulations was not incorporated in simulating the Boreal Shield watersheds. Moreover, the snowmelt parameters were reduced from 5 to 2 in the Boreal Shield watersheds by using a simpler snowmelt model recently incorporated into $\mathrm{SWAT}_{\mathrm{BF}}$. The remaining calibration parameters that are used in the Boreal Plain and Boreal Shield watersheds simulations are identical; however, the parameter values are different and representative of the prevailing conditions in each ecozone.

The major difference utilized in modelling the Boreal Plain and Boreal Shield watersheds was the soil representation. The Willow Creek watershed on the Boreal Plain is dominated by Orthic Gray Luvisolic soils, whereas the Chief Peter and Entwash watersheds on the Boreal Shield consist of Dystric Brunisolic soils. In addition, the soil depth in the Boreal Shield experimental watersheds modelled in this study was estimated to be approximately 500 mm based upon literature values, whereas, the soil depth in the Willow Creek watershed was known to be more than one meter in depth. Hence, the soil was represented as a single 500 mm layer of Dystric Brunisol in the Boreal Shield watersheds in contrast to a two layer system of approximately1000 mm total depth consisting of an organic layer and a layer of Orthic Gray Luvisol used in Boreal Plain watersheds.

A further difference in soil representation was utilized in this study in comparison to previous applications of $\mathrm{SWAT}_{\mathrm{BF}}$ on the Boreal Plain. The $\mathrm{SWAT}_{\mathrm{BF}}$ litter layer algorithm was not utilized in this study. This decision was made early in the study based upon preliminary model run results, the opinion of field personal regarding the relative depth of litter accumulations in experimental watersheds on the Boreal Plain and Shield, and a desire to reduce the number of calibration parameters.

Finally, it is concluded that the simplified version of the $\mathrm{SWAT}_{\mathrm{BF}}$ model utilized in this study that omits the Boreal Plain litter layer and wetlands representation and uses a simpler snowmelt model, was able to produce representative simulation results for monthly runoff. Therefore, forest managers could attempt to utilize this simplified model as a decision making support tool regarding forest operation effects upon streamflow in eastern Canadian Boreal Shield watersheds. However, the application of the model may be limited to predict hydrological phenomenon occurring in small-scale forested watersheds on the eastern Canadian Boreal Shield that possess similar soil and land use characteristics to those investigated in this research.

6.3 Recommendations for improvements to future studies

In this modelling investigation, due to the lack of a high resolution DEM, the input files for each case study had to be set up manually rather than relying upon automated GIS interface routines. As a result this task required guidance from a SWAT expert on file content and format. Therefore, it is highly recommended that future modelling investigations on the Boreal Shield be carried out in watersheds where a high resolution DEM is available.

The soil maps available for the watersheds investigated in this study did not contain the detailed information on soil properties that is required as input to the $SWAT_{BF}$ model. As a result soil properties had to be estimated based upon literature and on-line soils characterization tools. Therefore, it is strongly recommended that future modelling investigations on the Boreal Shield be carried out in watersheds where detailed measured soil data are available because soils are one of the most important characteristics that govern the reliability of hydrological modelling investigations. Alternatively a soil sampling and characterization program should be implemented in conjunction with the modelling investigation.

The meteorological data used for this study was obtained from a weather station established approximately 9 .5 km from the modelled watersheds. For future studies it is suggested the weather station be established in much closer proximity to the modelled watersheds to improve quantification of the precipitation input. Further, it is suggested additional precipitation gauges be installed within the watersheds to characterize the variability and spatial distribution of the precipitation. Alternative methods for quantifying the distribution of precipitation of over the watersheds such as remote sensing and radar should also be explored.

In addition it is recommended that future modelling investigations utilizing $\mathrm{SWAT}_{\mathrm{BF}}$ on the Boreal Shield have snow survey measurements available. The snow survey measurements should include snowpack depth, water equivalent, and snow distribution within the watersheds. Snow survey measurements would allow a cross check against the snowfall water equivalent recorded at a weather station for input into the model and accumulated within the model for use in the snowmelt routine.

It is further recommended that future studies have daily measured streamflow data available for the entire year rather than just the open water period from May to June. Observed data sets covering the entire year would allow calibration and validation periods to represent flow conditions during all seasons and to capture spring snowmelt events every year.

Finally, it is recommended an uncertainty analysis of the input data be performed in future modelling investigations on the Boreal Shield.

