Preliminary Watershed Hydrology Model for Reclaimed Oil Sands Sites

B.M. Watson and G. Putz

University of Saskatchewan

October 2013

Oil Sands Research and Information Network

Oil Sands Research and Information Network

The Oil Sands Research and Information Network (OSRIN) is a university-based, independent organization that compiles, interprets and analyses available knowledge about managing the environmental impacts to landscapes and water impacted by oil sands mining and gets that knowledge into the hands of those who can use it to drive breakthrough improvements in regulations and practices. OSRIN is a project of the University of Alberta's School of Energy and the Environment (SEE). OSRIN was launched with a start-up grant of $4.5 million from Alberta Environment and a $250,000 grant from the Canada School of Energy and Environment Ltd.

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Citation

This report may be cited as:

Watson, B.M. and G. Putz, 2013. Preliminary Watershed Hydrology Model for Reclaimed Oil Sands Sites. Oil Sands Research and Information Network, University of Alberta, School of Energy and the Environment, Edmonton, Alberta. OSRIN Report No. TR-39. 193 pp.

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REPORT SUMMARY

The main goal of this research project was to take the first steps towards development of an integrated hydrologic and water quality model to support oil sands mine reclamation efforts in Alberta. The model utilized in this study is a modified version of the Soil and Water Assessment Tool (SWAT), which has been called $SWAT_{BF}$. This report provides a detailed description of the $SWAT_{BF}$ model, a list of the key parameters (and their ranges) utilized in $SWAT_{BF}$ and the availability of data sets in the oil sands geographic area to set up and operate $SWAT_{BF}$. Furthermore, an application of the model to five regional watersheds and an industrial reclaimed watershed is described and discussed. Recommendations for further research directions are also provided.

Currently there are few high quality data sets available for reclaimed watersheds in the oil sands region that can be used to stringently test the performance of $SWAT_{BF}$ or similar models. Although several good quality data sets do exist in the oil sands region, they were not available to the authors of this report for testing purposes. The model was applied to five regional watersheds in the oil sands geographic area for the period 1976 to 1993. The overall performance of the model for predicting the long-term water yield from these regional watersheds was deemed to be satisfactory based upon statistical comparisons of predicted and measured streamflow. The modelling results for the regional watersheds were encouraging and demonstrate that $SWAT_{BF}$ has the potential to be utilized as a practical tool for conducting hydrologic assessments in the oil sands geographic area. It may also be suitable for water quality modelling purposes following future data collection. Limited data sets were available from the Wapisiw Lookout reclaimed watershed, which was constructed by Suncor Energy Inc. Using runoff estimates derived from changes in the water level of the Wapisiw wetland, it was possible to test calibrate $SWAT_{BF}$ for 2011 and 2012. The results achieved for 2011 were deemed to be good. It is recommended that further testing of the model on reclaimed watersheds be undertaken using high quality data sets. The data that are scheduled to be collected from the Wapisiw Lookout watershed by the Forest Watershed and Riparian Disturbance (FORWARD) Project will be used to further improve the performance of $SWAT_{BF}$ and extend its capabilities to chemical transport. However, it will take several years to collect the data sets necessary to further develop $SWAT_{BF}$ into a useful management tool to support reclamation efforts in the oil sands. Several proprietary data sets exist in the oil sands that, if made available, may expedite this research effort. The authors have made several recommendations on how future research efforts should proceed to aid and further develop the capabilities of $SWAT_{BF}$ for reclaimed watersheds in the oil sands region.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance and support of the following organizations and individuals. Without their input the project outcomes would not have been possible.

The Oil Sands Research and Information Network (OSRIN), School of Energy and the Environment (SEE), University of Alberta provided funding for this project.

Dr. Brett Purdy and Dr. Robert Magai (Alberta Environment) for providing guidance on the availability of data sets in the oil sands region and for providing several GIS data sets.

Dr. Preston McEachern (Tervita Corporation) for providing guidance and assistance on the availability of regional watershed studies in the oil sands geographic area.

Dr. Xiaoying Fan (Suncor) and Suncor Energy Inc. for providing access to internal unpublished data and reports on the Wapisiw Lookout site used in the reclaimed watershed preliminary modelling.

The staff of the Alberta Government Library, Great West Life site, Edmonton, Alberta.

Warren Wulff (Environment Canada), Head Librarian, National Hydrology Research Centre Library, Saskatoon, Saskatchewan at NHRC.

Toomas Parrat (University of Saskatchewan) for providing assistance with the LIDAR data for the Wapisiw Lookout watershed and analyzing the Wapisiw Pond water levels.

1 INTRODUCTION

It is expected that significant quantities of oil will be extracted by mining operations in the oil sands region in northeast Alberta, Canada, in the coming decades. Large tracts of boreal forest will be disturbed as a result of the mining operations taking place across the region. The impacts of this disturbance on the hydrological cycle are as yet undetermined. To complicate matters further, resource companies working in the oil sands region must reclaim the land so that it achieves equivalent capability as the pre-disturbance conditions. The changes in land use expected to occur across the oil sands region in the next few decades will have a significant impact on the water yield and water quality of rivers and creeks across the region. Therefore, there is an urgent need to develop and utilize integrated hydrologic and water quality models for evaluating reclaimed watershed design in the oil sands region such that equivalent capability can be achieved.

Over the last two decades the Forest Watershed and Riparian Disturbance (FORWARD) Project has engaged in an extensive monitoring and research program to understand the impacts of natural and anthropogenic disturbance in forested watersheds on the Boreal Plain. The results of FORWARD so far have indicated that vegetation, streamflow, water quality and bio-indicators follow predictable impact and recovery trajectories. A watershed scale model was developed using the Soil and Water Assessment Tool (SWAT), which has been utilized extensively by watershed managers around the world. SWAT has been modified for boreal forest watersheds by researchers at the University of Saskatchewan. The modified model, referred to as $SWAT_{BF}$, has since been successfully applied (based upon statistical comparisons of predicted and measured streamflow) to several reference watersheds monitored by FORWARD for the forestry sector in Alberta. In addition, a hydrologic modelling framework utilizing $SWAT_{BF}$ has been developed to model changes in water yield from harvested sites. The framework has since been a central planning tool used in two detailed forest management plans. Given the previous success of $SWAT_{BF}$ in Alberta, industry, government and academic partners have embarked on an extension of FORWARD to oil sand mining in Alberta.

At the request of funding partners, FORWARD extension to the oil sands was initiated with a current state evaluation beginning with the calibration and testing of $SWAT_{BF}$ from currently available data. In order to test the suitability of $SWAT_{BF}$ for oil sands mine reclamation, the soil, vegetation, meteorological and hydrological data sets collected from reclaimed watersheds over the past decade need to be compiled and used to set-up and calibrate the model. These data sets exist in several forms including theses, journal papers, grey literature (internal and external reports) and resource company and consultant databases.

The primary objective of this project is to utilize data sets that are available for watersheds in the oil sands region, assess their suitability for setting up and operating $SWAT_{BF}$ and to provide a summary report on the data and data gaps that FORWARD must fill over the next five years. A second objective is to apply $SWAT_{BF}$ to a reclaimed watershed using existing data sets as a preliminary test case. The second objective is contingent upon the existence and availability of the required data.

The current project is an initial exploratory step in preparation for a larger research program to develop, test and improve models of streamflow, water quality and vegetation at reclamation sites across the oil sands region. The oil sands industry has indicated a desire to make reports and unpublished or draft material available for this compilation effort to focus efforts on the larger research program.

This report contains the following elements:

- A comprehensive description of the theory behind $SWAT_{BF}$
- A list of key parameters (and their range) associated with $SWAT_{BF}$
- A summary of the data sets available for selected regional and reclaimed watersheds
- Results from preliminary applications of $SWAT_{BF}$
- Recommendations for further research required in Phase 2 of FORWARD III

2 DESCRIPTION OF SWAT

2.1 Background

Chapter 2 provides a comprehensive description of SWAT. $SWAT_{BF}$, a modified version of SWAT that was developed for boreal forests, is described in Chapter 3. Hence it is first necessary to describe SWAT in some detail since much of the underlying theory and equations used by SWAT are also used in $SWAT_{BF}$. Most of the following two chapters are based upon: Neitsch et al. (2005a,b), Watson (2006), Watson et al. (2008) and Watson and Putz (2012). A number of sections in Section 2.2 have been taken directly from Chapter 2 of Watson (2006).

2.2 Description of SWAT

2.2.1 *Overview*

The Soil and Water Assessment Tool (SWAT) is a semi-distributed conceptual model that operates continuously on a daily time step (Arnold et al. 1998). It is a comprehensive tool that enables the impacts of land management practices on water, sediment, nutrient and pesticide[1] yields to be predicted over long periods of time for watersheds that have varying soils, land use and management practices (Neitsch et al. 2005a). SWAT was developed to simulate the major processes of the hydrological cycle and their interactions as simply and realistically as possible and to use input data that are readily available for large scale watersheds so that it can be used in planning and decision making (Ogden et al. 2001). One of the main advantages of SWAT is that it is computationally efficient for even the largest of watersheds, which makes it of great value to land and water resources managers. The model was designed for the prediction of long-term

[1] The SWAT theoretical documentation (Neitsch et al. 2005a) discusses transport and transformation processes that contribute to the export of pesticides (agricultural chemicals) from agricultural fields to the watershed outlet. The same terminology is used in this report for consistency. The term *pesticide* can be interpreted more generally as *chemical species*.

yields rather than single flood events (Arnold et al. 1998). Therefore, a high degree of accuracy in predicting individual daily hydrographs is not the objective as for models that are used for flood control planning and flood forecasting (Arnold and Williams 1995).

2.2.2 *Development of SWAT*

The development of SWAT has taken place over the past thirty years. SWAT is a direct outgrowth of SWRRB (Simulator for Water Resources in Rural Basins) (Arnold and Williams 1995), which is a continuous time step model capable of simulating watersheds several hundred square kilometres in size. The model also incorporates features of several other hydrologic models including CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel and Williams 1995), EPIC (Erosion-Productivity Impact Calculator) (Williams 1995) and GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al. 1987). SWRRB was originally developed from CREAMS, which is a field-scale model designed to predict the impacts of land management on water, sediment, nutrients and pesticides leaving the edge of the field. The main limitations of SWRRB were that a watershed could not be subdivided into more than ten subwatersheds and water and sediment loadings from each subwatershed were routed directly to the outlet of the watershed. These limitations led to the development of a model called ROTO (Routing Outputs to Outlet) (Arnold et al. 1995), which took outputs from multiple SWRRB runs and routed the flows through a channel network (Neitsch et al. 2005a). The limitation on the number of subwatersheds was overcome by "linking" multiple SWRRB runs together (Neitsch et al. 2005a). However, the arrangement proved cumbersome. Consequently, SWRRB and ROTO were combined to form a single model which became known as SWAT. Since its development in the 1990s, SWAT has been continually updated and revised to improve various components of the model and to extend its capabilities. A detailed history of the development of SWAT can be found in Neitsch et al. (2005a) and Gassman et al. (2007).

2.2.3 *Discretization Scheme*

SWAT uses a two-level discretization scheme to represent the spatial variability of topography, land use and soils that exists across large watersheds. An overview of the discretization scheme employed by SWAT is provided below.

2.2.3.1 Subwatersheds

In the first level, a watershed is subdivided into any number of subwatersheds. Subwatersheds possess a geographic position in the watershed and are spatially related to one another (Neitsch et al. 2005b). The boundaries of the subwatersheds are defined by surface topography so that water from all parts of a subwatershed flows to the subwatershed outlet. The advantage of a subwatershed discretization scheme is that it preserves routing reaches and topographic flow paths unlike a grid cell discretization scheme (Neitsch et al. 2005b). Figure 1 provides an example of how a watershed is discretized into subwatersheds.

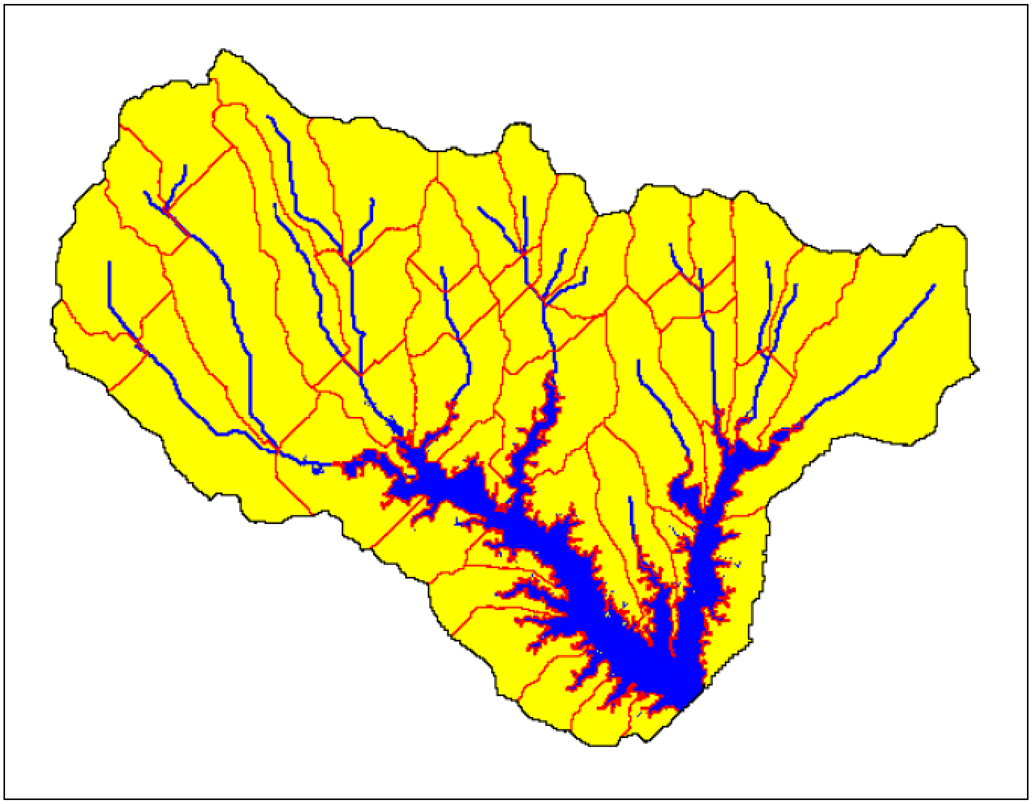

Figure 1. Subwatershed delineation of the Lake Fork watershed in Texas (Neitsch et al. 2005a).

2.2.3.2 Hydrologic Response Units

In the second level, subwatersheds are subdivided into Hydrologic Response Units (HRUs)[2], which are lumped land areas that are comprised of unique land use and soil type combinations. Each HRU is considered as homogenous in its parameter values (Beven 2001). HRUs in SWAT do not possess a specific geographical position and therefore no spatial relationship exists between them. The loadings of water, sediment, nutrients and pesticides from each HRU are calculated separately and then summed together to determine the total loadings from the subwatersheds (Neitsch et al. 2005b).

The benefit of HRUs is the increase in accuracy it adds to the prediction of loadings from the subwatersheds (Neitsch et al. 2005b). The growth and development of different species of plants can vary significantly. HRUs capture the diversity of plants within a subwatershed which enables the model to reflect differences in evapotranspiration, runoff and groundwater recharge generated from different vegetated areas within a subwatershed. Accounting for the

[2] The concept of HRUs have been used by numerous authors resulting in many variations in definition and application. The formulation specifically used within SWAT is described here.

heterogeneities within a subwatershed is also important for predicting the impacts of land use change on water yield and water quality. It is generally recommended that no more than 10 HRUs be defined for any given subwatershed (Neitsch et al. 2005b).

2.2.3.3 Main Channels

One main channel is associated with each subwatershed. The loadings of water, sediment, nutrients and pesticides from a subwatershed enter the channel network in the associated reach segment as well as the outflow from the upstream reach segment (Neitsch et al. 2005b). The loadings are then routed through the channel network to the outlet of the watershed.

2.2.4 *Land and Channel Routing Phases of the Hydrologic Cycle*

The hydrologic processes that occur within a watershed are represented as two separate divisions by SWAT (Neitsch et al. 2005a). The first division is the land phase which determines the loadings of water, sediment, nutrients and pesticides that reach the main channel in each subwatershed. The second division is the channel routing phase which can be defined as the movement of water, sediment, nutrients and pesticides through the channel network to the watershed outlet. Brief descriptions of the main processes simulated for the land and channel routing phases are presented below.

2.2.4.1 Land Phase of the Hydrologic Cycle

The climate of a watershed provides the moisture and energy inputs that control the land phase of the hydrological cycle in SWAT. The climatic variables required by SWAT include daily precipitation, maximum and minimum air temperature, solar radiation, relative humidity and wind speed (Neitsch et al. 2005a). Rainfall is intercepted by the canopy of the vegetation. The rainfall that reaches the ground surface becomes surface runoff or infiltrates into the soil. The infiltrated water contributes to streamflow as lateral flow, percolates to underlying soil layers and is returned to the atmosphere via evapotranspiration. Water that exits the bottom of the root zone recharges the shallow and deep aquifers. The model also accounts for the transport of sediments, nutrients and pesticides to the main channel in the land phase of the hydrologic cycle. A schematic representation of the main processes simulated by SWAT in the land phase of the hydrologic cycle is presented in Figure 2.

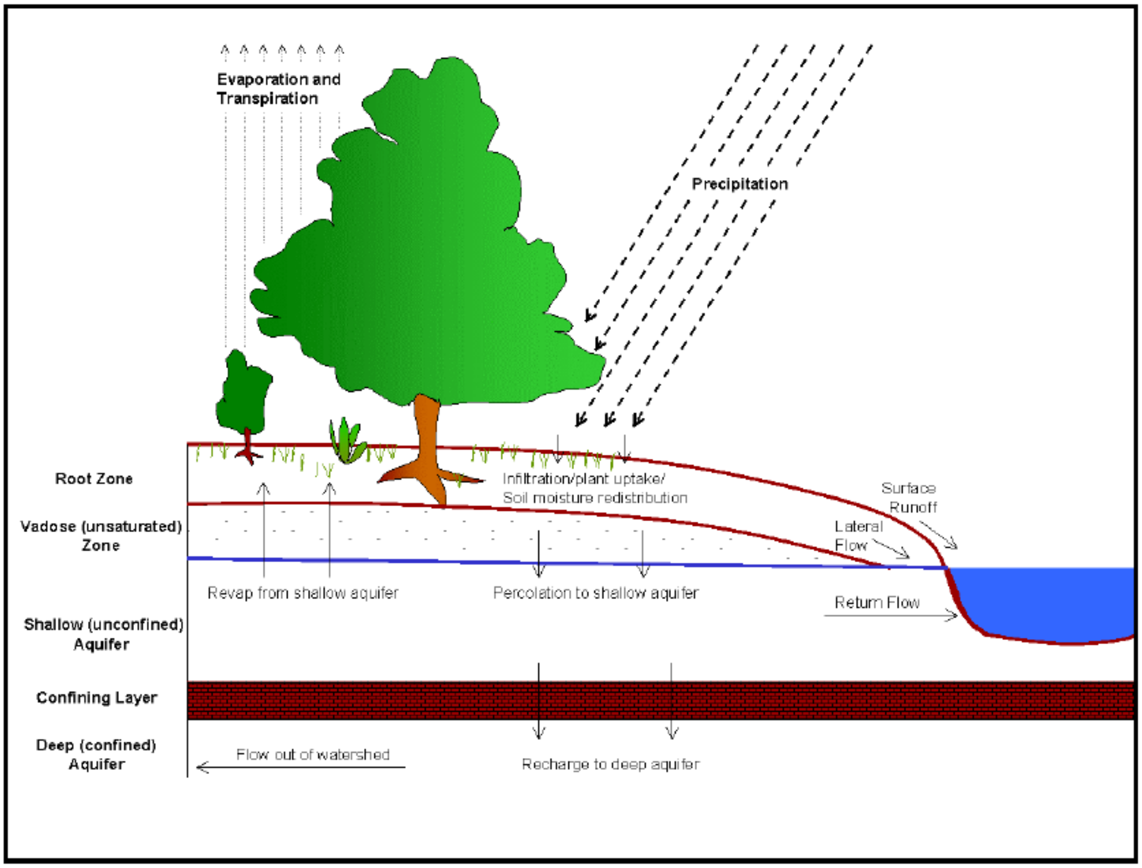

Figure 2. Schematic representation of the hydrologic cycle as simulated by SWAT (Neitsch et al. 2005a).

The water balance equation of the root zone (soil profile) is given by:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - E_a - Q_{surf} - Q_{lat} - w_{seep}\right)$$

Where SW_t = final soil water content (mm)

SW_0 = initial soil water content on day i (mm)

t = time (d)

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

E_a = amount of evapotranspiration on day i (mm)

Q_{surf} = amount of surface runoff on day $_i$ (mm)

Q_{lat} = amount of lateral flow on day i (mm)

w_{seep} = amount of percolation exiting the root zone on day i (mm)

SWAT allows a maximum of 10 soil layers to be defined within the soil profile.

2.2.4.2 Channel Routing Phase of the Hydrologic Cycle

The loadings of water, sediment, nutrients and pesticides to the main channel are determined in the land phase of the hydrologic cycle. The loadings must then be routed through the channel network of the watershed. This is the channel routing phase of the hydrologic cycle. Main channel processes simulated by SWAT include the movement of water, sediment, nutrients and pesticides in the stream network as well as in-stream nutrient cycling and in-stream pesticide transformations (Neitsch et al. 2005a). The in-stream processes modelled by SWAT are illustrated in Figure 3.

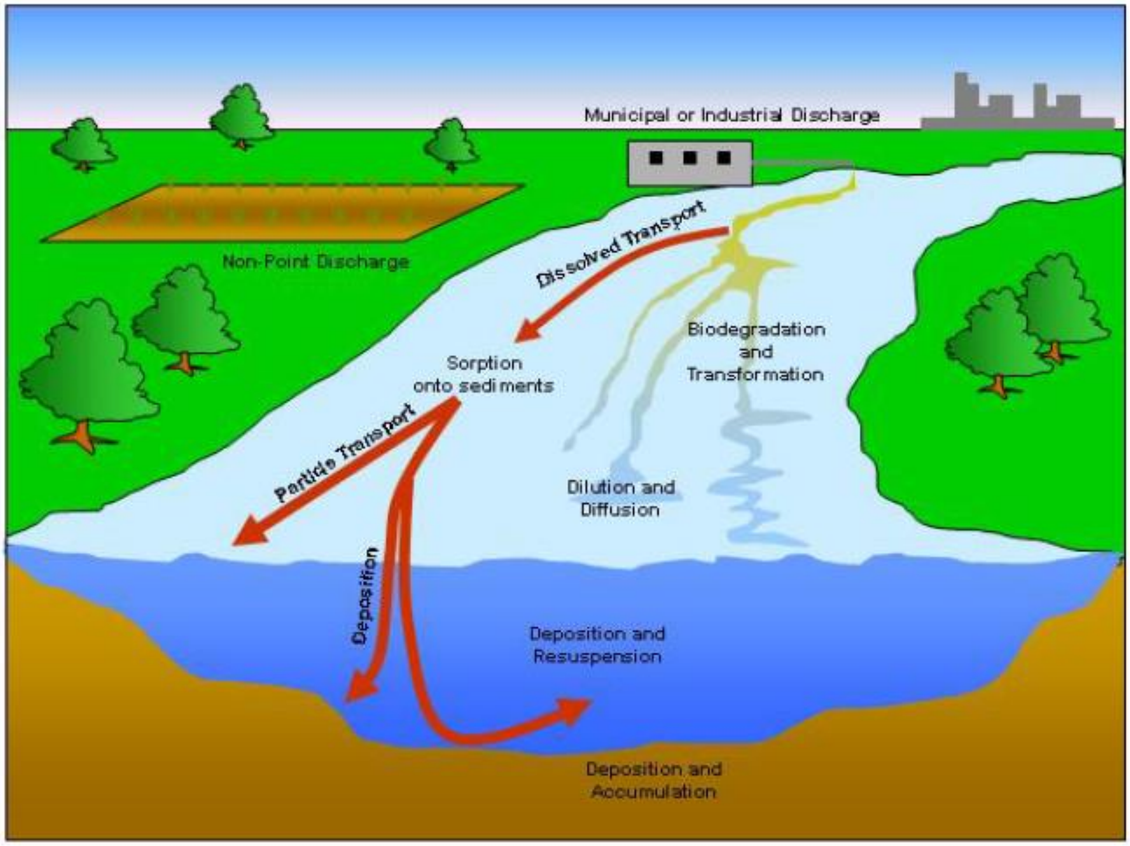

Figure 3. In-stream processes modelled by SWAT (Neitsch et al. 2005a).

2.2.5 *Hydrology*

2.2.5.1 Snow Cover

Precipitation is classified as rain or snow in SWAT using the daily air temperature. If the mean daily air temperature is less than the threshold temperature, which is defined by the user, then the precipitation is classified as snow and the water equivalent of the snow precipitation is added to the snow pack. Snowfall is stored at the ground surface in the form of a snow pack. The snow pack will increase in response to snowfall and decrease in response to snow melt or sublimation.

The mass balance for the snow pack is:

$$SNO = SNO + R_{day} - E_{sub} - SNO_{mlt}$$

Where SNO = water content of the snow pack on a given day (mm)

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

E_{sub} = amount of sublimation on a given day (mm)

SNO_{mlt} = amount of snow melt on a given day (mm)

The amount of water stored in the snow pack is reported as snow water equivalent.

2.2.5.2 Snow Melt

Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow (Neitsch et al. 2005a). A temperature-index model is used by SWAT to calculate snow melt. The equation used to calculate snow melt is given by:

$$SNO_{mlt} = b_{mlt} \cdot sno_{cov} \cdot \left[\frac{T_{snow} + T_{mx}}{2} - T_{mlt} \right]$$

Where SNO_{mlt} = amount of snow melt on a given day (mm)

b_{mlt} = melt factor for the day (mm/day/°C)

sno_{cov} = fraction of the HRU area covered by snow

T_{snow} = snow pack temperature on a given day (°C)

T_{mx} = maximum air temperature on a given day (°C)

T_{mlt} = base temperature above which snow begins to melt (°C)

2.2.5.3 Canopy Storage

SWAT accounts for interception by a simple canopy storage model. The maximum amount of water that can be stored by the canopy varies from day to day depending upon the leaf area index:

$$can_{day} = can_{mx} \cdot \frac{LAI}{LAI_{mx}}$$

Where can_{day} = maximum amount of water that can be stored in the canopy on a given day (mm)

can_{mx} = maximum amount of water that can be stored in the canopy when the canopy is fully developed (mm)

LAI = leaf area index for a given day (m^2/m^2)

LAI_{mx} = maximum leaf area index for the plant (m^2/m^2)

When precipitation falls on the watershed, the canopy storage must be filled before any water can reach the soil surface. If the capacity of the canopy storage is exceeded, the excess water is the precipitation that reaches the soil surface. If the capacity of the canopy storage is not exceeded, the water is held in storage where it will evaporate back into the atmosphere. The main equations of the canopy storage component are as follows:

$$R_{INT(f)} = R_{INT(i)} + R'_{day} \text{ and } R_{day} = 0 \quad \text{when } R'_{day} \le can_{day} - R_{INT(i)}$$

$$R_{INT(f)} = can_{day} \text{ and } R_{day} = R'_{day} - \left(can_{day} - R_{INT(i)}\right) \quad \text{when } R'_{day} > can_{day} - R_{INT(i)}$$

Where $R_{INT(i)}$ = initial amount of water stored in the canopy on a given day (mm)

$R_{INT(f)}$ = final amount of water stored in the canopy on a given day (mm)

R'_{day} = amount of precipitation on a given day before canopy interception is removed (mm)

R_{day} = amount of precipitation on a given day that reaches the soil surface (mm)

can_{day} = maximum amount of water that can be trapped in the canopy on a given day (mm).

2.2.5.4 Potential Evapotranspiration

Potential evapotranspiration can be calculated using one of three equations in SWAT: Penman-Monteith equation (Monteith 1965), Priestley-Taylor equation (Priestley and Taylor 1972) or Hargreaves equation (Hargreaves et al. 1985). The input data required for each equation varies. The Penman-Monteith equation requires air temperature, solar radiation, relative humidity and wind speed. The Priestley-Taylor equation requires air temperature, solar radiation and relative humidity. The Hargreaves equation only requires air temperature.

The Penman-Monteith equation combines the components that account for the energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapour and aerodynamic and surface resistance terms (Neitsch et al. 2005a). The Penman-Monteith equation is given by:

$$\lambda E = \frac{\Delta \cdot \left(H_{net} - G\right) + \rho_{air} \cdot c_p \cdot \left[e_z^o - e_z\right] / r_a}{\Delta + \gamma \cdot \left(1 + r_c / r_a\right)}$$

Where λE = latent heat flux density (MJ/m^2/d)

E = depth rate evaporation (mm/d)

Δ = slope of the saturation vapour pressure-temperature curve, de/dT (kPa/°C)

H_{net} = net radiation (MJ/m^2/d)

G = heat flux density to the ground (MJ/m^2/d)

ρ_{air} = air density (kg/m^3)

c_p = specific heat at constant pressure (MJ/kg/°C)

e_z^o = saturation vapour pressure of air at height z (kPa)

e_z = water vapour pressure of air at height z (kPa)

γ = psychrometric constant (kPa/°C)

r_c = plant canopy resistance (s/m)

r_a = diffusion resistance of the air layer (aerodynamic resistance) (s/m).

The Priestley-Taylor equation employs a simplified version of the combination equation for use when surface areas are wet. There is no aerodynamic component in the Priestley-Taylor equation and the energy component is multiplied by a coefficient, α_{pet} = 1.28, when the general surroundings are wet or under humid conditions (Neitsch et al. 2005a). It is calculated using the following equation:

$$\lambda E_o = \alpha_{pet} \frac{\Delta}{\Delta + \gamma} \left(H_{net} - G \right)$$

Where λ = latent heat of vaporisation (MJ/kg)

E_o = potential evapotranspiration (mm/d)

α_{pet} = coefficient equal to 1.28

Δ = slope of the saturation vapour pressure-temperature curve, de/dT (kPa/°C)

γ = psychrometric constant (kPa/°C)

H_{net} = net radiation (MJ/m^2/d)

G = heat flux density to the ground (MJ/m^2/d)

The Hargreaves equation, which is the simplest of three potential evapotranspiration equations incorporated into SWAT, is given by:

$$\lambda E_o = 0.0023 \cdot H_0 \cdot \left(T_{mx} - T_{mn} \right)^{0.5} \cdot \left(\overline{T}_{av} + 17.8 \right)$$

Where λ = latent heat of vaporization (MJ/kg)

E_o = potential evapotranspiration (mm/d)

H_0 = extraterrestrial radiation (MJ/m^2/d)

T_{mx} = maximum air temperature for a given day (°C)

T_{mn} = minimum air temperature for a given day (°C)

$\overline{T}_{av}$ = mean air temperature for a given day (°C)

2.2.5.5 Actual Evapotranspiration

Once potential evapotranspiration has been determined, the actual evapotranspiration must be calculated. Precipitation that has been intercepted by the canopy is evaporated first. SWAT utilizes a simple storage compartment approach to account for the storage of water in the canopy. If the amount of precipitation does not exceed the storage capacity of the canopy, then all of the precipitation will be held in the canopy. If the amount of precipitation exceeds the canopy storage capacity, then the excess precipitation will reach the soil surface.

Evaporation from the soil and vegetation is calculated separately using an approach based on Ritchie (1972). Potential transpiration is calculated as a linear function of potential evapotranspiration and LAI. This is the amount of transpiration that will occur when growing conditions for the plant are ideal. The actual transpiration will generally be less than potential transpiration due to the lack of available water in the soil profile. SWAT contains algorithms to calculate actual plant uptake and transpiration. Once the maximum amount of sublimation/soil evaporation for the day has been estimated, SWAT will then remove water from the snow pack (if present) to meet the evaporative demand. When there is an evaporation demand for soil water, SWAT partitions the evaporative demand between the different soil layers. SWAT does not allow one layer to compensate for another layer if it is unable to meet its evaporative demand. This situation results in a reduction in the amount of actual evapotranspiration calculated for the day. When the water content of a soil layer is below field capacity, the evaporative demand is further reduced.

For the sake of brevity, only a brief overview of the actual evapotranspiration component of SWAT has been provided in this subsection of the report. Readers are referred to Neitsch et al. (2005a) for a complete description of the actual evapotranspiration algorithms utilized by SWAT.

2.2.5.6 Surface Runoff

Surface runoff is calculated using the SCS curve number method (USDA-SCS 1972), which is an empirical formulation that was developed in the USA more than 50 years ago. The method was the product of more than 20 years of studies involving relationships between rainfall and runoff for small rural watersheds in the USA (Neitsch et al. 2005a). The SCS curve number method is given by the following equation:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$$

Where Q_{surf} = accumulated runoff or rainfall excess (mm)

R_{day} = rainfall depth for the day (mm)

I_a = initial abstractions (mm)

S = retention parameter (mm)

The initial abstractions include surface storage, interception and infiltration prior to runoff. The retention parameter for average soil moisture conditions is calculated by:

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

Where CN = curve number for the day based upon average soil moisture conditions (antecedent moisture condition II).

SWAT can also calculate the curve number and retention parameter for dry and wet soil moisture conditions based upon wilting point and field capacity for the soil type (antecedent moisture conditions I and III). Readers are referred to Neitsch et al. (2005a) for the equations used by SWAT to calculate curve numbers and retention parameters for antecedent moisture conditions I and III. The initial abstractions (I_a) are commonly approximated as 0.2S. Therefore, Q_{surf} is calculated using the following equation[3]:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}$$

Where Q_{surf} = accumulated runoff or rainfall excess (mm)

R_{day} = rainfall depth for the day (mm)

S = retention parameter (mm)

Runoff will only occur when $R_{day} > I_a$. The rainfall that does not become surface runoff is assumed to infiltrate into the soil.

There is also the option of calculating surface runoff using the Green-Ampt infiltration equation (Green and Ampt 1911). SWAT makes use of a modified version of the Green-Ampt infiltration equation that was developed by Mein and Larson (1973). They developed a methodology for determining ponding time with infiltration. This method requires sub-daily rainfall records be available. The Green-Ampt Mein-Larson infiltration equation is given by:

$$f_{inf,t} = K_e \cdot \left(1 + \frac{\Psi_{wf} \cdot \Delta\theta_v}{F_{inf,t}}\right)$$

Where f_{inf} = infiltration rate at time t (mm/hr)

K_e = effective hydraulic conductivity (mm/hr)

Ψ_{wf} = wetting front matric potential (mm)

$\Delta\theta_v$ = change in volumetric moisture content across the wetting front (mm/mm)

F_{inf} = cumulative infiltration at time t (mm).

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[3] The I_a approximation as 0.2S is hard coded within the SWAT algorithms. Minor coding modifications would allow the user to define I_a as a function of S and calibrate the parameter if desired.

SWAT calculates the amount of water entering the soil for each time step. Surface runoff is generated by the water that does not infiltrate into the soil.

2.2.5.7 Percolation

The percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Water is allowed to percolate from a given soil layer if the soil water content exceeds the field capacity of that layer. The amount of water that percolates from a given soil layer to the underlying soil layer is calculated by the following equation:

$$w_{perc,ly} = SW_{ly,excess}\left(1 - \exp\left[\frac{-\Delta t}{TT_{perc}}\right]\right)$$

Where $w_{perc,ly}$ = amount of water percolating to the underlying soil layer on a given day (mm)

$SW_{ly,excess}$ = drainable volume of water in the soil layer on a given day (mm)

Δt = time step (24 h)

TT_{perc} = travel time for percolation (h)

2.2.5.8 Lateral flow

Lateral flow is calculated for each soil layer using the kinematic storage model (Sloan and Moore 1984, Sloan et al. 1983). The kinematic storage model is a simple storage-discharge model that simulates lateral flow in a two-dimensional cross-section along a flow path down a hillslope. The hydraulic gradient is assumed to be equal to the bed slope according to the kinematic wave approximation (Beven 1981). The kinematic storage model is based on the mass continuity equation with the entire hillslope segment used as the control volume. The kinematic storage model is shown in Figure 4.

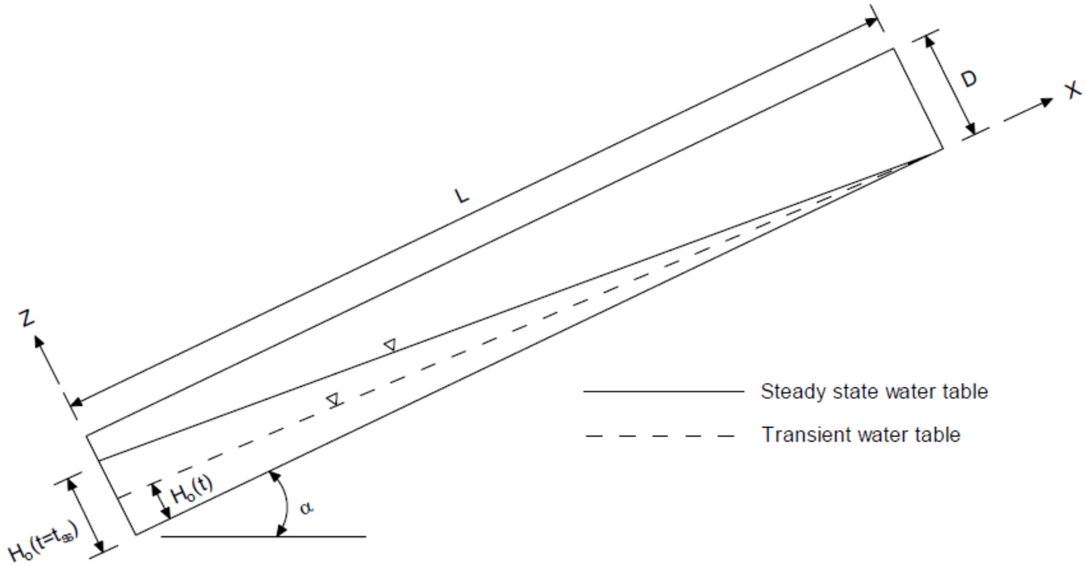

Figure 4.   The kinematic storage model (Sloan and Moore 1984).

The equation used to calculate lateral flow in SWAT is given by:

$$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}} \right)$$

Where Q_{lat} = lateral flow for the soil layer (mm)

$SW_{ly,excess}$ = drainable volume of water in the soil layer (mm)

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

slp = slope (m/m)

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

L_{hill} = hillslope length (m)

0.024 = unit conversion factor.

2.2.5.9 Groundwater Flow

SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes groundwater flow to streams within the watershed and a deep, confined aquifer which contributes groundwater flow to streams outside the watershed (Neitsch et al. 2005a). Water percolating past the bottom of the root zone is partitioned into two fractions with each fraction becoming recharge for one of the aquifers.

The shallow aquifer contributes groundwater flow to the main channel within each subwatershed. Groundwater flow from the shallow aquifer to the stream is estimated using the following equation:

$$Q_{gw,i} = Q_{gw,i-1} \exp^{-\alpha_{gw}\Delta t} + w_{rchrg}\left(1 - \exp^{-\alpha_{gw}\Delta t}\right)$$

Where $Q_{gw,i}$ = groundwater flow into the main channel on day i (mm)

$Q_{gw,i-1}$ = groundwater flow into the main channel on day i-1 (mm)

α_{gw} = baseflow recession constant

Δt = time step (d)

w_{rchrg} = amount of recharge entering the aquifer on day i (mm)

Water stored in the shallow aquifer may move upwards into the root zone in very dry conditions or be removed by deep-rooted vegetation which can uptake water directly from the shallow aquifer (Neitsch et al. 2005a). A fraction of the total daily recharge can also be routed to the deep aquifer. Water that enters the deep aquifer is not considered in any future water budget calculations in SWAT and is lost from the system (Neitsch et al. 2005a).

2.2.6 *Nutrients and Pesticides*

SWAT tracks the movement and transformation of nutrients (nitrogen and phosphorus) and pesticides in several different forms as they move through the watershed. The transformation of nitrogen (N) and phosphorus (P) in the soil is governed by the nitrogen and phosphorus cycles, respectively.

2.2.6.1 Nitrogen Cycle

There are three major forms of nitrogen (N) in mineral soils (Neitsch et al. 2005a):

1. Organic N associated with humus
2. Mineral forms of N held by soil colloids
3. Mineral forms of N in solution

Within SWAT N can be added to the soil through the application of fertilizer, manure or residue, fixation by symbiotic or non-symbiotic bacteria and rain. The processes responsible for N being removed from the soil include plant uptake, leaching, volatilization, denitrification and erosion.

SWAT accounts for five different pools of N in the soil. Two pools consist of mineral forms of N while the other three pools consist of organic forms of N. Fresh organic N is associated with crop residue and microbial biomass while the active and stable organic N pools are associated with the soil humus. Figure 5 shows the N pools accounted for in SWAT and their interactions with one another.

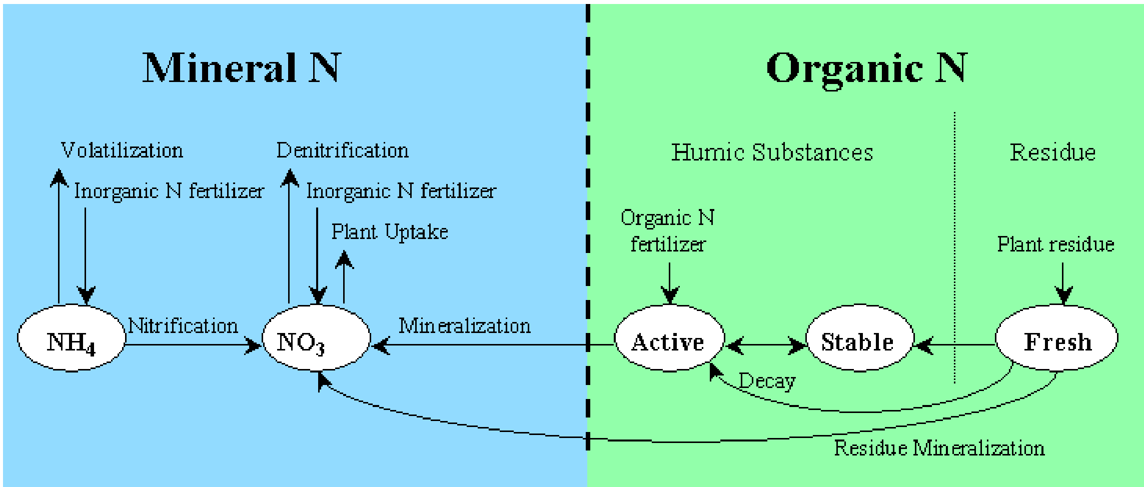

Figure 5. SWAT soil nitrogen (N) pools and processes that move N in and out of pools (Neitsch et al. 2005a).

A supply and demand approach is used to estimate the amount of N used by plants. In this approach the daily plant N demand is calculated as the difference between the actual concentration of the element in the plant and the optimal concentration (Neitsch et al. 2005a). The quantities of N that are transported in surface runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of N in the layer. The amount of organic N transported with sediment is estimated using a loading function that estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio (Neitsch et al. 2005a).

2.2.6.2 Phosphorus Cycle

The three major forms of P in mineral soils are (Neitsch et al. 2005a):

1. Organic P associated with humus
2. Insoluble forms of mineral P
3. Plant-available P in soil solution

Within SWAT P may be added to the soil by the application of fertilizer, manure or residue. The removal of P from the soil occurs through plant uptake and erosion.

SWAT is capable of simulating six different pools of P in the soil. Three pools consist of inorganic forms of P while the other three pools consist of organic forms of P. Fresh organic P is associated with crop residue while the active and stable organic P pools are associated with the soil humus. Mineral P is comprised of three pools, namely the solution, active, and stable pools. The P pools accounted for in SWAT and their interactions with one another are shown in Figure 6.

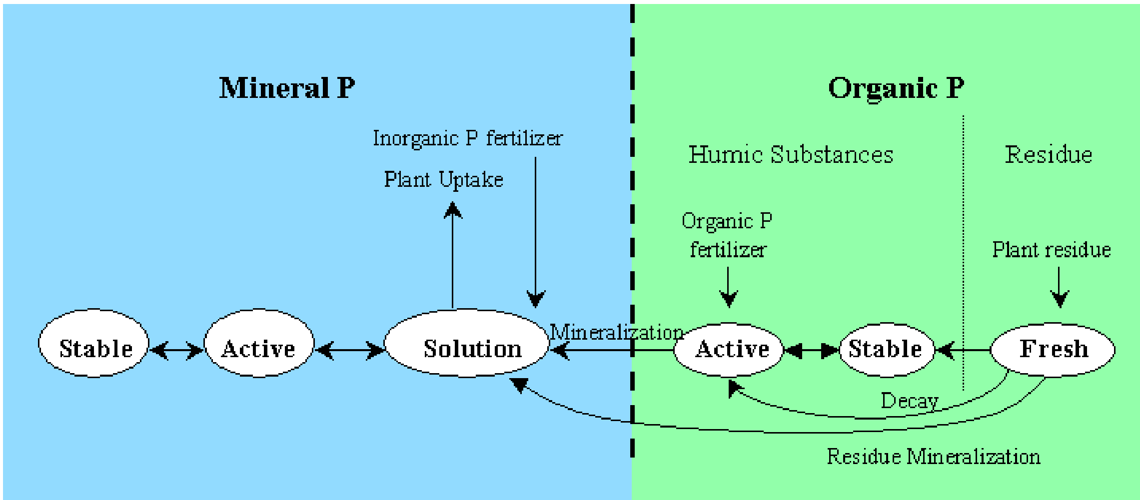

Figure 6. SWAT soil phosphorus (P) pools and processes that move P in and out of pools (Neitsch et al. 2005a).

Plant use of P is estimated using the same supply and demand approach used for the uptake of N. Since P is not a mobile nutrient, interaction between surface runoff with solution P in the top 10 mm of soil will not be complete (Neitsch et al. 2005a). The solution P concentration in the top 10 mm of the soil profile, the runoff volume and a partitioning factor are used to calculate the quantity of soluble P removed in runoff. The loading function used to predict sediment transport of organic N is also used to predict the sediment transport of P.

2.2.6.3 Pesticides

SWAT simulates the movement of pesticides into the main channel by the following two processes: (1) surface runoff (in solution and sorbed to sediment transported by the runoff), and (2) into the soil profile and aquifer by percolation (in solution). The solubility, degradation half-life, and soil organic carbon adsorption coefficient of a pesticide will govern its movement. SWAT accounts for pesticides on the foliage of plants and in the soil profile, which degrades exponentially in accordance with the pesticide half-life. The transportation of pesticides by water and sediment is calculated for each runoff event while the leaching of pesticides is estimated for each soil layer when percolation occurs. The transportation and fate of pesticides as simulated by SWAT is shown in Figure 7.