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APPENDIX A

Model Results for Case II and Case IV Simulations

1. Case II Chief Peter watershed (Calibration: 2008-2009; Validation: 2006-2007)

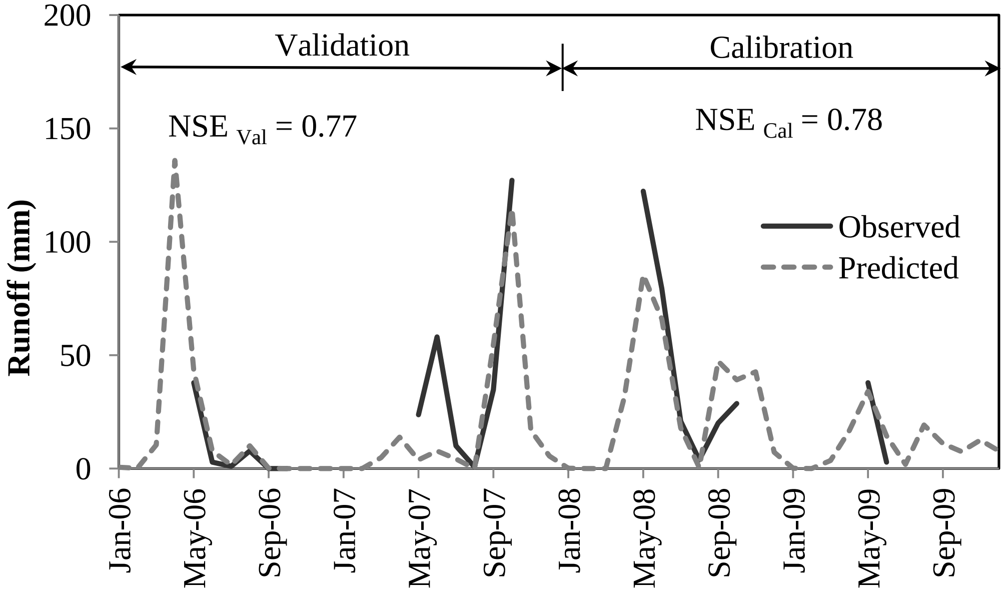


Figure A.1 Chief Peter watershed observed and predicted monthly runoff for the Case II calibration and validation periods.

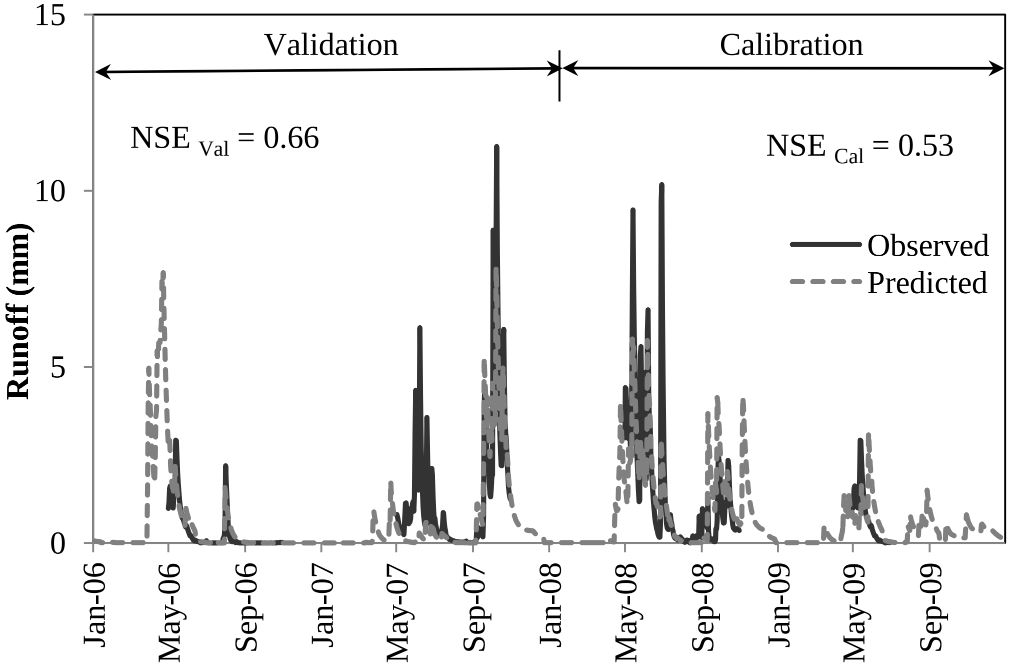


Figure A.2 Chief Peter watershed observed and predicted daily runoff for the Case II calibration and validation periods.

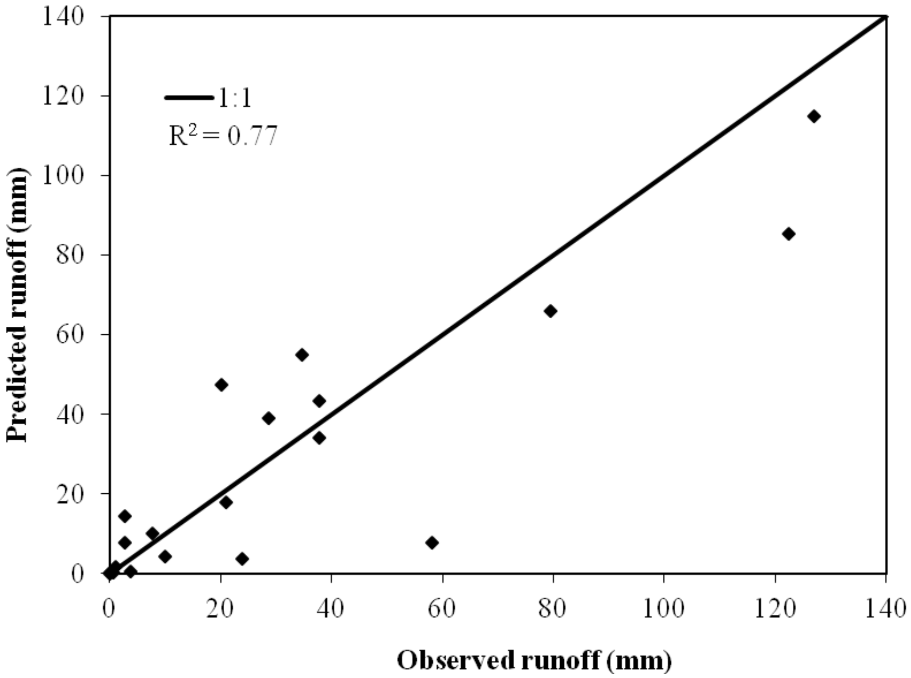


Figure A.3 Scatter diagram of the Chief Peter watershed observed and predicted monthly runoff for the Case II calibration and validation periods.

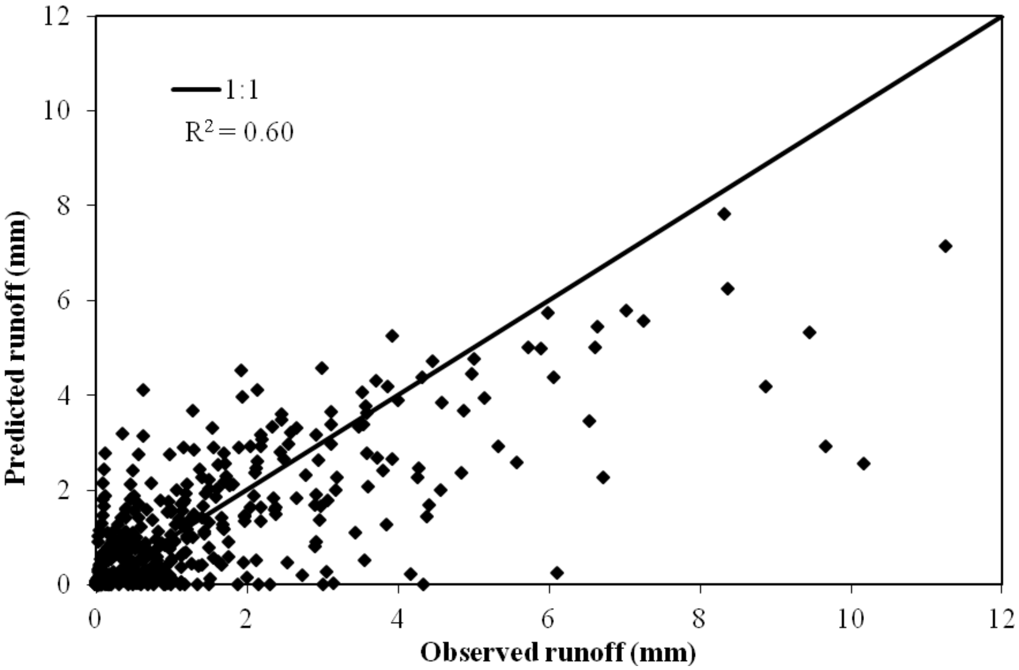


Figure A.4 Scatter diagram of the Chief Peter watershed observed and predicted daily runoff for the Case II calibration and validation periods.

Table A.1 Chief Peter observed and predicted runoff and deviation of runoff volume for Case II.

Observation period		**Observed runoff (mm)**	**Predicted runoff (mm)**	**Deviation of runoff volume (%)**
Validation Period	2006 (May-Oct)	49.6	63.2	27.4
	2007 (May-Oct)	254.5	185.7	-27.0
Calibration Period	2008 (May-Oct)	275.5	256.3	-7.0
	2009 (May-June)	40.7	48.6	19.4

Note: The deviation of runoff volume (D_v) is calculated for each observation period using Equation 4.2.