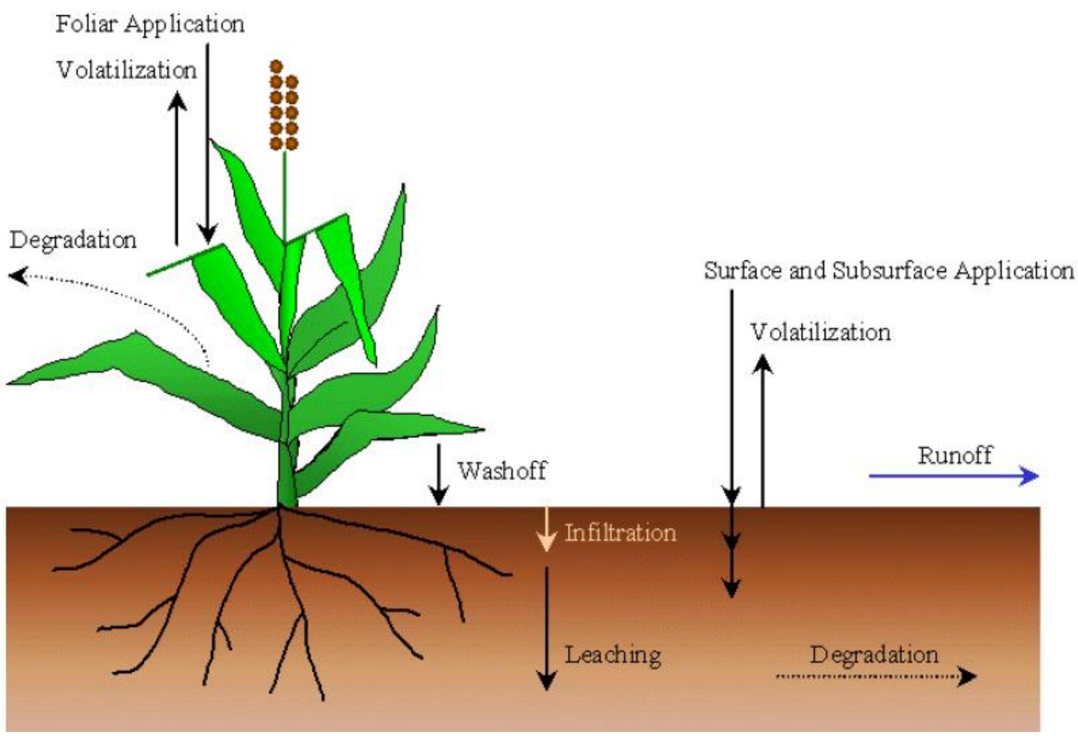

Figure 7. Transportation and fate of pesticides as simulated by SWAT (Neitsch et al. 2005a).

2.2.7 *Erosion*

2.2.7.1 Modified Universal Soil Loss Equation

SWAT employs the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) to calculate erosion and sediment yield. The MUSLE relies on the amount of runoff to simulate erosion and sediment yield instead of the rainfall as is the case with the Universal Soil Loss Equation (USLE). The MUSLE is defined by the following equation:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG$$

Where sed = sediment yield on a given day (metric tons)

Q_{surf} = surface runoff volume (mm/ha)

q_{peak} = peak runoff rate (m^3/s)

$area_{hru}$ = area of the HRU (ha)

K_{USLE} = USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))

C_{USLE} = USLE cover and management factor

P_{USLE} = USLE support practice factor

LS_{USLE} = USLE topographic factor

$CFRG$ = coarse fragment factor.

2.2.8 *Land Cover and Plant Growth Components*

2.2.8.1 Vegetation Growth

SWAT utilizes a single vegetation growth model to simulate the growth and development of all types of vegetation. It is a simplified version of the vegetation growth model used in EPIC. The vegetation growth model is used to assess the removal of water and nutrients from the root zone, transpiration and biomass/yield production (Neitsch et al. 2005a). Several features of the EPIC vegetation growth model not incorporated into SWAT include detailed root growth, micronutrient cycling and toxicity responses and the simultaneous growth of multiple plant species in the same HRU.

Phenological development is based on daily accumulated heat units. The heat unit theory postulates that plants have heat requirements that can be quantified and linked to the time it takes the plant to reach maturity (Neitsch et al. 2005a). The heat unit accumulation for a given day is calculated using the following equation:

$$HU = \overline{T}_{av} - T_{base} \qquad \text{when } \overline{T}_{av} > T_{base}$$

Where HU = number of heat units accumulated on a given day (heat units)

$\overline{T}_{av}$ = mean daily temperature (°C)

T_{base} = plant's base or minimum temperature for growth (°C)

The total number of heat units required for a plant to reach maturity is calculated as follows:

$$PHU = \sum_{d=1}^{m} HU$$

Where PHU = total heat units required for a plant to reach maturity (heat units)

HU = number of heat units accumulated on day d

d = 1 on the day of planting

m = number of days required for a plant to reach maturity.

The potential increase in plant biomass on a given day is defined as the increase in biomass under ideal growing conditions and is estimated as a function of intercepted energy and the efficiency of plants to convert energy to biomass (Neitsch et al. 2005a). The potential increase in biomass for a day is estimated using Beer's law. Leaf Area Index (LAI) is simulated as a function of heat units and biomass. Plant growth may be reduced due to extreme temperatures as well as insufficient water, nitrogen or phosphorus (Neitsch et al. 2005a). The uptake of nitrogen and phosphorus is estimated with a supply and demand approach where the daily plant nitrogen and phosphorus demands are calculated as the difference between the actual concentration of the element in the plant and the optimal concentration.

2.2.8.2 Management Practices

Very detailed management information can be defined by users when setting up SWAT for the watershed that is to be modelled. The management operations incorporated into SWAT can be divided into three main groups: general management, water management and urban areas. The practices that can be accounted for in each group are listed below. Users are referred to Neitsch et al. (2005a) for further details about the management operations in SWAT.

- General Management
  - Planting/beginning of growing season
  - Harvest operation
  - Grazing operation
  - Harvest and kill operation
  - Kill/end of growing season
  - Tillage
  - Fertilizer application
  - Auto-application of fertilizer
  - Pesticide application
  - Filter strips
- Water Management
  - Irrigation
  - Auto-application of irrigation
  - Tile drainage
  - Impounded/topographic depression areas
  - Water transfer
  - Consumptive water use
  - Point source loadings
- Urban Areas
  - Surface runoff from urban areas
  - Build up/wash off

2.2.9 *Main Channel Processes*

2.2.9.1 Water Routing

SWAT employs Manning's equation to calculate the rate and velocity of flow in a reach segment (Neitsch et al. 2005a). Water can be routed through the channel network using either the variable storage routing method or the Muskingum routing method.

The variable storage routing method was developed by Williams (1969). For a given reach segment, storage routing is based on the continuity equation:

$$V_{in} - V_{out} = \Delta V_{stored}$$

Where V_{in} = volume of inflow during the time step (m^3)

V_{out} = volume of outflow during the time step (m^3)

ΔV_{stored} = change in volume of storage during the time step (m^3).

The Muskingum routing method calculates the storage volume of a channel length as a combination of wedge and prism storages. A storage wedge is produced as a result of inflow exceeding outflow when a flood wave advances into a reach segment. A negative wedge is produced when the flood wave recedes because outflow will then exceed inflow. The reach segment also contains a prism of storage formed by a volume of water of constant cross-section along the reach length. The wedge and prism storages of the Muskingum routing method are shown in Figure 8.

The volume of prism storage and volume of wedge storage are summed together to give the total storage of the reach segment:

$$V_{stored} = K \cdot q_{out} + K \cdot X \cdot \left(q_{in} - q_{out}\right)$$

Where V_{stored} = storage volume (m^3)

q_{in} = inflow rate (m^3/s)

q_{out} = discharge rate (m^3/s)

K = storage time constant for the reach (s)

X = weighting factor.

The weighting factor (X) is a function of the wedge storage and has a lower limit of 0 and an upper limit of 0.5.

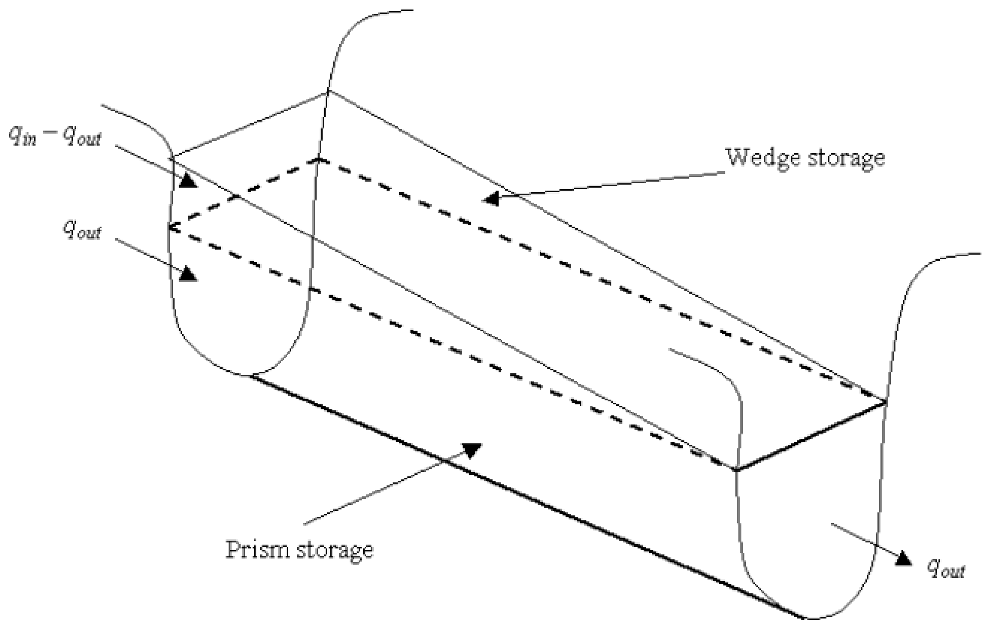

Figure 8. Prism and wedge storages in a reach segment (Neitsch et al. 2005a).

SWAT accounts for water that is lost from the main channel due to evaporation and transmission through the bed of the channel. The addition or removal of water from the channel through diversions can also be taken into account. Flow may be supplemented by rain that falls directly onto the channel as well as the addition of water from point source discharges.

2.2.9.2 Sediment Transport

Sediment transport in the channel network is a function of two processes, namely deposition and degradation, which operate simultaneously (Neitsch et al. 2005a). Using the stream power definition of Bagnold (1977), Williams (1980) developed a method to determine degradation as a function of channel slope and velocity. SWAT uses a simplified version of the Williams (1980) model, with the maximum amount of sediment transported from a reach being a function of peak channel velocity. The equation used to calculate the maximum amount of sediment that can be transported from a reach segment is given by:

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{\ spexp}$$

Where $conc_{sed,ch,mx}$ = maximum concentration of sediment that can be transported by the water (tonne/m^3 or kg/L)

c_{sp} = coefficient defined by the user

$v_{ch,pk}$ = peak channel velocity (m/s)

$spexp$ = an exponent defined by the user.

Available stream power is used to re-entrain loose and deposited material until all of the material is removed (Neitsch et al. 2005a). SWAT also takes into account the process of bed degradation, which is adjusted for stream erodibility and cover.

SWAT provides users with two choices with respect to the dimensions of the channel used throughout the course of the simulation period. Firstly, the same channel dimensions can be used for the entire simulation period when accounting for deposition and degradation. Secondly, it is possible to simulate downcutting and widening of the stream channel and update channel dimensions throughout the simulation period.

2.2.9.3 Nutrient Transport and In-Stream Nutrient Processes

SWAT accounts for nutrient transformations as water moves through the channel network. The in-stream water quality and nutrient transport algorithms incorporated into SWAT have been adopted from the QUAL2E model (Brown and Barnwell 1987). The in-stream water quality component of SWAT is capable of simulating the following variables:

- Algae
  - Chlorophyll A
  - Algal growth
- Nitrogen cycle
  - Organic nitrogen
  - Ammonium
  - Nitrite
  - Nitrate
- Phosphorus cycle
  - Organic phosphorus
  - Inorganic/soluble phosphorus
- Carbonaceous biological oxygen demand
- Oxygen
  - Oxygen saturation concentration
  - Reaeration

2.2.9.4 Pesticide Transport and In-Stream Pesticide Processes

The total number of pesticides that can be applied to any given HRU is unlimited. However, only one pesticide may be transported through the channel network of the watershed due to the complexity of the processes simulated (Neitsch et al. 2005a). Similar to the nutrient transport component described above, SWAT tracks the pesticide dissolved in the stream and the pesticide attached to the sediment. First-order decay relationships govern pesticide transformations in both the dissolved and sorbed phases (Neitsch et al. 2005a). Some of the in-stream pesticide transformations that are accounted for by SWAT include degradation, volatilization, resuspension, settling, diffusion, and burial.

2.2.10 *Water Bodies*

Four types of water bodies can be accounted for in SWAT: ponds, wetlands, depressions/potholes, and reservoirs. Ponds, wetlands, and depressions/potholes are located within a subwatershed off the main channel whereas reservoirs are located on the main channel network. The water that enters any given pond, wetland, and depression/pothole originates from the subwatershed in which that particular water body is located. In contrast, any given reservoir will receive water from all the subwatersheds upstream of that particular water body.

The water balance equation used to update the volume of water stored in ponds, wetlands, depressions/potholes and reservoirs is as follows:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}$$

Where V = volume of water in the impoundment at the end of the day (m^3)

V_{stored} = volume of water stored in the water body at the beginning of the day (m^3)

V_{flowin} = volume of water entering the water body during the day (m^3)

$V_{flowout}$ = volume of water flowing out of the water body during the day (m^3)

V_{pcp} = volume of precipitation falling on the water body during the day (m^3)

V_{evap} = volume removed from the water body by evaporation during the day (m^3)

V_{seep} = volume of water lost from the water body by seepage (m^3).

The methods used to calculate the terms on the right hand side of the equation can be different depending upon the type of water body. For example, pond outflow is calculated as a function of target storage whereas wetland outflow occurs whenever the water volume exceeds the normal storage volume.

2.2.11 *Sensitivity Analysis*

van Griensven (2003) developed the Latin Hypercube – One-factor-At-a-Time (LH-OAT) sensitivity analysis method incorporated into SWAT. The LH-OAT method combines the OAT design and LH sampling by taking the LH samples as initial points for the OAT design (van Griensven 2003). According to van Griensven (2003), this method combines “the robustness of the LH sampling that ensures that the full range of all parameters has been sampled with the precision of an OAT design assuring that the changes in the output in each model run can be unambiguously attributed to the input changed in such a simulation leading to a robust and efficient sensitivity analysis method.”

The Latin-Hypercube is a sophisticated technique that can be used to perform random sampling, such as Monte-Carlo sampling, so that a robust analysis can be conducted without the need for an excessive number of model runs. The concept of the LH simulation, which was developed by McKay et al. (1979) and McKay (1988), is based on the Monte Carlo simulation but uses a stratified sampling approach that allows efficient estimation of the output statistics (van Griensven 2003).

The OAT (One-factor-At-a-Time) design, which was proposed by Morris (1991), is an example of an integration of a local to a global sensitivity method (van Griensven 2003). Similar to local methods, one parameter is changed per run which enables the changes in the model output to be attributed exclusively to the single input parameter that was changed. There are several advantages to using this approach (Morris 1991). The OAT design has proven to be a useful method for performing a sensitivity analysis with SWAT as it is capable of handling a large number of parameters (van Griensven 2003).

2.2.12 *Automatic Calibration and Uncertainty Analysis*

SWAT uses Parasol (Parameter Solutions method) to perform automatic calibration and uncertainty analysis. Parasol performs a combined optimisation and uncertainty analysis in a single run. Further details about Parasol can be found in van Griensven (2003). Brief descriptions of the different components of Parasol are provided in the following section and are based mostly on van Griensven (2003).

2.2.12.1 SCE-UA Algorithm

van Griensven and Bauwens (2003) implemented a multi-objective automatic calibration procedure in a modified version of SWAT called ESWAT. The procedure was based on the Shuffled Complex Evolution (SCE-UA) algorithm developed by Duan et al. (1992). It has since been incorporated into the official version of SWAT released by the USDA. A detailed discussion of the SCE-UA algorithm can be found in Duan et al. (1992). The following overview of the SCE-UA algorithm is based on that reference.

The SCE-UA algorithm allows the parameters of a model to be calibrated based on a single function. It combines the direct search method of the simplex procedure developed by Nelder and Mead (1965) with the concept of a controlled random search, a systematic evolution of points in the direction of global improvement, competitive evolution and the concept of complex shuffling (Duan et al. 1992). The SCE-UA algorithm is based on the notion of sharing information and on concepts drawn from principles of natural biological evolution (Duan et al. 1992).

2.2.12.2 Objective Function

An objective function is an indicator of the deviation between the observed and predicted time series (van Griensven and Bauwens 2003). Two objective functions have been made available in SWAT. The first is the sum of the squares of the residuals (*SSQ*) which is calculated as:

$$SSQ = \sum_{i=1,n} \left(x_{i,obs} - x_{i,pred} \right)^2$$

Where n = number of pairs of values in the time series

x_{obs} = measured value

x_{pred} = predicted value

i = position in the times series.

The second objective function is the sum of the squares of the difference of the measured and simulated values after ranking (*SSQR*). Unlike the *SSQ* method, the *SSQR* method does not account for the time of occurrence of a given value of the variable. After the observed and predicted values of the variable are independently ranked, new pairs are formed and the *SSQR* is calculated as (van Griensven 2003):

$$SSQR = \sum_{j=1,n} \left(y_{j,obs} - y_{j,pred} \right)^2$$

Where j = the rank of the pair of values in the series

y_{obs} = measured value

y_{pred} = predicted value

2.2.12.3 Uncertainty Analysis

The uncertainty analysis component divides the simulations that have been performed by the SCE-UA algorithm into "good" simulations and "not good" simulations (van Griensven 2003). Since the SCE-UA algorithm samples over the entire parameter space with a focus of solutions near the global optimum, the simulations have great value for performing an uncertainty analysis. Parasol employs two separation techniques to select the "good" simulations. Both techniques are based on a threshold value for the objective function (or global optimization criterion). Any simulation that achieves an objective function below the threshold is deemed to be "good". With respect to the threshold value, van Griensven (2003) states "the threshold value can be defined by χ^2-statistics where the selected simulations correspond to the confidence region (CR) or Bayesian statistics that are able to point out the high probability density (HPD) region for the parameters or the model outputs."

2.2.13 *SWAT GIS Interfaces*

To run SWAT for a particular watershed a number of ASCII input files containing the model parameters must be created. Depending upon the size of the watershed, a very large number of input files may need to be created. Creating the necessary input files manually can be a time consuming and tedious task. However, several GIS interfaces have been developed for SWAT in ArcView, ArcGIS and MapWindow to create all the necessary input files needed to run the model. Utilization of a GIS interface saves users a considerable amount of time in setting up the model.

A GIS interface provides adequate and efficient data support to SWAT, which is accomplished by several modules that offer a full range of user-friendly and interactive input/output manipulation capabilities to help the user perform a number of different tasks in setting up the model (Di Luzio et al. 2004). The input files for SWAT are created in a straightforward series of steps. The SWAT GIS interfaces are very easy to use and have been developed with intuitive user-friendly graphics to provide an efficient interaction with the model and the associated parameter databases (Di Luzio et al. 2004). The GIS interfaces are used to perform the following tasks (Di Luzio et al. 2001, 2004):

1. Delineate subwatersheds and define HRUs using topographic, land use and soil maps
2. Edit SWAT databases for soils, weather stations, vegetation growth, urban land use, tillage, fertilizers and pesticides (optional)
3. Define the location of weather stations and input respective time series for precipitation, air temperature, solar radiation, relative humidity and wind speed
4. Apply the default input files writer
5. Edit the default input files (optional)
6. Set simulation control codes including simulation length, potential evapotranspiration method and frequency of outputs (annual, monthly or daily)
7. Model execution (optional)
8. Apply calibration and uncertainty tools (optional)
9. Create and analyse SWAT outputs in graphic and map formats (optional)

Figure 9 shows the SWAT ArcView GIS interface main screen while Figure 10 shows the SWAT View screen for an example data set provided with the model.

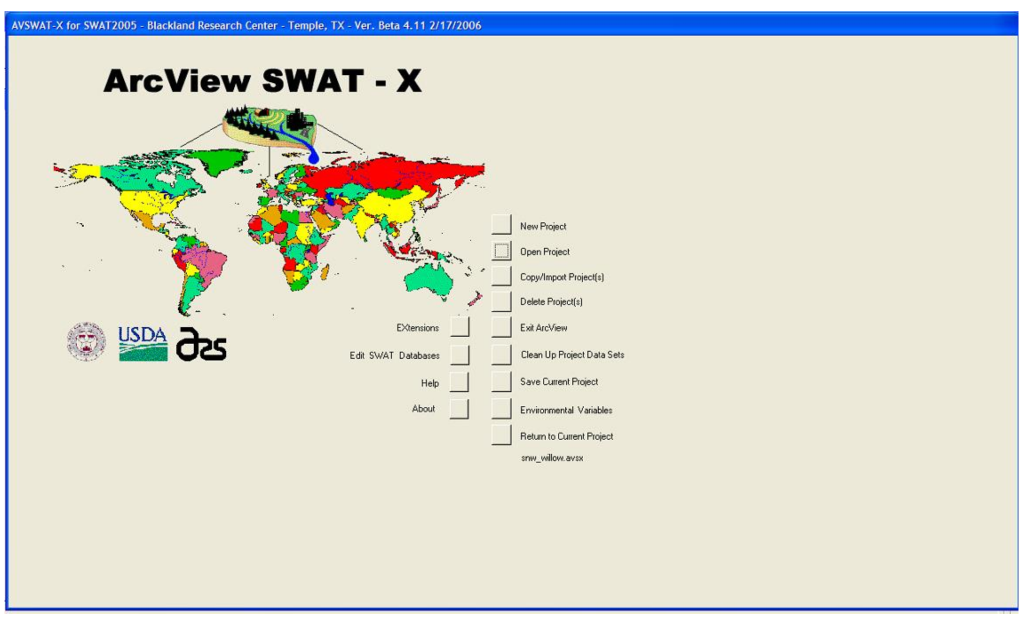

Figure 9. SWAT ArcView GIS interface main screen.

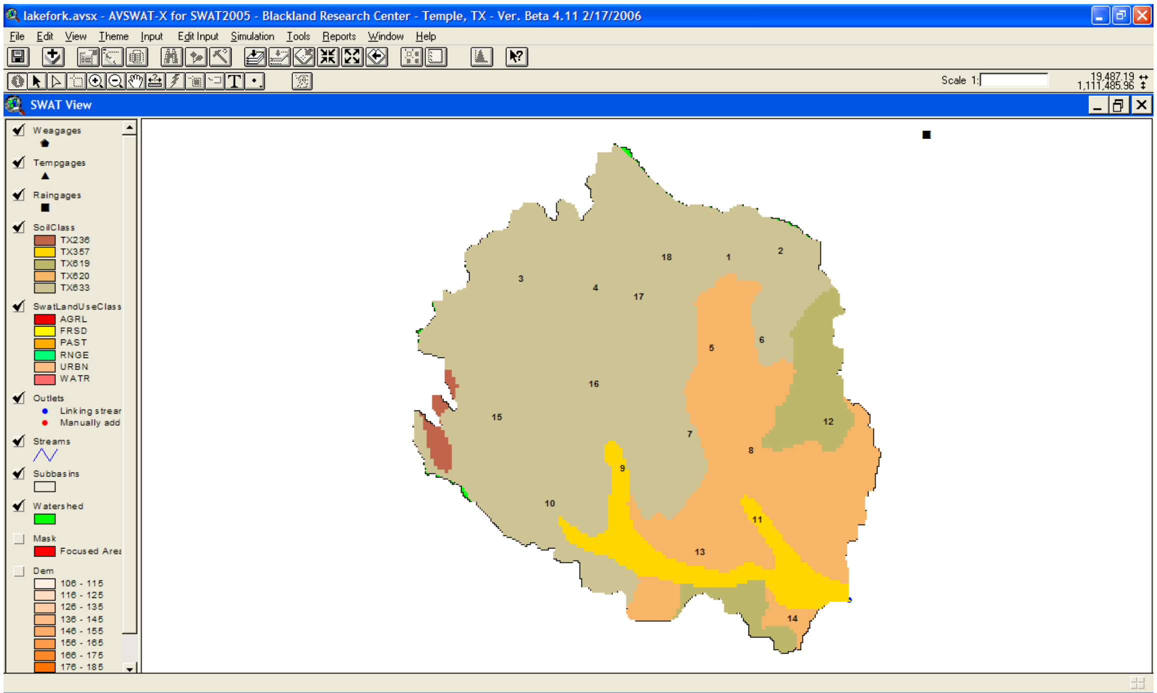

Figure 10. SWAT View screen for an example data set provided with model.

3 DESCRIPTION OF $SWAT_{BF}$

3.1 Background

$SWAT_{BF}$ is a modified version of SWAT that was developed primarily for forested watersheds on the Boreal Plain in Canada. It can be used with ArcView, ArcGIS or MapWindow GIS interfaces that are capable of producing input files for SWAT2005.

The original version of SWAT does not accurately represent or account for several important hydrological processes that occur in watersheds dominated by boreal forest. $SWAT_{BF}$ has been developed to represent the hydrological processes of boreal forests so that it can be used as a sound and reliable tool by forestry managers to predict the impacts of anthropogenic and natural land use changes (e.g., logging and wildfire) on long-term water and pollutant yields (Watson and Putz 2012). SWAT was developed primarily for agricultural watersheds in the United States. Therefore, several components of the model (i.e., plant growth and management operations) are only suitable for agricultural watersheds. The main developer of SWAT, Dr. Jeff Arnold of the USDA, pointed out “we chose good agricultural management models” and “the plant growth component of SWAT was originally developed for agricultural crops” (Arnold and Fohrer 2005). To make the model more suitable for forested watersheds on the Boreal Plain, the plant growth and management practices components have been removed from the version of $SWAT_{BF}$ utilized in this study.

$SWAT_{BF}$ is one of several hydrological modelling tools that have been developed as part of the FORWARD project[4]. It is the outcome of research that has been carried out over the past decade to develop a series of tools specifically for the forestry industry. It is important to bear in mind that $SWAT_{BF}$ was developed for practical purposes. Therefore, we have tried to make modifications that would not greatly increase model complexity or require large amounts of additional data but would still manage to capture the important physical processes occurring within forested watersheds on the Boreal Plain.

Further details about $SWAT_{BF}$, including applications and modifications, can be found in a series of papers published over the past decade (McKeown et al. 2003, 2005, Watson et al. 2008, Watson and Putz 2012). The major developments that have been incorporated into $SWAT_{BF}$ to date are outlined in Watson et al. (2008). It is important to point out that the model is still being updated and refined. Future developments will be incorporated into the model in the next few years. It is expected that a definitive version of the model will be finalized in the next few years.

Before outlining the developments that have been incorporated into $SWAT_{BF}$, it is important to point out the version of SWAT that was used as the "base" version for developing $SWAT_{BF}$. Several versions of SWAT have been released since its introduction in the 1990s. SWAT2005 was the version used to develop $SWAT_{BF}$. The main reason for selecting SWAT2005 was that previous versions of the model released (e.g., SWAT98, SWAT99 and SWAT2000) did not include components for sensitivity analysis, automatic calibration and uncertainty analysis. These procedures are becoming critically important in hydrological modelling studies. Therefore, it was felt that SWAT2005 should serve as the model from which the development of $SWAT_{BF}$ would proceed, thereby taking advantage of the additional components not available in the previous versions of SWAT.

The following section provides an overview of some of the modifications incorporated into $SWAT_{BF}$ to date. It is based predominantly on the papers listed above, particularly Watson et al. (2008).

3.2 Modifications

3.2.1 *Solar Radiation*

It is well established that surface orientation can have a significant influence on the amount of radiation that reaches the ground surface. South-facing slopes in the Northern Hemisphere can receive up to three times as much direct solar radiation as north-facing slopes with equivalent slopes (Klein 1977). Given that topography can significantly affect the amount of solar radiation reaching the ground surface in watersheds at higher latitudes, a simple algorithm was incorporated into $SWAT_{BF}$ to account for the effects of slope and aspect on the incoming solar radiation. One of the main advantages of this algorithm is its simplicity compared to other solar

[4] See http://forward.lakeheadu.ca

radiation models. Furthermore, it does not rely on parameters or coefficients that are site-specific and require calibration using local data.

The algorithm, which was developed by Swift (1976), computes the daily total of potential solar radiation on any sloping surface at any latitude in the world and then, using measured solar radiation from a nearby horizontal surface, estimates the actual radiation on any slope. The only input data required are the Julian day, latitude, inclination and aspect of the slope. The Julian day, latitude and inclination of slope are already used by $SWAT_{BF}$. An Avenue Script that is used in conjunction with ArcView GIS was developed in collaboration with the SWAT development team at the USDA to derive the average aspect for individual subwatersheds. This information is written to a separate input file (aspect.asp) that is read by $SWAT_{BF}$.

3.2.2 *Potential Evapotranspiration*

The potential evapotranspiration equation proposed by Oudin et al. (2005) was incorporated into $SWAT_{BF}$ as an option in addition to the Penman-Monteith, Priestley-Taylor and Hargreaves equations. The Hargreaves equation and the Oudin equation both only require air temperature as input. However, the Oudin equation has a slight advantage over the Hargreaves equation as it only requires the mean daily air temperature whereas the Hargreaves equation requires the maximum and minimum daily air temperature. The Oudin equation is given by:

$$\lambda E_o = H_0 \cdot \frac{\overline{T}_{av} + 5}{100}$$

Where λ = latent heat of vaporization (MJ/kg)

E_o = potential evapotranspiration (mm/d)

H_0 = extraterrestrial radiation (MJ/m^2/d)

$\overline{T}_{av}$ = mean air temperature for a given day (°C)

3.2.3 *Snow Melt*

Watson and Putz (2012) incorporated temperature index snow melt models from the following hydrological models into $SWAT_{BF}$:

- HBV light (Seibert 2005)
- INCA (Rankinen et al. 2004)
- LIARDFLOW (van der Linden and Woo 2003)
- SLURP (Kite 1995)

They also slightly increased the complexity of the snow melt model already utilized in SWAT (the extended version of the SWAT snow melt model was called SWAT-EXT). The snow melt models considered by Watson and Putz (2012) were of varying complexity. The number of parameters required by each model were as follows (number of parameters in brackets): LIARDFLOW (2), SLURP (3), INCA (5), HBV light (5), SWAT (7), and SWAT-EXT (11).

Watson and Putz (2012) compared the performance of the temperature index snow melt models in $SWAT_{BF}$ for five watersheds on the Boreal Plain. They found that the complexity of the snow melt model did not have a significant impact upon the prediction of runoff at the watershed outlet. Therefore, they recommended that simpler snow melt models be used in hydrological models to reduce the overall complexity and keep the number of parameters that must be calibrated to a minimum.

The LIARDFLOW snow melt model is now used exclusively for all applications of $SWAT_{BF}$, although any of the above models could be used. A single threshold temperature is used by the LIARDFLOW snow melt model to determine whether precipitation falls as snow or rain and whether snowmelt can proceed on a given day. The amount of precipitation that falls as snow is given by:

$$R_{snow} = \begin{cases} R_{day} & \text{if } \left(\overline{T}_{av} \le T_{sfm}\right) \\ 0 & \text{if } \left(\overline{T}_{av} > T_{sfm}\right) \end{cases}$$

Where R_{snow} = amount of snowfall on a given day (mm)

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

$\overline{T}_{av}$ = mean air temperature on a given day (°C)

T_{sfm} = threshold temperature for snowfall and snowmelt (°C)

The amount of snowmelt is calculated using the following equation:

$$SNO_{mlt} = \begin{cases} b_{mlt} \cdot \left(\overline{T}_{av} - T_{sfm}\right) & \text{if } \left(\overline{T}_{av} > T_{sfm}\right) \\ 0 & \text{if } \left(\overline{T}_{av} \le T_{sfm}\right) \end{cases}$$

Where SNO_{mlt} = amount of snowmelt on a given day (mm)

b_{mlt} = constant melt factor (mm/°C/day)

$\overline{T}_{av}$ = mean air temperature on a given day (°C)

T_{sfm} = threshold temperature for snowfall and snowmelt (°C)

Solar radiation and aspect are not considered in the LIARDFLOW snow melt model.

3.2.4 *Litter Layer*

The litter layer can influence the timing and magnitude of surface runoff generation in forested watersheds. This is because the litter on the ground acts as an energy absorbing macro-porous material that can store a large amount of water (Wattenbach et al. 2005). Peltoniemi et al. (2007) reported that the litter layer in boreal forests is thick and distinctive and has the potential to store significant quantities of water. Given that the litter layer can play an important role in the water balance of watersheds dominated by boreal forest, a simple litter layer model developed by Wattenbach et al. (2005) has been incorporated into $SWAT_{BF}$.

The litter layer in $SWAT_{BF}$ is represented as storage compartment similar to the canopy storage model already implemented in SWAT. Precipitation that falls from the canopy must first pass through the litter. If the water falling from the canopy exceeds the storage capacity of the litter layer, the excess water will reach the soil surface otherwise it is held in storage and allowed to evaporate back into the atmosphere.

The main equations of the litter layer are given by:

$$R_{LIT(f)} = R_{LIT(i)} + R'_{day} \text{ and } R_{day} = 0 \qquad \text{when } R'_{day} \le lit_{day} - R_{LIT(i)}$$

$$R_{LIT(f)} = lit_{day} \text{ and } R_{day} = R'_{day} - \left(lit_{day} - R_{LIT(i)}\right) \qquad \text{when } R'_{day} > lit_{day} - R_{LIT(i)}$$

Where $R_{LIT(i)}$ = initial amount of water stored in the litter layer (mm)

$R_{LIT(f)}$ = final amount of water stored in the litter layer (mm)

R'_{day} = amount of precipitation after canopy interception has been removed (mm)

R_{day} = amount of precipitation that reaches the soil surface (mm)

lit_{day} = maximum amount of water that can be stored in the litter layer (mm).

Compared to other litter layer models described in the literature, the model of Wattenbach et al. (2005) is relatively simple. However, the simplicity of the model is deemed to be an important advantage because it enables $SWAT_{BF}$ to remain as simple as possible without increasing the complexity of the model significantly.

3.2.5 *Anisotropic Soils*

The SWAT model assumes that the saturated hydraulic conductivity of each soil layer is the same in the horizontal and vertical directions. However, Dun et al. (2009) reported the layering of porous soil and low-permeability bedrock, together with the effect of lateral tree roots, leads to an anisotropic system in forested watersheds. Consequently, the horizontal saturated hydraulic conductivity in many watersheds will be different from the vertical saturated hydraulic conductivity.

Eckhardt et al. (2002) incorporated an anisotropy factor (aniso) into SWAT to account for the anisotropic soils that may exist in a watershed. The same factor has been incorporated into $SWAT_{BF}$. The equation used to calculate lateral flow in SWAT becomes:

$$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot aniso \cdot slp}{\phi_d \cdot L_{hill}} \right)$$

Where Q_{lat} = lateral flow (mm)

$SW_{ly,excess}$ = drainable volume of water in the soil layer (mm)

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

$aniso$ = anisotropy factor

slp = slope (m/m)

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

L_{hill} = hillslope length (m)

0.024 = a unit conversion factor.

3.2.6 *Percolation*

An algorithm was incorporated into $SWAT_{BF}$ to limit the rate of percolation through soil profiles that exhibit a strong texture contrast from one layer to the next. For soil profiles that possess this morphological feature, the saturated hydraulic conductivity of one layer may be several orders of magnitude higher than that of the underlying layer. Consequently, the lack of vertical flow capacity in the underlying soil layer impedes the vertical movement of water (Cox and McFarlane 1995). The vertical movement of water from one layer to the next is limited by the water content of the underlying layer in SWAT. This means that if the underlying soil layer is completely saturated, water will not be able to move into the saturated soil layer. However, the movement of water is not limited by the saturated hydraulic conductivity of the underlying layer. This means for certain soil types that it is possible for more water to percolate into the underlying layer than is permitted by the ability of the underlying layer to transmit water.

The following equation limits the rate of percolation in $SWAT_{BF}$ based on the saturated hydraulic conductivity:

$$w_{perc,ly} = \min\left(24 \cdot K_{sat,ly}, 24 \cdot K_{sat,ly+1}, w'_{perc,ly}\right)$$

Where $w_{perc,ly}$ = amount of water percolating to the underlying soil layer (mm)

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

$K_{sat,ly+1}$ = saturated hydraulic conductivity of the underlying soil layer (mm/h)

$w'_{perc,ly}$ = amount of percolation calculated using the storage routing technique (mm).

The following equation limits the rate of percolation from the bottom layer in the soil profile to the underlying bedrock:

$$w_{perc,ly=n} = \min\left(24 \cdot K_{sat,ly=n}, 24 \cdot K_{sat,bed}, w'_{perc,ly=n}\right)$$

Where $w_{perc,ly=n}$ = amount of water percolating out of the lowest layer, *n*, in the soil profile (mm)

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

$K_{sat,bed}$ = saturated hydraulic conductivity of the bedrock underlying the soil profile (mm/h)

$w'_{perc,ly=n}$ = amount of percolation from the lowest layer, *n*, in the soil profile calculated using the storage routing technique (mm).

Both of these equations were adopted from the Catchment Resources and Soil Hydrology (CRASH) model (Maréchal and Holman 2005).

3.2.7 *Groundwater*

Small streams in Canada often become frozen solid during winter due to an extended period of extremely cold temperatures. Although small quantities of groundwater do in fact seep into the channel during winter, the water freezes shortly afterwards. To account for this phenomenon, a simple modification was incorporated into $SWAT_{BF}$ whereby any groundwater entering the channel in winter is stored in the snow pack until spring when it melts. This corresponds to the same time that ice in the channel would also melt.

3.2.8 *Wetlands*

A new wetlands model was developed for $SWAT_{BF}$ because the wetlands model currently available in SWAT is not considered representative of Boreal Plain wetlands. Wetlands in SWAT are considered as open-water bodies and do not consider the contribution of surface runoff, lateral flow and groundwater flow from these water bodies to the channel. Furthermore, the wetlands in SWAT are considered to be devoid of vegetation, a situation that is clearly not the case for boreal forest wetlands.

Watson et al. (2008) utilized a bucket model approach to simulate bog and fen wetlands in $SWAT_{BF}$. This wetland model is still relatively simple and does not require detailed data sets that can be difficult to obtain for wetlands in remote regions. Despite the simplicity of the model, it was designed to represent the main hydrological processes influencing the output from bogs and fens.

The wetland model in $SWAT_{BF}$ consists of two layers: an upper organic layer and a lower organic layer. The water balance equation for the wetlands model is given by:

$$SW_t = SW_0 + R_{day} - E_a - Q_{surf} - Q_{lat} - w_{seep}$$

Where SW_t = final soil water content (mm)

SW_0 = initial soil water content (mm)

R_{day} = amount of precipitation that reaches the soil surface (mm)

E_a = actual evapotranspiration (mm)

Q_{surf} = surface runoff (mm)

Q_{lat} = lateral flow (mm)

w_{seep} = amount of water exiting the bottom of the soil profile.

A conceptual diagram of the wetland model incorporated into $SWAT_{BF}$ is presented in Figure 11.

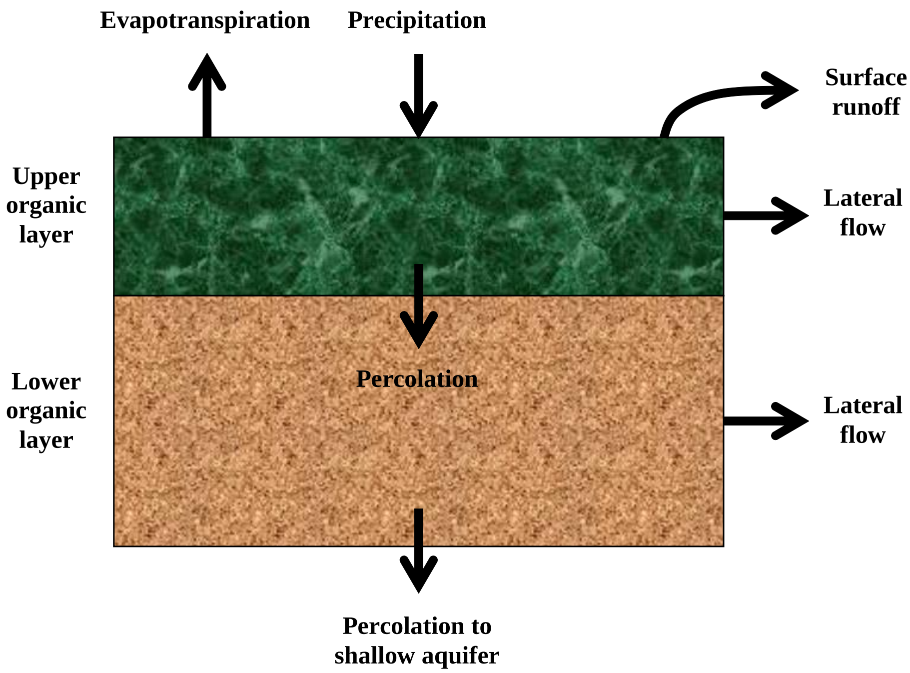

Figure 11. Conceptual diagram of the wetland model incorporated into $SWAT_{BF}$ (adapted from Watson et al. 2008).

3.2.9 *HRU Connectivity*

As mentioned earlier, no spatial relationship exists between the HRUs of a subwatershed in SWAT. This means that the water generated in one HRU cannot pass through another HRU. For many watersheds, this is not considered to be a major constraint for simulating the movement of water from the landscape to the stream network. However, for some watersheds the movement of water from one HRU to another could be critically important. For example, in some forested watersheds on the Boreal Plain, wetlands may be found adjacent to streams. These landscape units receive water from upland areas and hence can have controlling effects on the hydrologic response of a watershed. Therefore, when modelling these watersheds there is a need to have the upland HRUs interact with the lowland wetlands.

A basic degree of HRU connectivity has been incorporated into $SWAT_{BF}$, whereby a portion of the lateral flow and groundwater flow from upland HRUs can be diverted to lowland wetlands. A conceptual diagram of the connectivity between the upland HRUs and the lowland wetlands is provided in Figure 12. Complete details of the procedure used to connect upland HRUs with lowland wetlands can be found in Watson et al. (2008) and will not be repeated here for the sake of brevity. It should also be noted that this component of the model is currently under review. The procedure outlined in Watson et al. (2008) relies on manually altering the input files and can be a time-consuming task. An alternative procedure that is less cumbersome to implement is currently being designed. It is expected that this alternative procedure will be implemented in $SWAT_{BF}$ in the next few years.

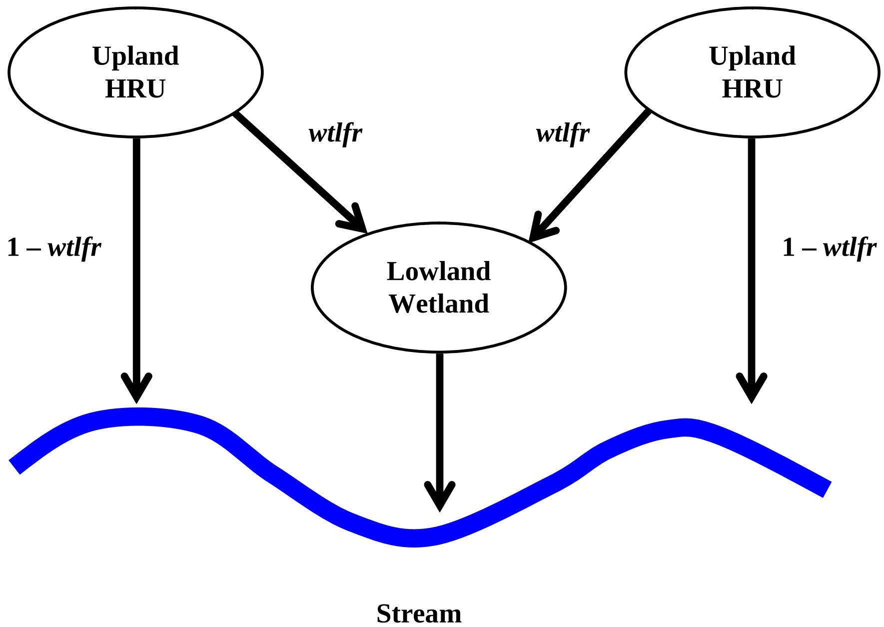

Figure 12. Conceptual diagram of the connectivity between upland HRUs and lowland wetlands in $SWAT_{BF}$ (adapted from Watson et al. 2008).
Note: *wtlfr* is a parameter that represents the fraction of lateral flow and groundwater flow from upland HRUs that is diverted to the lowland wetlands.

3.3 Future Developments

As mentioned earlier, $SWAT_{BF}$ is continually being modified and refined as more research is being carried out. It is expected that further developments will be made to the model in the next few years. Some of the proposed future developments include:

- Coupling the forest growth model 3-PG (Landsberg and Waring 1997) to $SWAT_{BF}$ to improve the simulation of LAI and biomass of forests over long periods of time. Watson (2006) coupled 3-PG to SWAT-OZ in Australia to improve the simulation of LAI and biomass for eucalyptus forests and pine plantations. Watson (2006) showed that 3-PG was capable of producing more realistic estimates of LAI and biomass for forests than the vegetation growth model incorporated into SWAT.

- Coupling $ALMANAC_{BF}$ (MacDonald et al. 2008) to $SWAT_{BF}$ to simulate the successional stages of forest reestablishment. MacDonald et al. (2008) modified ALMANAC, which is a multi-species growth model developed for agricultural crops, to produce $ALMANAC_{BF}$ which is capable of simulating vegetation regeneration on forest sites after disturbance. Utilizing $ALMANAC_{BF}$ will be important for simulating the regrowth of forests in the first few years after the disturbance has occurred.

- Coupling the groundwater model MODFLOW (McDonald and Harbaugh 1984) to $SWAT_{BF}$. The groundwater component of $SWAT_{BF}$ is very simple. For most applications that $SWAT_{BF}$ is used for the current groundwater component is deemed acceptable. However, a more sophisticated groundwater model would be needed for watersheds with complex geology. Several researchers around the world have coupled SWAT and MODFLOW.

- Revision of the water quality components. Kumar et al. (2011) assessed the nitrogen component of $SWAT_{BF}$ for a forested watershed on the Boreal Plain. They found several deficiencies with the simulation of nitrogen. One of the main reasons for this was attributed to the nitrogen component of the model being more suitable for agricultural watersheds (NO_3^- dominated) than forested watersheds (both NH_4^+ and NO_3^- prominent). Therefore, the water quality component needs to be revised to make it more suitable for forested watersheds.