2. Case IV Entwash (Calibration: 2008-2009; Validation: 2006-2007)

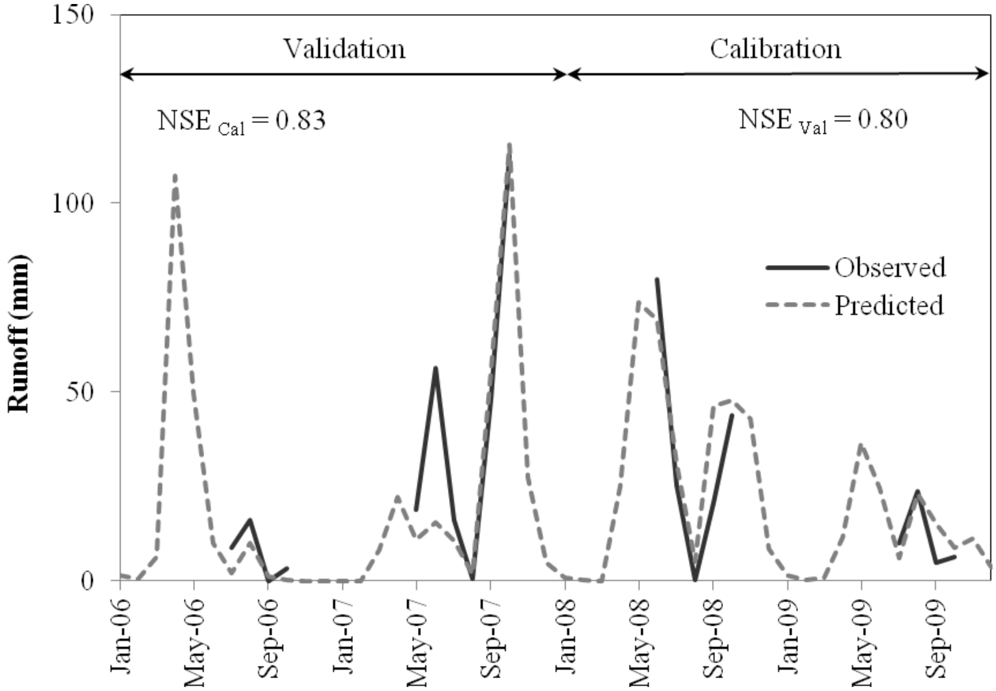


Figure A.5 Entwash watershed observed and predicted monthly runoff for the Case IV calibration and validation periods.

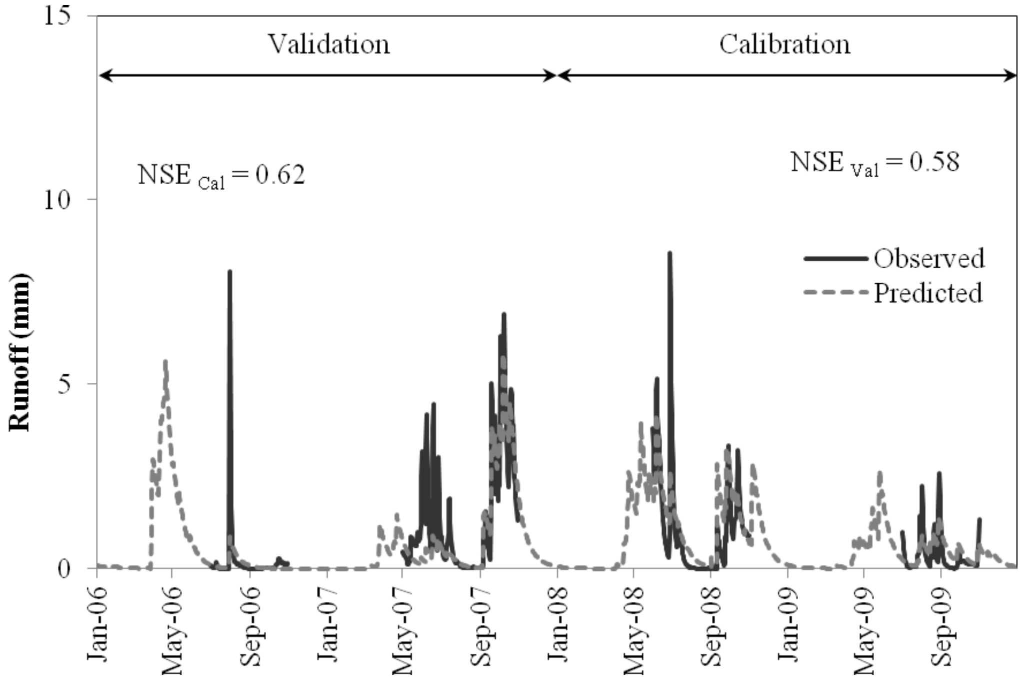


Figure A.6 Entwash watershed observed and predicted daily runoff for the Case IV calibration and validation periods.