3.4 Model Purpose and Scaling Considerations

It is crucially important to realize that hydrological models are usually developed with a specific purpose in mind. Therefore, when choosing a hydrological model it is strongly recommended that a “horses for courses” approach be adopted (CRCCH 2005). In other words, models should be used for the purpose they were originally intended for and not for applications that are far beyond their carrying capacity. Scaling issues are an important factor to consider when choosing a hydrological model. Models are usually developed for specific spatial and temporal scales. Therefore, it is not advisable to apply a model to different spatial and temporal scales. For example, an event based hydrological model should not be used to predict long-term water yields. Similarly, a hydrological model developed at the field scale should not be used to predict continental scale water balances.

As pointed out earlier, SWAT and $SWAT_{BF}$ were developed to predict long-term yields and not single events. It is also important to understand that both models were designed for making predictions at the watershed scale. This means neither model is suitable at the hillslope, field or plot scale. Predictions that need to be made at the hillslope, field or plot scale will require models that were developed specifically for these scales to be utilized.

Another important factor to consider is the output variables that SWAT and $SWAT_{BF}$ have been designed to predict. In discussing the development of SWAT, Arnold et al. (1998) explicitly state "the objective in model development was to predict the impact of management on water, sediment and agricultural chemical yields" at the watershed outlet. Although SWAT and $SWAT_{BF}$ update a number of other variables on a daily basis, such as soil moisture and actual evapotranspiration, they were not developed specifically for predicting these variables.

Much of the research conducted to date on the reclaimed watersheds in the oil sands region has focused on the prediction of soil moisture. Based on the "horses for courses" approach advocated by CRCCH (2005), $SWAT_{BF}$ would not be a suitable model for such a purpose. Models that have been developed specifically for predicting soil moisture at the watershed scale would be far more suitable to utilize for such applications. It is to be expected that $SWAT_{BF}$ would not perform as well as a model developed specifically for predicting soil moisture, making comparisons between the different types of models a rather meaningless exercise.

It is important to keep these issues in mind when determining the applicability of $SWAT_{BF}$ for reclaimed watersheds in the oil sands region. It should be used to predict water and chemical yields at the outlet of the reclaimed watersheds, not variations in soil moisture or groundwater levels at different locations across the watersheds. We also strongly agree with the statement of CRCCH (2005) that "there is no particular style of model inherently better for applications than another." Model developers, model users and stakeholders should appreciate that many different models have been developed for many different purposes and that they all have their strengths and weaknesses.

4 INPUT DATA AND MODEL PARAMETERS FOR $SWAT_{BF}$

4.1 Input Data

The availability of data sets is of critical importance in any hydrological modelling study. Beven (2001) pointed out that "the success of a hydrological model depends critically on the data availability to set it up and drive it." Similarly, Grayson and Chiew (1994) reported that "data availability is perhaps the single most important constraint to a modelling exercise." The utilization of insufficient data sets usually produces poor modelling results. The importance of obtaining accurate data sets to set up and calibrate hydrological models cannot be stressed enough. Although data acquisition techniques have improved greatly in the past several decades, due largely to significant advances in computer technology, it is evident that the availability of data sets required for hydrologic models is still often limited.

4.1.1 *Input Data Required by $SWAT_{BF}$*

$SWAT_{BF}$ requires specific information about the climate, soils, topography and vegetation found across a watershed. The following list provides a summary of the main data sets that are required by $SWAT_{BF}$ for most applications:

- Daily meteorological data[5]
  - Precipitation
  - Maximum air temperature
  - Minimum air temperature
  - Solar radiation
  - Relative humidity
  - Wind speed
- Digital Elevation Model (DEM)
- Stream network map
- Land use map
- Vegetation parameters
- Leaf Area Index (LAI)
- Management operations and practices
  - Planting and harvesting dates
  - Fertilization information
  - Tillage operation
  - Irrigation grazing
  - Tile drains pesticide applications
  - Crop rotation
- Soils map

[5] $SWAT_{BF}$ can also be run on a sub-daily time-step. However, this requires sub-daily meteorological data be available. For most watersheds in Canada and around the world, such a detailed data set is not available. It should also be noted that SWAT was developed primarily as a daily time-step model and the vast majority of applications of SWAT reported in the literature used a daily time-step.

- Soil properties[6]
    - Soil depth
    - Bulk density
    - Available water capacity
    - Saturated hydraulic conductivity
    - Percent sand, silt and clay
    - Anisotropy
- Daily streamflow
- Water quality parameters
    - Sediment
    - Organic N
    - Organic P
    - NO_3
    - NH_3
    - NO_2
    - Mineral P
    - Soluble pesticide
    - Sorbed pesticide

4.2 Model Parameters

In accordance with the model classification scheme proposed by Grayson and Chiew (1994), $SWAT_{BF}$ can be considered a complex conceptual model (i.e., usually more than 8 parameters are calibrated). Although $SWAT_{BF}$ is less complex than fully-distributed physically-based models such as SHE (Abbott et al. 1986), it still requires several hundred input parameters to be defined. Although this number seems overwhelming at first, it is important to remember that not all of the parameters need to be adjusted during the calibration procedure. Relying on default values for the remaining parameters is sufficient to achieve satisfactory results in most cases. A review of the literature reveals that SWAT users rarely adjust more than 15 parameters during the calibration procedure. However, the parameters that are adjusted vary considerably from one study to the next.

[6] The soil properties are required for each soil layer in the soil profile. $SWAT_{BF}$ allows a maximum of ten soil layers to be defined for any given soil profile.

4.2.1 *Model Parameter Ranges*

Tables 1 to 12 provide descriptions of some of the more important parameters used in $SWAT_{BF}$. Readers are referred to Neitsch et al. (2005a) for a complete description of all the parameters used in SWAT. Also provided in Tables 1 to 12 is the range of values that each parameter can take as well as the input file in which each parameter is located. The parameters presented in Tables 1 to 12 have been selected based on our experience of using $SWAT_{BF}$ for the past decade. In addition, we have noted the parameters that other users of SWAT have reported adjusting in the literature.

Table 1. Parameters influencing snow hydrology in $SWAT_{BF}$.

Parameter	**Definition**	**Range**	**File**
SFMTMP	Threshold temperature for snowfall and snowmelt (ºC)	-5ºC to 5ºC	.bsn
SMFCN	Melt factor for snow (mm/ºC/day) Melt factor that is constant all year round	0.0 to ∞	.bsn
SNO_SUB	Initial snow water content (mm)	0.0 to ∞	.sub

Table 2. Parameters influencing evapotranspiration in $SWAT_{BF}$.

Parameter	**Definition**	**Range**	**File**
CANMX	Maximum canopy storage (mm) CANMX is the maximum amount of water that can be trapped in the canopy when the canopy is fully developed	0.0 to ∞	.hru
LITMX	Maximum litter storage (mm) LITMX is the maximum amount of water that can be stored in the litter layer	0.0 to ∞	.hru
ESCO	Soil evaporation compensation factor This coefficient has been incorporated to allow the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks	0.01 to 1.0	.hru
EPCO	Plant uptake compensation factor If upper layers in the soil profile do not contain enough water to meet the potential water uptake, users may allow lower layers to compensate	0.01 to 1.0	.hru

Parameter	Definition	Range	File
GW_REVAP	Groundwater “revap” coefficient Influences the movement of water from the shallow aquifer to the root zone	0.02 to 0.20	.gw
REVAPMN	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm) Movement of water from the shallow aquifer to the unsaturated zone is allowed only if the volume of water in the shallow aquifer is equal to or greater than REVAPMN	0.0 to ∞	.gw

Table 3. Parameters influencing surface runoff in $SWAT_{BF}$.

Parameter	Definition	Range	File
SURLAG	Surface runoff lag coefficient In large subwatersheds with a time of concentration greater than 1 day, only a portion of the surface runoff will reach the main channel on the day it is generated. A surface runoff storage feature lags a portion of the surface runoff release to the main channel	0.0 to ∞	.bsn
CN2	Initial SCS runoff curve number for moisture condition II The SCS curve number is a function of the soil’s permeability, land use and antecedent soil water conditions	0 to 100	.mgt

Table 4. Parameters influencing “time of concentration” in $SWAT_{BF}$.

Parameter	Definition	Range	File
CH_N(1)	Manning’s “n” value for the tributary channels	0.0 to ∞	.sub
SLSUBBSN	Average slope length (m)	0.0 to ∞	.hru

Table 5. Parameter influencing transmission losses in $SWAT_{BF}$.

Parameter	Definition	Range	File
CH_K(1)	Effective hydraulic conductivity in tributary channel alluvium (mm/h) This parameter controls transmission losses from surface runoff as it flows to the main channel in the subwatershed	0.0 to ∞	.sub

Table 6. Parameters influencing soil water content in $SWAT_{BF}$.

Parameter	Definition	Range	File
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0.0 to 1.0	.bsn
SOL_Z	Depth from soil surface to bottom of layer (mm)	0.0 to ∞	.sol
SOL_BD	Moist bulk density (Mg/m^3 or g/cm^3) The soil bulk density expresses the ratio of the mass of solid particles to the total volume of the soil	1.1 to 1.9	.sol
SOL_AWC	Available water capacity of the soil layer (mm/mm) Calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity	0.0 to 1.0	.sol
SOL_K	Saturated hydraulic conductivity (mm/hr) The saturated hydraulic conductivity relates soil water flow rate (flux density) to the hydraulic gradient and is a measure of the ease of water movement through the soil	0.0 to ∞	.sol
ANISO	Anisotropy factor Allows the horizontal saturated hydraulic conductivity of a soil to be different from the vertical saturated hydraulic conductivity	0.0 to ∞	.sol

Table 7. Parameters influencing lateral flow in $SWAT_{BF}$.

Parameter	Definition	Range	File
SLSOIL	Slope length for lateral subsurface flow (m)	0.0 to ∞	.hru
HRU_SLP	Average slope steepness (m/m)	0.0 to ∞	.hru
LAT_TTIME	Lateral flow travel time (days)	0.0 to ∞	.hru

Table 8. Parameters influencing groundwater in $SWAT_{BF}$.

Parameter	Definition	Range	File
SHALLST	Initial depth of water in the shallow aquifer (mm)	0.0 to ∞	.gw
GW_DELAY	Groundwater delay time (days) The time taken for the water that exits the soil profile to travel through the vadose zone and enter the shallow aquifer.	0.0 to ∞	.gw
ALPHA_BF	Baseflow alpha factor (days) The baseflow recession constant is a direct index of groundwater flow response to changes in recharge	0.0 to ∞	.gw
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm) Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than GWQMN	0.0 to ∞	.gw
RCHRG_DP	Deep aquifer percolation fraction The fraction of percolation from the root zone which recharges the deep aquifer	0.0 to 1.0	.gw
SOL_KBED	Saturated hydraulic conductivity of bedrock (mm/h)	0.0 to ∞	.gw

Table 9. Parameters influencing sediment transport in $SWAT_{BF}$.

Parameter	Definition	Range	File
ADJ_PKR	Peak rate adjustment factor for sediment routing in the subwatershed (tributary channels) This factor is used in the MUSLE equation and impacts the amount of erosion generated in the HRUs	unspecified	.bsn
USLE_K	USLE equation soil erodibility (K) factor (0.013 (metric ton/m^2/hr)/(m^3/metric ton/cm)) Defined as the soil loss rate per erosion index unit for a specified soil as measured on a unit plot	unspecified	.sol

Table 10. Parameters influencing nitrogen transport in $SWAT_{BF}$.

Parameter	Definition	Range	File
CMN	Rate factor for humus mineralization of active organic nutrients (N and P)	unspecified	.bsn
CDN	Denitrification exponential rate coefficient	0.0 to 3.0	.bsn
SDNCO	Denitrification threshold water content Fraction of field capacity water content above which denitrification takes place	unspecified	.bsn
N_UPDIS	Nitrogen uptake distribution parameter	unspecified	.bsn
NPERCO	Nitrate percolation coefficient NPERCO controls the amount of nitrate removed from the surface layer	0.01 to 1.0	.bsn
SOL_NO3	Initial NO_3 concentration in the soil layer (mg N/kg soil or ppm)	0.0 to ∞	.chm
SOL_ORGN	Initial organic N concentration in the soil layer (mg N/kg soil or ppm)	0.0 to ∞	.chm
ERORGN	Organic N enrichment ratio for loading with sediment	unspecified	.hru

Table 11. Parameters influencing phosphorus transport in $SWAT_{BF}$.

Parameter	**Definition**	**Range**	**File**
CMN	Rate factor for humus mineralization of active organic nutrients (N and P)	unspecified	.bsn
PPERCO	Phosphorus percolation coefficient (10 m^3/Mg) The phosphorus percolation coefficient is the ratio of the solution phosphorus concentration in the surface 10 mm of soil to the concentration of phosphorus in percolate	10.0 to 17.5	.bsn
PHOSKD	Phosphorus soil partitioning coefficient (m^3/Mg) The phosphorus soil partitioning coefficient is the ratio of the soluble phosphorus concentration in the surface 10 mm of soil to the concentration of soluble phosphorus in surface runoff	unspecified	.bsn
PSP	Phosphorus availability index	unspecified	.bsn
SOL_SOLP	Initial soluble P concentration in soil layer (mg P/kg soil or ppm)	0.0 to ∞	.chm
SOL_ORGP	Initial organic P concentration in soil layer (mg P/kg soil or ppm)	0.0 to ∞	.chm
ERORGP	Phosphorus enrichment ratio for loading with sediment The enrichment ratio is defined as the ratio of the concentration of phosphorus transported with the sediment to the concentration of phosphorus in the soil surface layer	unspecified	.hru

Table 12. Parameters influencing routing in $SWAT_{BF}$.

Parameter	**Definition**	**Range**	**File**
MSK_CO1	Calibration coefficient used to control impact of the storage time constant (Km) for normal flow (where normal flow is when river is at bankfull depth) upon the Km value calculated for the reach	unspecified	.bsn

Parameter	Definition	Range	File
MSK_CO2	Calibration coefficient used to control impact of the storage time constant (Km) for low flow (where low flow is when river is at 0.1 bankfull depth) upon the Km value calculated for the reach	unspecified	.bsn
MSK_X	MSK_X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach	unspecified	.bsn
CH_N(2)	Manning's "n" value for the main channel	unspecified	.rte
CH_K(2)	Effective hydraulic conductivity in main channel alluvium (mm/h)	0.0 to ∞	.rte
PRF	Peak rate adjustment factor for sediment routing in the main channel	unspecified	.bsn
SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0001 to 0.01	.bsn
SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing	1.0 to 2.0	.bsn

5 AVAILABILITY OF OIL SANDS REGION DATA SETS

5.1 Introduction

The following chapter provides an overview of data sets that are available in the oil sands geographic area for setting up and operating $SWAT_{BF}$. Although the primary focus of this study is to determine the data sets available for reclaimed watersheds in the oil sands geographic area, supplementary data sets have also been included. These data sets are used primarily for regional reference watersheds in the oil sands geographic area. However, some of the supplementary data sets can be also used to fill in missing records that exist in the data sets for the reclaimed watersheds. Further, it is also important to realize that a hydrological model developed for reclaimed watersheds should also be capable of reproducing the hydrologic response of regional watersheds. This is a significant issue because the purpose of the reclaimed watersheds is to return the landscape to a state similar to that before the disturbance occurred. Reclaimed watersheds in the oil sands geographic area have just become operational in the past decade. Hence, there has been little opportunity as yet to collect the long-term data sets needed to stringently test hydrological models such as $SWAT_{BF}$ for reclaimed watersheds.

5.2 Reclaimed Watersheds

Suncor Energy Inc. and Syncrude Canada Ltd. have been operating in the oil sands geographic area since the 1960s. Most other oil companies in the region have commenced operations only recently. Based upon a search of the available literature, very few companies have constructed reclaimed watersheds that are currently being monitored. There are no legal obligations to monitor the water and chemicals that exit reclaimed watersheds so long as those waters and chemicals are retained somewhere else on the land being leased by the oil companies (Purdy pers. comm.).

Data sets from two well-known reclaimed watersheds in the oil sands geographic area are described below. These watersheds are Wapisiw Lookout (Suncor Energy Inc.) and Southwest 30 Dump (Syncrude Canada Ltd.). Canadian Natural Resources Limited (CNRL) has constructed a compensation lake (Horizon Lake) and Imperial Oil has built the first of three compensation lakes at the Kearl mine site. However, these are not considered reclaimed watersheds since they were constructed in unmined areas. The main purpose for the construction of the lakes was to compensate for the future loss of fish habitat due to mining operations. Therefore, we have not included descriptions of these lakes in this report.

5.2.1 *Wapisiw Lookout*

Wapisiw Lookout is a reclaimed watershed located approximately 30 km north of Fort McMurray at the Suncor mine site (Figure 13). It is also known as Suncor Pond 1 or Tar Island Dyke in the literature. It is situated on the west bank of the Athabasca River (Figure 14). The total area of the Wapisiw Lookout watershed is approximately 2.19 km^2 (Suncor n.d.). Construction of the watershed was completed in 2010.

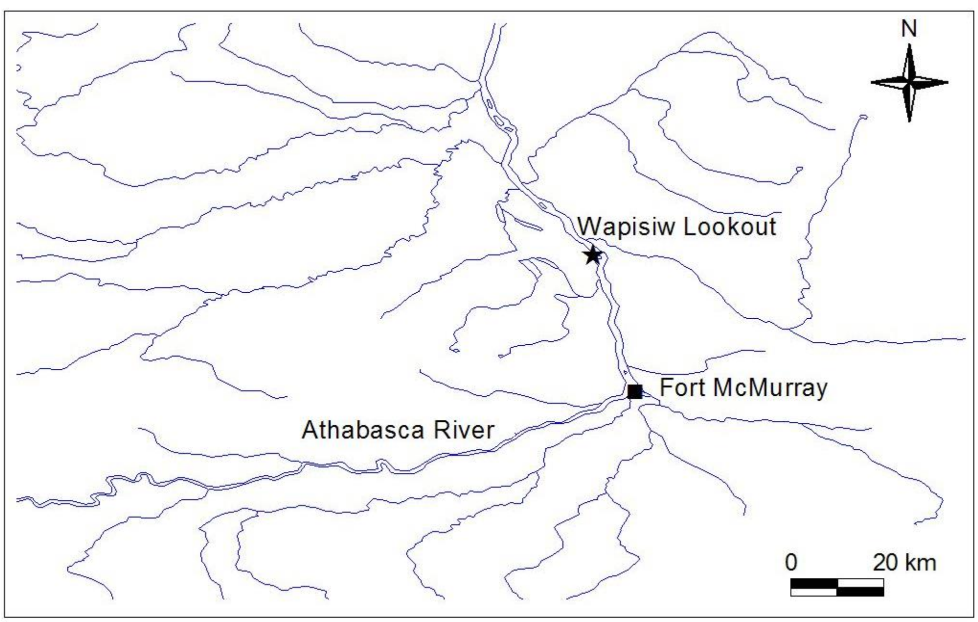

Figure 13. Location of the Wapisiw Lookout watershed.

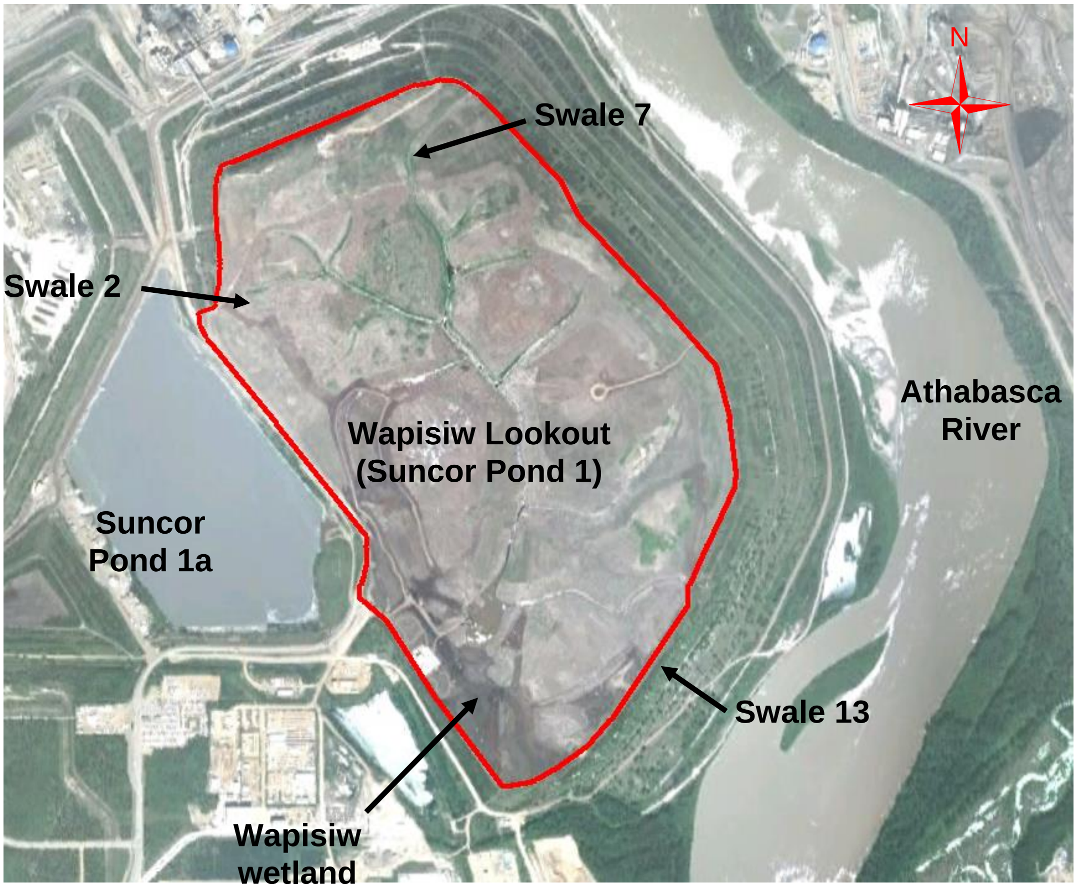

Figure 14. Annotated satellite image showing Wapisiw Lookout and Athabasca River (Google Earth 2013).

The following description of the Wapisiw Lookout watershed was provided by Suncor (Suncor n.d). A number of swales have been constructed to collect surface water runoff and transport it to a small wetland, called Wapisiw wetland, situated in the southwest corner of the watershed. An outlet pipe has been installed in the wetland at an elevation of approximately 323 m. Once the water in the wetland rises above 323 m, the excess water drains into a sump where it is pumped periodically to Suncor Pond 1a (Figure 14). The purpose of the outlet pipe is to control the level of water in the wetland. The watershed is lined with a Geosynthetic Clay Liner (GCL) that prevents water infiltrating beneath the reclamation cover. The GCL also prevents the upward movement of deep groundwater to the soil profile. Shallow groundwater and subsurface flow above the GLC is collected and piped directly to the sump.

A limited amount of instrumentation has been installed on the Wapisiw Lookout watershed to date (Suncor n.d.). A meteorological station has been installed in the northwest corner of the watershed to measure precipitation, air temperature, relative humidity and wind speed. A V-notch weir has been installed in the northwest corner on Swale 2 to measure runoff. The water level in Swales 7 and 13 is measured as is the water level in the wetland.

The FORWARD project has plans to install further instrumentation in the Wapisiw Lookout watershed in 2013 including several streamflow gauges on the main Swale, soil moisture probes and another meteorological station. Water quality samples will be taken during and after peak runoff events. Snow surveys will be taken at the end of winter to obtain the snow depth and snow water equivalent. Soil moisture probes will also be installed at various locations across the watershed.

$SWAT_{BF}$ was applied to the Wapisiw Lookout watershed in this study. It is important to point out that the runoff measured on Swale 2 was not available for this study. Since runoff is not directly measured elsewhere on the Wapisiw Lookout watershed, the change in water level of the Wapisiw wetland was used to estimate the amount of runoff generated from the watershed.

5.2.2 *Southwest 30 Dump*

The Southwest 30 Dump is located northwest of Fort McMurray at the Syncrude Mildred Lake mine site (Figure 15). It has also been referred to as the Southwest 30 Overburden Hill, Southwest 30 Overburden Research Site, Wood Bison Hills and South Bison Hills and South Hills in the literature. It will be referred to as the SW30 Dump in this report. Approximately 100 million m^3 of shale overburden were used in the construction of the SW30 Dump, which covers 85 hectares (Boese 2003).

Three prototype covers that are approximately 1 hectare in area have been established on the SW30 Dump. These prototype covers are effectively small watersheds. They have been called D1, D2 and D3 and are shown in Figure 16.

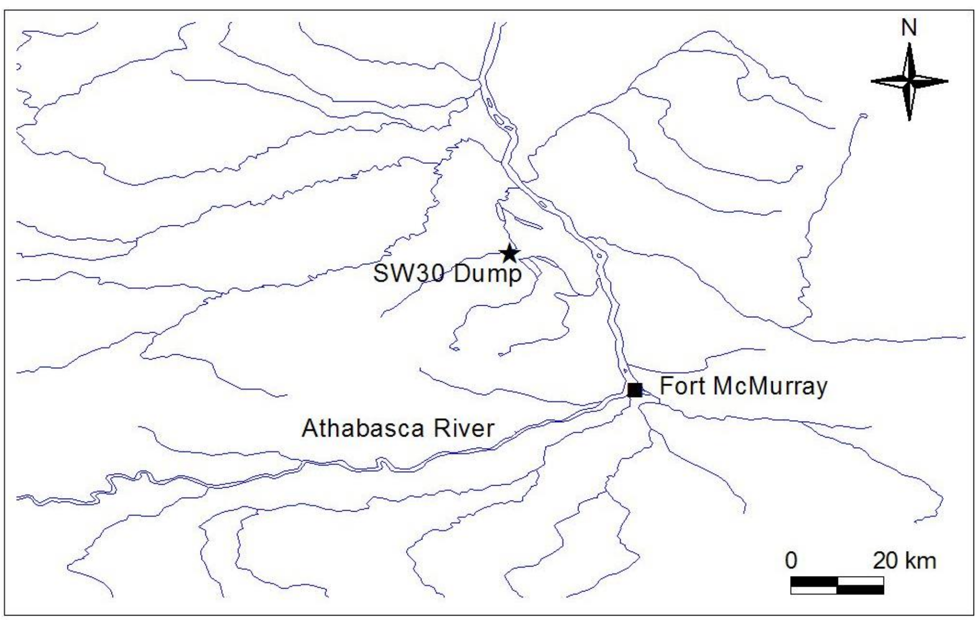

Figure 15. Location of the SW30 Dump.

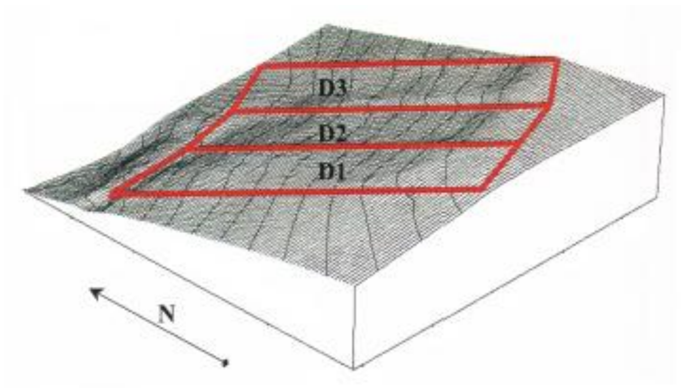

Figure 16. D1, D2 and D3 prototype covers located on the SW30 Dump (Shurniak 2003).

The soil profile for each prototype cover consists of peat and till overlying shale overburden. The depth of peat and till is different for each prototype cover. The soil depths for each prototype cover are shown in shown in Figure 17.

Another reconstructed watershed, called Bill's Lake (BL), is also located on the SW30 Dump. The BL watershed was established 3 years before the D1, D2 and D3 prototype covers. It consists of a one metre soil layer comprised of a peat/till mix overlying the shale overburden. The BL watershed drains into a small wetland. The BL watershed is shown in Figure 18. The location of the D1, D2 and D3 prototype covers with respect to Bill's Lake is shown in Figure 19.

Since its construction, numerous instruments have been installed on the SW30 Dump to collect long-term records for a wide range of meteorological and hydrological parameters. A list of the data sets that would be useful in terms of setting up and operating $SWAT_{BF}$ for the SW30 Dump watershed is provided in Table 13. More data sets are available but they are of little relevance in terms of applying $SWAT_{BF}$. Figure 20 is a cross-section of the prototype covers that shows the position of the instrumentation in the landscape.

Comprehensive descriptions of the instrumentation that has been installed on SW30 Dump to monitor meteorological and hydrological parameters can be found in Barbour et al. (2001, 2004), Boese (2003), Kelln et al. (2006), Meier and Barbour (2002) and Shurniak (2003).

The long-term hydrological measurements available from the SW30 Dump are high quality data sets that could be used to test the performance of $SWAT_{BF}$ for reproducing runoff from a reclaimed watershed in the oil sands geographic area. However, the data sets from the SW30 Dump are not available at the present time.

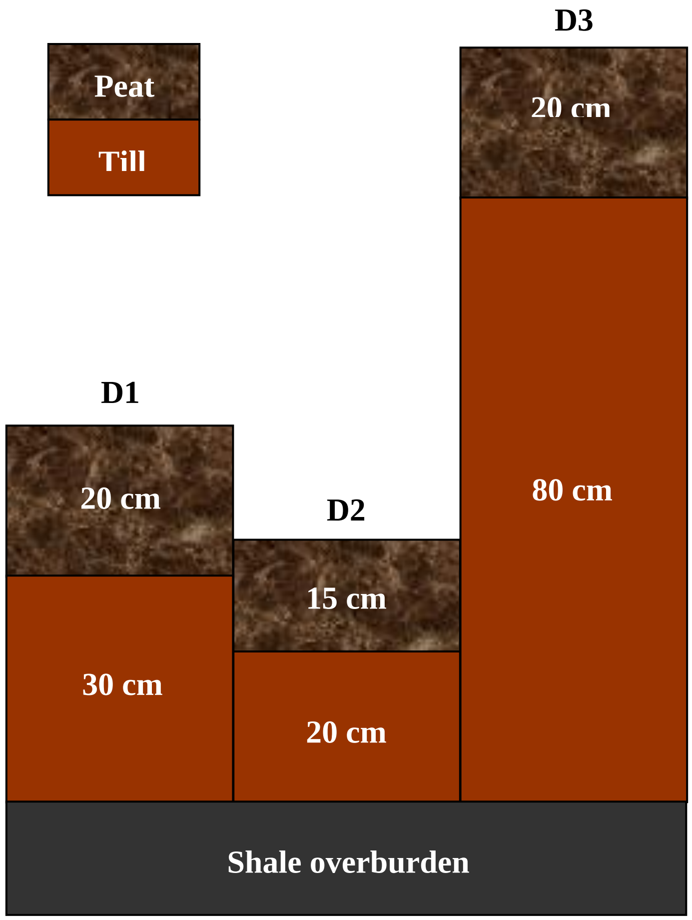

Figure 17. Depth of peat and till in the D1, D2 and D3 prototype covers on SW30 Dump (Shurniak 2003 and Rodger 2008).

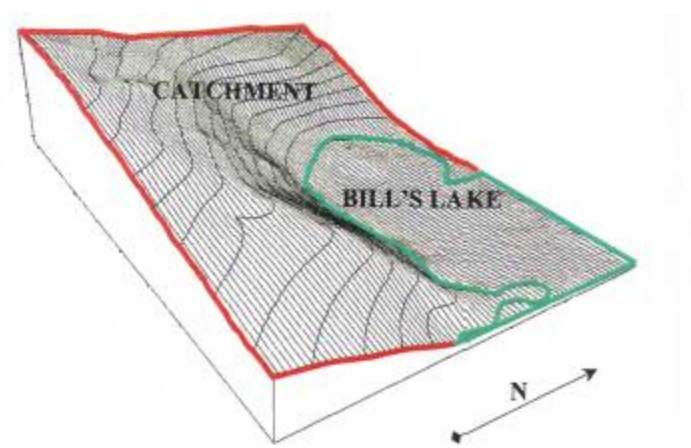

Figure 18. Bill's Lake watershed located on the SW30 Dump (Shurniak 2003).

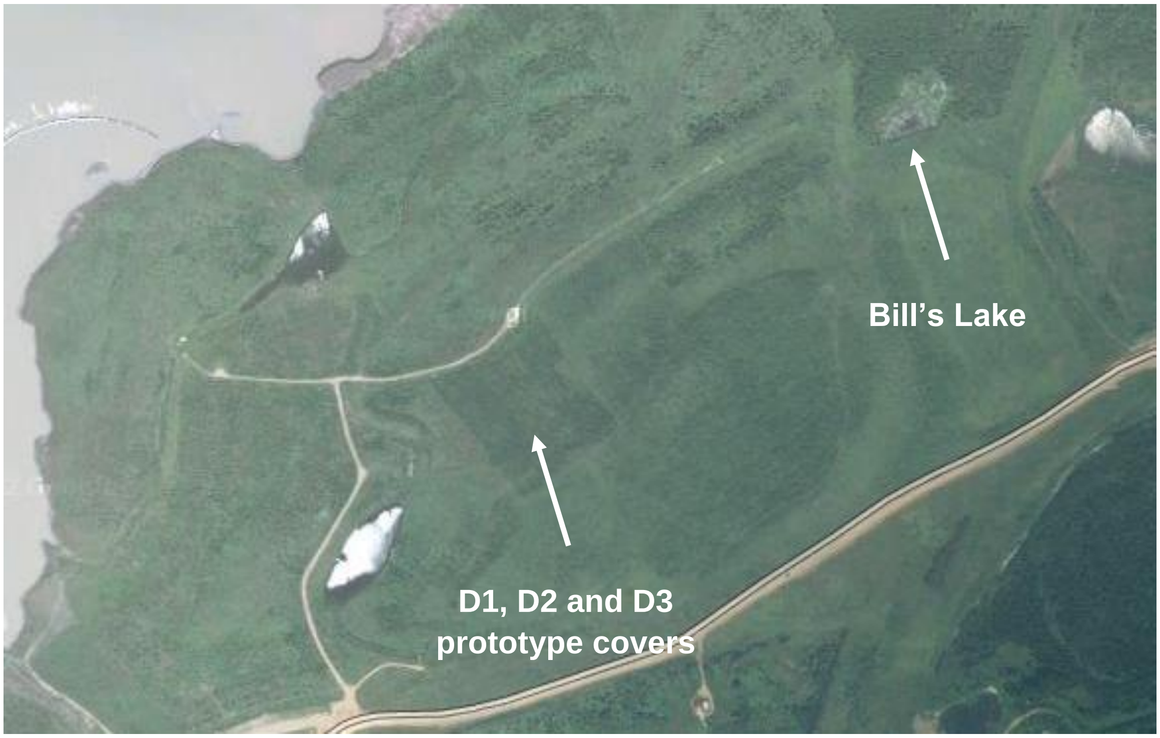

Figure 19. Satellite image showing prototype covers and Bill's Lake (Google Earth 2013).

Table 13. Overview of site instrumentation and measurements at SW30 Dump (Barbour et al. 2001 and Shurniak 2003).

Instrumentation/method	**Parameters measured**
Meteorological station	Precipitation, air temperature, relative humidity and wind speed
Bowen Ratio Energy Balance (BREB) apparatus	Air temperature, dew-point temperature, net radiation and wind speed
Pan evaporation	Potential evaporation
Snow survey	Snow depth and snow water equivalent
Guelph Permeameter and Frozen Ground Infiltration Rings	Hydraulic conductivity
Frequency Domain Reflectometry (FDR) Unit	Soil moisture
Temperature probe	Soil temperature
Neutron probe	Water content and soil density profile
V-notch weir	Runoff

Instrumentation/method	Parameters measured
Interflow collection system	Amount of water flowing down-slop along the cover/overburden interface
Seepage monitor	Seepage from base of pond
Staff gauge	Water level in pond
Vegetation sampling	Leaf Area Index (LAI, biomass, root depth and plant transpiration rates)

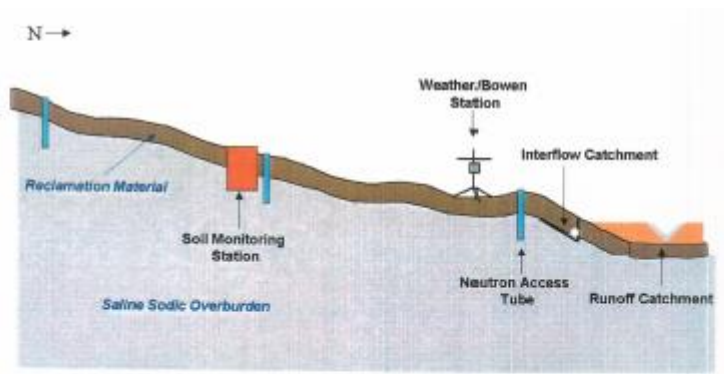

Figure 20. Cross section of the SW30 Dump prototype covers showing the position of the instruments in the landscape (Boese 2003).

5.3 Supplementary Data

In addition to the data sets available for the reclaimed watersheds, sources of supplementary data were also identified. These supplementary data sets are useful for two main reasons:

1. They can be used to fill in missing data that may exist for the reclaimed watersheds
2. They can be used to set up $SWAT_{BF}$ for regional watersheds in the oil sands geographic area

A list of readily available supplementary data sets is provided below. There are many more sources of data available for the oil sands geographic area; however those described below are more accessible than most, hence they have the greatest value at the present time.

5.3.1 *Meteorology*

The main meteorological parameters required by $SWAT_{BF}$ are:

- Daily precipitation (mm)
- Daily air temperature (°C)

The two parameters listed above are the minimum meteorological requirements. The potential evapotranspiration equation proposed by Oudin et al. (2005) has been incorporated into $SWAT_{BF}$

due to its low data requirements. The only meteorological parameter required by the Oudin equation is air temperature. It is also possible to utilize the Penman-Monteith or Priestley-Taylor equations for estimating potential evapotranspiration in $SWAT_{BF}$. To estimate potential evapotranspiration using either one of these equations requires further meteorological parameters to be input into the model. The additional meteorological parameters required by $SWAT_{BF}$ if the Penman-Monteith or Priestley-Taylor equations are utilized are:

- Daily solar radiation (MJ/m^2)
- Daily relative humidity (expressed as a fraction)
- Daily wind speed (m/s)

Note that wind speed is not required by the Priestley-Taylor equation.

5.3.1.1 Environment Canada

All of the meteorological data that are collected by Environment Canada are stored in the National Climate Data and Information Archive[7]. Data are available at hourly, daily and monthly intervals. Much of the data can be freely downloaded from the National Climate Data and Information Archive website. The data that have not been made available online can be ordered through the Climate Services office, although a cost recovery service charge will apply.

Meteorological parameters available are:

- Precipitation
- Air temperature
- Solar radiation
- Relative humidity
- Wind speed

The Environment Canada meteorological stations measuring precipitation and temperature in the oil sands geographic area are shown in Figures 21 and 22, respectively.

5.3.1.2 Canadian Forest Service

Dr. Dan McKenney and his colleagues at the Canadian Forest Service have developed a web application that enables users to generate precipitation, maximum temperature and minimum temperature at any point in Canada or the United States[8]. The point estimates can be obtained on monthly or daily time scales. Access to the data is free of charge and data can be downloaded online. It is advisable to contact Dr. McKenney personally to obtain large data sets. The precipitation and temperature at a specific location are generated using thin-plate smoothing

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[7] See www.climate.weatheroffice.gc.ca

[8] See http://gmaps.nrcan.gc.ca/cl_p/climatepoints.php

splines (McKenney et al. 2011). The application of the thin-plate smoothing splines is carried out using the ANUSPLIN climate modelling software (Hutchison 1995).

Meteorological parameters available are:

- Precipitation
- Air temperature

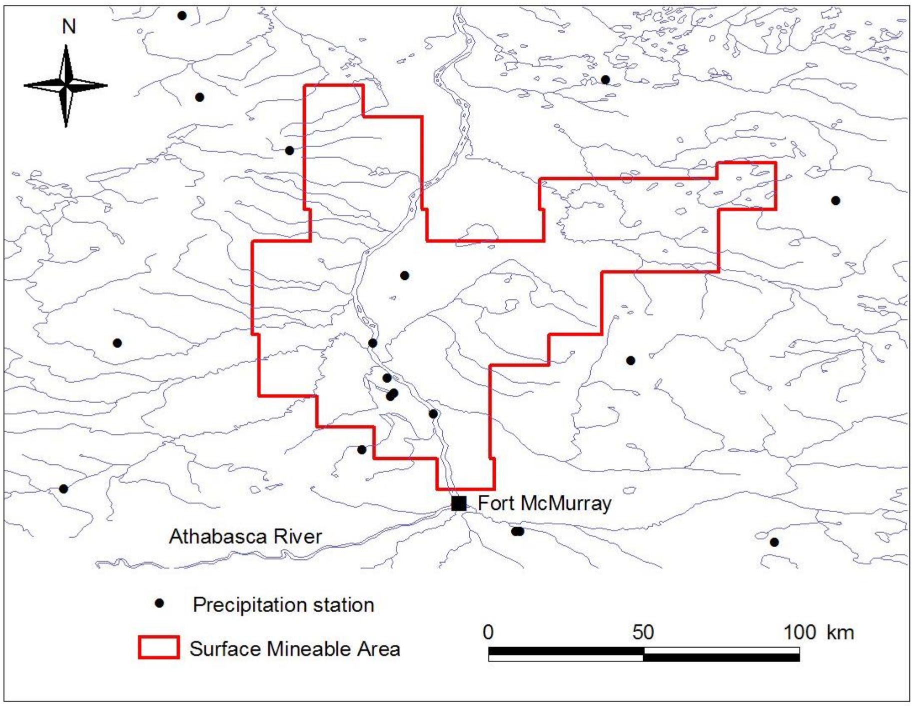

Figure 21. Environment Canada precipitation stations located in the oil sands geographic area.

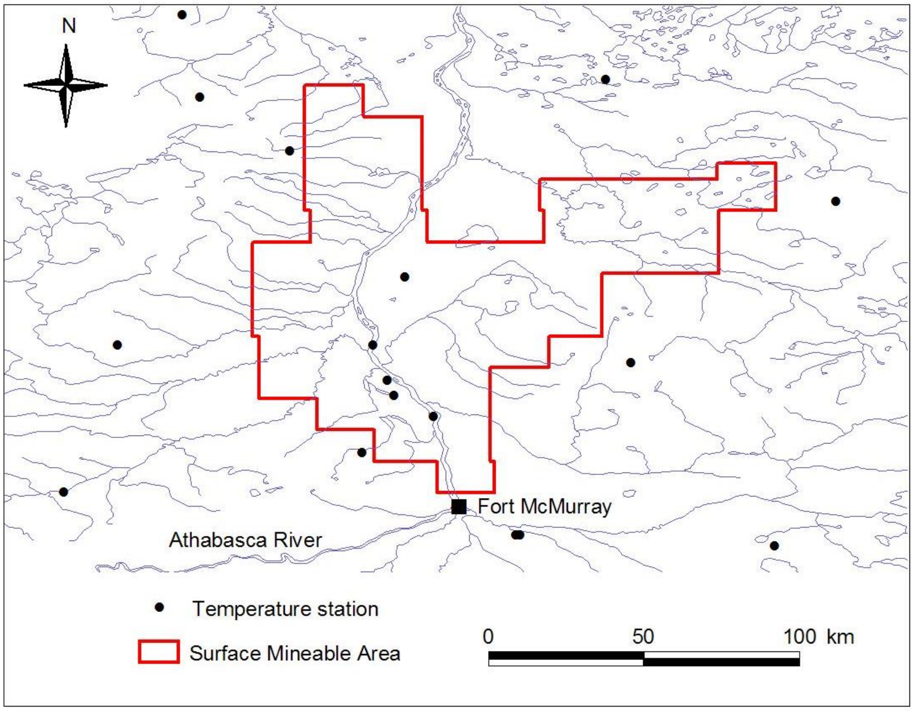

Figure 22. Environment Canada air temperature stations located in the oil sands geographic area.

5.3.1.3 Regional Aquatic Monitoring Program (RAMP)

RAMP is an industry-funded, multi-stakeholder environmental monitoring program that monitors a range of aquatic data across the oil sands geographic area. A range of meteorological parameters are currently being monitored at more than 20 stations (Figure 23). The data are freely available from the RAMP website[9].

Meteorological parameters available are:

- Precipitation
- Air temperature
- Solar radiation
- Relative humidity
- Wind speed

[9] See http://www.ramp-alberta.org/RAMP.aspx

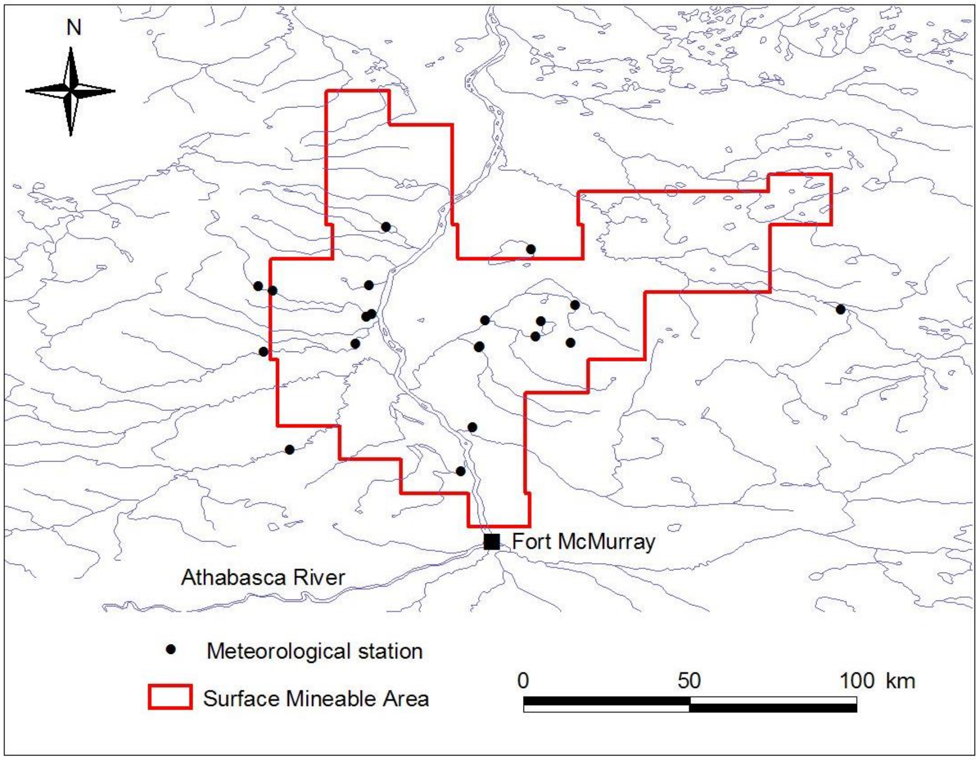

Figure 23. RAMP meteorological stations located in the oil sands geographic area.