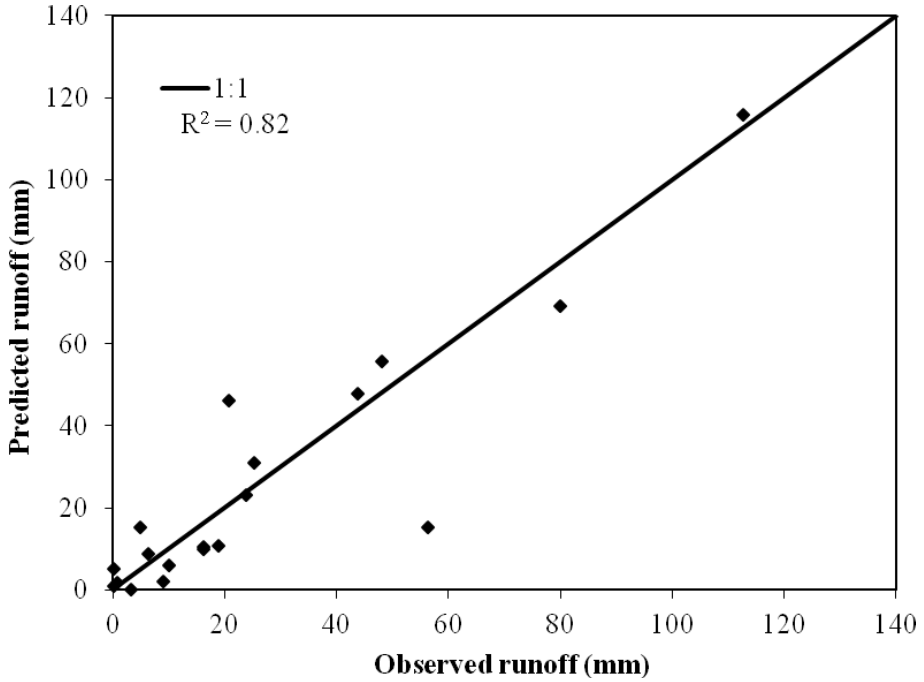


Figure A.7 Scatter diagram of Entwash watershed observed and predicted monthly runoff for Case IV calibration and validation periods.

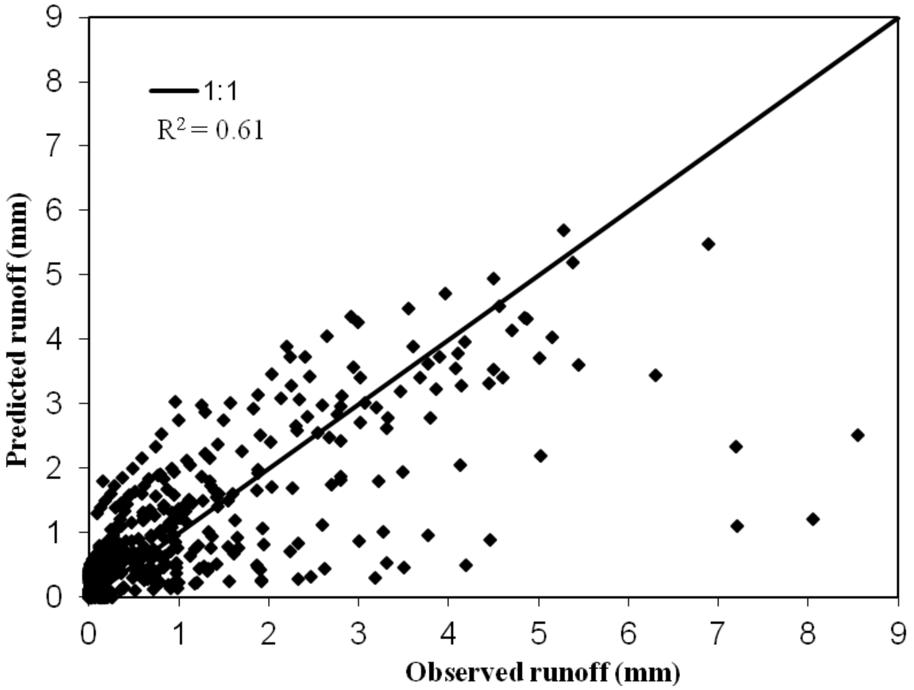


Figure A.8 Scatter diagram of Entwash watershed observed and predicted daily runoff for Case IV calibration and validation periods.

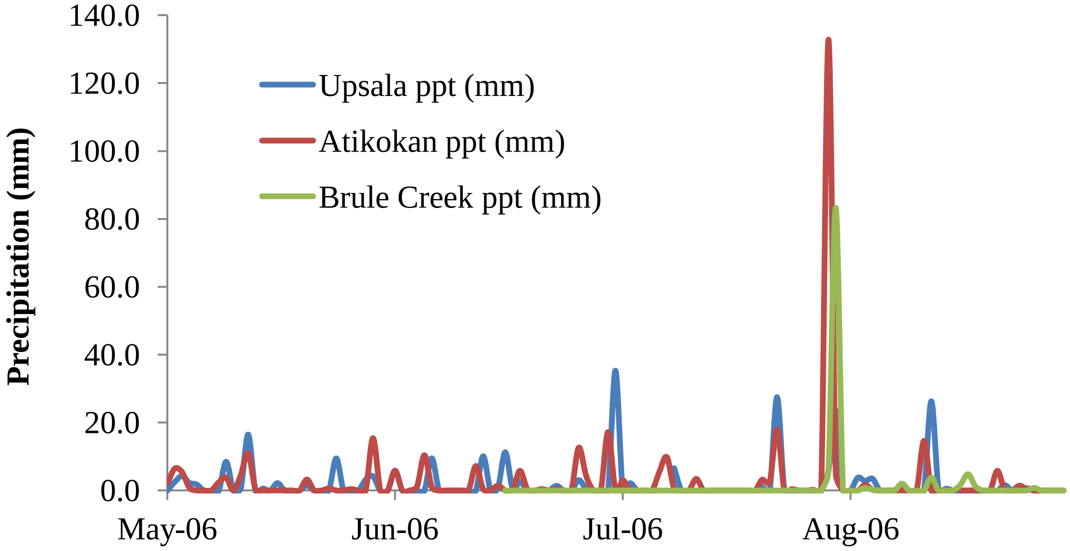
Table A.2 Entwash watershed observed and predicted runoff and deviation of runoff volumes for Case IV.