5.3.1.4 Wood Buffalo Environmental Association (WBEA)

WBEA monitors air quality in the Regional Municipality of Wood Buffalo at 15 permanent monitoring stations between Anzac and Fort Chipewyan (Figure 24)[10]. The majority of the stations, however, are situated between Fort McMurray and Fort MacKay. Although the WBEA monitoring stations mainly collect air quality parameters (e.g. SO_2, NO, NO_2, NO_X), they also monitor air temperature and wind speed.

[10] See www.wbea.org

Figure 24. WBEA air quality monitoring stations located in the oil sands geographic area (www.wbea.org/monitoring-stations-aamp-data).

Meteorological parameters available are:

- Precipitation
- Air temperature
- Solar radiation
- Relative humidity
- Wind speed

5.3.2 *Streamflow*

$SWAT_{BF}$, or other hydrological models, can be used to generate a time series of streamflow predictions. Those predictions may or may not be representative of actual streamflow. Hence, observed streamflow measurements are required to assess how well a hydrological model performs. Observed streamflow measurements are also required for the model calibration procedure. The model parameters can be adjusted until a representative fit between the observed and predicted streamflow is achieved.

5.3.2.1 Water Survey of Canada (WSC)

WSC is the national authority responsible for monitoring streamflow in Canada[11]. WSC operates several thousand active streamflow gauges across the country. In addition, data are available for several thousand discontinued streamflow gauges. The streamflow data collected by WSC can be downloaded for free online. The active and discontinued streamflow gauging stations operated by WSC in the oil sands geographic area are shown in Figure 25.

5.3.2.2 Regional Aquatic Monitoring Program (RAMP)

In addition to meteorological data, RAMP monitors daily streamflow from numerous rivers and creeks across the oil sands geographic area (Figure 26)[12]. The data are freely available from the RAMP website.

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[11] See www.ec.gc.ca/rhc-wsc

[12] See http://www.ramp-alberta.org/RAMP.aspx

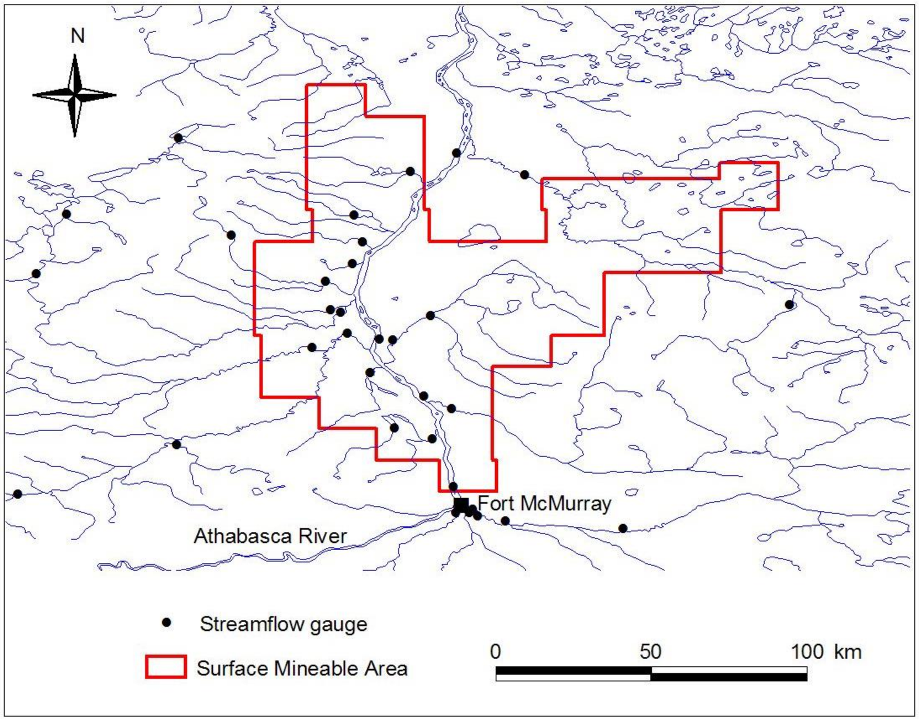

Figure 25. WSC streamflow gauging stations located in the oil sands geographic area.

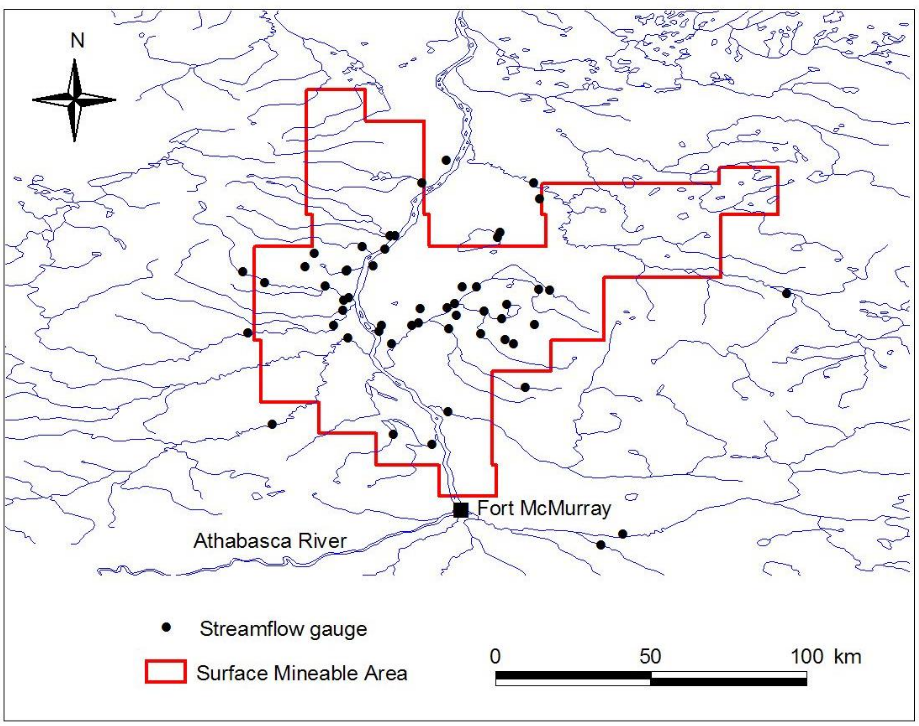

Figure 26. RAMP streamflow gauging stations located in the oil sands geographic area.

5.3.3 *Water Quality*

In addition to water yield, $SWAT_{BF}$ can be used to simulate sediment, nutrient and chemical yields. Water quality data are essential for calibration purposes. Several water quality data sets are readily available for the oil sands geographic area.

5.3.3.1 Water Survey of Canada (WSC)

WSC collects sediment data at many streamflow gauging stations across Canada[13]. Sediment data are available from a number of active and discontinued WSC stations in the oil sands geographic area (Figure 27). Unlike the streamflow data collected by WSC, sediment data are collected less frequently and at irregular intervals. Most of the sediment data measured by WSC are based on a grab sample. The sediment data can be downloaded free of charge from the WSC website.

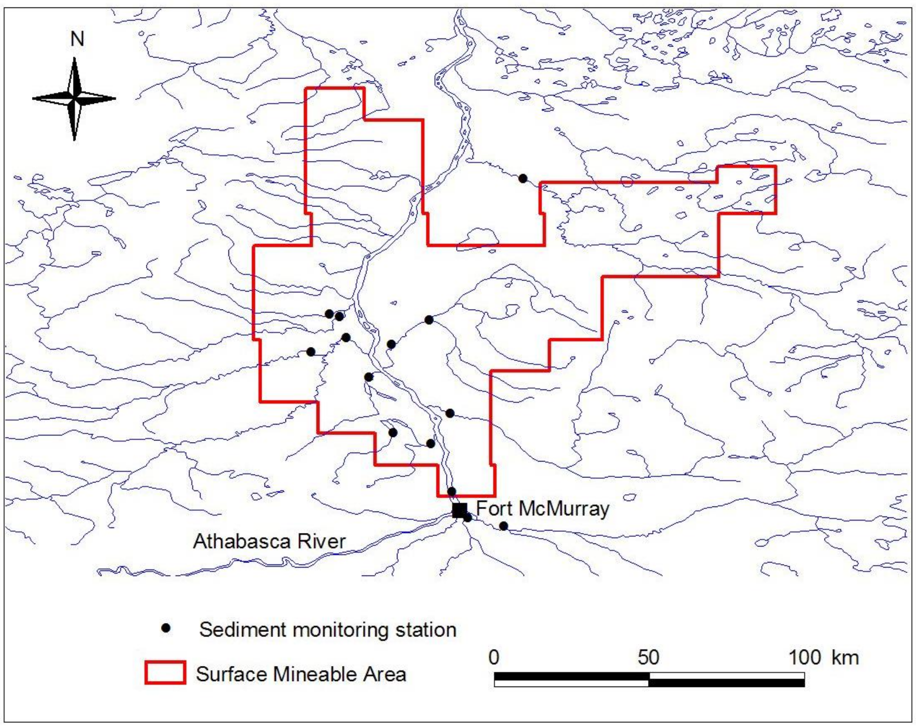

Figure 27. WSC sediment monitoring stations in the oil sands geographic area.

5.3.3.2 Regional Aquatic Monitoring Program (RAMP)

RAMP[14] monitors sediment (Figure 28) and various water quality parameters (Figure 29) at a number of locations across the oil sands geographic area. The data are freely available from the RAMP website.

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[13] See www.ec.gc.ca/rhc-wsc

[14] See http://www.ramp-alberta.org/RAMP.aspx

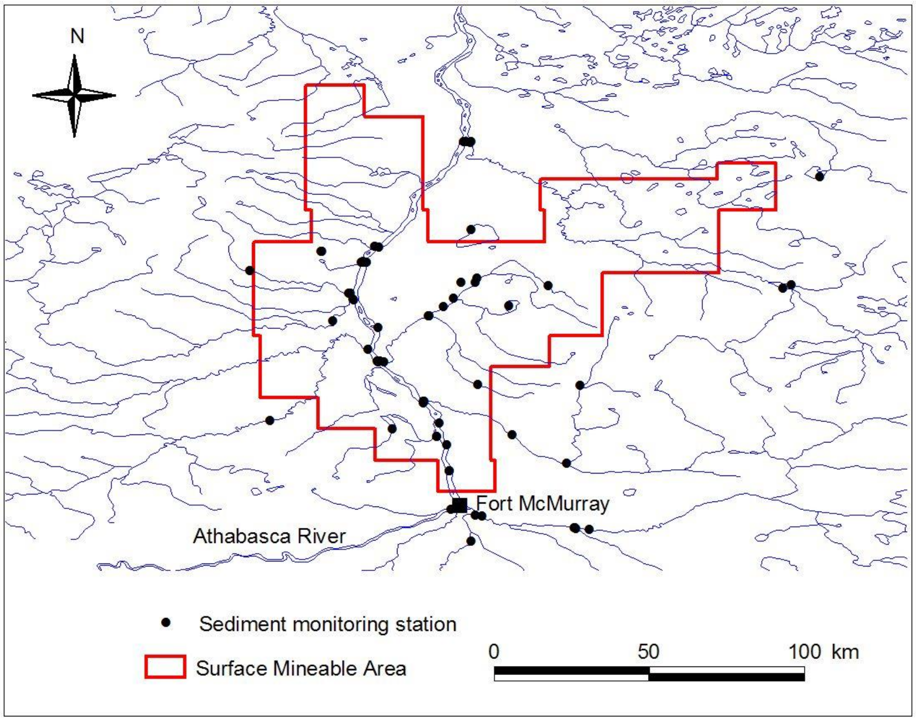

Figure 28. RAMP sediment monitoring stations in the oil sands geographic area.

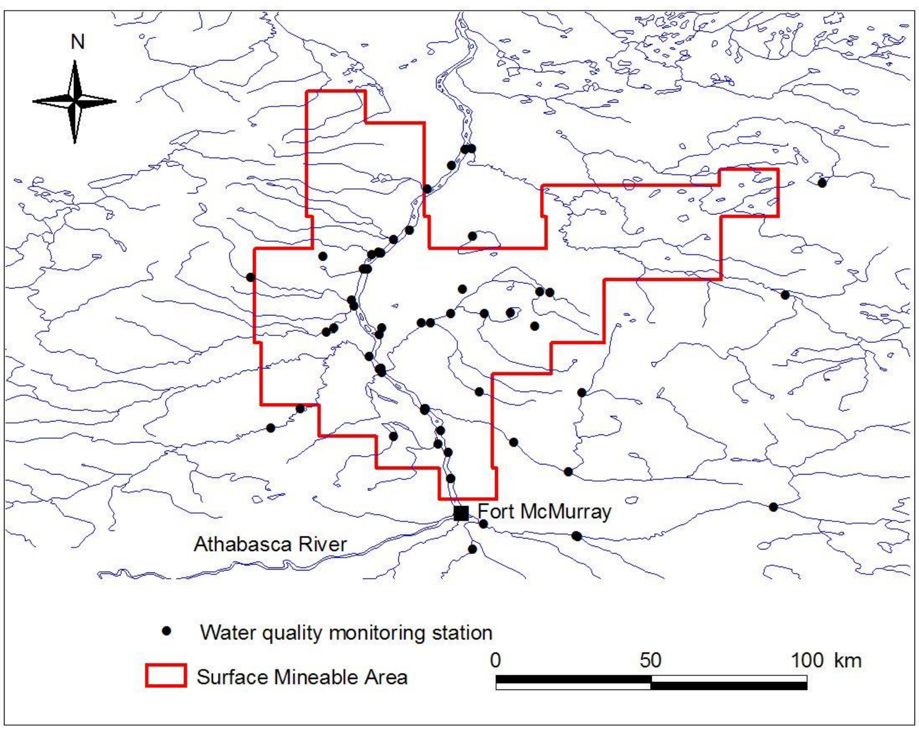

Figure 29. RAMP water quality monitoring stations in the oil sands geographic area.

5.3.4 *Land Use*

A land use map is required by $SWAT_{BF}$ for the creation of the HRUs. As mentioned earlier, HRUs are the smallest spatial unit considered in $SWAT_{BF}$ and consist of a unique land use and soil combination. A detailed land use map is not necessary; van Griensven (2002) commented that detailed soil and land use maps are not useful in SWAT since only the most common combinations appear in the HRUs and less common types disappear. A range of vegetation parameters are also required for each land use type. The SWAT crop database contains the parameters for more than 100 different vegetation types, the majority of which are agricultural crops.

5.3.4.1 WaterBase

A land use map for the entire world can be freely obtained from WaterBase[15]. This land use map was constructed by Dr. Karim Abbaspour at Eawag in Switzerland from the USGS Global Land Cover Characterization (GLCC) database[16]. The spatial resolution of the map is 1 kilometre and 24 land use categories are represented. The WaterBase land use map covering the oil sands geographic area is presented in Figure 30 and was utilized in this study for the application of $SWAT_{BF}$ to the regional watersheds.

WaterBase is responsible for the development of MWSWAT, a GIS interface for SWAT that uses MapWindow GIS. MWSWAT is also freely available from the WaterBase website.

5.3.4.2 Natural Resources Canada (NRCan)

Abbaspour et al. (2010) applied SWAT to the entire province of Alberta. They reported using the Earth Observation for Sustainable Development of Forests (EOSD) forest cover map to set up SWAT. The EOSD map was developed by Natural Resources Canada and the Canadian Space Agency using Landsat satellite data[17]. A total of 21 land cover classes have been represented. The EOSD map has a resolution of 250 metres.

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[15] See www.waterbase.org

[16] See http://edc2.usgs.gov/glcc/glcc.php

[17] See www.cfs.nrcan.gc.ca/pages/337

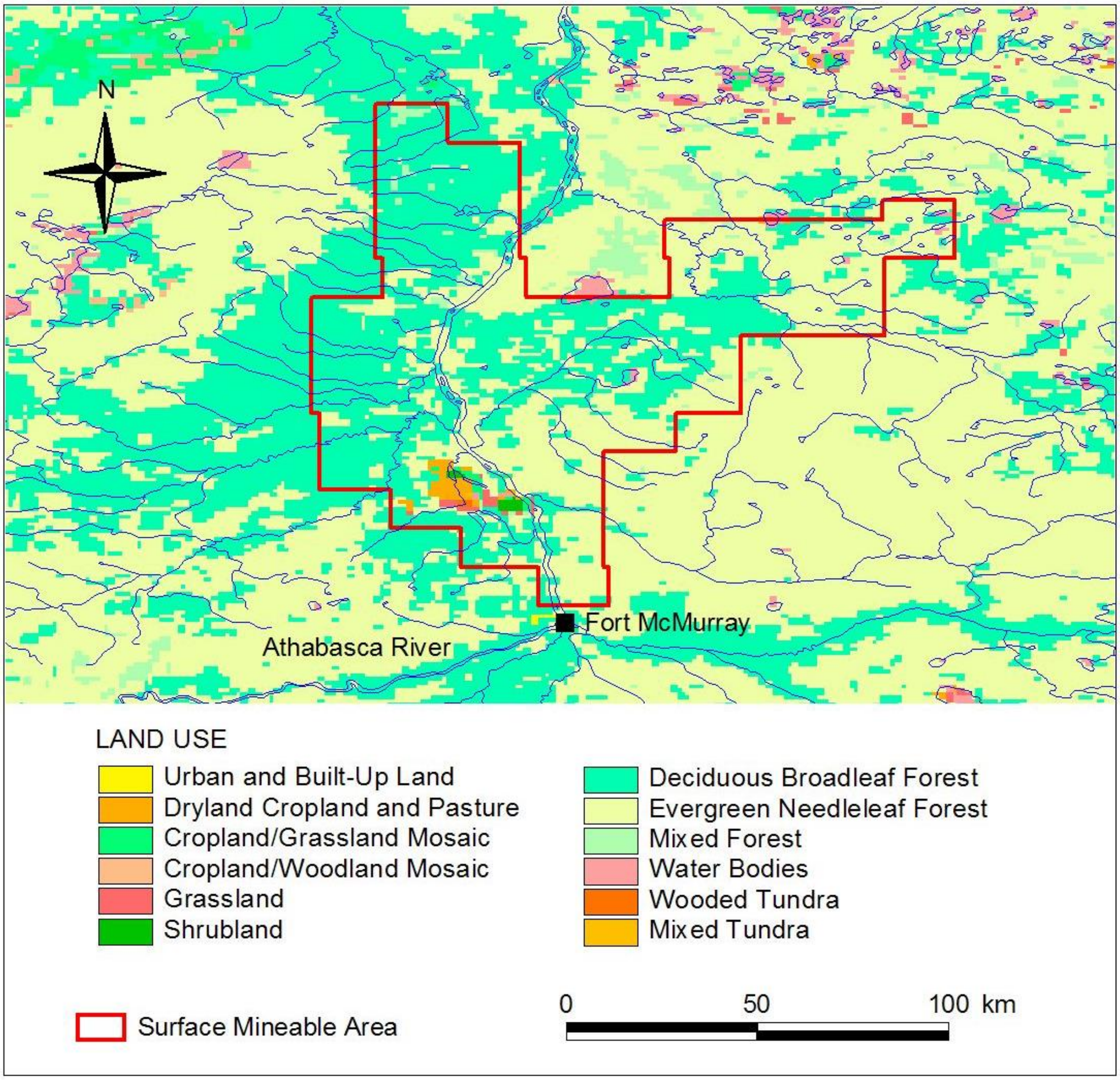

Figure 30. WaterBase land use map for the oil sands geographic area.

5.3.5 *Soils*

A soils map is required by $SWAT_{BF}$ for the creation of the HRUs. As noted above, van Griensven (2002) pointed out that detailed soil and land use maps are not useful in SWAT since only the most common combinations appear in the HRUs and less common types disappear. Soil properties must be assigned to each type of soil that is found in the soils map. Some of the properties that must be defined for each soil layer include:

- Depth of soil layer (mm)
- Available water capacity (mm/mm)
- Saturated hydraulic conductivity (mm/h)

- Moist bulk density (g/cm^3)
- Clay content (%)
- Silt content (%)
- Sand content (%)

The soil properties can be based on measured values, but in most cases have to be estimated using pedotransfer functions.

5.3.5.1 WaterBase

A soils map for the entire world can be downloaded from the WaterBase website. This soils map was produced by the Food and Agriculture Organization of the United Nations (FAO 1995). The spatial resolution of the map is 10 kilometres. Although this is a very coarse resolution, the WaterBase soils map does have an important advantage which makes it useful for practical applications. Dr. Karim Abbaspour at Eawag in Switzerland has estimated soil properties for each soil type using pedotransfer functions which is why the WaterBase soils map[18] was utilized in this study for the application of $SWAT_{BF}$ to the regional watersheds.

5.3.5.2 Alberta Oil Sands Environmental Research Program (AOSERP)

Turchenek and Lindsay (1982) produced a soils map for the oil sands geographic area in the 1980s as part of AOSERP. The resolution of the soils map developed by Turchenek and Lindsay (1982) was 1.27 km. They classified soils according to the Canadian System of Soil Classification (Canadian Soil Survey Committee 1978). To our knowledge, the soils map of Turchenek and Lindsay (1982) represents the only large-scale soils map developed specifically for the oil sands geographic area. The map is available in paper and .pdf format at the present time. However, it is highly recommended that this map be made available in a format that can be used in GIS software.

5.3.6 *Digital Elevation Model (DEM)*

A DEM is needed for defining the watershed boundary as well as for creating subwatersheds. A number of watershed properties, including slope length, slope angle and area, are estimated from the DEM.

5.3.6.1 Alberta Environment and Sustainable Resource Development

Alberta Environment has developed a DEM for the oil sands geographic area at a spatial resolution of 20 metres. A copy of the DEM was acquired from Dr. Robert Magai of Alberta Environment and Sustainable Resource Development.

[18] See www.waterbase.org

5.3.6.2 GeoGratis

A DEM, which is referred to as Canada3D, has been developed for the entire Canadian Landmass using the cells of the Canadian Digital Elevation Data (CDED)[19]. The Canada3D DEM is available in two resolutions: 30 arc-seconds (approximately 1 km) and 300 arc-seconds (approximately 10 km).

5.3.6.3 Shuttle Radar Topographic Mission (SRTM)

The SRTM has developed a DEM that covers approximately 80% of the globe[20]. The spatial resolution of the DEM is 90 m. It is distributed free of charge. The SRTM DEM was utilized in the application of $SWAT_{BF}$ to the regional watersheds. Although it is coarser than the DEM available from Alberta Environment and Sustainable Resource Development, it is already in the format required by the MWSWAT interface. The portion of the SRTM DEM covering the oil sands geographic area is shown in Figure 31.

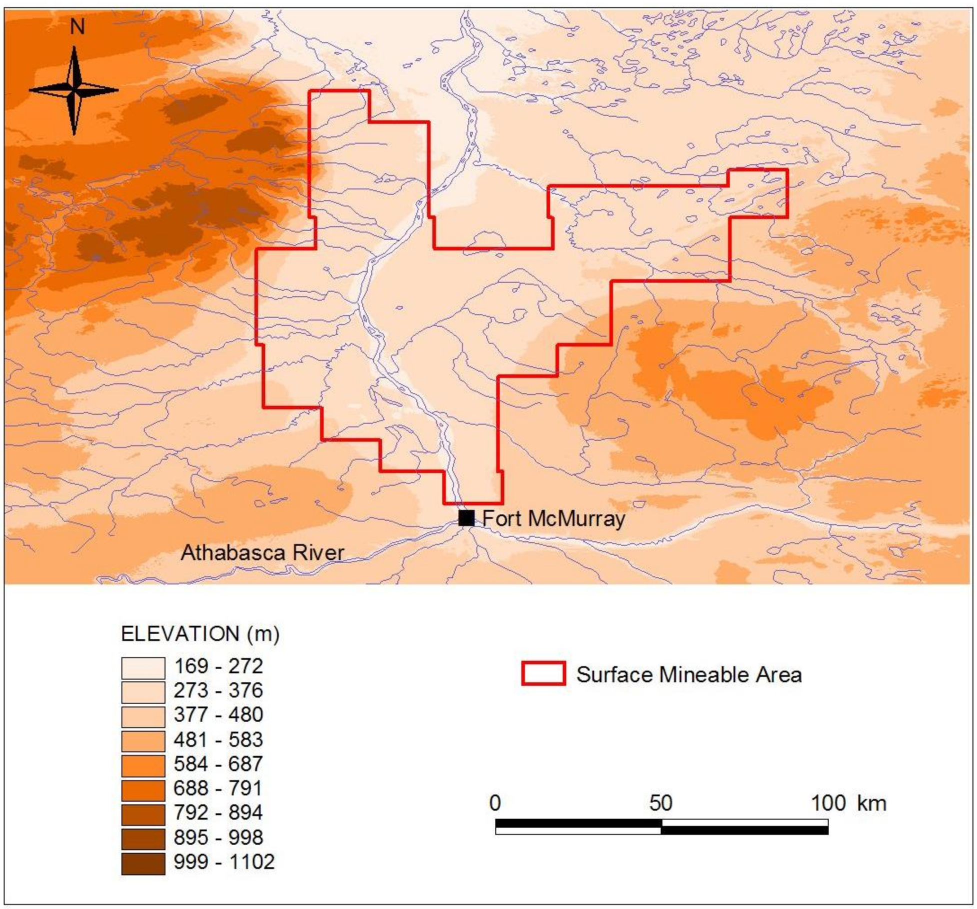

Figure 31. SRTM DEM for the oil sands geographic area.

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[19] See http://geogratis.gc.ca/geogratis/search?lang=en

[20] See http://srtm.csi.cgiar.org/

5.4 Environmental Impact Assessments (EIAs)

More than 50 Environmental Impact Assessments have been submitted to Alberta Environment and Sustainable Resource Development by oil sands companies in the past decade[21]. These EIAs are comprehensive documents that contain a wealth of information on the climate, hydrology, water quality, land use and soils for the oil sands geographic area. Much of this information has been synthesized by the consulting companies who produced the EIAs for the oil sands companies. As such, the data sets remain the property of the consulting companies not the oil sands companies (Purdy pers. comm.). This means that access to the data sets is limited at the present time. Most of the data sets found in the EIAs are strictly related to regional conditions. However, these data sets would still be extremely beneficial to utilize for applications of $SWAT_{BF}$ to the regional watersheds in the oil sands geographic area.

Some of the most important data sets found in the EIAs, at least in terms of setting up and operating $SWAT_{BF}$, are the land use and soils maps. The resolution of these maps is finer than many of the data sets described above. Therefore, they represent one of the best sources of information on the land use and soils for the oil sands geographic area. Although the extent of the maps only cover the lease areas that the individual companies plan to operate within, it would be possible to construct a map covering a large portion of the oil sands geographic area by "stitching" together many smaller maps. This task should be relatively easy to accomplish since most of these maps were produced in GIS.

The streamflow and water quality data collected by the consulting companies can also be used to test the performance of $SWAT_{BF}$. Although the time period covered by these data sets is relatively short compared to, say, the streamflow monitored by the Water Survey of Canada for many of the rivers and creeks in the region, they would still be useful for evaluating the suitability of $SWAT_{BF}$ for the oil sands geographic area.

There are two ways to obtain the EIAs. Firstly, many of the recent EIAs have been made available in digital form on the Alberta Government website. Secondly, the EIAs can be borrowed from the Alberta Government library (Great West Life Suite) in Edmonton. Most of the raw data that are needed for $SWAT_{BF}$ are not made available with the EIAs. For example, daily values for meteorological parameters such as precipitation and temperature are not provided. Similarly, the GIS files for the land use and soils map are not included with any of the EIAs.

A list of EIAs has been provided in Appendix 1. These EIAs contain data sets that could potentially be used to support future applications of $SWAT_{BF}$ in the oil sands geographic area. An in-depth analysis of these EIAs is required to determine the data sets that are useful for $SWAT_{BF}$. However, access to these data sets would still be limited because they belong to the consulting companies and not the oil companies or Albertan Government.

[21] See https://external.sp.environment.gov.ab.ca/DocArc/EIA/Pages/default.aspx for digital copies of recent EIAs.

5.5 Additional Literature

It is possible to find "snippets" of data related to the oil sands geographic area in a wide variety of literature. Such data, which can be used by $SWAT_{BF}$, includes soil properties, channel dimensions, and vegetation parameters. The sources of literature include Masters and PhD theses, books, consulting reports, government reports, journal articles, conference papers and other miscellaneous literature[22]. A listing of selected publications with relevant information to the oil sands geographic area and potential data sets is presented in Appendix 2. However, finding and extracting these data sets would prove to be a very time consuming and expensive task. Furthermore, there would be a need to process and then store the data in a location that is secure and easily accessible. Despite the difficulties that may be associated with obtaining further data sets from the vast amount of literature that is stored in libraries and available on-line, undertaking such a project would be extremely worthwhile. The data could be used as input into other hydrological and ecological models including $SWAT_{BF}$. The oil sands industry could potentially develop some very high quality data sets, which would almost certainly attract more scientists and engineers to conduct research in the region.

The first author of this study found a considerable amount of literature containing data sets that could be used as input into $SWAT_{BF}$ (and other hydrological models) while visiting the Alberta Government Library (Great West Life Suite) in Edmonton. That library alone holds, at the very least, several hundred books and reports that contain data sets that have the potential to be utilized for applications of $SWAT_{BF}$ to the oil sands geographic area. Due to a limited amount of time and resources, it was simply not possible to search through all the materials held in the library, analyze their suitability and then extract the useful data sets. Such an undertaking would probably require 1 to 2 years of full-time work at the library itself, which was beyond the scope of this study. However, as pointed out in the preceding paragraph, this would be a highly beneficial project to carry out.

Van Dijk and Podger (2005) discussed many of the issues facing the development of an integrated modelling framework for the Murray-Darling Basin (1.1 million km^2) in Australia. Although much of their paper has great relevance for the oil sands geographic area, two comments about data collection are particularly relevant to the present study:

> "In the medium term (2-5 years), data collection and modelling should be consolidated, standardised and shared to achieve great consistency across the basin."
>
> "Data is currently scattered across agencies in a range of formats, and this is one of the major impediments towards model integration. Saving real-time data and accessing historic data through a 'one stop shop' should have priority."

The oil sands industry would benefit tremendously by implementing the recommendations of Van Dijk and Podger (2005).

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[22] The Oil Sands Environmental Management Bibliography (http://osemb.cemaonline.ca/rrdcSearch.aspx) provides search capabilities to access some of these documents.

6 APPLICATION OF $SWAT_{BF}$ TO REGIONAL WATERSHEDS

6.1 Introduction

The results from the preliminary application of $SWAT_{BF}$ to the regional watersheds are presented and discussed in this chapter. Although the primary focus of this study was to apply $SWAT_{BF}$ to reclaimed watersheds in the oil sands geographic area, it was decided that $SWAT_{BF}$ would also be applied to several regional watersheds as a means to further demonstrate its capabilities as a hydrological model. The application of the model to regional watersheds is a valuable investigation because the purpose of the reclaimed watersheds is to return the landscape to similar conditions before the disturbance occurred. In other words, the reclaimed watersheds will eventually transition back to watersheds that resemble regional watersheds. Therefore, it is critical for a hydrological model to accurately reproduce runoff from both reclaimed and regional watersheds as well as from watersheds in the transition phase.

The performance of $SWAT_{BF}$ for predicting runoff [23] from five regional watersheds was assessed at monthly and daily time steps using the evaluation criteria described earlier. The results presented in this chapter represent a first attempt at modelling watersheds in the oil sands with $SWAT_{BF}$. Although this study provides important insights into the capabilities of $SWAT_{BF}$ for reproducing runoff from watersheds in the oil sands geographic area, a more stringent test of the model should be undertaken when higher quality data sets become available.

6.2 Description of Regional Watersheds and Data Sets

The following section provides a brief overview of the five regional watersheds that $SWAT_{BF}$ was applied to in this study. Basic properties of the watersheds considered in this study are provided in Table 14 and their boundaries are shown in Figure 32.

Table 14. Regional watersheds in the oil sands geographic area utilized in this study.

Watershed	WSC Station	Area [1] (km^2)	Min. Elev. [2] (m)	Mean Elev. [2] (m)	Max. Elev. [2] (m)
Beaver River	07DA018	165	263	427	550
Hangingstone River	07CD004	962	198	541	772
Joslyn Creek	07DA016	257	238	542	850
MacKay River	07DB001	5569	213	515	840
Muskeg River	07DA008	1457	225	373	592

[1] Area drained to streamflow gauging station (www.ec.gc.ca/rhc-wsc)
[2] Derived from DEM

[23] $SWAT_{BF}$ predicts streamflow as a discharge rate (e.g., m^3/day). Streamflow is often expressed in terms of runoff which is discharge rate divided by watershed area expressed as mm depth. Streamflow expressed as runoff (mm) can readily be compared to precipitation input (mm) and evapotranspiration (mm).

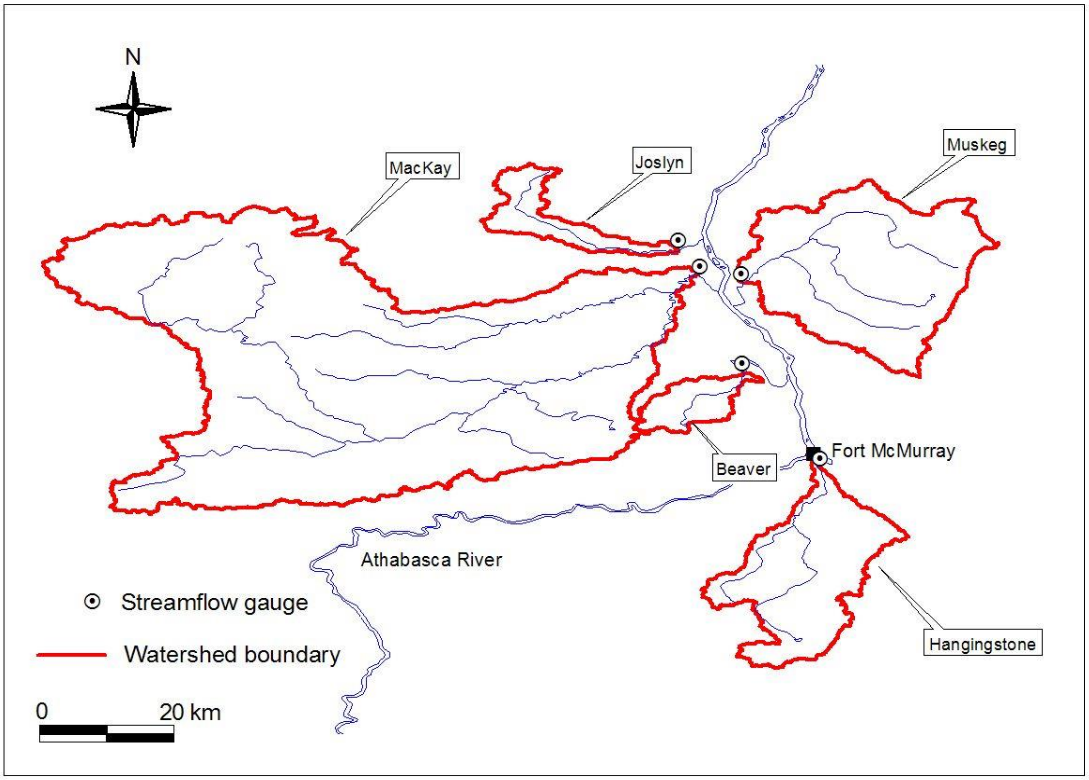

Figure 32. Boundaries of the five regional watersheds utilized in this study.

The watersheds shown in Figure 32 were selected for this study because long-term streamflow data were available for all five watersheds. Since $SWAT_{BF}$ is a long-term yield model it must be able to reproduce the long-term runoff from watersheds in the oil sands geographic area to give confidence in its applicability. Short-term streamflow data would not provide a stringent test of the capabilities of $SWAT_{BF}$. The gauging stations measuring streamflow from the five regional watersheds are maintained by the Water Survey of Canada. The precipitation and air temperature data used for each watershed were acquired from the Canadian Forest Service.

The watersheds were subdivided into multiple subwatersheds and HRUs (Table 15).

Table 15. Number of subwatersheds and HRUs created for each watershed.

Watershed	**Subwatersheds**	**HRUs**
Beaver	7	13
Hangingstone	13	21
Joslyn	9	15
MacKay	11	27
Muskeg	11	24

The subwatershed delineation of the MacKay River watershed applied to $SWAT_{BF}$ is shown in Figure 33.

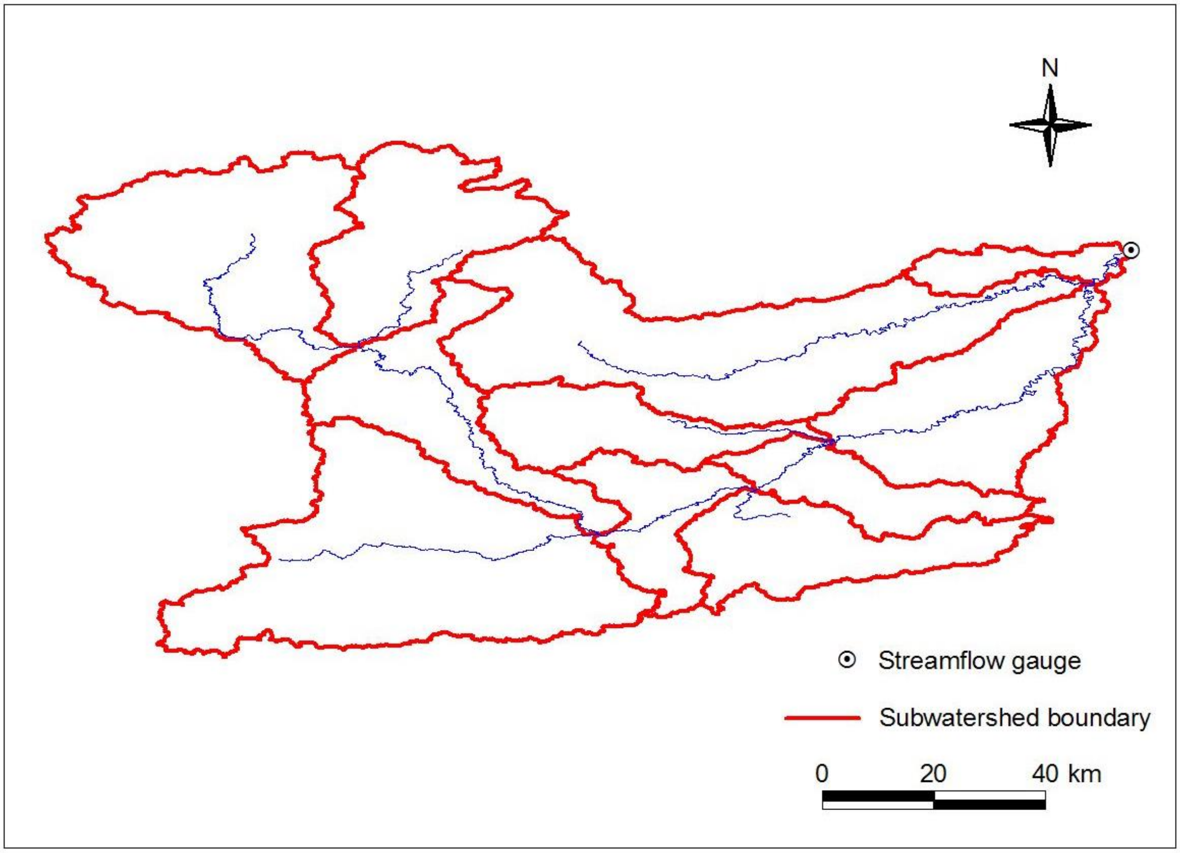

Figure 33. Subwatersheds delineated for the MacKay River watershed.

The predominant vegetation cover for the five regional watersheds considered in this study is evergreen needleleaf[24] forest and deciduous broadleaf forest. The percentage of area these forest types cover in each watershed are provided in Table 16. The land use map available from WaterBase was used in this study. It is very likely that more vegetation types would be identified for each watershed if a land use map with a finer resolution were used instead.

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[24] The landuse category "evergreen needleleaf forest" from the WaterBase land use map is used in this study to refer to conifer dominant forests.

Table 16. Percentage of area each forest type occupies in the regional watersheds.

Watershed	Evergreen Needleleaf	Deciduous Broadleaf
Beaver	29.5	70.5
Hangingstone [#]	84.3	15.4
Joslyn	33.7	66.3
MacKay	70.8	29.2
Muskeg	66.7	33.3

[#] The remaining 0.3% of the watershed was comprised of Mixed Forest.

As mentioned earlier, the version of $SWAT_{BF}$ utilized in this study requires the Leaf Area Index (LAI) of the vegetation to be prescribed. Users can adopt any method they deem appropriate to estimate LAI for the various vegetation types in the watershed being investigated. Numerous methods have been described in the literature to estimate LAI at the landscape scale. The types of LAI estimates used as input into hydrological models include standard LAI values (Andersen et al. 2001, Jain et al. 1992), constant mean LAI values (Ye et al. 1997, Zhang et al. 2009), mean annual LAI values multiplied by a seasonality factor (Zammit and Sivapalan 2002), remotely sensed LAI values (Andersen et al. 2002, Zhang et al. 2009), LAI values derived from LAI-age relationships (Feikema et al. 2009, Watson 1999) and LAI values based on field measurements (Watson 1999).

For the purpose of this study we used mean monthly values of LAI as input into $SWAT_{BF}$. Bourque and Hassan (2009) estimated the LAI for six forest cover types across the oil sands geographic area using a 2005 MODIS satellite image. They estimated the mean LAI for each forest cover type on the following Julian days of the year: 17, 41, 73, 105, 137, 169, 193, 225, 257, 289, 321 and 353. Since these Julian days occur approximately during the middle of each month of the year, we assumed that the values of LAI estimated for these days were representative of the mean LAI for that month. Bourque and Hassan (2009) estimated LAI for the following forest cover types: hardwoods, mixed woods, white spruce, black spruce forests, black spruce fens and jack pine forests. The forest types defined by Bourque and Hassan (2009) did not correspond directly to the forest types defined in the land use map from WaterBase. Therefore, we assumed the LAI for the hardwoods applied to the deciduous broadleaf forests while the average LAI for the white spruce, black spruce forests, black spruce fens and jack pine forests was applicable for the evergreen needleleaf forests. The mean monthly LAI for the deciduous broadleaf and evergreen needleleaf forests is shown in Figure 34.

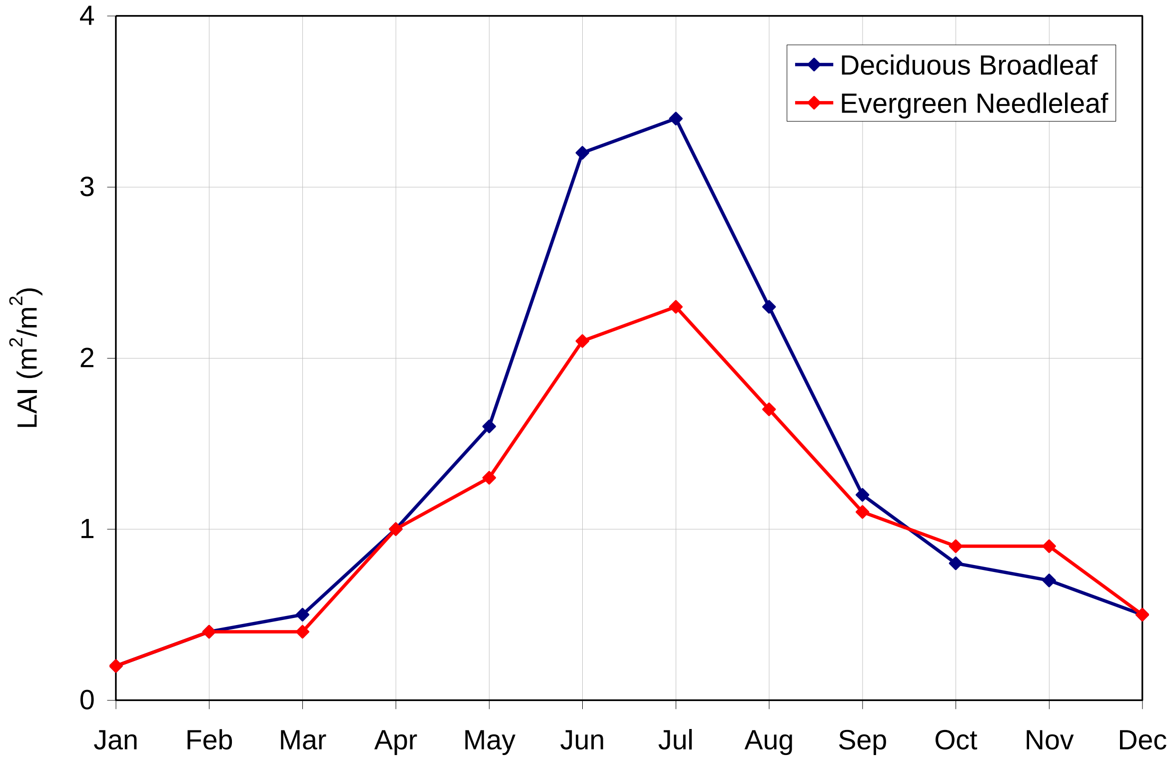

Figure 34. Mean monthly LAI values estimated for deciduous broadleaf and evergreen needleleaf forests.

Since Bourque and Hassan (2009) only estimated LAI for 2005, we assumed that the mean monthly values were applicable for all years of the evaluation period (1976 to 1993) in this study. More accurate estimates of LAI would lead to improvements in model performance. Given that the application of $SWAT_{BF}$ in this study represents a preliminary attempt to assess the performance of the model, and that several other data sets used in this study are not the most comprehensive ones available, the LAI estimates utilized in this study were deemed to be sufficient.

The $SWAT_{BF}$ input files for all five regional watersheds can be obtained from the FORWARD Data Management System website[25]. Users must complete a Data Request Form and agree to a "terms of use agreement" to obtain the data. The Data ID for this data set is 7789. The source code and executable for $SWAT_{BF}$ are also included along with the spreadsheets used to analyze the results.

[25] See http://forward.theforestrycorp.com

6.3 Evaluation of Model Performance

6.3.1 *Operational Testing Procedure*

Klemeš (1986) outlined a hierarchal scheme for the operational testing of hydrologic models. The "split-sample" test is the one that is most widely used to evaluate the performance of hydrological models. In fact, only a handful of studies have ever been undertaken in which the other tests were implemented (Beven 2001). A split-sample test involves splitting the available record into two segments, one of which is used for calibration and the other for validation. The first step is to calibrate the model which involves the adjustment of model parameters to obtain a better fit between the observed and predicted time series. The second step is to validate the model which involves the application of the calibrated model to a period that was not used during the calibration period. A strict requirement of this step is that the model parameters optimized during the calibration step are not changed but are held constant. This second step provides an independent test of how well the model is capable of predicting runoff when applied to a different period of record. The model is considered to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits or to provide acceptable errors (Refsgaard 1996).

Hydrologists and engineers typically utilize a "warm-up" period during the calibration step, whereby the model is run for a period of time before the calibration period in an attempt to estimate the initial values of the internal state variables simulated by the model. It is extremely difficult to determine the initial values of certain variables updated by a model including soil water content, groundwater levels and snow pack depth. The utilization of a warm-up period is an attempt to reduce this problem.

6.3.2 *Evaluation Criteria*

Numerous evaluation criteria have been utilized by hydrological modellers in the past few decades to assess the performance of hydrologic models. However, it is evident from the wide range of evaluation criteria utilized in the literature that no accepted standards for evaluating the agreement between the output of models and the observed data have been agreed upon (ASCE 1993). Although a large number of evaluation criteria can be used to assess model performance, it is usually recommended that the number of criteria be kept to a minimum as there is a better chance that more meaningful information can be extracted from the data (Martinec and Rango 1989). An assessment of model performance becomes difficult for the user if too many criteria are used (Martinec and Rango 1989). We used three evaluation criteria in this study, which are described below.

6.3.2.1 Deviation of Runoff Volumes

The deviation of runoff volumes is a measure of a model's ability to predict the total volume of runoff for the period of analysis (ASCE 1993). The deviation of runoff volumes is computed as follows:

$$D_V = \frac{V_{pred} - V_{obs}}{V_{obs}} \cdot 100$$

Where D_V = deviation of runoff volumes expressed as a percentage (%)

V_{obs} = total observed runoff for the simulation period (mm)

V_{pred} = total predicted runoff for the simulation period (mm).

The deviation of runoff volumes can range from $-\infty$ to $+\infty$. A value of zero indicates that there is no difference between the total observed and predicted runoff.

6.3.2.2 Nash-Sutcliffe Coefficient

Since its introduction in 1970, the Nash-Sutcliffe coefficient has become one of the most widely used statistics in hydrology. It indicates the proportion of the variance of the observed runoff that is accounted for by the model (Nash and Sutcliffe 1970). The Nash-Sutcliffe coefficient is given by the following equation:

$$NSE = 1 - \frac{\sum \left(Q_{obs} - Q_{pred}\right)^2}{\sum \left(Q_{obs} - Q_{mean}\right)^2}$$

Where NSE = Nash-Sutcliffe coefficient

Q_{obs} = observed runoff (mm)

Q_{pred} = predicted runoff (mm)

Q_{mean} = mean observed runoff for the simulation period (mm)

Values of the Nash-Sutcliffe coefficient can range from $-\infty$ to 1, with 1 indicating a perfect fit between the observed and predicted time series. The Nash-Sutcliffe coefficient was computed at monthly (NSE_M) and daily (NSE_D) time scales for this study.

6.3.2.3 Hydrographs

Observed and predicted hydrographs were visually compared at monthly and daily time scales. Although the visual comparison of observed and predicted hydrographs is a subjective technique, it does provide an additional means to assess the performance of a hydrological model. Modellers can determine if a model was able to reproduce important components of a hydrograph such as peak flows or recessions. Insights into how well a model performs at reproducing these features of a hydrograph would be virtually impossible by utilizing only goodness-of-fit statistics.

6.3.2.4 Residuals

A time series of monthly residuals, defined as the difference between the observed and predicted monthly runoff, was produced for the entire evaluation period. A plot of the monthly residuals reveals useful information about how much the model overestimated or underestimated monthly runoff. Such plots are also very useful for determining how well a model has reproduced peak monthly runoff events.

6.3.2.5 Flow Duration Curves

Observed and predicted daily flow duration curves were produced for the entire evaluation period and compared. Flow duration curves are useful in describing the adequacy of the simulation of flows of different magnitudes (Chiew and McMahon 1993).

6.3.3 *Model Performance*

Andersen et al. (2002) developed numerical performance criteria for the statistics D_V, NSE_M and NSE_D to define the level of model performance. According to their criteria, model performance is defined as very good, good, fair and poor. Watson and Putz (2012) utilized similar performance criteria to define the performance of $SWAT_{BF}$ for five watersheds in central Alberta (Table 17).

Table 17. Performance criteria used to define the level of model performance.

Performance	**D_V (%)**	**NSE_M**	**NSE_D**
Very good	$D_V \leq \pm 5$	$NSE_M \geq 0.8$	$NSE_D \geq 0.7$
Good	$\pm 5 > D_V \leq \pm 10$	$0.6 \geq NSE_M < 0.8$	$0.5 \geq NSE_D < 0.7$
Fair	$\pm 10 > D_V \leq \pm 20$	$0.4 \geq NSE_M < 0.6$	$0.3 \geq NSE_D < 0.5$
Poor	$D_V > 20$	$NSE_M < 0.4$	$NSE_D < 0.3$

6.3.4 *Calibration and Validation Periods*

The evaluation period for all five regional watersheds was 1976 to 1993. A long evaluation period was utilized to test whether $SWAT_{BF}$ could reproduce the long-term water yield of the regional watersheds. Utilizing a short evaluation period would not stringently test the model for reproducing the dynamics of the long-term water balance of the study watersheds.

The warm-up, calibration and validation periods utilized for all five regional watersheds in this study were as follows:

- Warm-up period → 1974 to 1975
- Calibration period → 1976 to 1984

- Validation period → 1985 to 1993

6.3.5 *Parameters Adjusted During Calibration Procedure*

For the calibration of a distributed hydrologic model, Refsgaard (1997) recommended that the number of parameters adjusted be kept to a minimum to avoid the problem of overparameterization. In keeping with this recommendation, nine parameters were calibrated during the application of $SWAT_{BF}$ to the regional watersheds (Table 18). The definition of each parameter is provided along with the lower and upper bounds that the parameter values could take during the calibration procedure. The selection of the parameters was based on a previously performed sensitivity analysis as well as the experience gained from using the model over the past decade (Watson et al. 2008).

Table 18. Parameters adjusted during the calibration of $SWAT_{BF}$ for the regional watersheds.

Parameter	**Definition (units)**	**Lower bound**	**Upper bound**
ALPHA_BF	Baseflow recession constant (d)	0.01	0.05
CN2	Soil Conservation Service runoff curve number (–)	-25%	25%
SOL_K	Saturated hydraulic conductivity (mm/h)	-50%	50%
SOL_Z	Soil depth (mm)	-50%	50%
SOL_AWC	Available water capacity (mm/mm)	-50%	50%
ANISO	Anisotropy factor (–)	1	5
SURLAG	Surface runoff lag coefficient (d)	0.01	2
SMFCN	Melt factor (mm/°C/d)	1	5
SFMTMP	Snowfall and snowmelt threshold temperature (°C)	-2	2

6.4 Results

6.4.1 *Optimized Parameters*

The optimized values for each parameter in the regional watersheds that were adjusted during the calibration procedure are presented in Table 19.

Table 19. Optimized values for each parameter adjusted during the calibration of $SWAT_{BF}$ for the regional watersheds.

Parameter	Beaver	Hangingstone	Joslyn	MacKay	Muskeg
ALPHA_BF	0.032	0.010	0.032	0.032	0.024
CN2	5.8%	25.0%	4.2%	15.6%	16.6%
SOL_K	24.3%	-45.6%	27.1%	-47.0%	-44.0%
SOL_Z	26.0%	-22.1%	30.2%	38.9%	19.8%
SOL_AWC	12.8%	-34.0%	6.7%	0.72%	20.3%
ANISO	2.5	1.0	4.5	1.0	1.3
SURLAG	0.14	0.16	0.13	0.13	0.05
SMFCN	1.0	1.0	1.6	1.2	1.3
SFMTMP	0.89	1.5	-0.49	0.74	2.0

6.4.2 *Total Runoff*

Tables 20 and 21 show the total observed and predicted runoff from the regional watersheds for the calibration and validation periods, respectively. Also presented in Tables 20 and 21 are the deviation of runoff volumes (D_V) along with the performance ratings achieved by the model. Table 20 shows that the performance of $SWAT_{BF}$ for reproducing the total runoff for the calibration period was very good for all five regional watersheds.

However, the performance of the model for the validation period varied significantly (Table 21). The performance of the model for reproducing the total runoff from Joslyn Creek watershed was deemed to be very good for the validation period. In contrast, the model performed poorly at reproducing the total runoff from MacKay River watershed for the validation period. It is difficult to determine the cause of this phenomenon. The total observed runoff from Joslyn Creek and MacKay River watersheds was significantly greater for the validation period than for the calibration period.

It is common for a hydrological model to perform well for a “dry” period but then fail when applied to a “wet” period. This can be explained by the information content of the runoff record not being rich enough to activate every model process during the calibration period (Ye et al. 1997). The fact that the model performed well at reproducing the runoff from Joslyn Creek watershed and not MacKay River watershed raises a number of interesting questions. Given the very good performance of the model for Joslyn Creek watershed, it is unlikely that the poor performance of the model for MacKay River watershed can be attributed to model deficiencies, which are simplifications or limitations that exist in a model to prevent it from adequately accounting for physical processes occurring in a watershed (Jacomino and Fields 1997). It is more likely that data deficiencies, which are errors in the data used to calibrate a model (Jacomino and Fields 1997), played a significant role in the decline of model performance for the validation period. Data deficiencies often apply to a small portion of the entire data set. There is a possibility that there may have been problems with the precipitation records used for the MacKay River watershed during the validation period. Further testing of the model with improved data sets is required to fully resolve this issue.

Table 20. Total cumulative observed and predicted runoff, deviation of runoff volumes (D_V) and performance for the calibration period.

Watershed	**Observed (mm)**	**Predicted (mm)**	**D_V (%)**	**Performance**
Beaver	700	699	-0.1	Very Good
Hangingstone	1,051	1,009	-4.0	Very Good
Joslyn	552	572	3.6	Very Good
MacKay	501	524	4.6	Very Good
Muskeg	579	604	4.3	Very Good

Table 21. Total cumulative observed and predicted runoff, deviation of runoff volumes (D_V) and performance for the validation period.

Watershed	**Observed (mm)**	**Predicted (mm)**	**D_V (%)**	**Performance**
Beaver	936	792	-15.4	Fair
Hangingstone	911	1,001	9.9	Good
Joslyn	748	782	4.5	Very Good
MacKay	857	646	-24.6	Poor
Muskeg	880	714	-18.9	Fair

6.4.3 *Monthly Runoff*

Figures 35 to 44 show the observed and predicted monthly runoff from the five regional watersheds for the calibration and validation periods. It can be observed that the monthly runoff fluctuated significantly for all five regional watersheds. The peak monthly events varied considerably from one year to the next. Figures 35 to 44 reveal that $SWAT_{BF}$ reproduced the seasonal variations in monthly runoff relatively well for all of the watersheds considered in this study. The most obvious shortcoming of the model for predicting monthly runoff was its tendency to underestimate peak monthly events. Streamflow is not always measured by the

Water Survey of Canada during the winter months. Therefore, there are extended periods (i.e., several months) when no records exist.

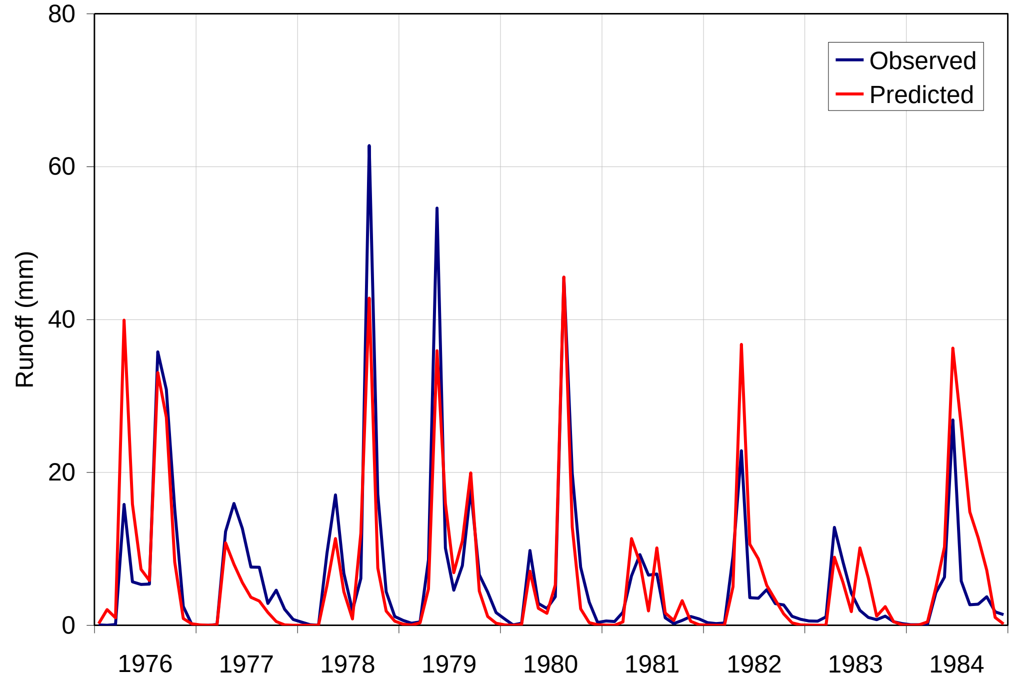

Figure 35. Observed and predicted monthly runoff from Beaver River watershed for the calibration period.

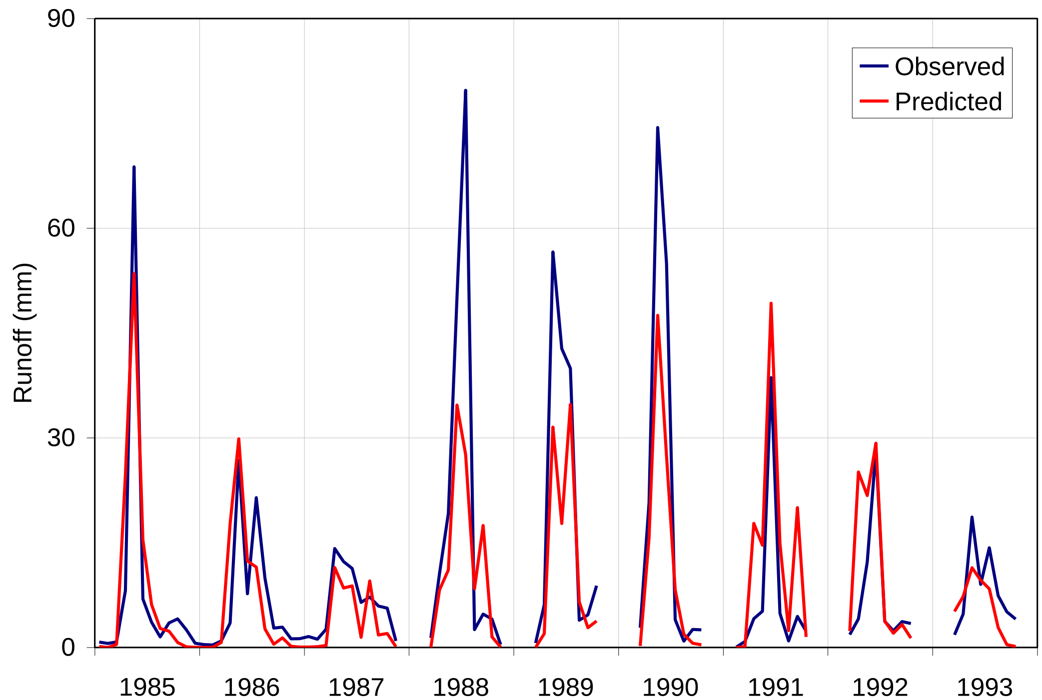

Figure 36. Observed and predicted monthly runoff from Beaver River watershed for the validation period.

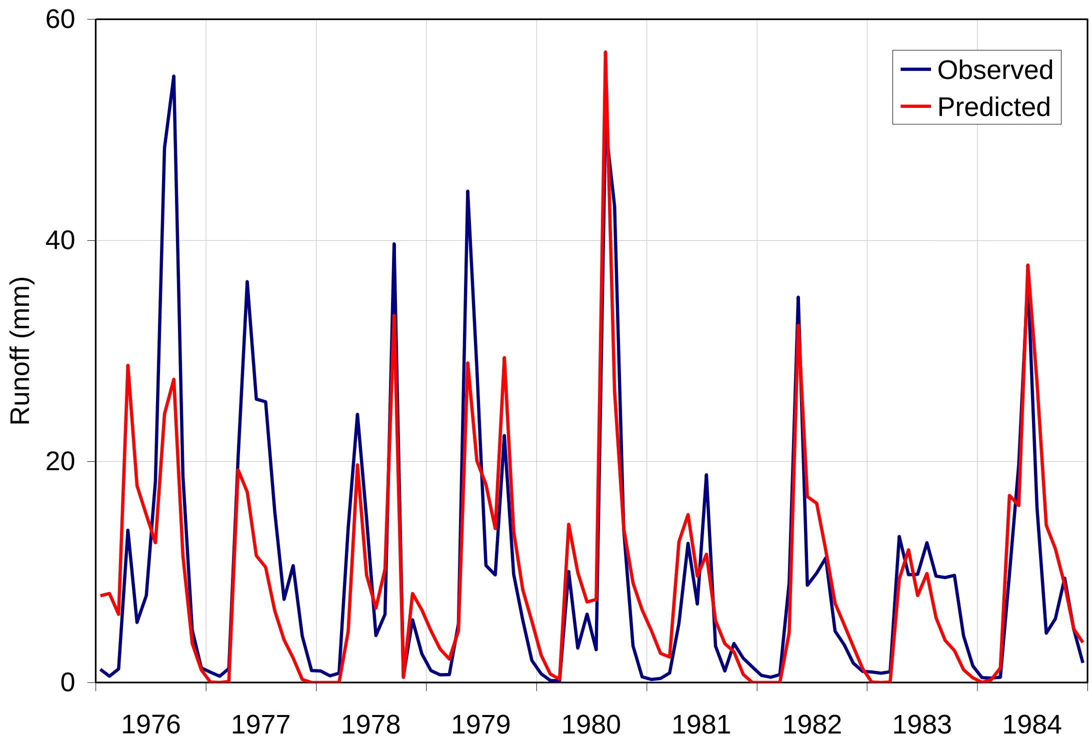

Figure 37. Observed and predicted monthly runoff from Hangingstone River watershed for the calibration period.

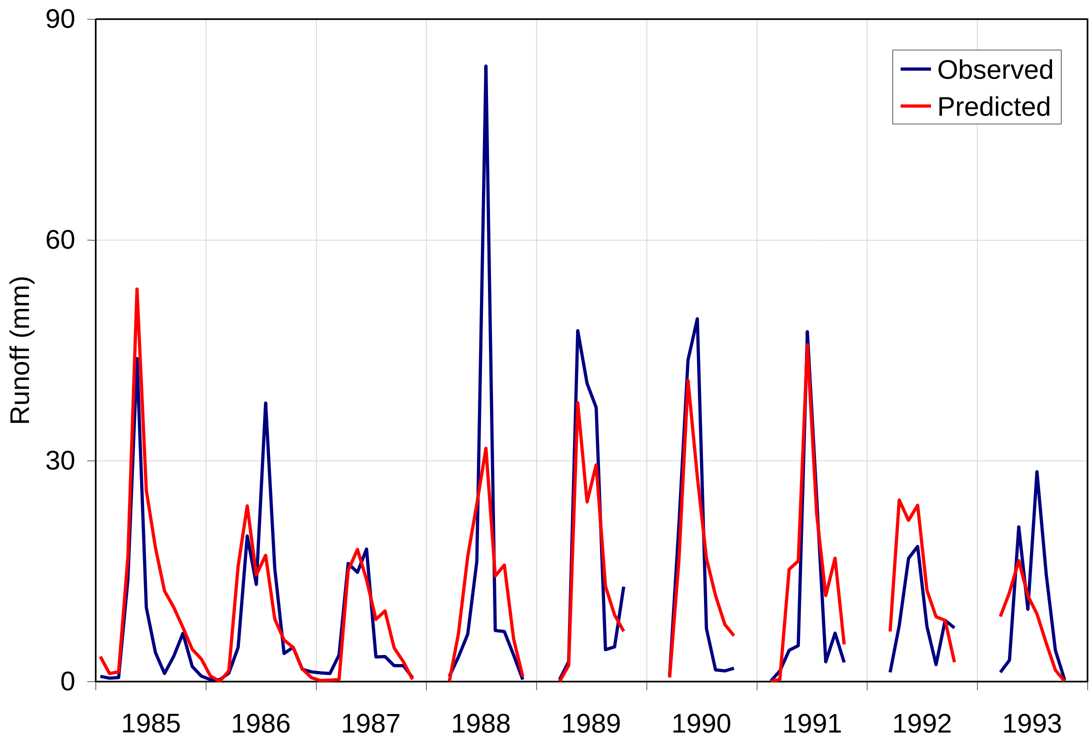

Figure 38. Observed and predicted monthly runoff from Hangingstone River watershed for the validation period.

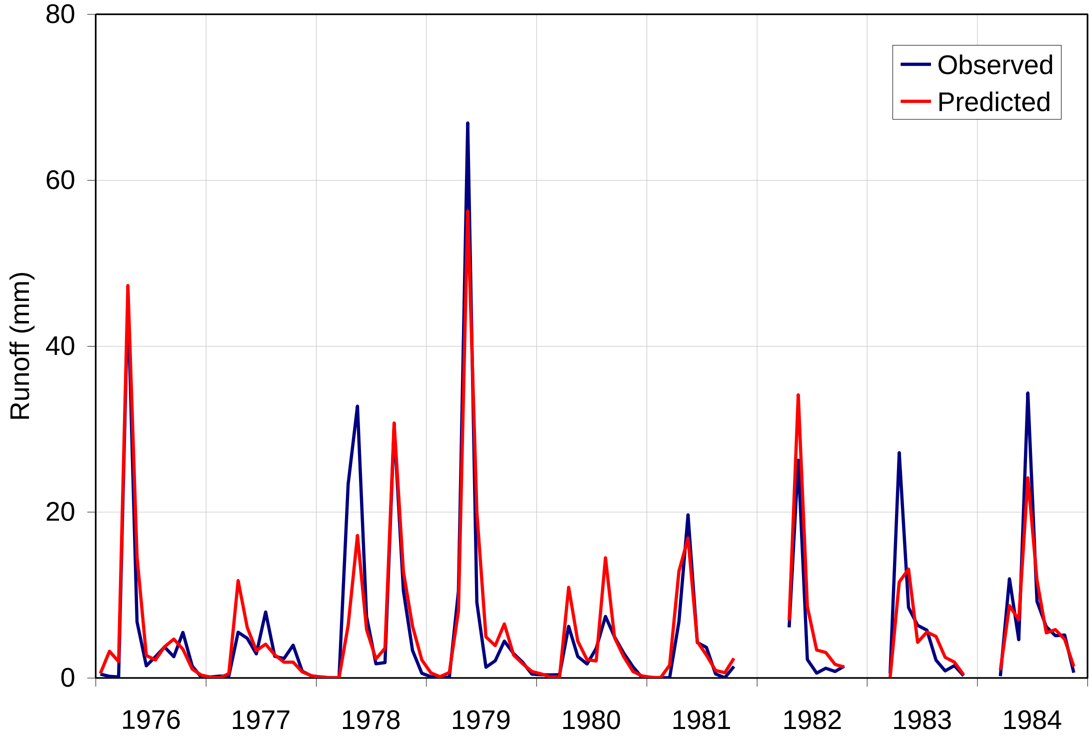

Figure 39. Observed and predicted monthly runoff from Joslyn Creek watershed for the calibration period.

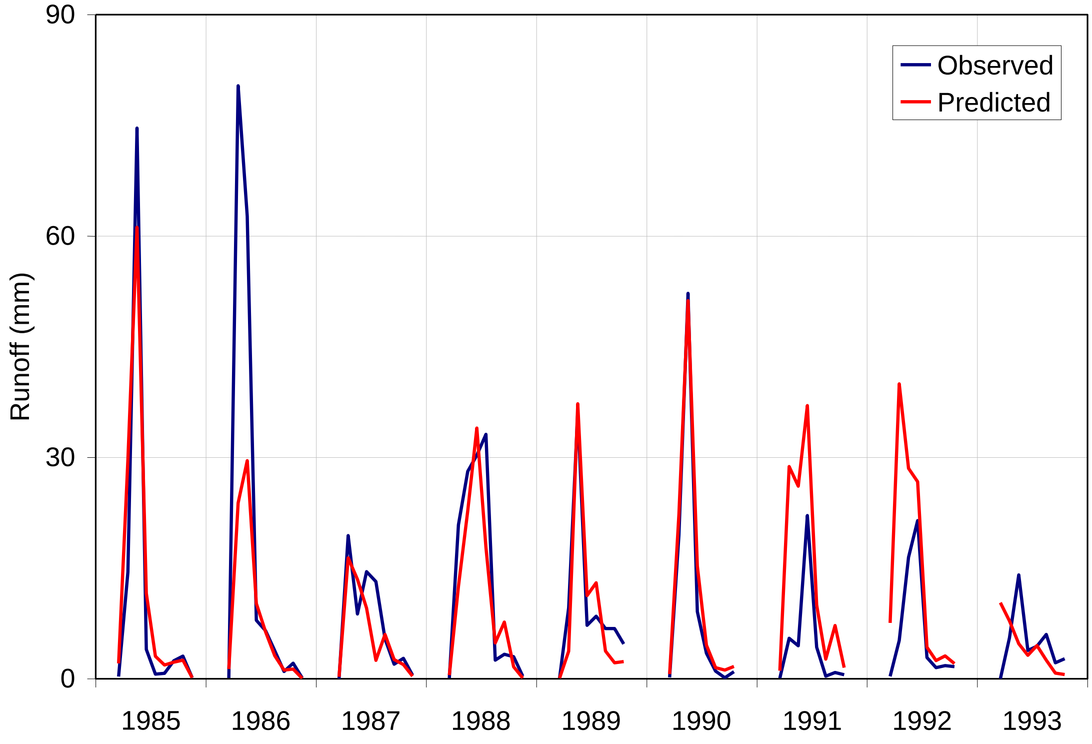

Figure 40. Observed and predicted monthly runoff from Joslyn Creek watershed for the validation period.

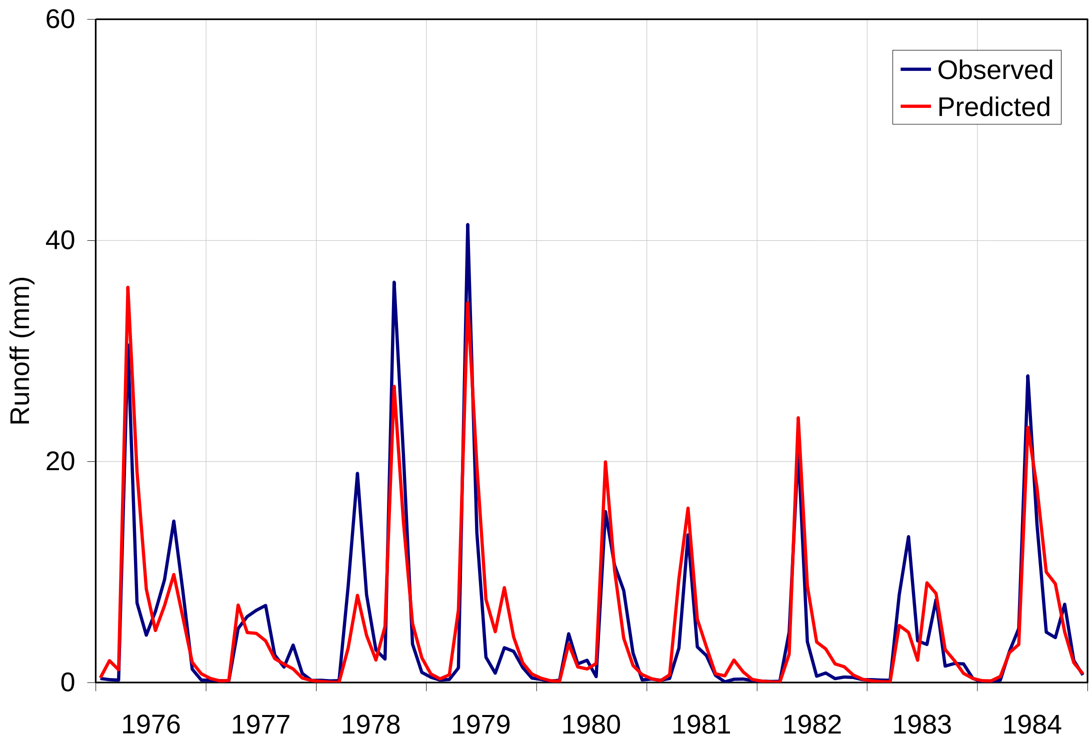

Figure 41. Observed and predicted monthly runoff from MacKay River watershed for the calibration period.

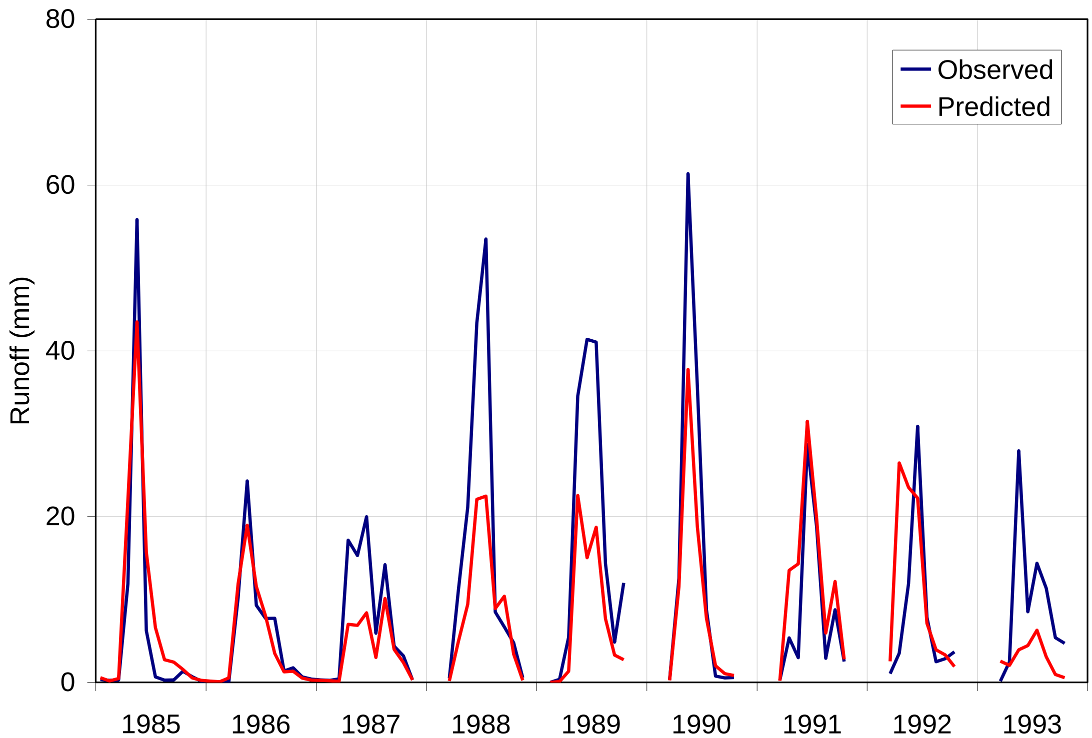

Figure 42. Observed and predicted monthly runoff from MacKay River watershed for the validation period.

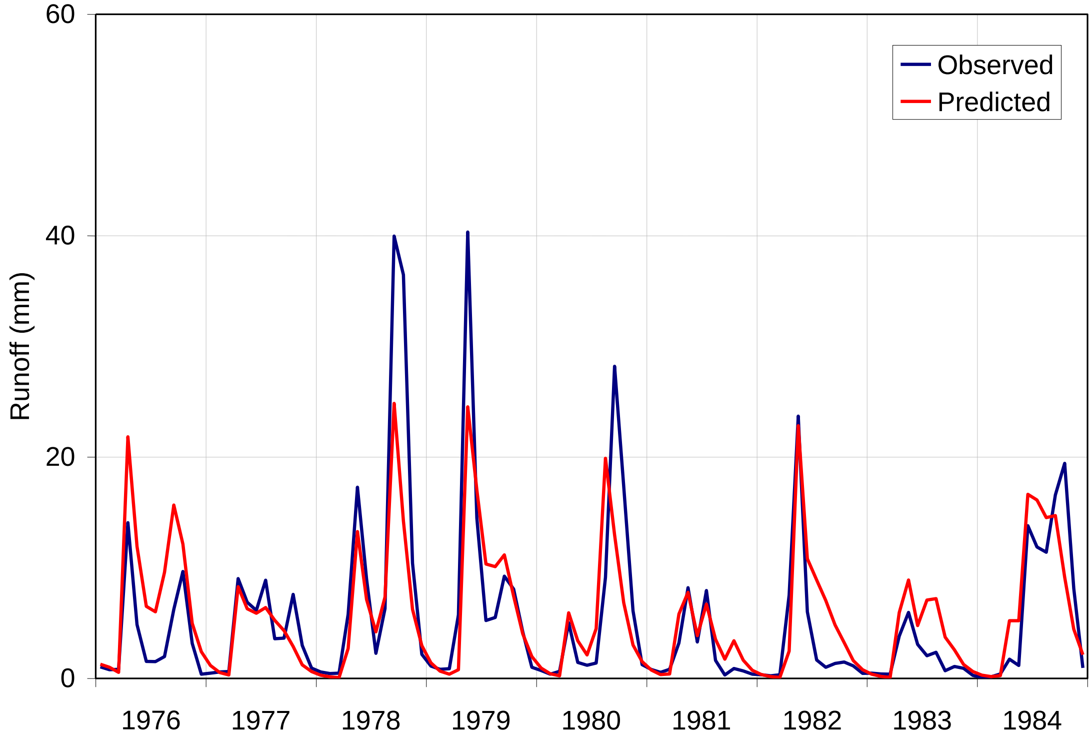

Figure 43. Observed and predicted monthly runoff from Muskeg River watershed for the calibration period.

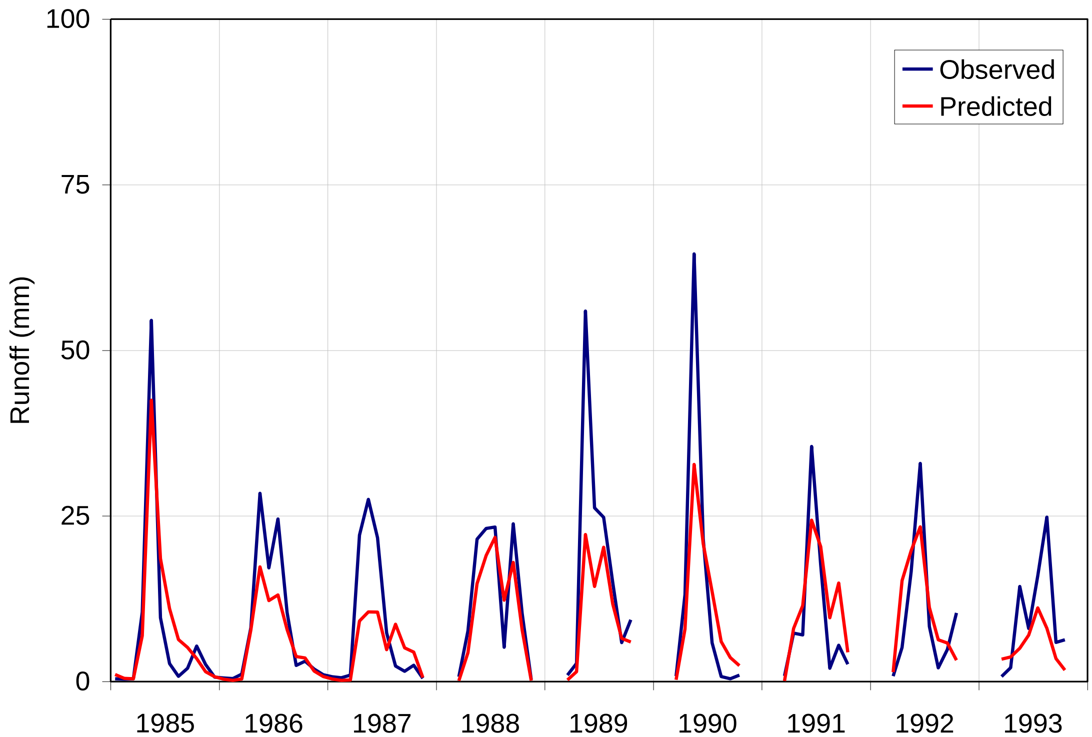

Figure 44. Observed and predicted monthly runoff from Muskeg River watershed for the validation period.

Figures 45 to 49 show the residuals of the monthly runoff for the entire evaluation period. The majority of the monthly residuals were less than ±20 mm; however several of the residuals exceeded +50 mm, which indicates $SWAT_{BF}$ significantly underestimated these peak monthly events. Inspection of Figures 45 to 49 reveals that the number of positive and negative residuals was approximately equal. This indicates the model did not have a major bias for overestimating or underestimating monthly runoff.

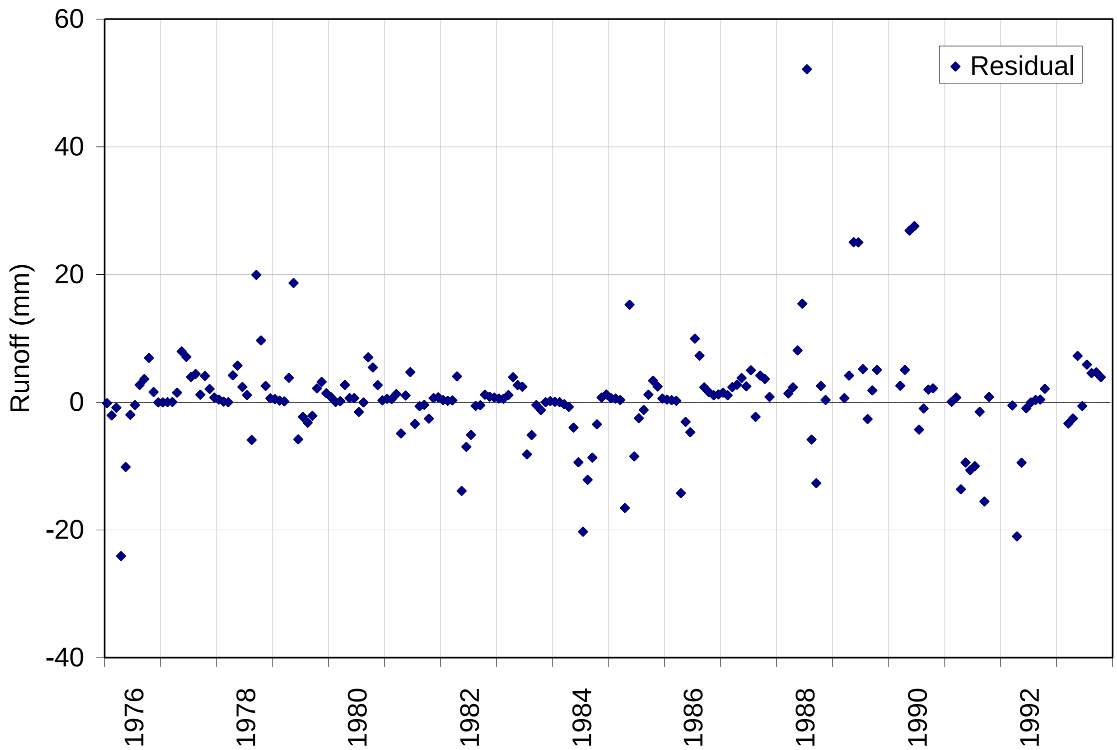

Figure 45. Residuals of monthly runoff (mm) from Beaver River watershed.

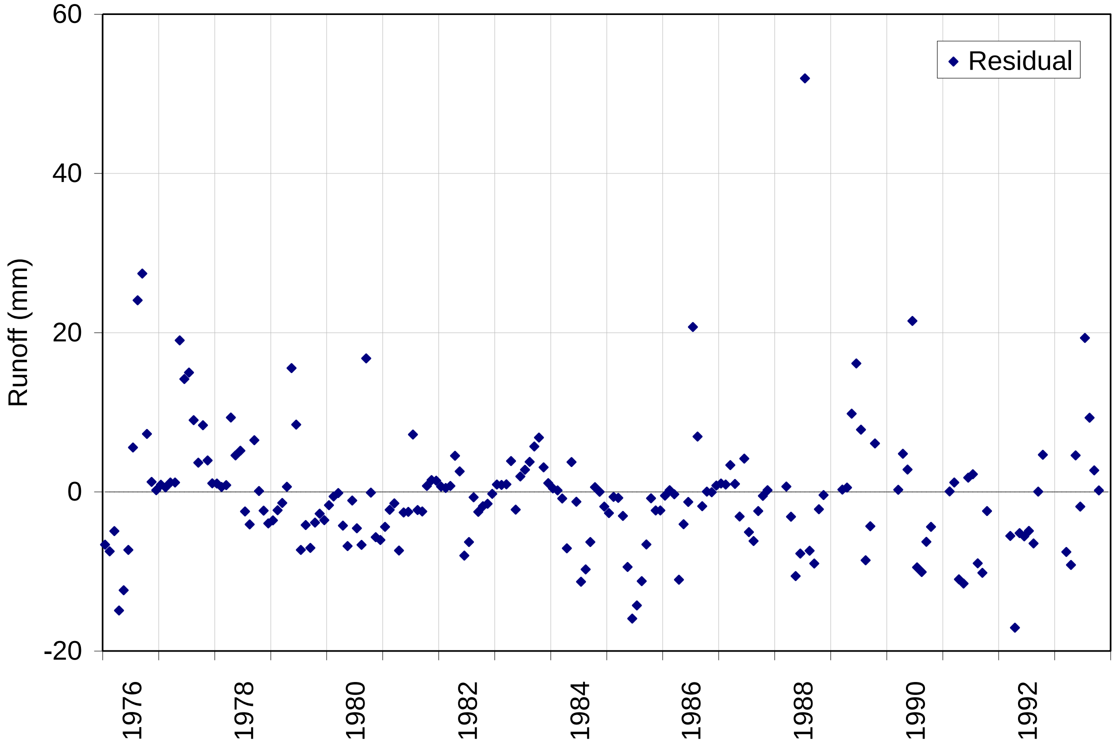

Figure 46. Residuals of monthly runoff (mm) from Hangingstone River watershed.

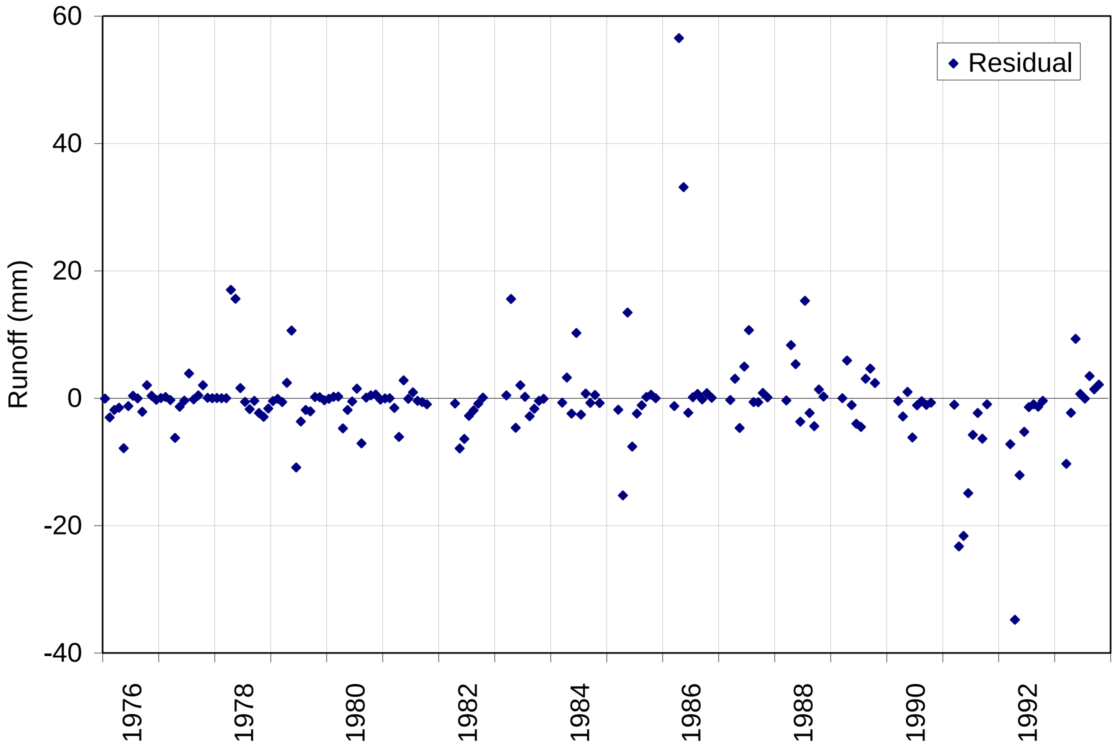

Figure 47. Residuals of monthly runoff (mm) from Joslyn Creek watershed.

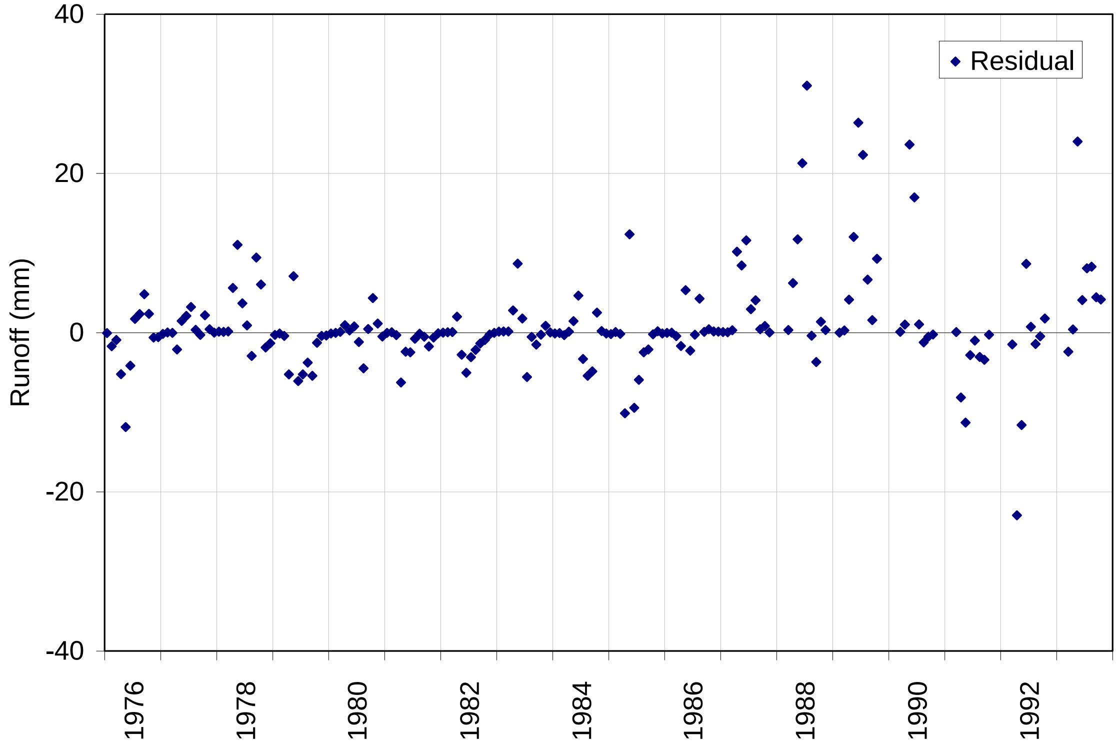

Figure 48. Residuals of monthly runoff (mm) from MacKay River watershed.