Observation period		Observed runoff (mm)	Predicted runoff (mm)	Deviation of runoff volume (%)
Validation Period	2006 (July-Oct)	28.4	13.3	-53.1
	2007 (May-Oct)	253.0	209.8	-17.1
Calibration Period	2008 (June-Oct)	169.9	199.2	17.3
	2009 (July-Oct)	44.8	53.5	19.6

Note: The deviation of runoff volume (D_v) is calculated for each observation period using Equation 4.2.

APPENDIX B

Precipitation data from three meteorological stations



Note: Brule Creek Meteorological Station, Upsala (AUT) Meteorological Station and Atikokan (marmion) Meteorological Stations are approximately 9.5 km SSE, 40 km NE and 50 km W of Chief Peter watershed respectively.

Figure B.1 Daily precipitation data recorded over the three meteorological stations in 2006.

Table B.1 Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2006.

Date	**Atikokan (marmion) precipitation (mm)**	**Brule Creek Precipitation (mm)**	**Upsala (AUT) precipitation (mm)**
1-May-06	2.0	No data	0
2-May-06	6.4	No data	2.5
3-May-06	5.4	No data	4.3
4-May-06	0.8	No data	2.3
5-May-06	0.0	No data	1.8
6-May-06	0.0	No data	0
7-May-06	0.0	No data	0
8-May-06	2.4	No data	0
9-May-06	3.8	No data	8.5
10-May-06	0.0	No data	0
11-May-06	4.5	No data	0.6
12-May-06	11.0	No data	16.5

Table B.1 cont. Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2006.

Date	Atikokan (marmion) precipitation (mm)	Brule Creek Precipitation (mm)	Upsala (AUT) precipitation (mm)
13-May-06	0.4	No data	0
14-May-06	0.0	No data	0.6
15-May-06	0.0	No data	0
16-May-06	0.0	No data	2.2
17-May-06	0.0	No data	0
18-May-06	0.0	No data	0
19-May-06	0.0	No data	0
20-May-06	3.2	No data	1.5
21-May-06	0.0	No data	0
22-May-06	0.0	No data	0
23-May-06	0.6	No data	0
24-May-06	0.0	No data	9.5
25-May-06	0.0	No data	0
26-May-06	0.4	No data	0
27-May-06	0.0	No data	0
28-May-06	0.0	No data	3.2
29-May-06	15.4	No data	4.2
30-May-06	0.0	No data	0
31-May-06	0.0	No data	0
1-Jun-06	5.8	No data	5.9
2-Jun-06	0.0	No data	0
3-Jun-06	0.0	No data	0
4-Jun-06	1.2	No data	0
5-Jun-06	10.4	No data	0
6-Jun-06	1.0	No data	9.5
7-Jun-06	0.0	No data	0
8-Jun-06	0.0	No data	0
9-Jun-06	0.0	No data	0
10-Jun-06	0.0	No data	0
11-Jun-06	0.0	No data	0
12-Jun-06	7.2	No data	0
13-Jun-06	0.4	No data	10.1
14-Jun-06	0.0	No data	0
15-Jun-06	1.4	No data	0.7
16-Jun-06	0.0	0.0	11.3
17-Jun-06	0.0	0.0	0.6

Table B.1 cont. Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2006.

Date	**Atikokan (marmion) precipitation (mm)**	**Brule Creek Precipitation (mm)**	**Upsala (AUT) precipitation (mm)**
18-Jul-06	0.0	0.0	0
19-Jul-06	0.0	0.0	0
20-Jul-06	0.0	0.0	0
21-Jul-06	3.2	0.0	1.1
22-Jul-06	2.4	0.0	0
23-Jul-06	18.0	0.0	27.5
24-Jul-06	0.0	0.0	0
25-Jul-06	0.4	0.0	0
26-Jul-06	0.0	0.0	0
27-Jul-06	0.0	0.0	0
28-Jul-06	0.2	0.0	0
29-Jul-06	0.0	0.0	0
30-Jul-06	132.8	5.6	5.9
31-Jul-06	4.8	83.3	23.5
1-Aug-06	0.0	0.0	0
2-Aug-06	0.0	0.0	0
3-Aug-06	0.0	0.0	3.8
4-Aug-06	1.6	0.8	2.8
5-Aug-06	0.2	0.3	3.5
6-Aug-06	0.0	0.0	0
7-Aug-06	0.0	0.0	0
8-Aug-06	0.0	0.0	0
9-Aug-06	0.0	2.0	1
10-Aug-06	0.0	0.0	0
11-Aug-06	0.0	0.0	0
12-Aug-06	14.6	0.0	0
13-Aug-06	0.0	3.8	26.3
14-Aug-06	0.0	0.0	0
15-Aug-06	0.0	0.0	0.6
16-Aug-06	0.0	0.0	0
17-Aug-06	0.0	1.8	0
18-Aug-06	0.0	4.8	0
19-Aug-06	0.0	1.3	0
20-Aug-06	0.0	0.0	0
21-Aug-06	0.0	0.0	0
22-Aug-06	5.8	0.0	0

Table B.1 cont. Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2006.