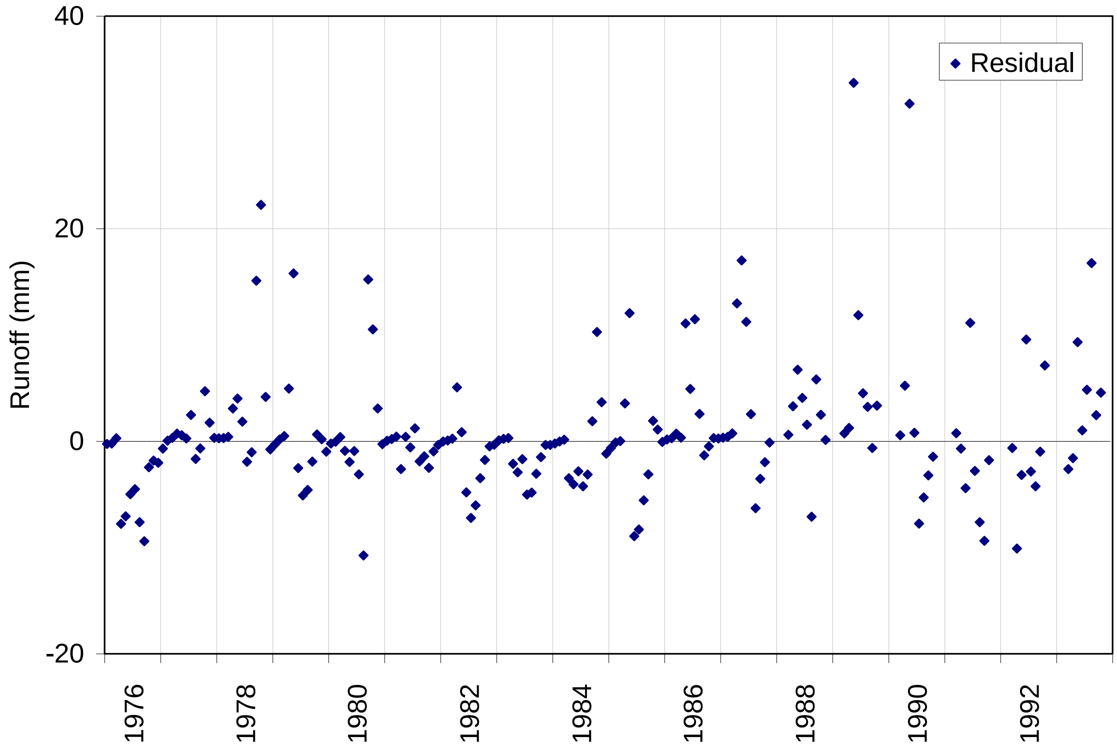

Figure 49. Residuals of monthly runoff (mm) from Muskeg River watershed.

The values of NSE_M achieved by $SWAT_{BF}$ for the five regional watersheds are presented in Tables 22 and 23 along with the performance ratings. The overall performance of the model for predicting monthly runoff can be considered good with nine out of the ten NSE_M values being equal to or greater than 0.60. Two of the NSE_M values (for Joslyn and MacKay) exceeded 0.80, demonstrating that the model has the potential to obtain very good results for predicting monthly runoff. The most significant decline in model performance when moving from the calibration period to the validation period occurred for Joslyn Creek watershed. This is very interesting because it was shown earlier that the least amount of decline in the value of D_V occurred for Joslyn Creek watershed.

The prediction of monthly runoff by $SWAT_{BF}$ in this study compares favourably to other applications of SWAT from around the world (see Table 1 in Gassman et al. 2007). Although the WaterBase data sets used in this test are of reasonable quality, it is expected that the performance of the model will increase once higher resolution data sets are available in a format that can be used to setup $SWAT_{BF}$.

Table 22. Monthly Nash-Sutcliffe coefficients (NSE_M) and performance for the calibration period.

Watershed	NSE_M	**Performance**
Beaver	0.73	Good
Hangingstone	0.69	Good
Joslyn	0.84	Very Good
MacKay	0.81	Very Good
Muskeg	0.64	Good

Table 23. Monthly Nash-Sutcliffe coefficients (NSE_M) and performance for the validation period.

Watershed	NSE_M	**Performance**
Beaver	0.66	Good
Hangingstone	0.61	Good
Joslyn	0.57	Fair
MacKay	0.60	Good
Muskeg	0.66	Good

6.4.4 *Daily Runoff*

The observed and predicted daily hydrographs are compared in Figures 50 to 79. Each hydrograph depicts three years of data. Rather than presenting the hydrographs in only two graphs (i.e., one for the calibration period and one for the validation period), it was decided that the daily hydrographs should be plotted for three year intervals so that the performance of the model could be better assessed. Seibert (1999) pointed out that squeezing long series of observed and predicted daily runoff over many years into a single plot is not a good practice because it is difficult to distinguish between the two time series, thereby making it difficult to critically evaluate the performance of the model.

The performance of $SWAT_{BF}$ on a daily time step was relatively good. The agreement between the observed and predicted runoff was good for most years, although there were some years when the agreement was less than satisfactory (e.g., 1993 – Joslyn Creek watershed). $SWAT_{BF}$ had a tendency to underestimate peak runoff events; however, the model still responded to most of the rainfall events that produced runoff. It is also interesting to note that many of the peak events observed in the record can be attributed to rainfall events that occurred in the summer and autumn. The need to predict such events in addition to the snowmelt runoff occurring in spring adds further complexity to the modelling exercise.

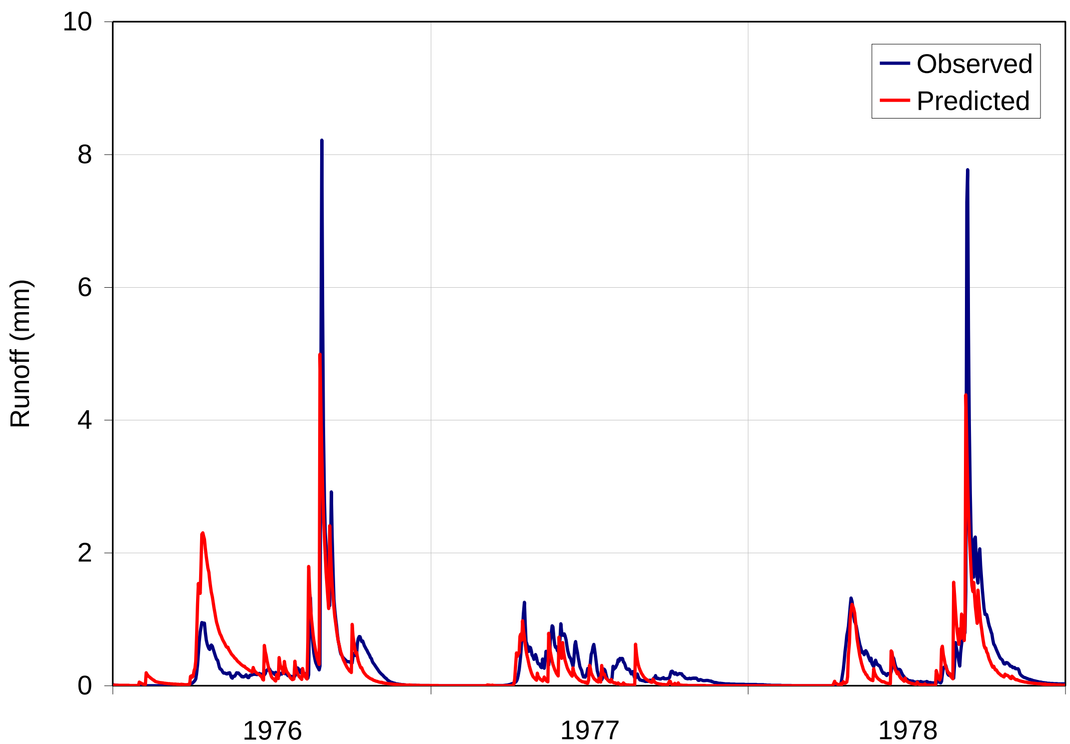

Figure 50. Observed and predicted daily runoff from Beaver River watershed for 1976 to 1978.

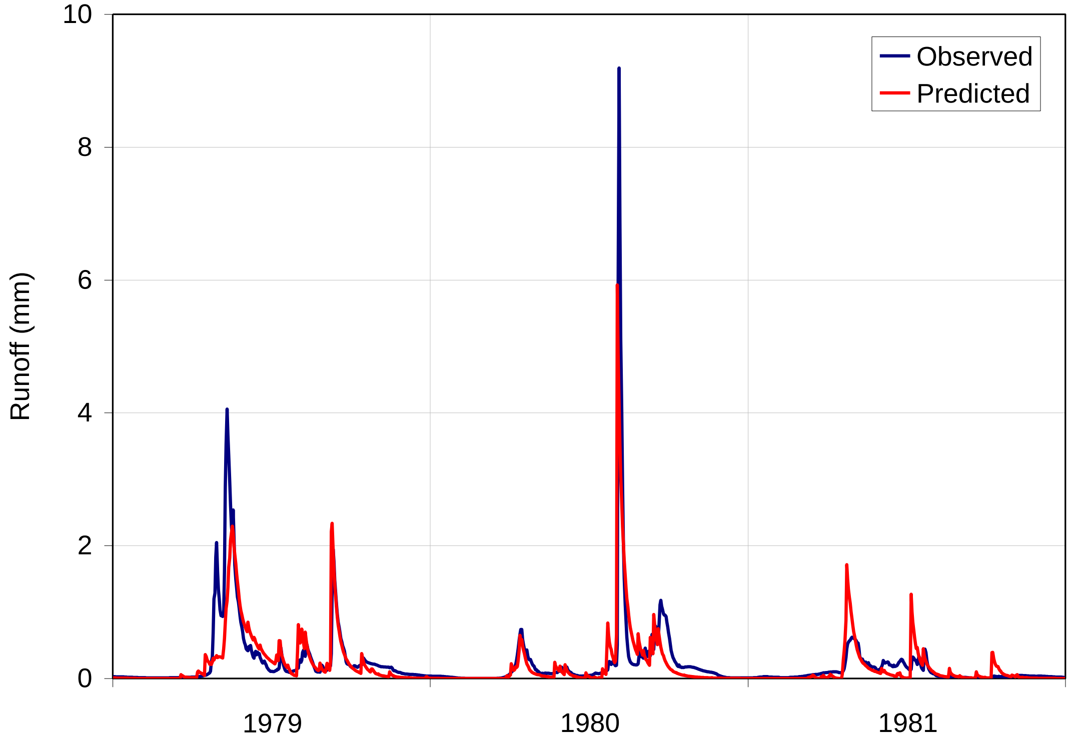

Figure 51. Observed and predicted daily runoff from Beaver River watershed for 1979 to 1981.

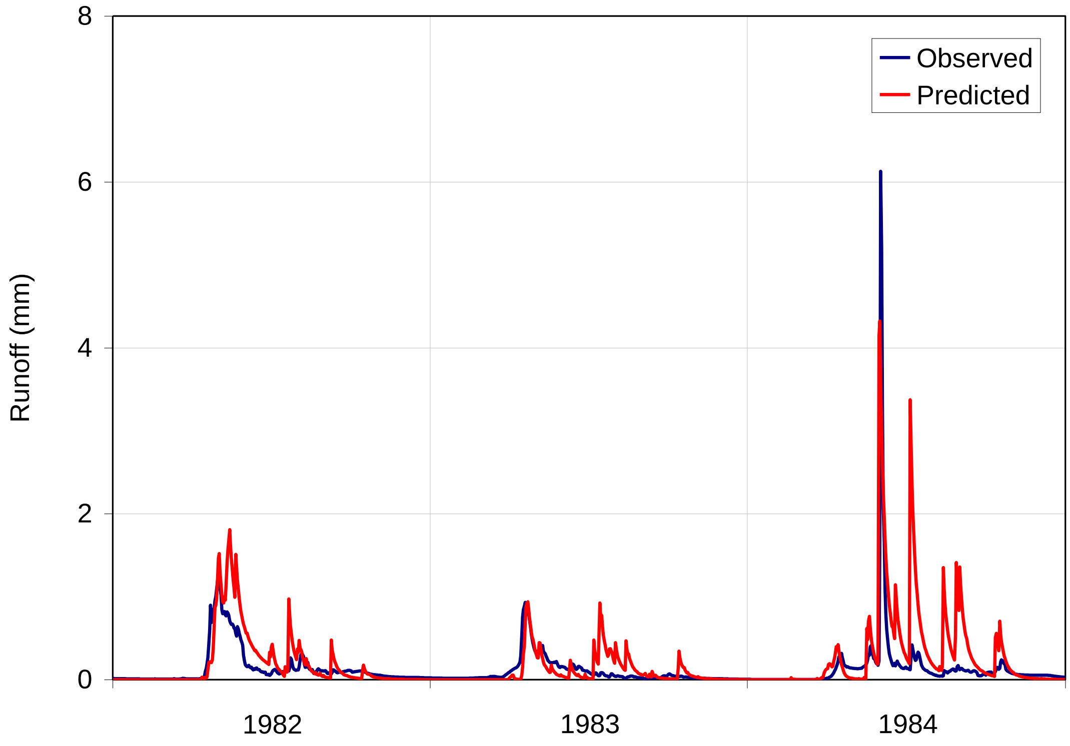

Figure 52. Observed and predicted daily runoff from Beaver River watershed for 1982 to 1984.

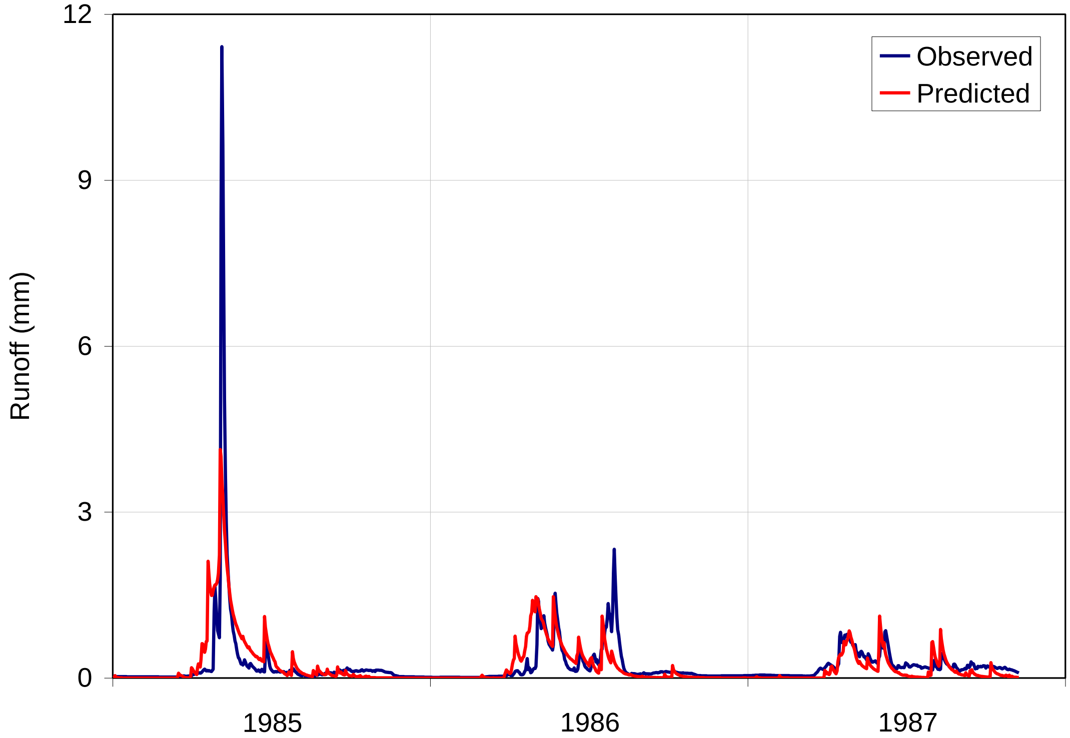

Figure 53. Observed and predicted daily runoff from Beaver River watershed for 1985 to 1987.

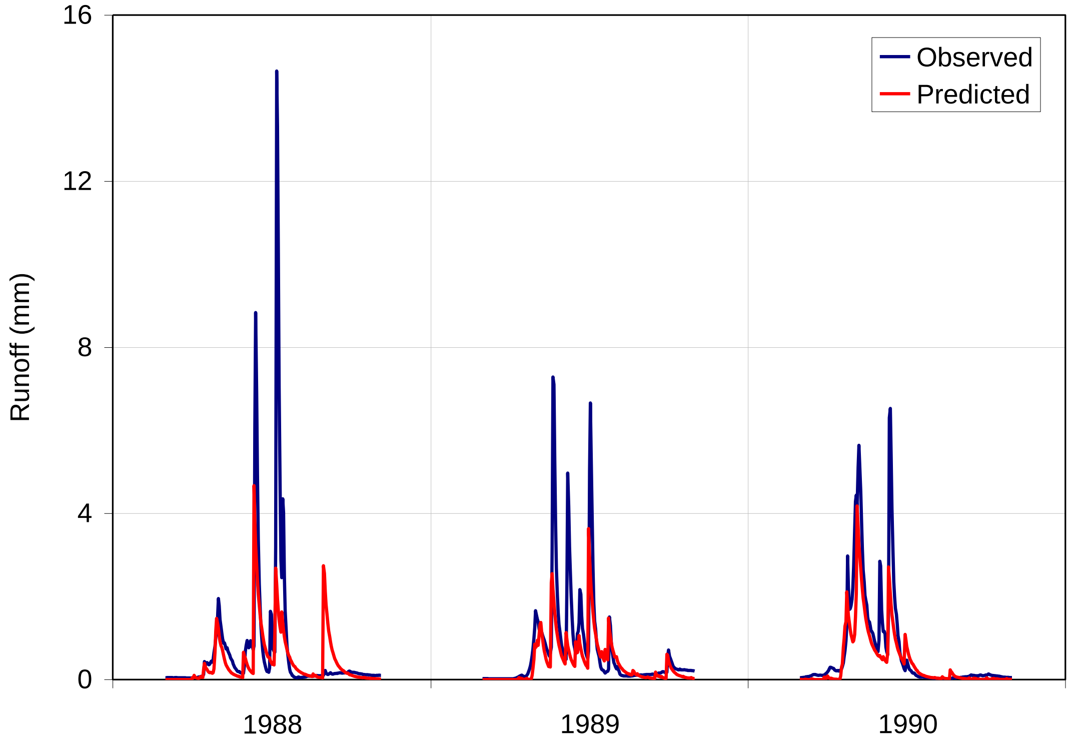

Figure 54. Observed and predicted daily runoff from Beaver River watershed for 1988 to 1990.

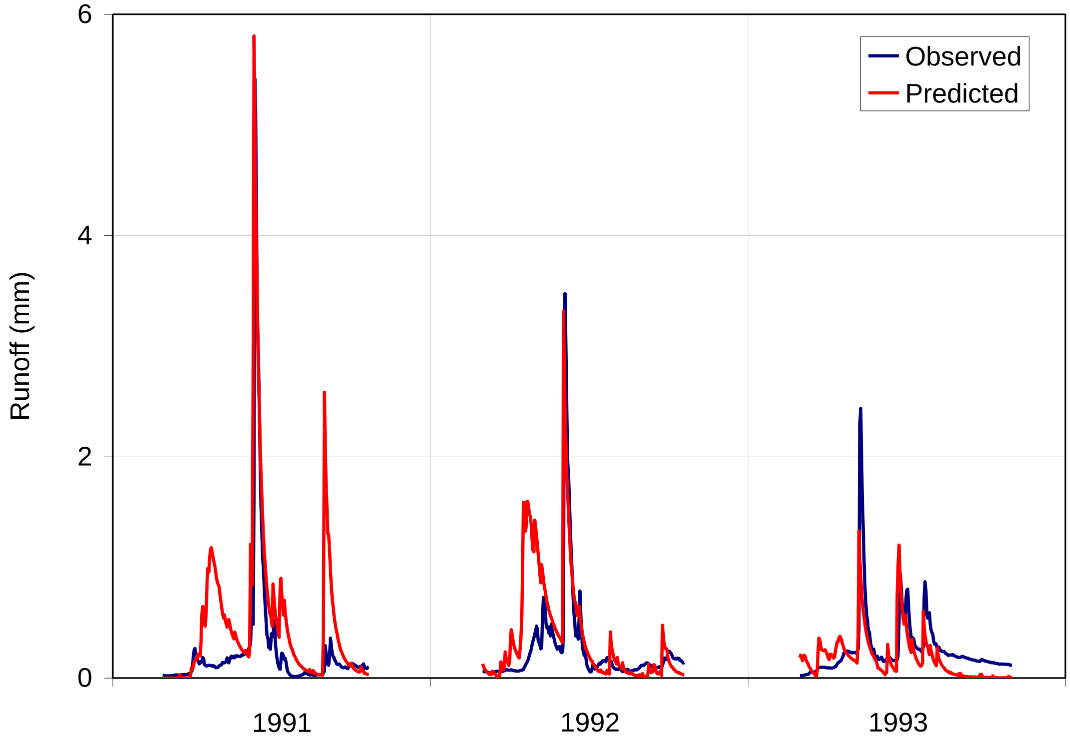

Figure 55. Observed and predicted daily runoff from Beaver River watershed for 1991 to 1993.

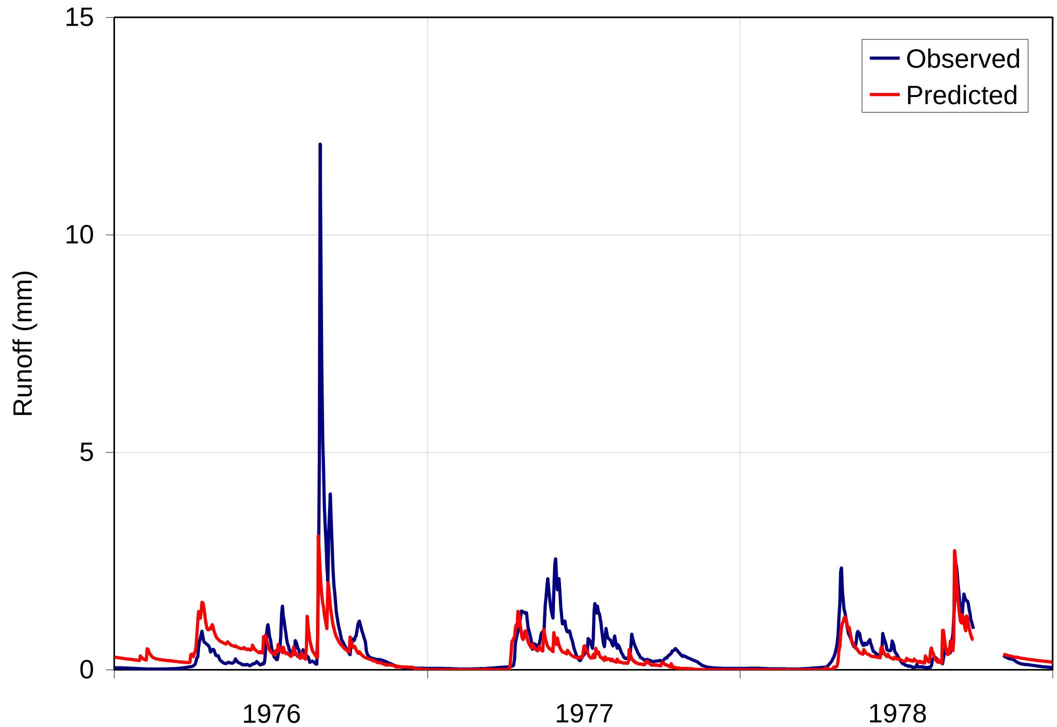

Figure 56. Observed and predicted daily runoff from Hangingstone River watershed for 1976 to 1978.

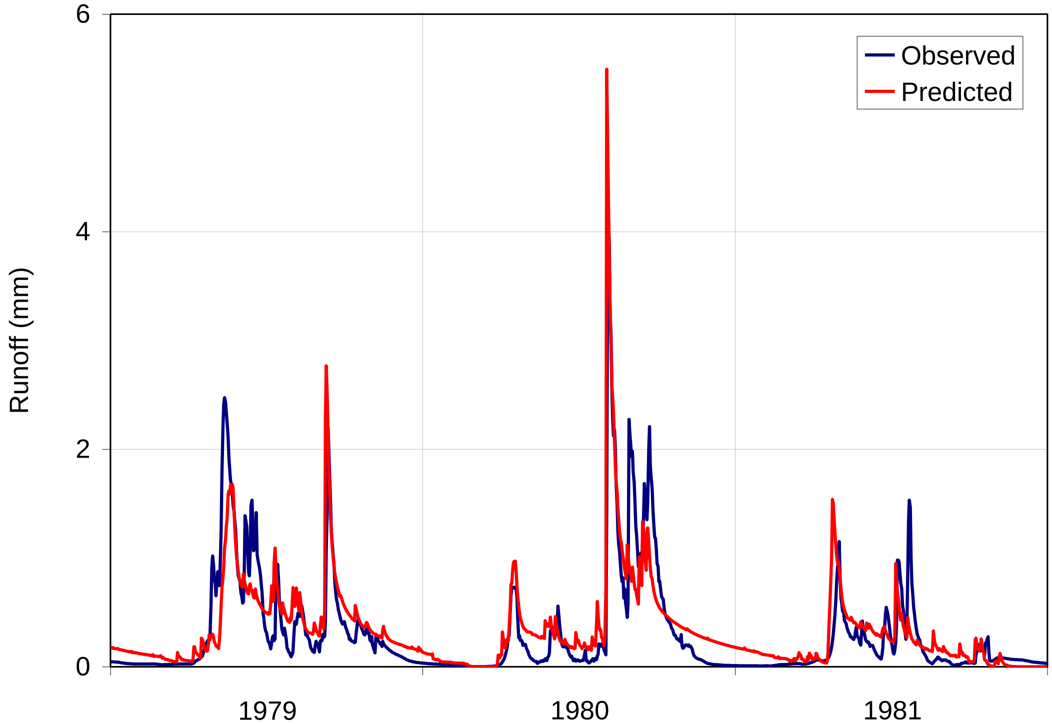

Figure 57. Observed and predicted daily runoff from Hangingstone River watershed for 1979 to 1981.

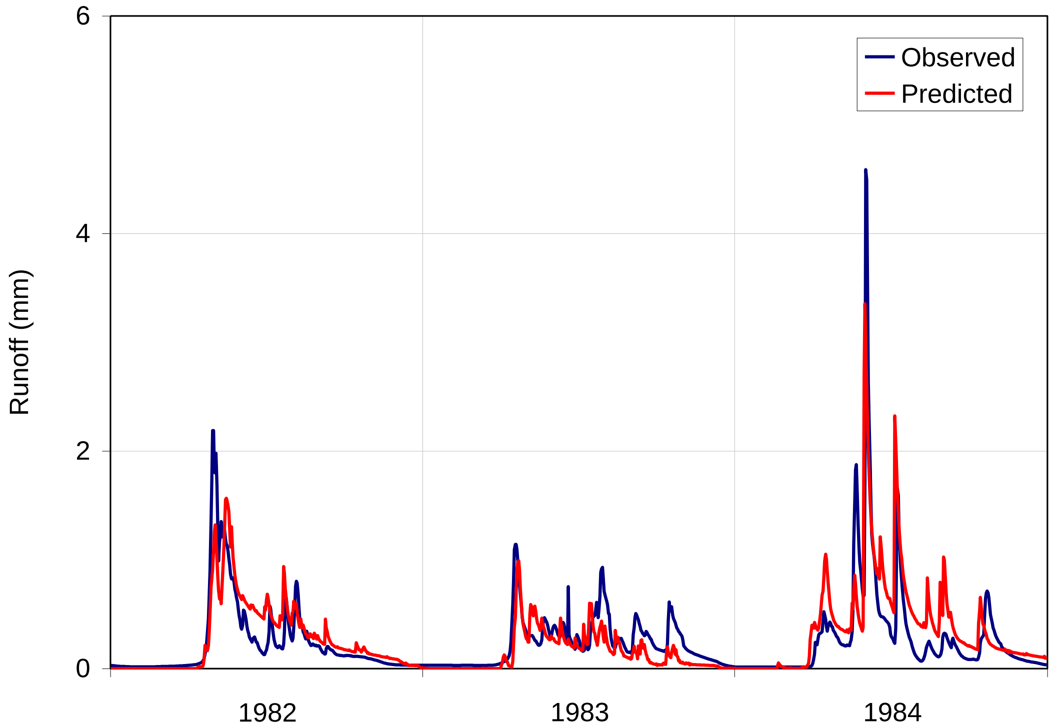

Figure 58. Observed and predicted daily runoff from Hangingstone River watershed for 1982 to 1984.

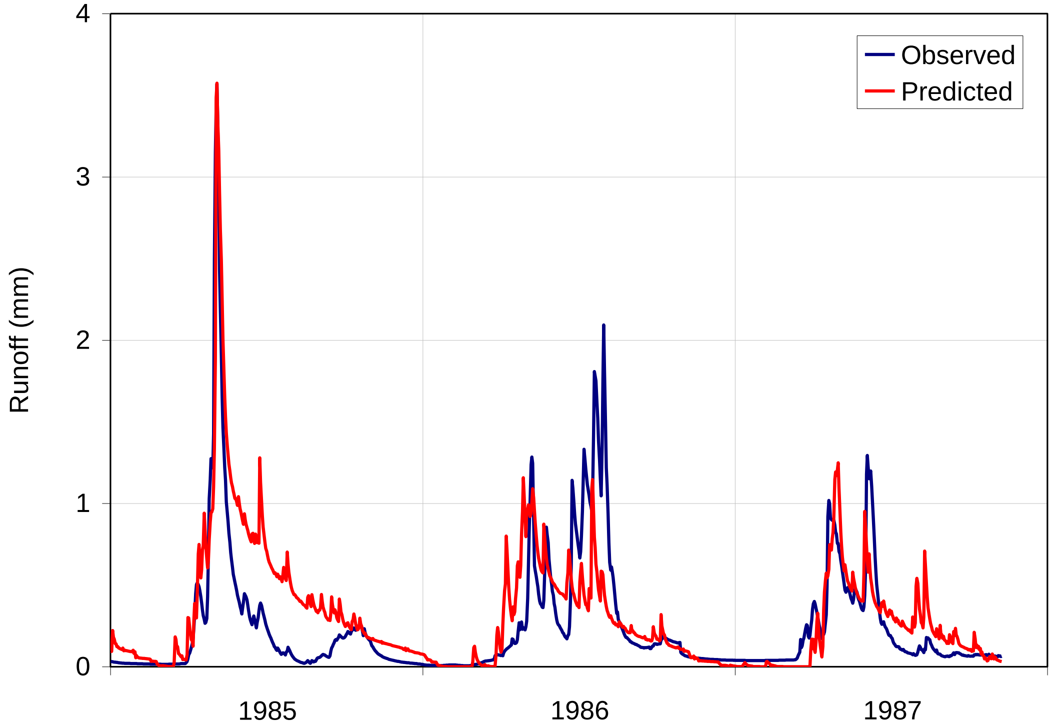

Figure 59. Observed and predicted daily runoff from Hangingstone River watershed for 1985 to 1987.

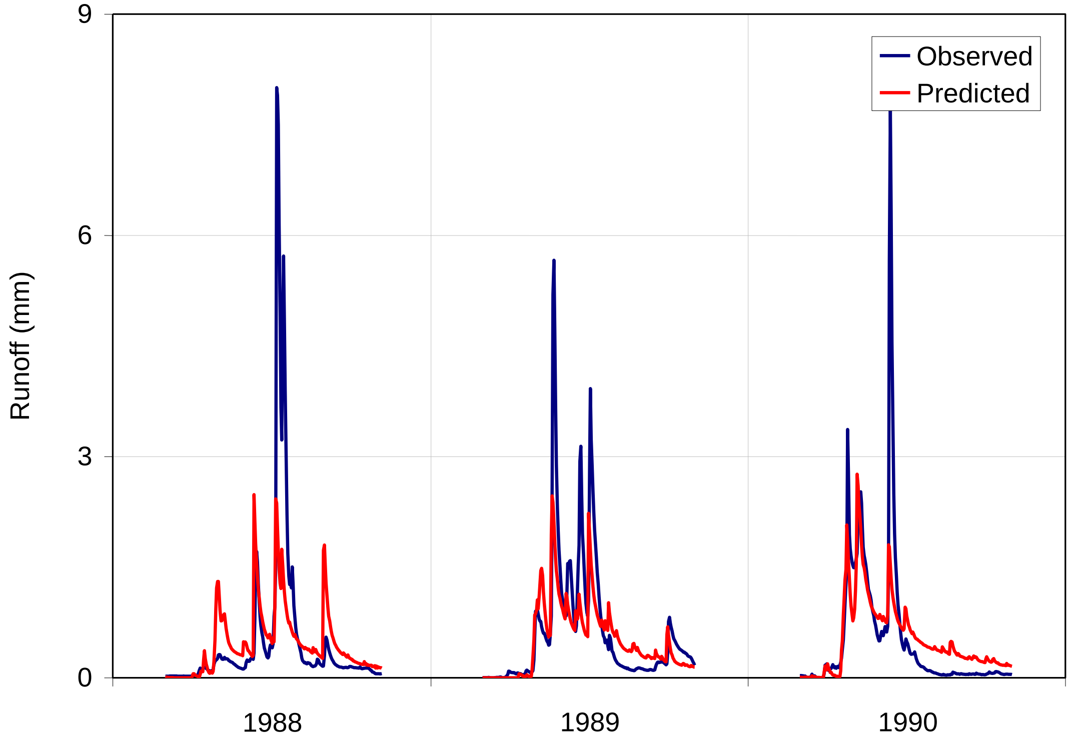

Figure 60. Observed and predicted daily runoff from Hangingstone River watershed for 1988 to 1990.

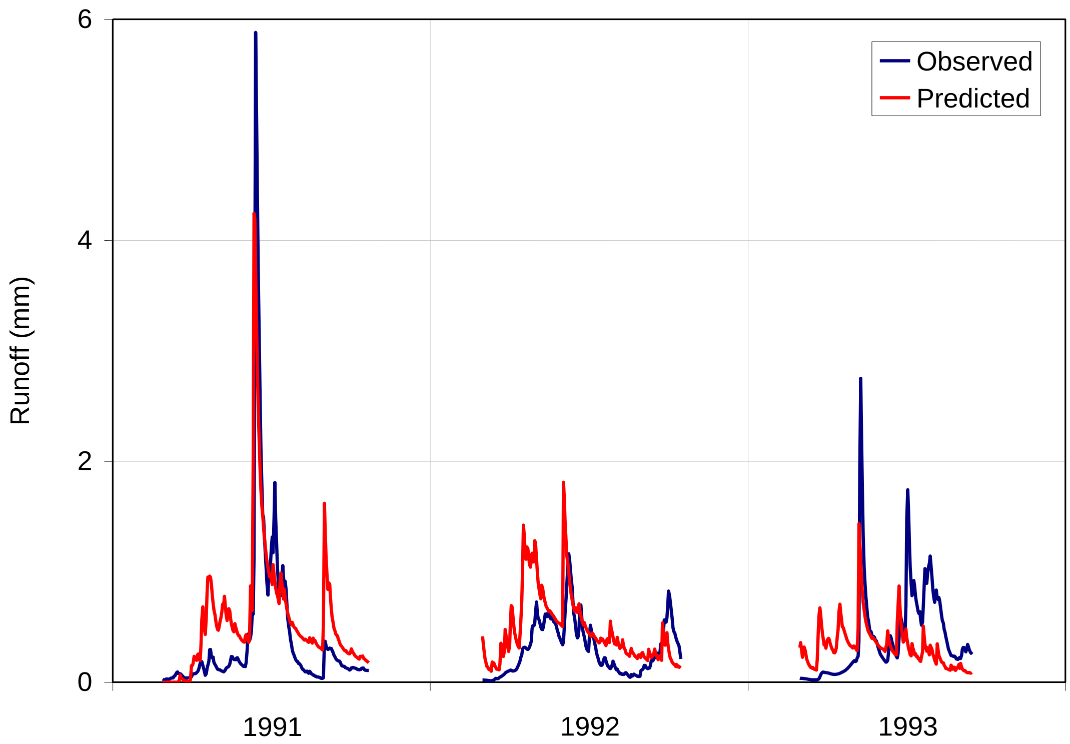

Figure 61. Observed and predicted daily runoff from Hangingstone River watershed for 1991 to 1993.

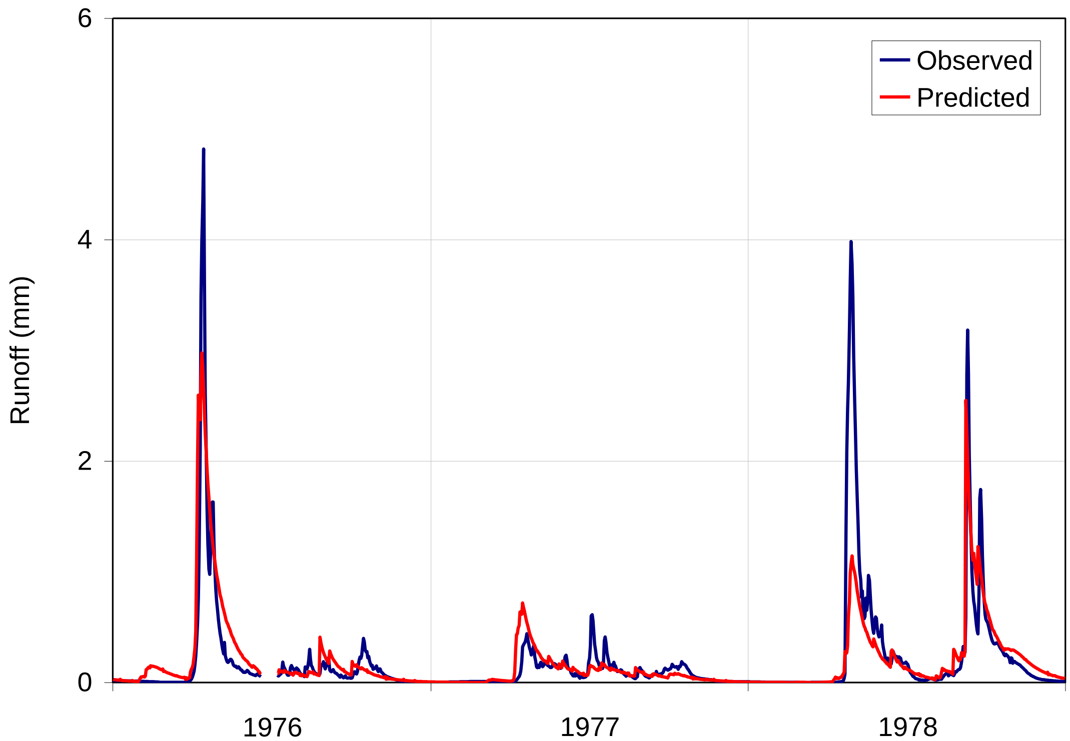

Figure 62. Observed and predicted daily runoff from Joslyn Creek watershed for 1976 to 1978.

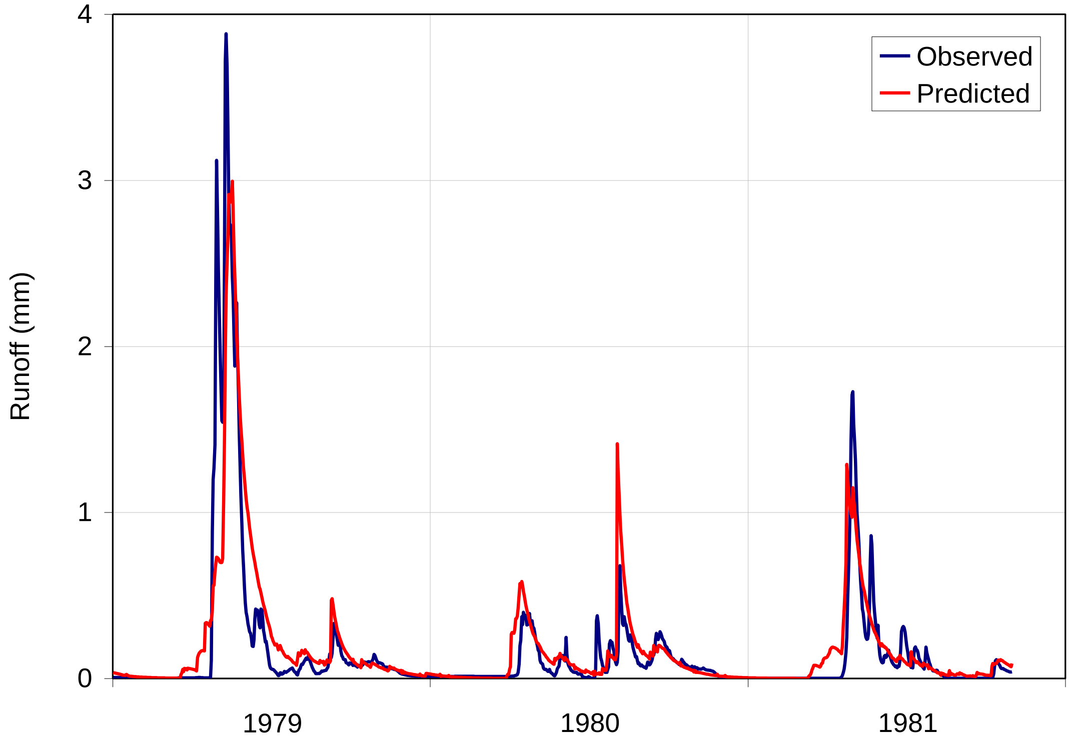

Figure 63. Observed and predicted daily runoff from Joslyn Creek watershed for 1979 to 1981.

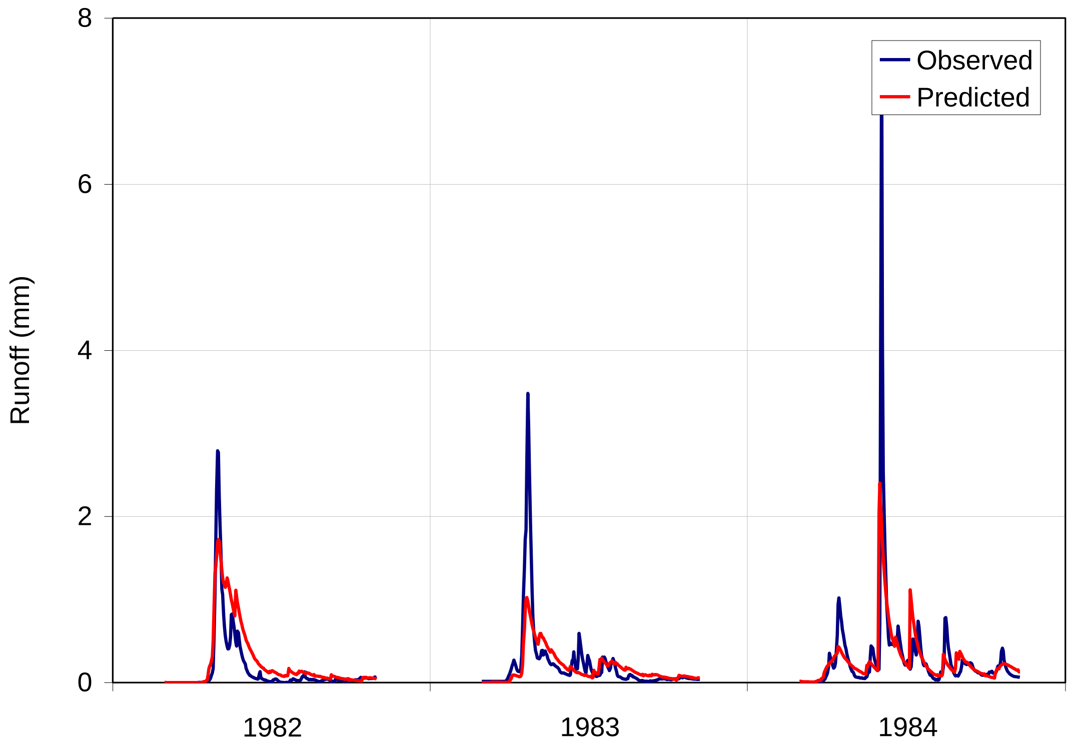

Figure 64. Observed and predicted daily runoff from Joslyn Creek watershed for 1982 to 1984.