Date	**Atikokan (marmion) precipitation (mm)**	**Brule Creek Precipitation (mm)**	**Upsala (AUT) precipitation (mm)**
23-Aug-06	0.0	0.0	1.6
24-Aug-06	0.0	0.0	0
25-Aug-06	1.4	0.0	0
26-Aug-06	0.4	0.0	0.7
27-Aug-06	0.0	0.8	0
28-Aug-06	0.0	0.0	0
29-Aug-06	0.0	0.0	0
30-Aug-06	0.0	0.0	0
31-Aug-06	0.0	0.0	0

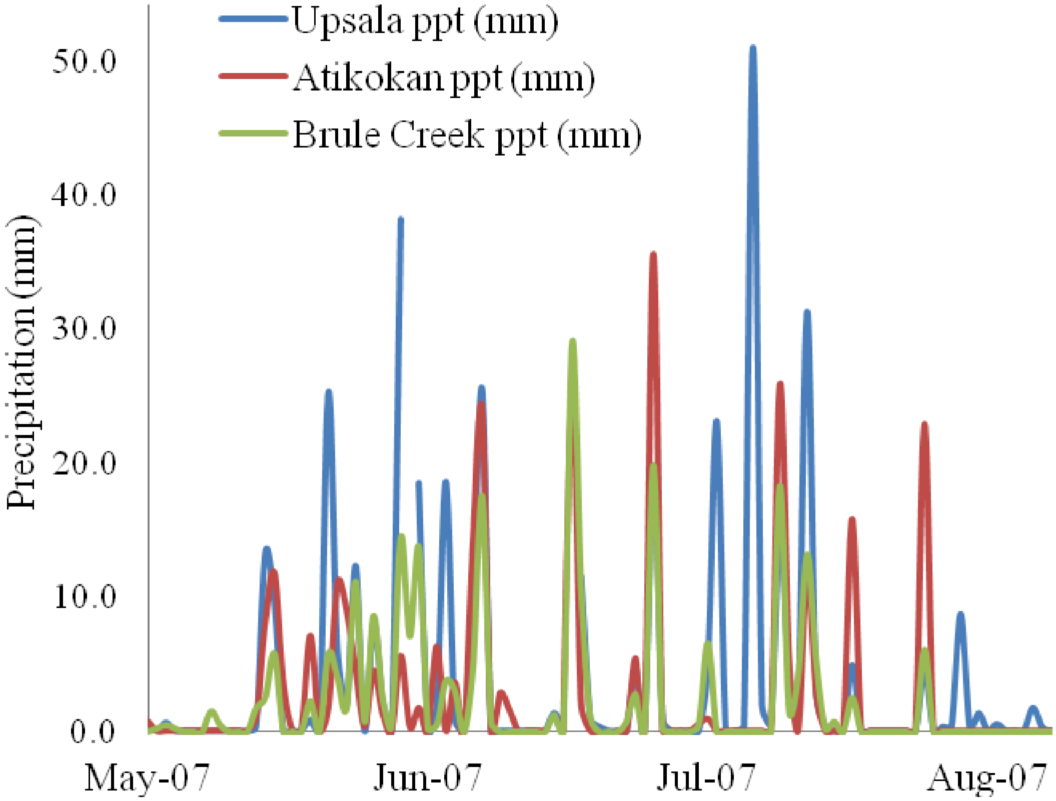


Figure B.2 Daily precipitation data recorded from the three meteorological stations in 2007.

Table B.2 Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2007.

Date	**Atikokan (marmion) precipitation (mm)**	**Brule Creek Precipitation (mm)**	**Upsala (AUT) precipitation (mm)**
1-May-07	0.7	0.0	0.4
2-May-07	0	0.3	0
3-May-07	0	0.5	0.6
4-May-07	0	0.3	0
5-May-07	0	0.0	0
6-May-07	0	0.0	0
7-May-07	0	0.0	0
8-May-07	0	1.5	0
9-May-07	0	0.5	0
10-May-07	0	0.0	0
11-May-07	0	0.0	0
12-May-07	0	0.0	0
13-May-07	1	1.8	0.3
14-May-07	8.1	2.5	13.3
15-May-07	11.8	5.8	9.7
16-May-07	3.5	0.0	0
17-May-07	0	0.0	0
18-May-07	0	0.0	0
19-May-07	7.1	2.3	0.8
20-May-07	0	0.0	0
21-May-07	1.7	5.8	25.3
22-May-07	11	4.1	6
23-May-07	9	1.8	1.9
24-May-07	4.6	11.2	12.3
25-May-07	0.3	0.8	0
26-May-07	4.5	8.6	8.1
27-May-07	1.3	2.5	2.3
28-May-07	0	0.5	0
29-May-07	5.6	14.5	38.2
30-May-07	0.3	7.1	
31-May-07	1.7	13.7	18.5
1-Jun-07	0	0.3	0
2-Jun-07	6.3	0.5	2
3-Jun-07	0	3.8	18.6
4-Jun-07	3.6	3.0	0.8
5-Jun-07	0	0.0	0

Table B.2 cont. Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2007.