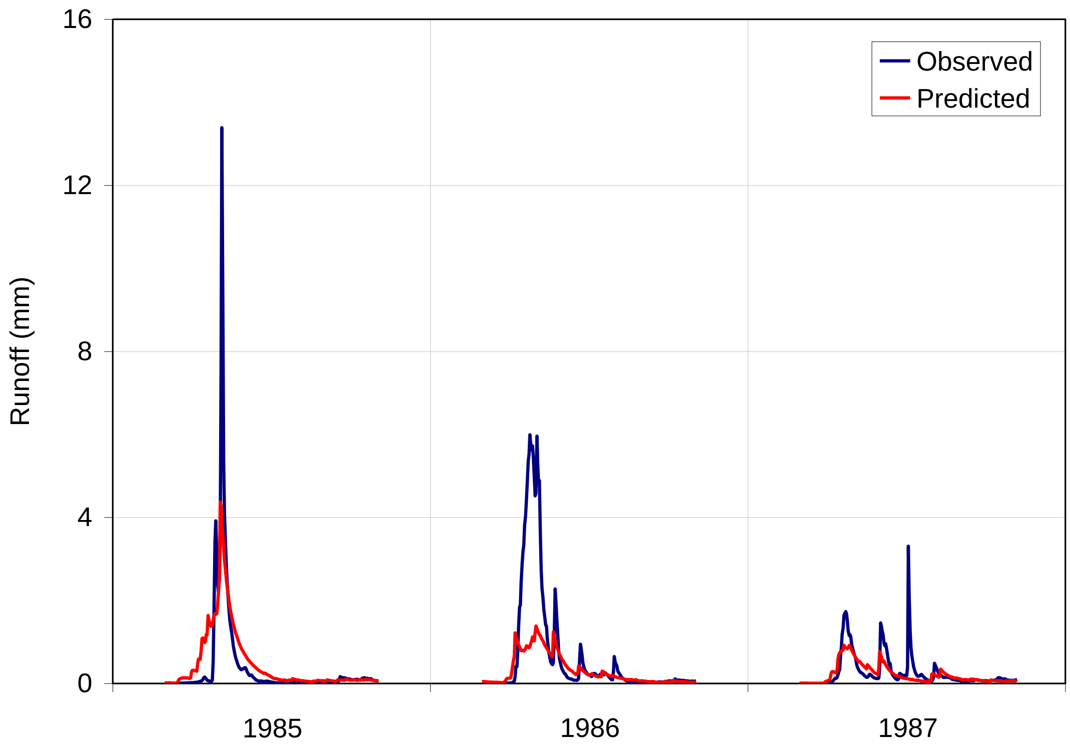

Figure 65. Observed and predicted daily runoff from Joslyn Creek watershed for 1985 to 1987.

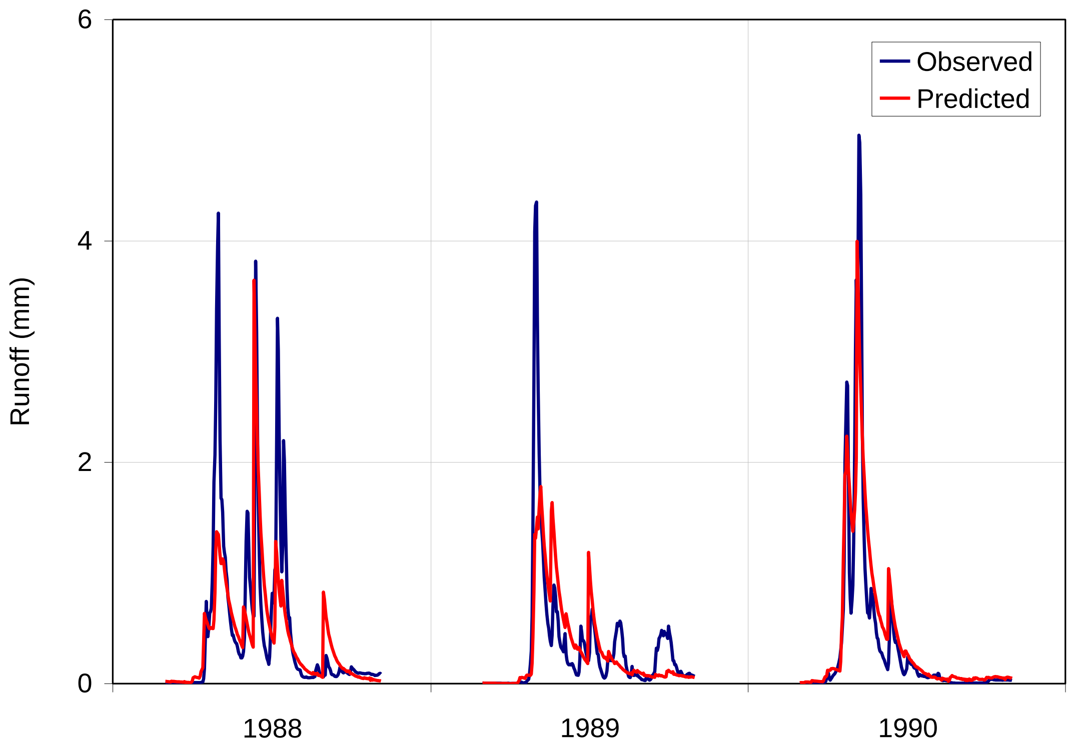

Figure 66. Observed and predicted daily runoff from Joslyn Creek watershed for 1988 to 1990.

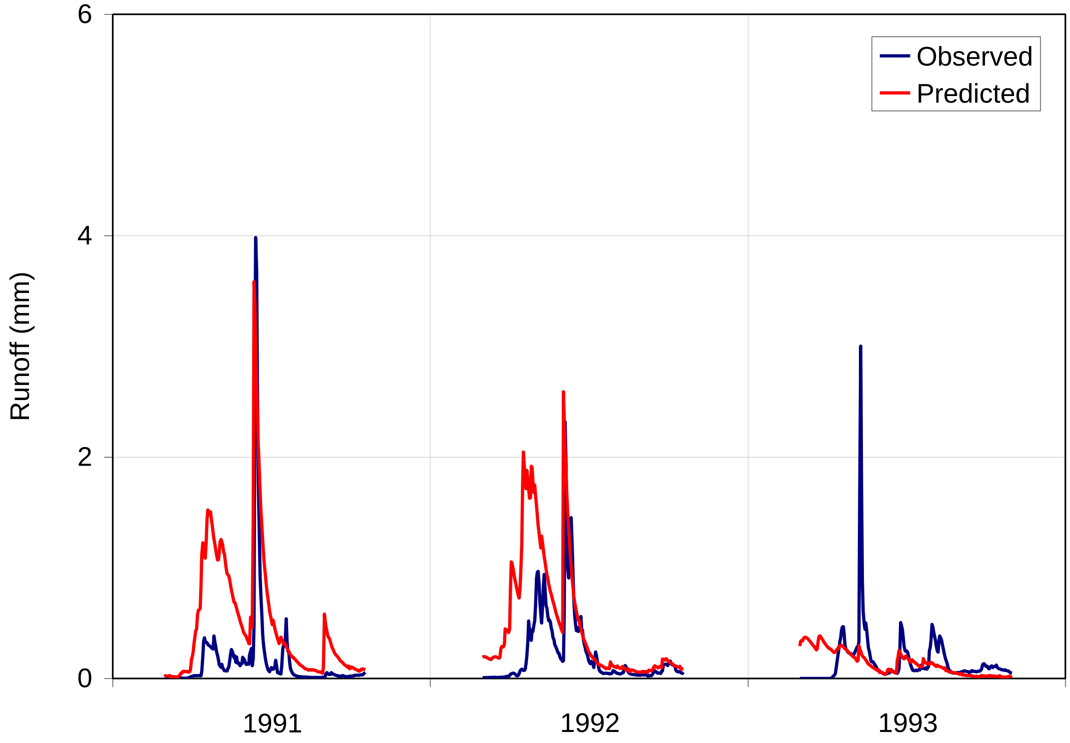

Figure 67. Observed and predicted daily runoff from Joslyn Creek watershed for 1991 to 1993.

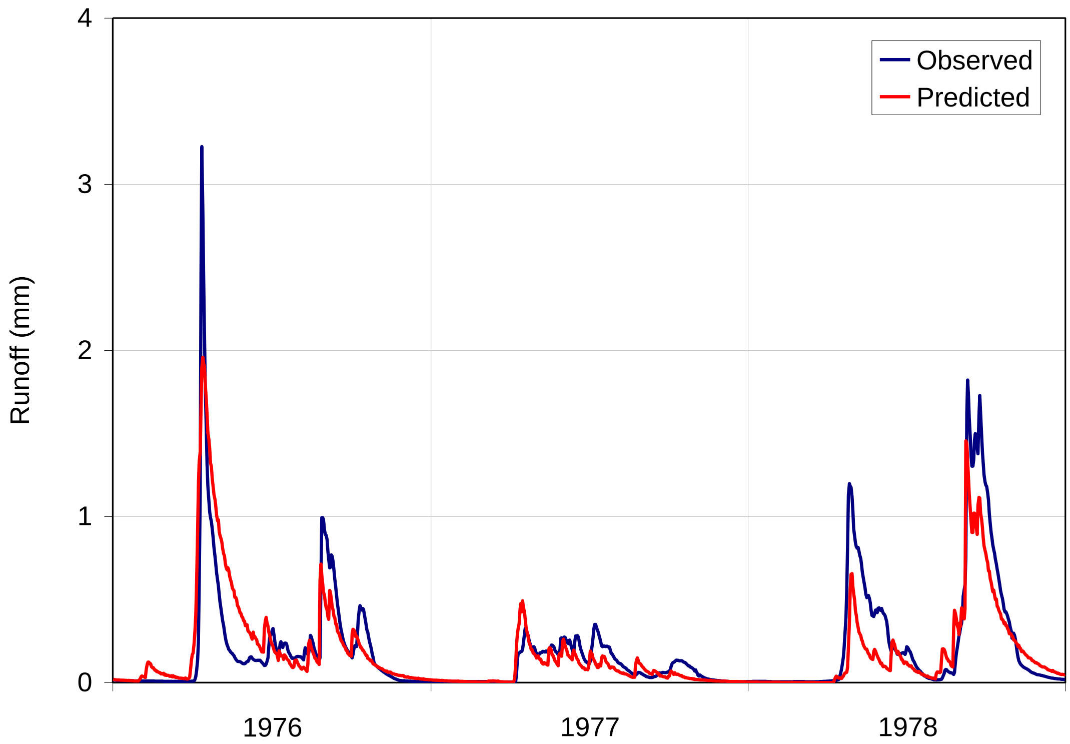

Figure 68. Observed and predicted daily runoff from MacKay River watershed for 1976 to 1978.

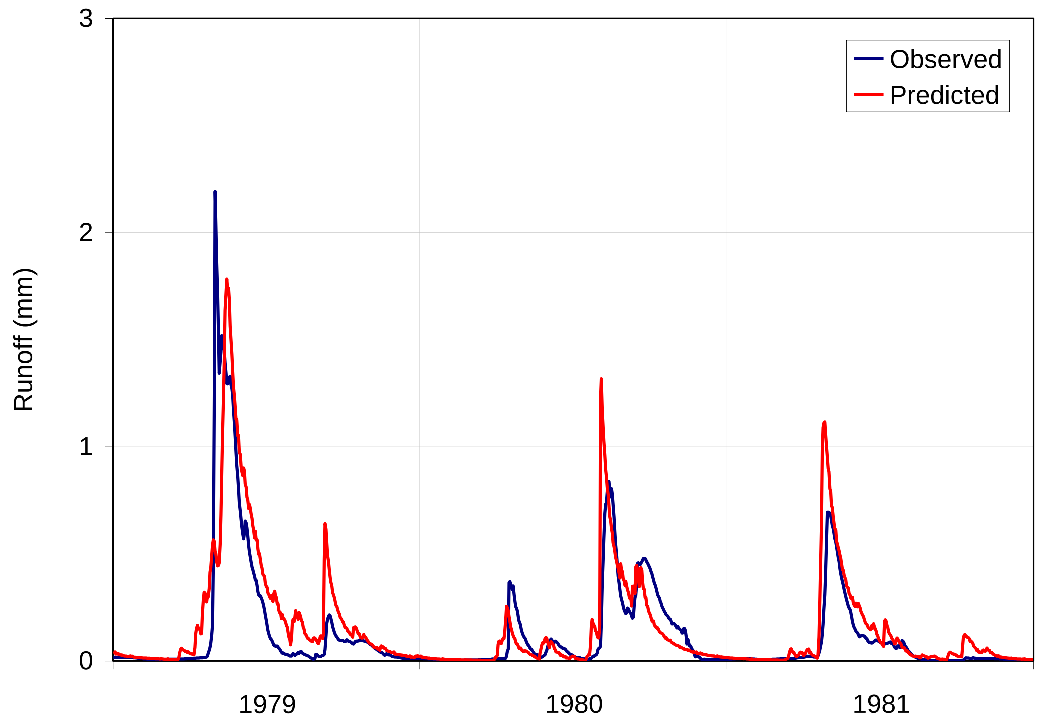

Figure 69. Observed and predicted daily runoff from MacKay River watershed for 1979 to 1981.

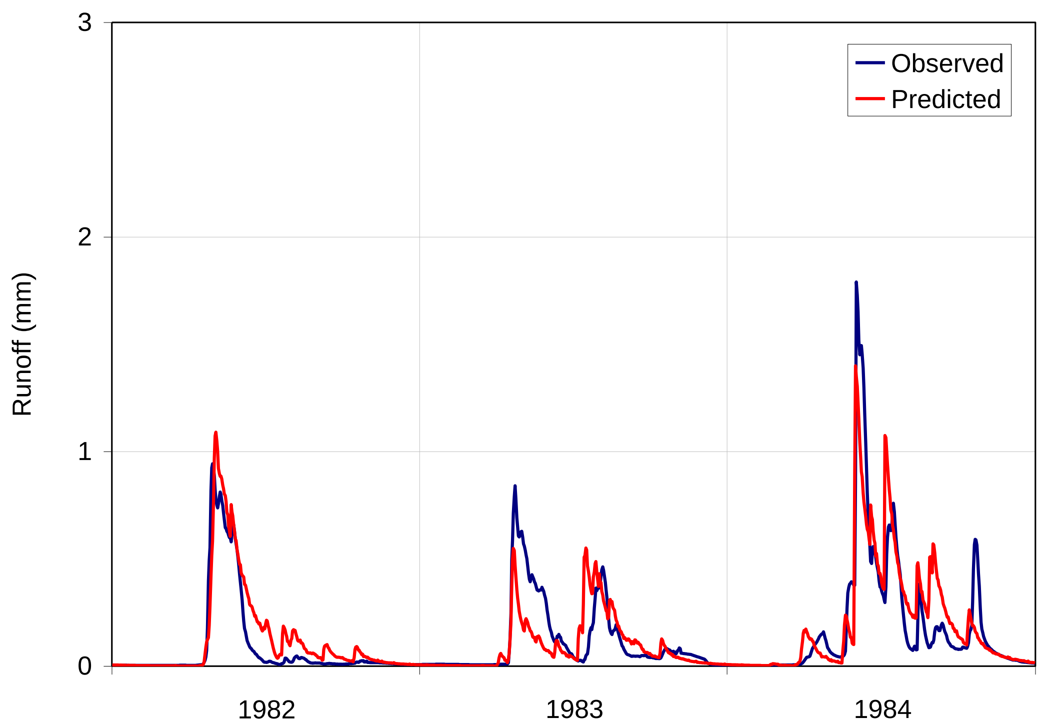

Figure 70. Observed and predicted daily runoff from MacKay River watershed for 1982 to 1984.

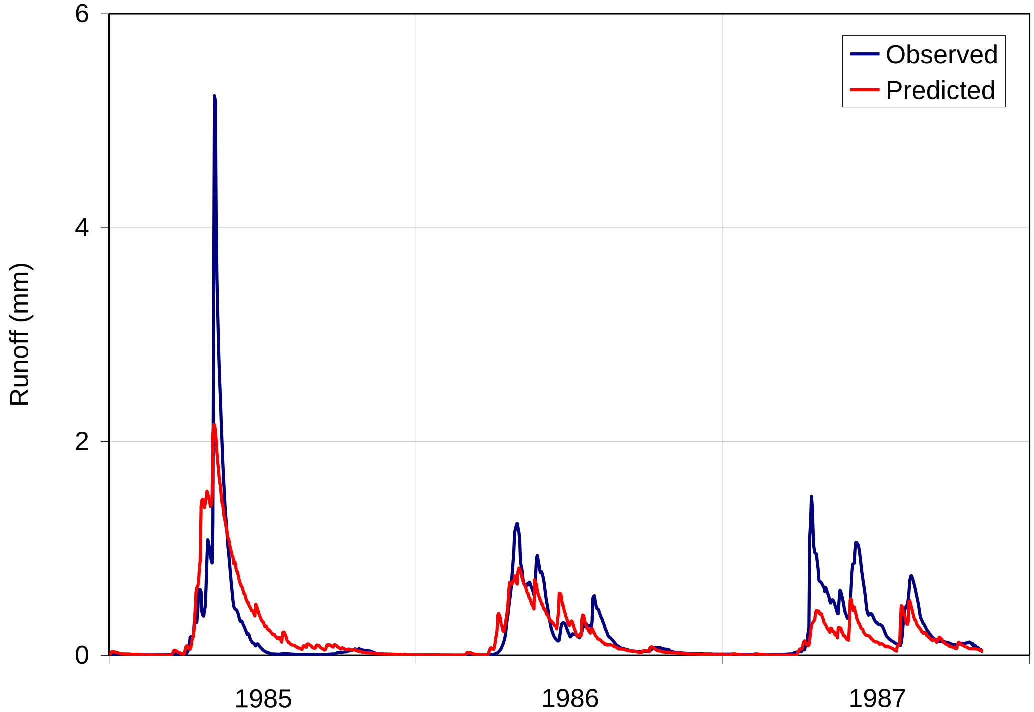

Figure 71. Observed and predicted daily runoff from MacKay River watershed for 1985 to 1987.

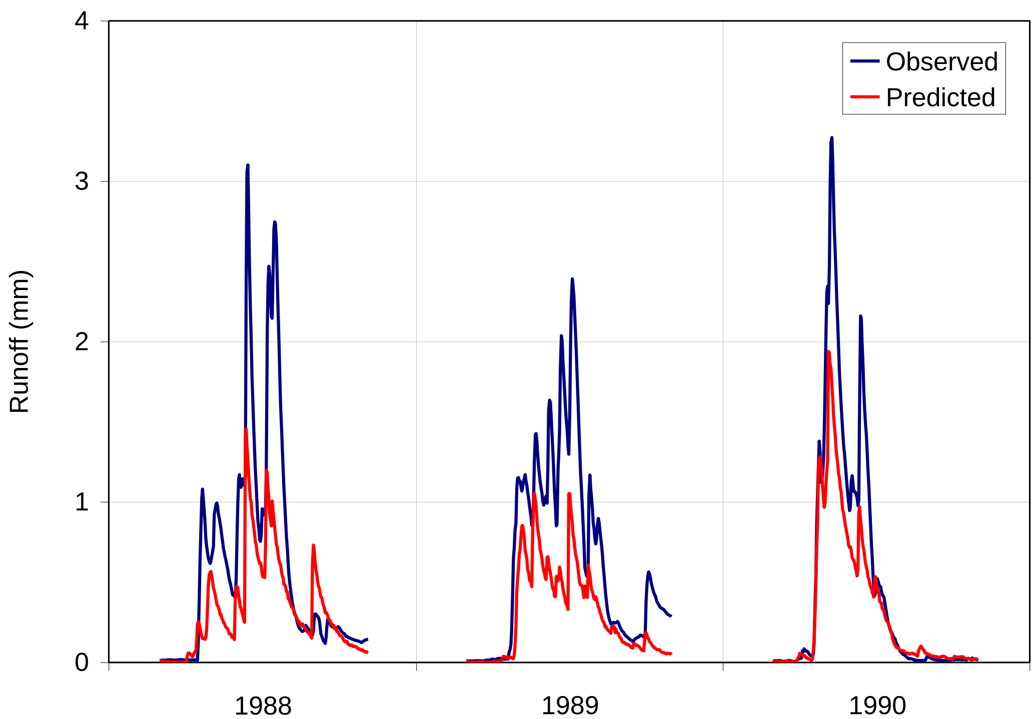

Figure 72. Observed and predicted daily runoff from MacKay River watershed for 1988 to 1990.

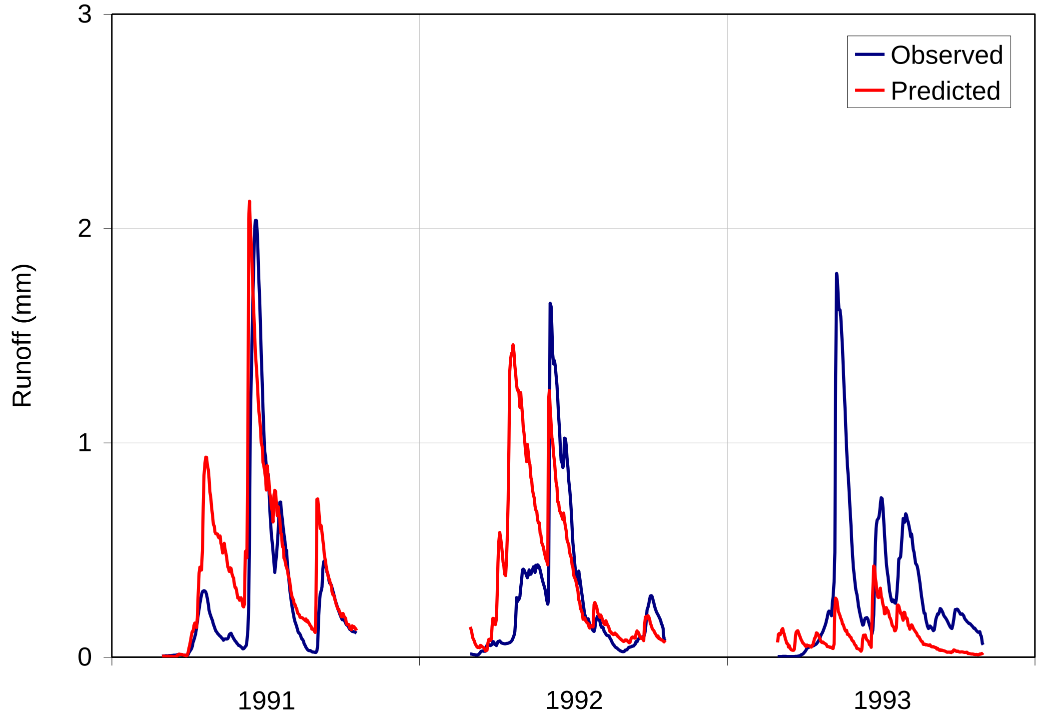

Figure 73. Observed and predicted daily runoff from MacKay River watershed for 1991 to 1993.

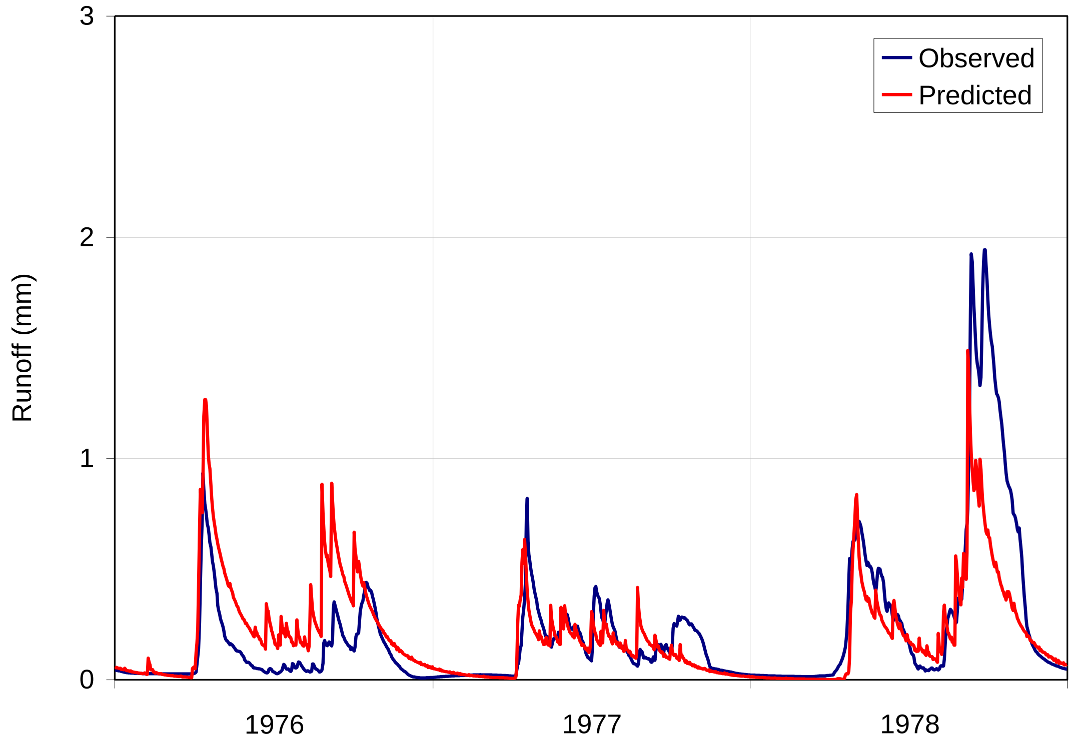

Figure 74. Observed and predicted daily runoff from Muskeg River watershed for 1976 to 1978.

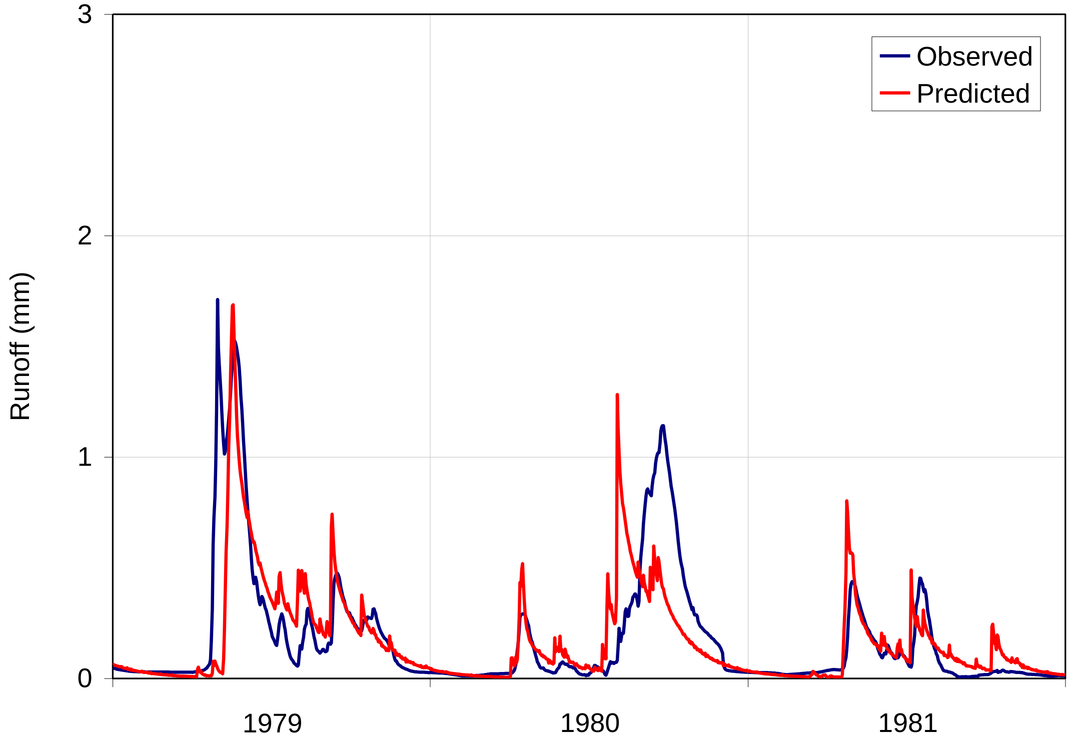

Figure 75. Observed and predicted daily runoff from Muskeg River watershed for 1979 to 1981.

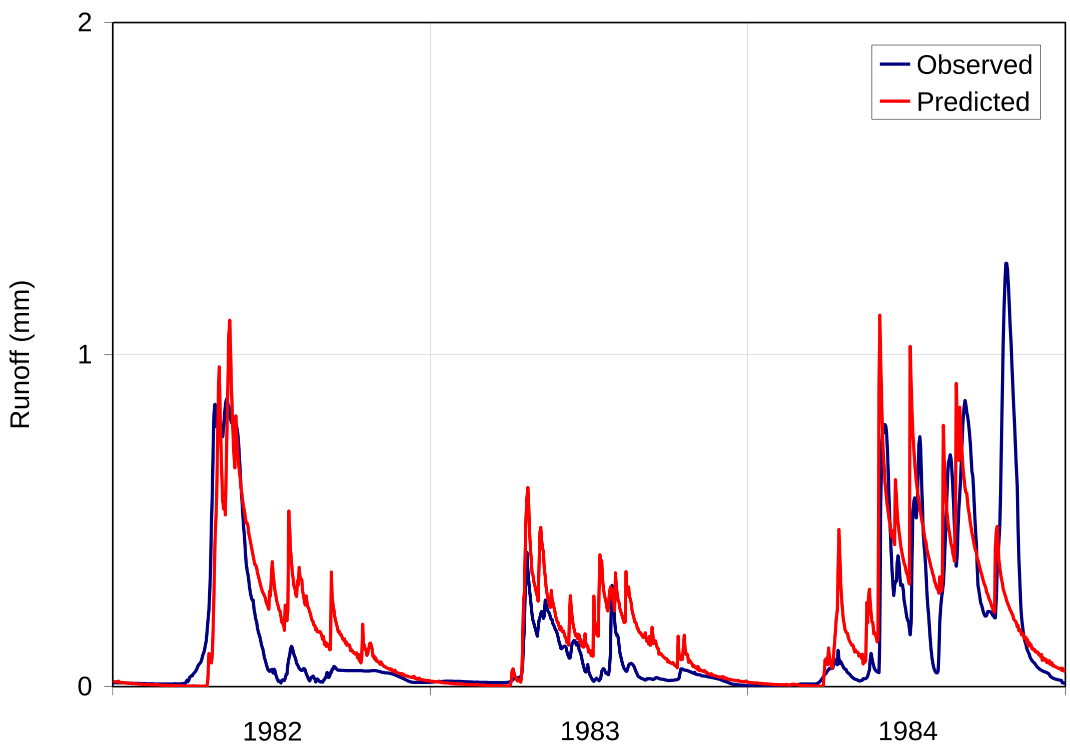

Figure 76. Observed and predicted daily runoff from Muskeg River watershed for 1982 to 1984.

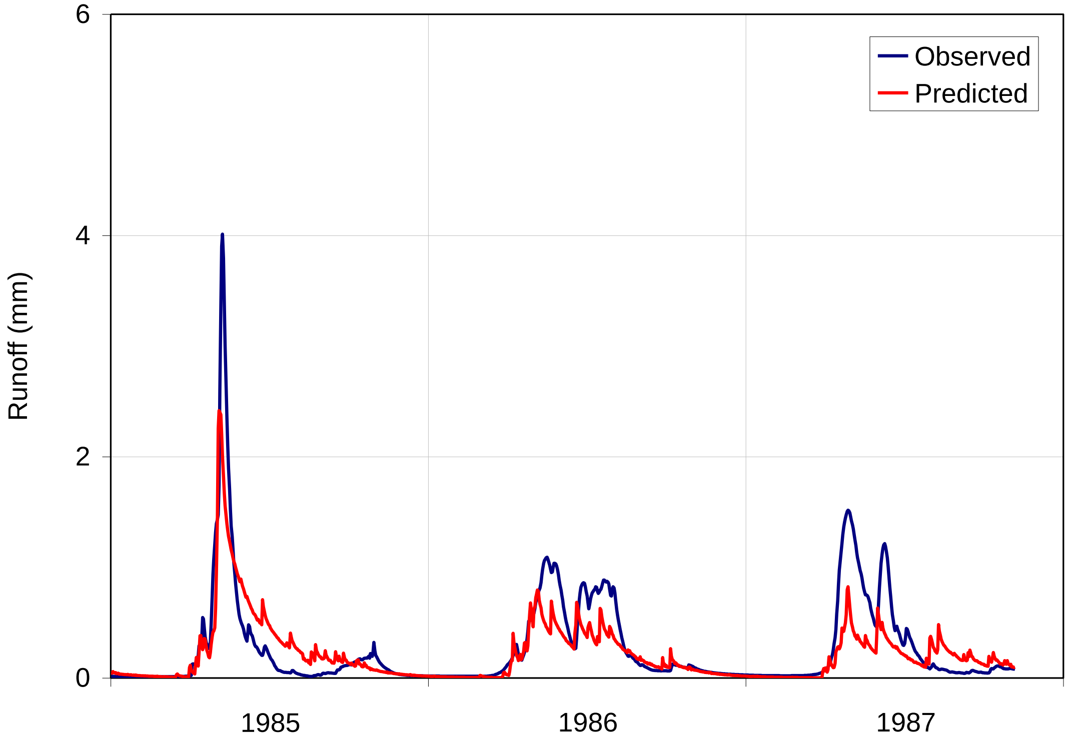

Figure 77. Observed and predicted daily runoff from Muskeg River watershed for 1985 to 1987.

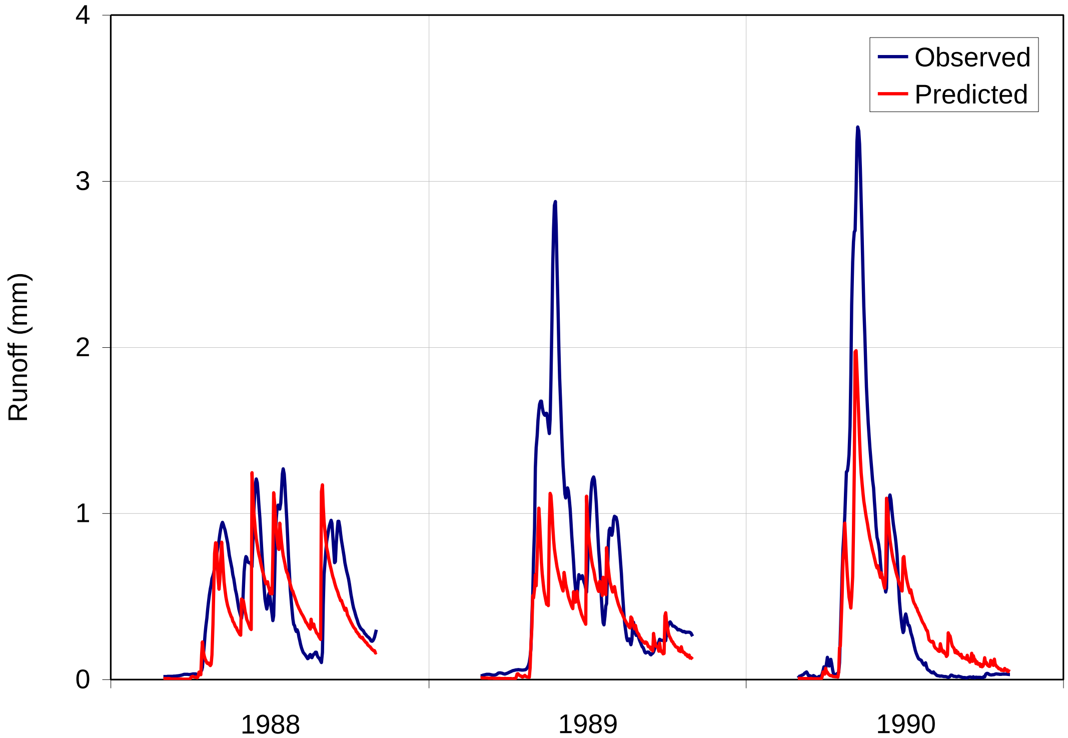

Figure 78. Observed and predicted daily runoff from Muskeg River watershed for 1988 to 1990.

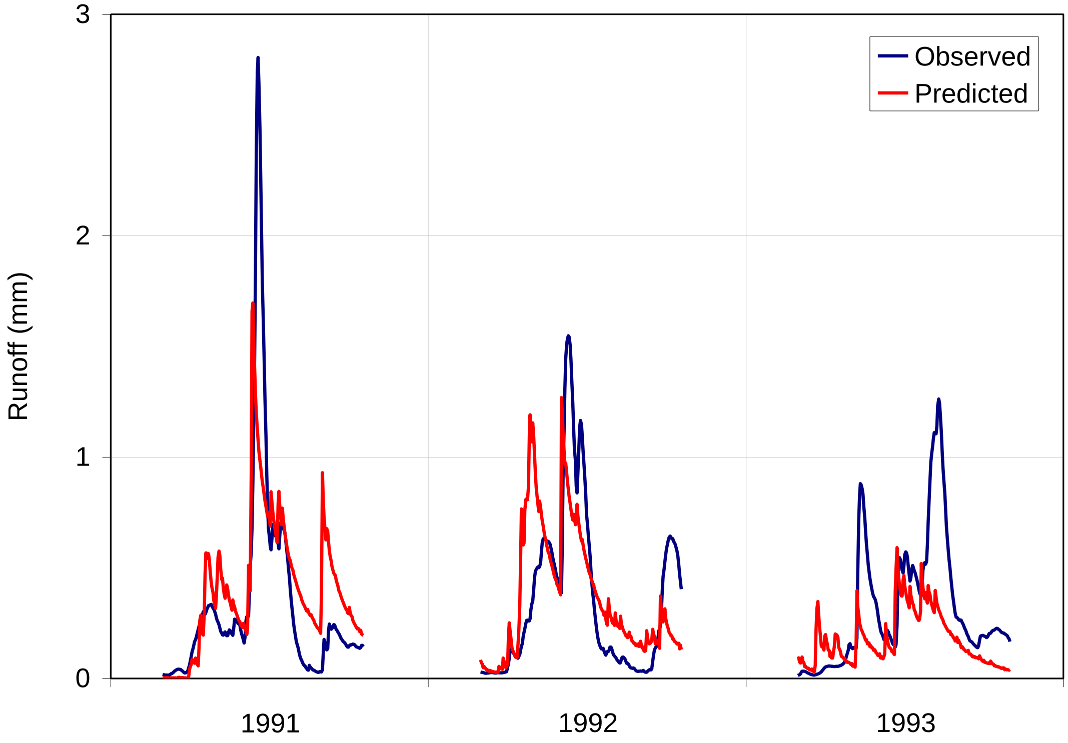

Figure 79. Observed and predicted daily runoff from Muskeg River watershed for 1991 to 1993.

Figures 80 to 84 show the observed and predicted flow duration curves for the five regional watersheds for the entire evaluation period (i.e., 1976 to 1993). The overall agreement between the observed and predicted daily flow duration curves for Joslyn Creek, MacKay River and Muskeg River watersheds was relatively good. In the case of Beaver River and Hangingstone River watersheds, however, low flows at the tail end of the curves were underestimated by the model. The reasons for this are unclear at the present time. However, one possible explanation might be that the simple groundwater component of $SWAT_{BF}$ was not sufficient to reproduce low flows in the Beaver River and Hangingstone River watersheds. The coupling of $SWAT_{BF}$ to an existing groundwater model such as MODFLOW may help improve the simulation of groundwater flow, given that MODFLOW can handle complex geological formations across a watershed unlike the simple groundwater component of $SWAT_{BF}$.

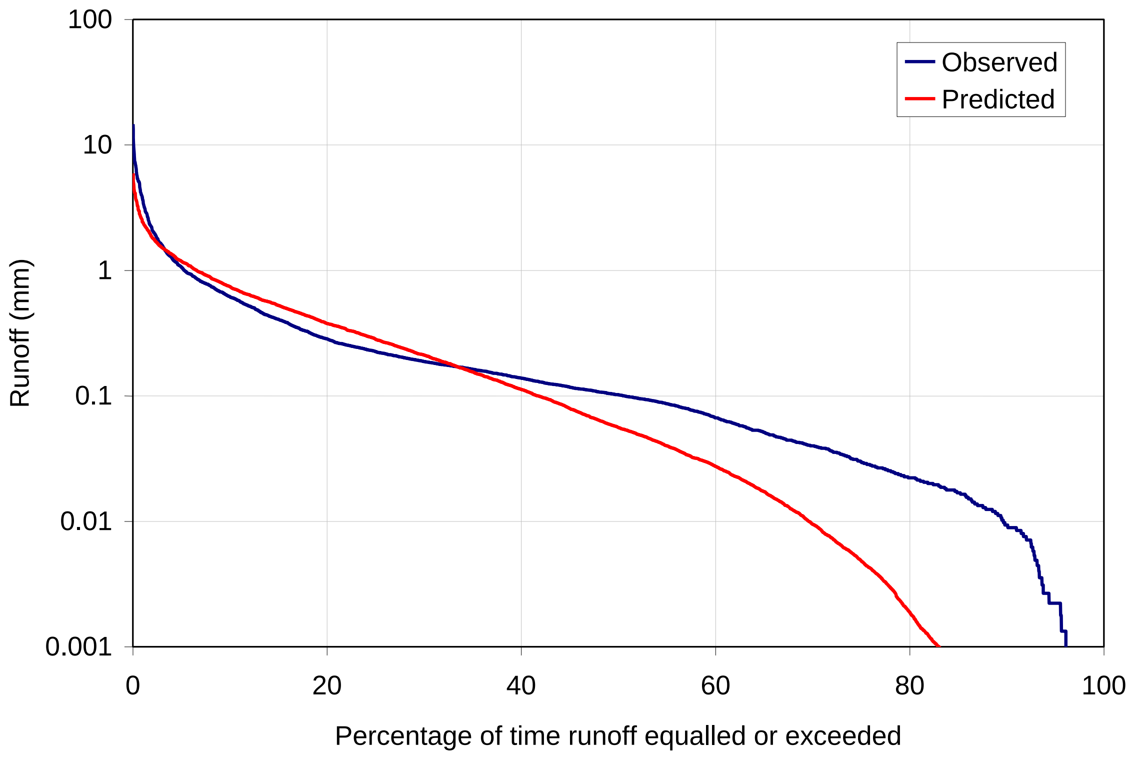

Figure 80. Observed and predicted daily flow duration curves for Beaver River watershed.

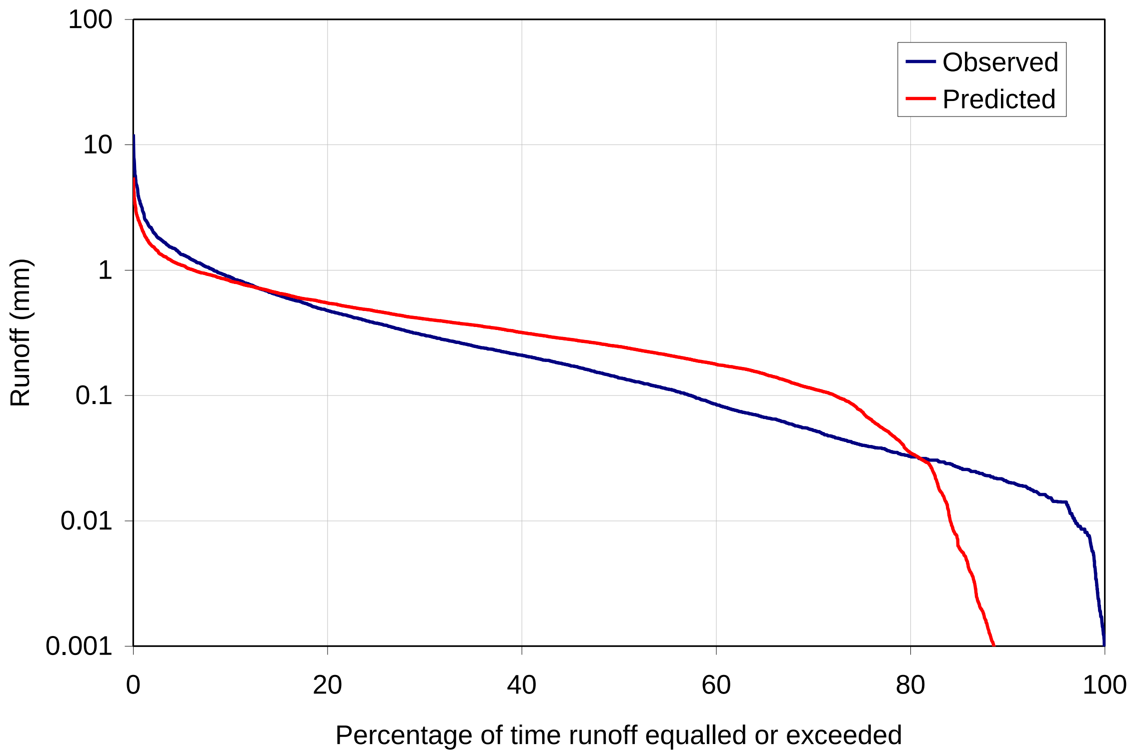

Figure 81. Observed and predicted daily flow duration curves for Hangingstone River watershed.

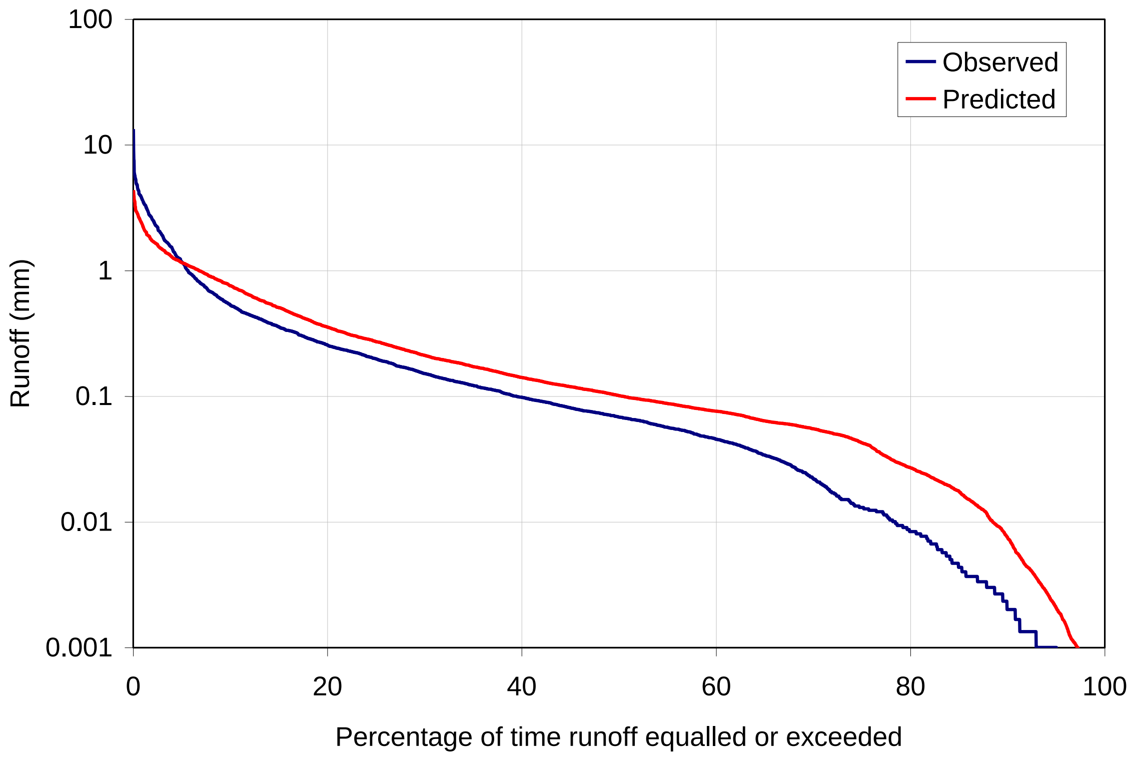

Figure 82. Observed and predicted daily flow duration curves for Joslyn Creek watershed.