Date	**Atikokan (marmion) precipitation (mm)**	**Brule Creek Precipitation (mm)**	**Upsala (AUT) precipitation (mm)**
6-Jun-07	14.3	4.8	9.4
7-Jun-07	24	17.5	25.5
8-Jun-07	0	0.8	0
9-Jun-07	2.8	0.0	0
10-Jun-07	1.6	0.0	0
11-Jun-07	0	0.0	0
12-Jun-07	0	0.0	0
13-Jun-07	0	0.0	0
14-Jun-07	0	0.0	0
15-Jun-07	0	1.3	1.3
16-Jun-07	0	0.0	0
17-Jun-07	25.5	29.0	
18-Jun-07	1.9	10.4	11.5
19-Jun-07	0	1.0	0.9
20-Jun-07	0	0.0	0.3
21-Jun-07		0.0	0
22-Jun-07	0	0.0	0
23-Jun-07	0	0.8	0
24-Jun-07	5.4	2.8	4.7
25-Jun-07	0	0.0	0
26-Jun-07	35.6	19.8	19.8
27-Jun-07	0	0.3	0.8
28-Jun-07	0	0.0	0
29-Jun-07	0	0.0	0
30-Jun-07	0	0.0	0
1-Jul-07	0.5	0.5	0
2-Jul-07	0.9	6.6	4.8
3-Jul-07	0	0.0	23.1
4-Jul-07	0	0.0	0
5-Jul-07	0	0.0	0
6-Jul-07	0	0.0	0.4
7-Jul-07	0	0.0	51
8-Jul-07	0	0.0	1.9
9-Jul-07	0	0.0	0.4
10-Jul-07	25.9	18.3	15
11-Jul-07	5.5	1.5	3.6

Table B.2 cont. Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2007.

Date	Atikokan (marmion) precipitation (mm)	Brule Creek Precipitation (mm)	Upsala (AUT) precipitation (mm)
12-Jul-07	0	4.1	1.9
13-Jul-07	11.9	13.2	31.3
14-Jul-07	2.7	5.3	2.8
15-Jul-07	0	0.3	0.3
16-Jul-07	0	0.8	0
17-Jul-07	0	0.0	0
18-Jul-07	15.8	2.5	4.9
19-Jul-07	0	0.0	0
20-Jul-07	0	0.0	0
21-Jul-07	0	0.0	0
22-Jul-07	0	0.0	0
23-Jul-07	0	0.0	0
24-Jul-07	0	0.0	0
25-Jul-07	0	0.0	0
26-Jul-07	22.9	6.1	4.5
27-Jul-07	0	0.0	0
28-Jul-07	0	0.0	0.3
29-Jul-07	0	0.0	0.4
30-Jul-07	0	0.0	8.7
31-Jul-07	0	0.0	0.3
1-Aug-07	0	0.0	1.3
2-Aug-07	0	0.0	0
3-Aug-07	0	0.0	0.5
4-Aug-07	0	0.0	0
5-Aug-07	0	0.0	0
6-Aug-07	0	0.0	0
7-Aug-07	0	0.0	1.7
8-Aug-07	0	0.0	0.3
9-Aug-07	0	0.0	0
10-Aug-07	0	0.0	0
11-Aug-07	0	0.0	0
12-Aug-07	0	0.0	0
13-Aug-07	0	0.0	0
14-Aug-07	0	0.0	0
15-Aug-07	5.2	2.8	3.6
16-Aug-07	0	0.0	0

Table B.2 cont. Precipitation data from Environment Canada Weather Stations and Brule Creek Meteorological Station from May to August 2007.

Date	**Atikokan (marmion) precipitation (mm)**	**Brule Creek Precipitation (mm)**	**Upsala (AUT) precipitation (mm)**
17-Aug-07	0	0.0	0
18-Aug-07	0	0.0	0
19-Aug-07	0	0.0	0
20-Aug-07	0	0.0	0
21-Aug-07	0	12.7	0
22-Aug-07	0	0.0	0
23-Aug-07	0	0.0	0
24-Aug-07	0	0.0	0.3
25-Aug-07	0	0.0	0
26-Aug-07	0	0.0	0
27-Aug-07	5.9	15.0	9.3
28-Aug-07	0	0.8	0
29-Aug-07	0	0.0	0
30-Aug-07	0	0.0	0
31-Aug-07	0	0.0	0