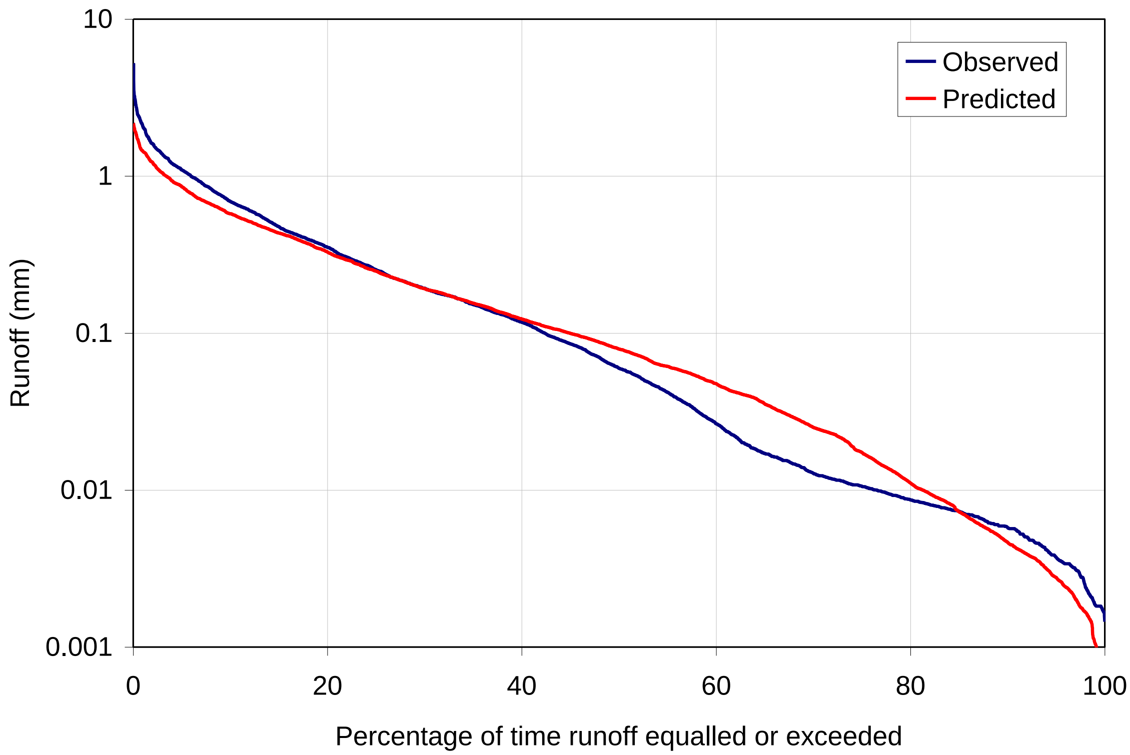

Figure 83. Observed and predicted daily flow duration curves for MacKay River watershed.

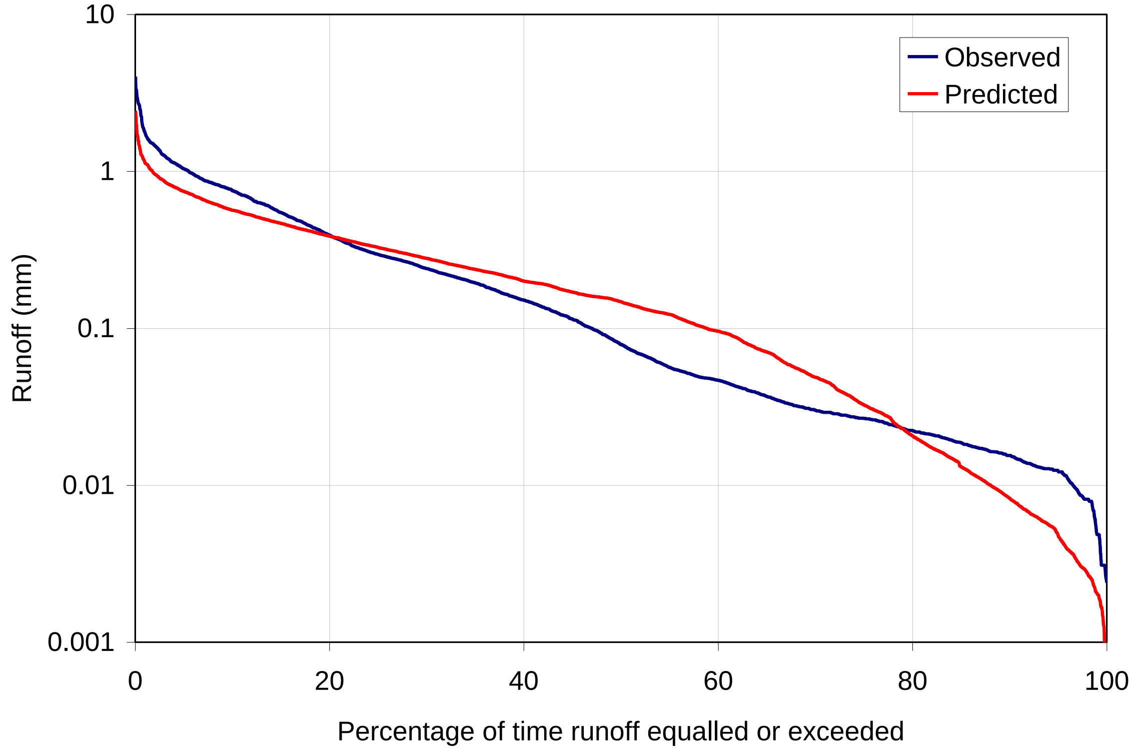

Figure 84. Observed and predicted daily flow duration curves for Muskeg River watershed.

The daily Nash-Sutcliffe coefficients are presented in Tables 24 and 25 for the calibration and validation periods, respectively, along with the performance ratings. The NSE_D values ranged from 0.44 to 0.63, which indicates that the performance of $SWAT_{BF}$ for predicting daily runoff ranged from good to fair for the five watersheds. With the exception of Muskeg River watershed, model performance declined for the validation period. It is important to remember that SWAT was developed to predict long-term yields and not detailed, single-event flood routing (Arnold et al. 1998). Therefore, it is not critical that the model reproduce the exact structure of the daily hydrographs as would be required in event-based modelling (Arnold and Williams 1995). As a first attempt of modelling watersheds in the oil sands geographic area the performance of $SWAT_{BF}$ can be considered sufficient for the prediction of daily runoff.

Table 24. Daily Nash-Sutcliffe coefficients (NSE_D) and performance for the calibration period.

Watershed	NSE_D	**Performance**
Beaver	0.52	Good
Hangingstone	0.50	Good
Joslyn	0.63	Good
MacKay	0.69	Good

Watershed	***NSE_D***	Performance
Muskeg	0.50	Good

Table 25. Daily Nash-Sutcliffe coefficients (NSE_D) and performance for the validation period.

Watershed	***NSE_D***	Performance
Beaver	0.45	Fair
Hangingstone	0.48	Fair
Joslyn	0.44	Fair
MacKay	0.53	Good
Muskeg	0.56	Good

6.4.5 *Performance Ratings*

A total of 30 performance ratings were assigned in this study (10 for each statistic). The total number of occurrences for each performance rating is as follows:

- Very good → 8
- Good → 15
- Fair → 6
- Poor → 1

More than two-thirds of the performance ratings were very good or good indicating that $SWAT_{BF}$ has very good potential for being utilized in the oil sands geographic area.

6.5 Summary

Overall, the performance of $SWAT_{BF}$ for predicting the long-term water yield from the five regional watersheds is considered satisfactory. The values of D_V, NSE_M and NSE_D obtained by $SWAT_{BF}$ in this study compare quite favourably to other applications of SWAT from around the world. The fact that 23 of the 30 performance ratings achieved for the three statistics adopted in this study were in the very good or good range of values demonstrates that $SWAT_{BF}$ can perform satisfactorily at reproducing the long-term water yield from regional watersheds in the oil sands geographic area. This is an important result because it is critical that any model used to predict the water balance of reclaimed watersheds also be able to reproduce the water balance of regional reference watersheds. It is important to remember that the results from this application of $SWAT_{BF}$ were achieved with data sets that are not the most comprehensive available for the oil sands geographic area. Therefore, once more comprehensive data sets have been compiled and utilized to set up $SWAT_{BF}$, it is expected that the performance of the model for predicting runoff from regional watersheds in the oil sands geographic area would improve.

7 APPLICATION OF $SWAT_{BF}$ TO A RECLAIMED WATERSHED

7.1 Introduction

The application of $SWAT_{BF}$ to the Wapisiw Lookout (Suncor Pond 1) watershed represents a first effort to apply $SWAT_{BF}$ to a reclaimed watershed in the oil sands geographic area. The data sets that were available to set up and operate the model for the Wapisiw Lookout watershed are preliminary at the present time. This situation is expected to be rectified in the future, with the FORWARD project planning to collect a variety of data sets (soils, vegetation, meteorology, streamflow and water quality) from the Wapisiw Lookout watershed. Therefore, as the FORWARD project progresses a more a stringent test of the performance of $SWAT_{BF}$ for predicting runoff from the Wapisiw Lookout watershed will be conducted

7.2 Data Sets and Model Setup

7.2.1 *Meteorology*

A meteorological station has been installed on the Wapisiw Lookout watershed and has been collecting data since 2011. The meteorological variables measured at this station include precipitation, air temperature, relative humidity, wind speed and net radiation. For the application of $SWAT_{BF}$ in this study, only the precipitation and air temperature data were utilized.

An analysis of the records revealed that precipitation was not measured during the following periods:

- January 2011 – March 2011
- November 2011 – March 2012
- November 2012 – December 2012

Precipitation data were acquired from the following three meteorological stations maintained by Environment Canada to fill-in the missing periods of record:

- Fort McMurray (3062697)
- Fort McMurray AWOS A (3062700)
- Fort McMurray CS (3062696)

Although the air temperature was measured year round at the Wapisiw Lookout station, there were still missing records. Therefore, temperature data were acquired from the three stations listed above and used to fill-in the days that were missing records. The total precipitation, average maximum temperature and average minimum temperature for 2011 and 2012 are presented in Table 26.

Table 26. Total precipitation, average maximum temperature and average minimum temperature for Wapisiw Lookout watershed.

Year	Total Precipitation (mm)	Average minimum temperature (°C)	Average maximum temperature (°C)
2011	267	-2.8	8.0
2012	402	-3.0	7.5

7.2.2 *Runoff*

Streamflow is not currently measured at any point within the Wapisiw Lookout watershed. Pumpage to Suncor Pond 1a (see Section 5.2.1) the sump that collects overflow water from Wapisiw wetland and subsurface seepage is monitored via a water level sensor located downstream of the discharge pipe outlet (Suncor n.d.). Unfortunately it is not possible to reliably convert the water level recording to discharge due to the unsteady, non-uniform nature of the flow in the channel resulting from the pump discharge cycle. The lack of streamflow data is problematic for the purposes of this study because streamflow is the main variable used to assess the performance of hydrological models that operate at the watershed scale. Although $SWAT_{BF}$ can be applied to the Wapisiw Lookout watershed without calibration to produce a time series of daily runoff, it is impossible to assess how good the model predictions are without observed measurements being available. Streamflow data also serve another important purpose in most modelling exercises. The calibration of a hydrological model involves the adjustment of input parameters to obtain a good fit between the observed and predicted streamflow. This procedure can only be performed when observed streamflow measurements are available for the watershed being studied. It is extremely unlikely that an uncalibrated version of any given hydrological model would be capable of outperforming a calibrated version of the same model. To stringently evaluate the capabilities of $SWAT_{BF}$ for predicting runoff from reclaimed watersheds, it is crucial that streamflow data be available.

Suncor Energy Inc. has measured the water level in Wapisiw wetland since 2011. By determining the change in storage of the wetland, it is possible to estimate an approximate value of the volume of water entering the wetland as runoff. Since high resolution LIDAR data are available for Wapisiw Lookout watershed, an approximate value of the volume of water stored in the wetland can be determined by relating the depth of water in the wetland at a given point in time to the area of the wetland at that particular depth. Although bathymetry data would be the most accurate means to estimate the wetland area, it was felt the high resolution of the LIDAR data would permit a reasonably accurate estimation of wetland area to be achieved. Once the daily volume of water (m^3) entering the wetland has been determined, it can be converted to runoff (mm) because the area of the watershed is known.

The water level data were acquired from Suncor Energy Inc. and analysed to determine their suitability for estimating the volume of runoff entering the wetland from the watershed. Figures 85 and 86 show the water level of the wetland in 2011 and 2012, respectively. The time series shown in Figures 85 and 86 represent the best quality data for both years. It was evident that some of the observations were grossly inaccurate, probably due to instrumentation malfunction, and were therefore excluded from any further analyses.

For both years, there were considerable fluctuations in the water level of the wetland over very short periods of time. It would appear that water enters the wetland and then exits shortly afterwards. Since the exact elevation of the pressure transducer is unknown, thereby making it impossible to determine the exact elevation of the water level of the wetland above a known datum (e.g., mean sea level), the exact cause of the fluctuations can only be speculated at the present time.

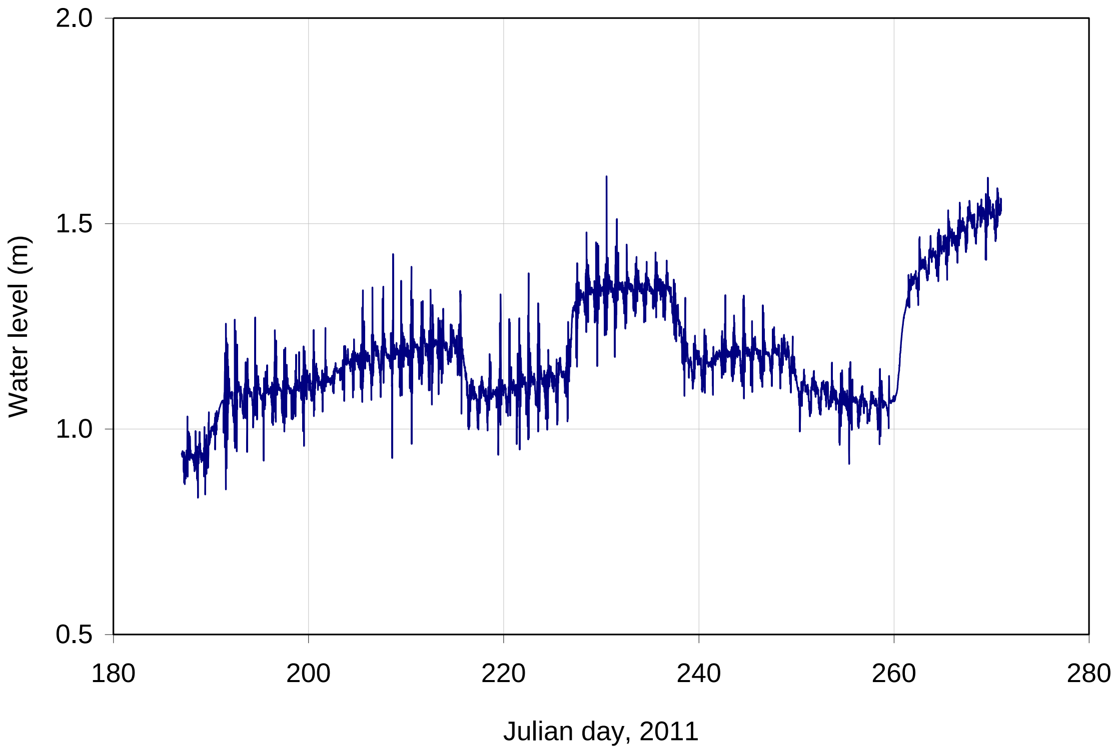

Figure 85. Water level of Wapisiw wetland in 2011.

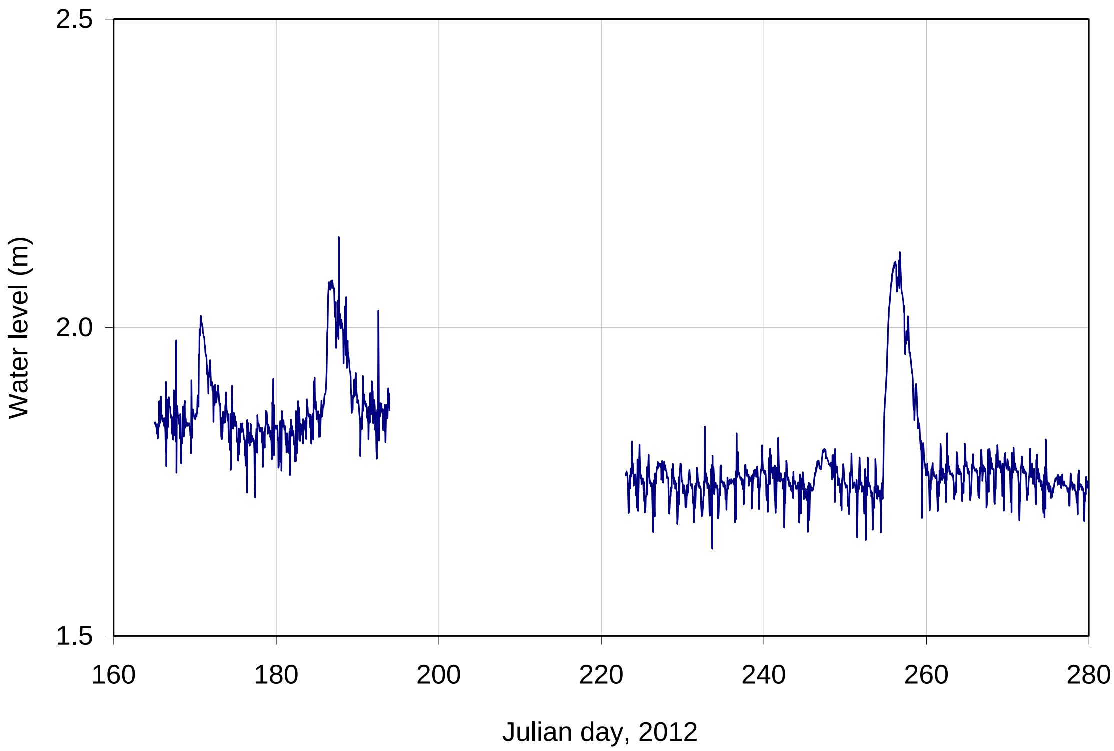

Figure 86. Water level of Wapisiw wetland in 2012.

Figures 87 and 88 show the change in water level corresponding to the time of day for 2011 and 2012, respectively. There are far more data points available for 2011 than 2012 because the water level in 2011 was measured every 15 minutes, whereas in 2012 it was measured every hour. Figures 87 and 88 are very interesting because they reveal that the greatest change in water level usually happened during the day, while at night the water level of the wetland was reasonably stable. This indicates that considerable volumes of water were entering and exiting the wetland over very short periods of time during daylight hours or there is a problem with the instrumentation during those periods. Such a phenomenon cannot be attributed to runoff being generated in response to rainfall, since rainfall events are just as likely to occur during the night as they are during the day. Water was pumped into swales 7 and 13 from the base of Tar Island dyke during certain periods which would account for some of the fluctuations during the daylight hours. However, it is impossible to determine the volume of water that was pumped into both swales since only the level of water in the swales was measured. Without a detailed cross-section of the swales being available, the water level of the swales cannot be related to discharge accurately.

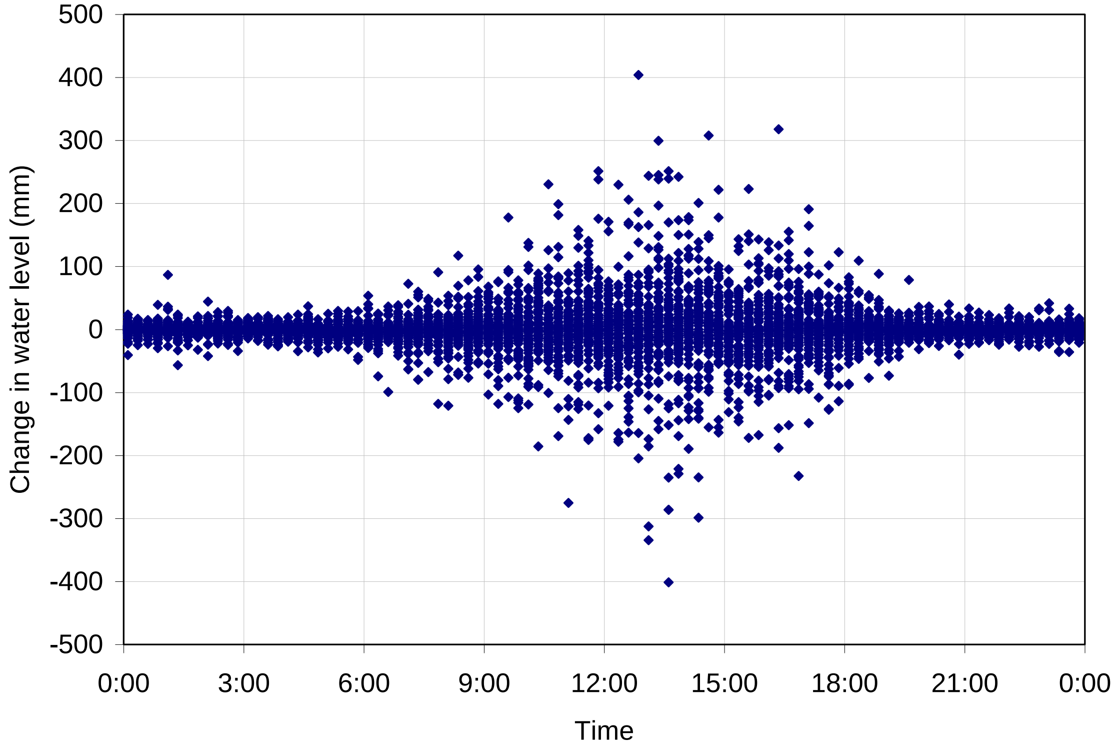

Figure 87. Change in water level corresponding to time of day for 2011.

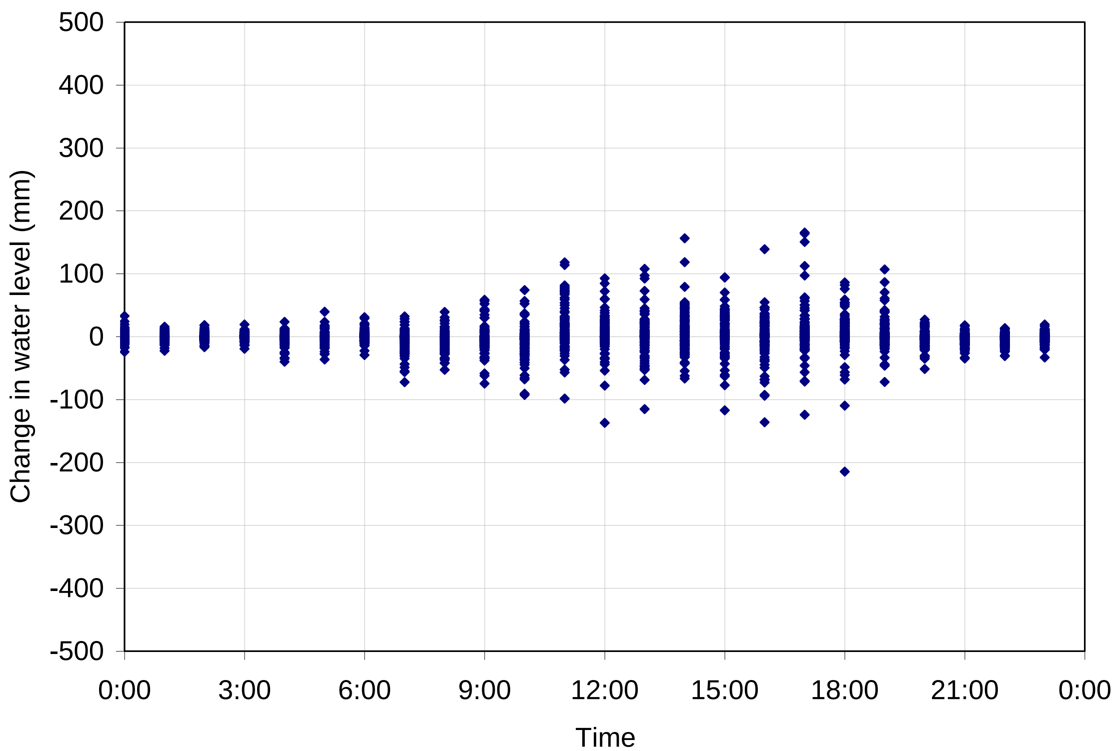

Figure 88. Change in water level corresponding to time of day for 2012.

Based on the above analysis, it is apparent that the source of water entering the wetland during daylight hours cannot be identified with any accuracy. That is, it is extremely difficult to determine whether the water entering the wetland during daylight hours is runoff generated in response to a rainfall event or water that was pumped into swales 7 and 13 from the base of the dyke.

In an attempt to make use of the data, the change in water level of the wetland over a 24 hour period (from midnight to midnight) was analyzed. The change in daily water level is presented in Figures 89 and 90 for 2011 and 2012, respectively. There were six data points (circled in red) that corresponded to large positive changes in water level in 2011. Similarly, there were four data points (circled in red) in 2012 that corresponded to large positive changes in water level. It is likely that these large positive changes in water level occurred in response to rainfall events. An analysis of the precipitation records revealed that considerable quantities of precipitation fell during the periods leading up to the days when the water level rose significantly. It is likely that the soil of the watershed was being saturated during these periods. Further analysis revealed that a significant quantity of precipitation was recorded either the day before or on the same day when the wetland level rose significantly. Given that the soil was likely saturated by this point in time, the precipitation would not have been able to infiltrate. Significant quantities of surface runoff would have been generated instead, thereby causing the water level in the wetland to rise significantly.

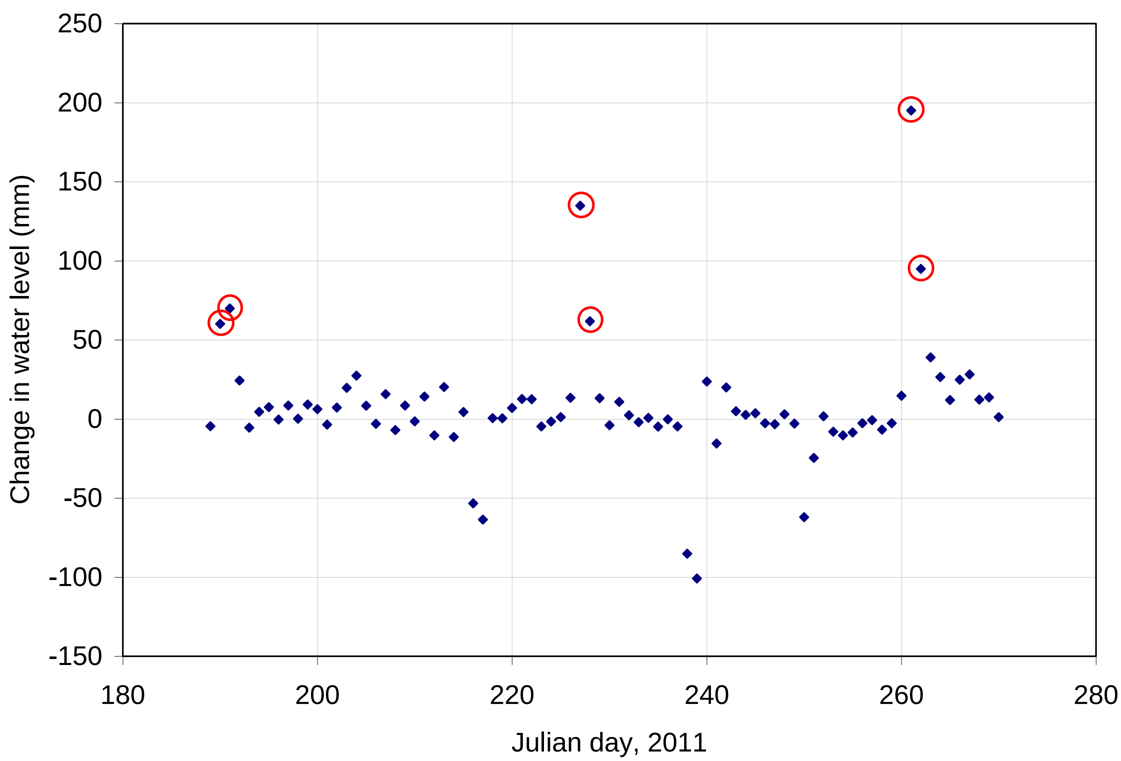

Figure 89. Change in water level from midnight to midnight for 2011.

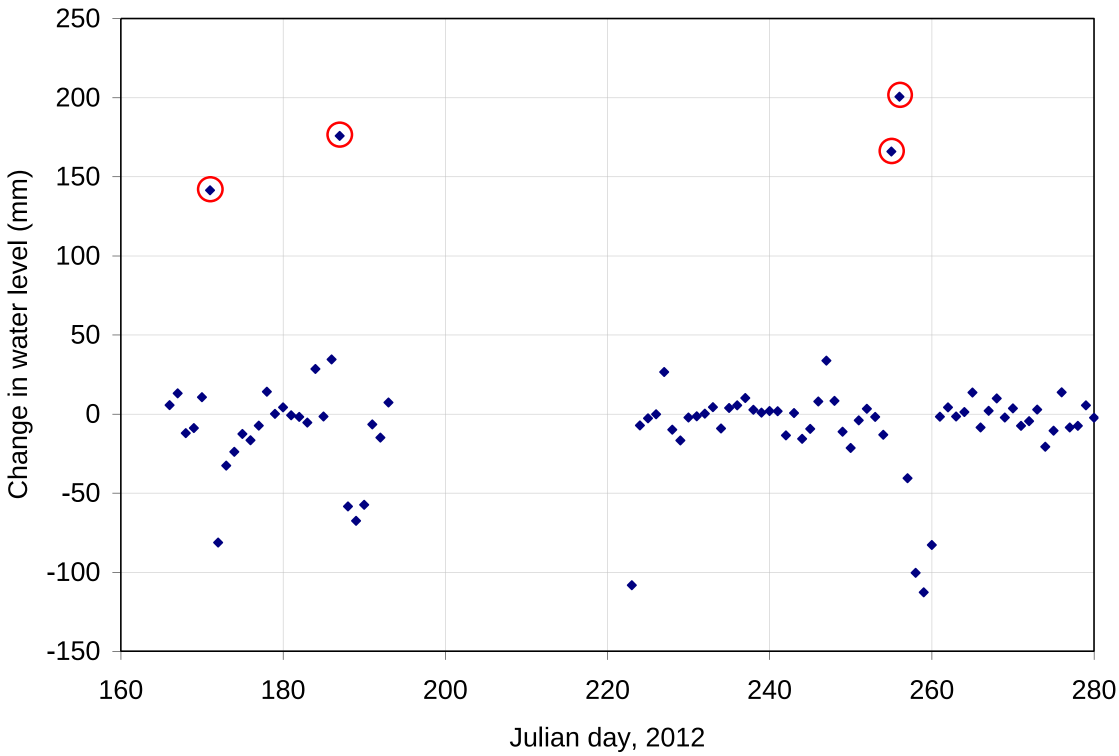

Figure 90. Change in water level from midnight to midnight for 2012.

The change in water level was converted to change in water volume using the area of the wetland, which was determined to be approximately 3.9 ha from the LIDAR data. The change in water volume for the day was then converted to runoff using the area of the watershed. The runoff values for the 10 dates on which a significant amount of surface runoff was believed to have been generated and entered the wetland are provided in Table 27.

Due to the lack of data, it is almost impossible to determine the source of water that gave rise to the small changes in water level. Before this analysis was undertaken, it was hoped that a continuous record of daily runoff entering the Wapisiw Lookout wetland for 2011 and 2012 could be obtained. However, it became apparent that this goal was not achievable once the data were analyzed. The analysis performed in this study has revealed that only ten data points could be used to estimate the amount of runoff entering the wetland. Although the ten runoff values calculated from the above analysis can be used to calibrate $SWAT_{BF}$, a continuous record of daily runoff values for several months is needed to stringently evaluate model performance.

Table 27. Estimated runoff generated on days when the water level of the wetland rose significantly.

Date	Julian day	Change in water level (mm)	Runoff (mm)
9 Jul 2011	190	60.1	1.2
10 Jul 2011	191	69.9	1.4
15 Aug 2011	227	134.8	2.6
16 Aug 2011	228	61.8	1.2
18 Sep 2011	261	195.1	3.8
19 Sep 2011	262	95.0	1.9
19 Jun 2012	171	141.4	2.8
5 Jul 2012	187	175.7	3.4
11 Sep 2012	255	165.9	3.2
12 Sep 2012	256	200.5	3.9

7.2.3 *Vegetation*

Barley is the predominant vegetation type growing on the Wapisiw Lookout watershed. In the future, trees will be established to recreate a forested watershed. However, barley is being grown at the present time as a means to stabilize the soils. There is a lack of data on the Leaf Area Index (LAI) of barley in the oil sands geographic area. The LAI of the barley was set equal to zero in this study, thereby making the vegetation component of the model redundant. Most hydrological models reported in the literature do not account for LAI in their formulation. For example, LAI is not needed as an input into the HBV model (Seibert 1999), yet this model can still be used for predicting the impacts of land use change on water yield (Viney et al. 2005). The modified version of $SWAT_{BF}$ utilized in this study resembles a typical rainfall-runoff model.

7.2.4 *Soils*

Several different types of reclamation material were used in the construction of Wapisiw Location watershed. The main materials that comprise the watershed are as follows:

- Beach Above Water Tailings (BAW)
- Densified Tailings Sand (DT)
- Plant 4 Tailings (P4)
- Flyash (FA)

- Mature Fine Tailings (MFT)
- Sand Berm (SB)

Descriptions and properties of each material listed above were provided by Suncor (Suncor n.d.). The distribution of the reclamation materials across the watershed is shown in Figure 91.

Phase 3 in Figure 91 is an area of soft Plant 4 tailings that is being mechanically stabilized using geogrid and tailings sand (Suncor n.d.). Phase 3 has been designed in such a way that it will eventually integrate into the watershed and create a seamless landscape (Suncor n.d.).

Only one HRU was created for this application of $SWAT_{BF}$ to the Wapisiw Lookout watershed. The soil of the HRU consisted of Densified Tailings Sand (DT). The soil properties of the Densified Tailings Sand were derived from the following sources: Suncor (n.d.), Shurniak (2003) and www.pedosphere.ca. The main properties of the Densified Tailings Sand are presented in Table 28. The accuracy of the soil properties is somewhat limited; the FORWARD project has begun a comprehensive soil survey of the Wapisiw Lookout watershed but data will not become available until later in 2013.

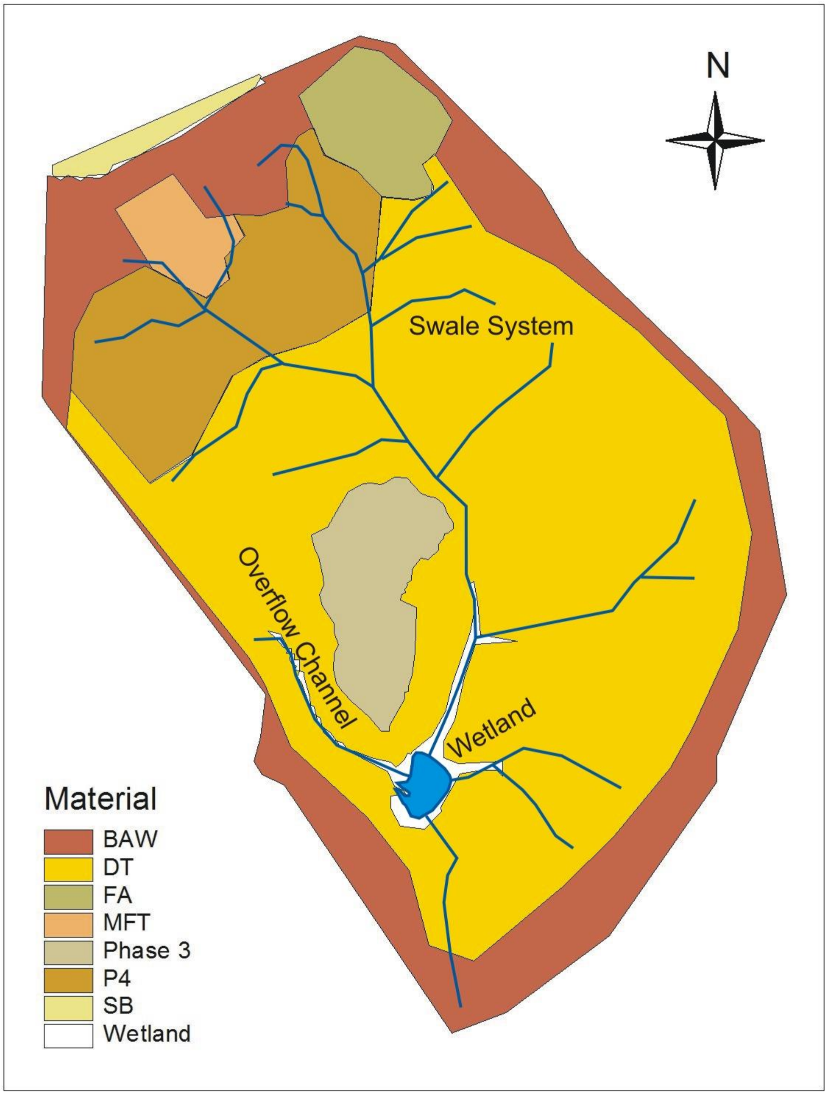

Figure 91. Distribution of materials used in the construction of Wapisiw Lookout watershed (Suncor n.d.).

Table 28. Soil properties of Densified Tailings Sand.

Soil property (units)	**Soil layer 1**	**Soil layer 2**	**Soil layer 3**
Depth of layer (mm)	400	1,200	10
Bulk density (g/cm^3)	0.92	1.56	1.51
Available water capacity (mm/mm)	0.12	0.10	0.21
Saturated hydraulic conductivity (mm/h)	36	36	3.6×10^{-5}

7.2.5 *Watershed Delineation*

Due to the small size of the Wapisiw Lookout watershed, it was decided that it could be treated as a single entity for this application of $SWAT_{BF}$. In other words, the watershed was not subdivided into smaller spatial units but rather treated as one subwatershed. Figure 91 shows that Densified Tailings Sand (DT) comprises the major portion of the material used in the construction of the Wapisiw Lookout watershed. Given that the dominant vegetation cover at the present time is barley and that Densified Tailings Sand is the dominant soil for the watershed, only one HRU was created for this application of $SWAT_{BF}$. Although it would be possible to create more HRUs, the lack of detailed soil properties for the other materials used in the construction of the watershed makes it difficult to parameterize the model without creating further uncertainties in the model predictions.

Although there are at least six different types of reclaimed materials found across the Wapisiw Lookout watershed, it is not necessary to account for all of these materials when utilizing $SWAT_{BF}$. In fact, van Griensven (2002) pointed out that detailed soil and land use maps are not useful in SWAT since only the most common combinations appear in the HRUs and less common soil types disappear. To avoid overparameterization a maximum of two or three HRUs should be sufficient to represent most of the spatial heterogeneity in land use and soils for the Wapisiw Lookout watershed. Therefore, relying on only one HRU for this application of $SWAT_{BF}$ is not regarded as a major constraint.

7.2.6 *Modifications to $SWAT_{BF}$*

It was necessary to make some minor modifications to $SWAT_{BF}$ so that it was suitable for the Wapisiw Lookout watershed. Firstly, the groundwater component of $SWAT_{BF}$ was modified so that groundwater flow would not contribute to the amount of runoff entering the wetland. This is because the Wapisiw Lookout watershed is lined with a Geosynthetic Clay Liner (GCL) that prevents groundwater contribution to the swales. Since water from the underlying aquifer cannot contribute to streamflow in the channel due to the GCL, it was felt the best way to ensure absolutely no groundwater contributed to streamflow in the model was simply to "shut off" the groundwater component of the model. The source code of the model was modified so that the groundwater flow was set to zero. Normally, water that enters the shallow aquifer from the overlying soil profile can contribute to streamflow. However, in this version of $SWAT_{BF}$, any water entering the shallow aquifer could not contribute to the system and, hence, was considered lost from the system.

The routing of streamflow was not considered in this application of $SWAT_{BF}$. Given the small size of the Wapisiw Lookout watershed, it is reasonable to assume that any surface runoff or lateral flow will reach the wetland in less than one day. Watson and Putz (2010) removed the streamflow routing component of SWAT when developing a simplified version of the model called SWAT-Simple. The same modification was implemented in $SWAT_{BF}$ for this study. Although it would be possible to simulate channel routing for the Wapisiw Lookout watershed, it would only increase the complexity of the model. Ye et al. (1997) did not activate the streamflow routing component of the Large Scale Catchment Model (LASCAM) (Sivapalan et al. 2002) when applying it to the Salmon Brook, Stones Brook and Canning River catchments in Australia. The areas of these catchments were 0.82, 15 and 517 km^2. The study of Ye et al. (1997) clearly reveals it is not necessary to route streamflow for every model application.

7.3 Evaluation of Model Performance

Due to the limited number of runoff observations available for the Wapisiw Lookout watershed, it was decided that the model would only be calibrated; it was felt that it would not be possible to adequately validate the model. A much longer time series of runoff should be used for such a purpose. Therefore, the purpose of the application of $SWAT_{BF}$ to the Wapisiw Lookout watershed is simply to demonstrate that it is capable of predicting runoff from a reclaimed watershed rather than providing a stringent test of model performance.

Three calibration periods were adopted in this study:

- Calibration period 1 (CP1) → 2011
- Calibration period 2 (CP2) → 2012
- Calibration period 3 (CP3) → 2011-2012

The year 2010 was utilized as the warm-up period. The lack of observations does not permit D_V or NSE_M to be calculated as they were for the regional watersheds. Therefore, only NSE_D has been calculated for this application of $SWAT_{BF}$ to the Wapisiw Lookout watershed. It was also not possible to plot monthly hydrographs and flow duration curves. Daily hydrographs have been plotted that include the observed daily runoff measurements that were estimated for the Wapisiw Lookout watershed.

7.4 Results

7.4.1 *Optimized Parameters*

The optimized parameter values for the three calibration periods are presented in Table 29, along with the lower and upper bounds. Several of the parameters were equal to the defined lower and upper bounds; this phenomenon has occurred in other modelling exercises reported in the literature so it is not isolated to this study. Ideally fewer parameters would be equal to the lower or upper bounds. The situation will improve as measured data sets become available in the future to set up and calibrate the model. It can also be observed that there is considerable variation in some parameters from one calibration period to another. It is important to remember that different parameter sets can produce equally good results. This phenomenon is commonly referred to as equifinality in the literature (Beven 2001). Only one parameter set was selected for each calibration period in this study. It is likely that there are several sets of parameters that could produce similar results for each calibration period.

Table 29. Optimized values for each parameter adjusted during the calibration of $SWAT_{BF}$.

Parameter	Lower bound	Upper bound	CP1	CP2	CP3
CN2	-25%	25%	-3.1%	-25.0%	-25.0%
SOL_K	-50%	50%	50.0%	-13.9%	-5.5%
SOL_Z	-50%	50%	25.3%	-16.7%	-17.4%
SOL_AWC	-50%	50%	-49.9%	50%	49.9%
ANISO	1	10	10.0	9.9	10.0
SURLAG	0.01	1	1.0	1.0	0.01
SMFCN	1	5	1.9	4.2	2.3
SFMTMP	-2	2	-0.1	1.7	-0.9

7.4.2 *Daily Runoff*

The observed and predicted daily runoff is compared in Figures 92, 93 and 94 for the calibration periods 1, 2 and 3, respectively. Figure 94 shows that $SWAT_{BF}$ significantly underestimated the observed daily runoff in 2011 when it was calibrated for the period 2011-2012. However, when $SWAT_{BF}$ was calibrated for the individual year of 2011, the agreement between the observed and predicted runoff was much better (Figure 92). When calibrated for individual years, it appears that $SWAT_{BF}$ responded reasonably well to the precipitation events that produced the runoff generated from the Wapisiw Lookout watershed.

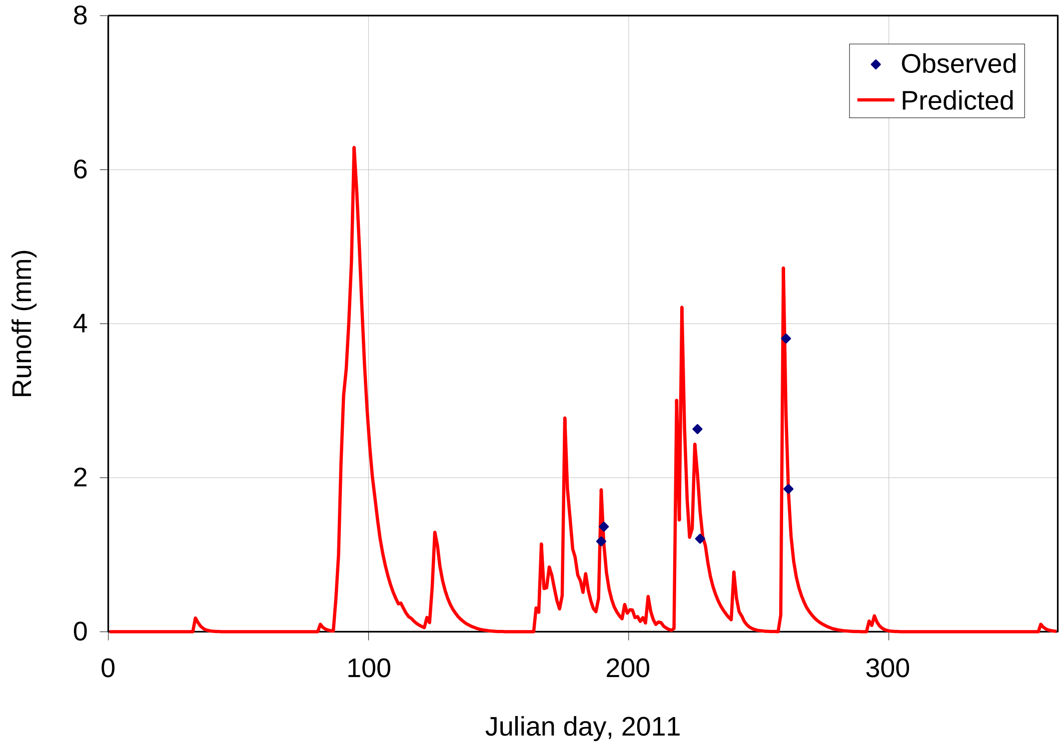

Figure 92. Observed and predicted daily runoff from Wapisiw Lookout watershed for CP1.

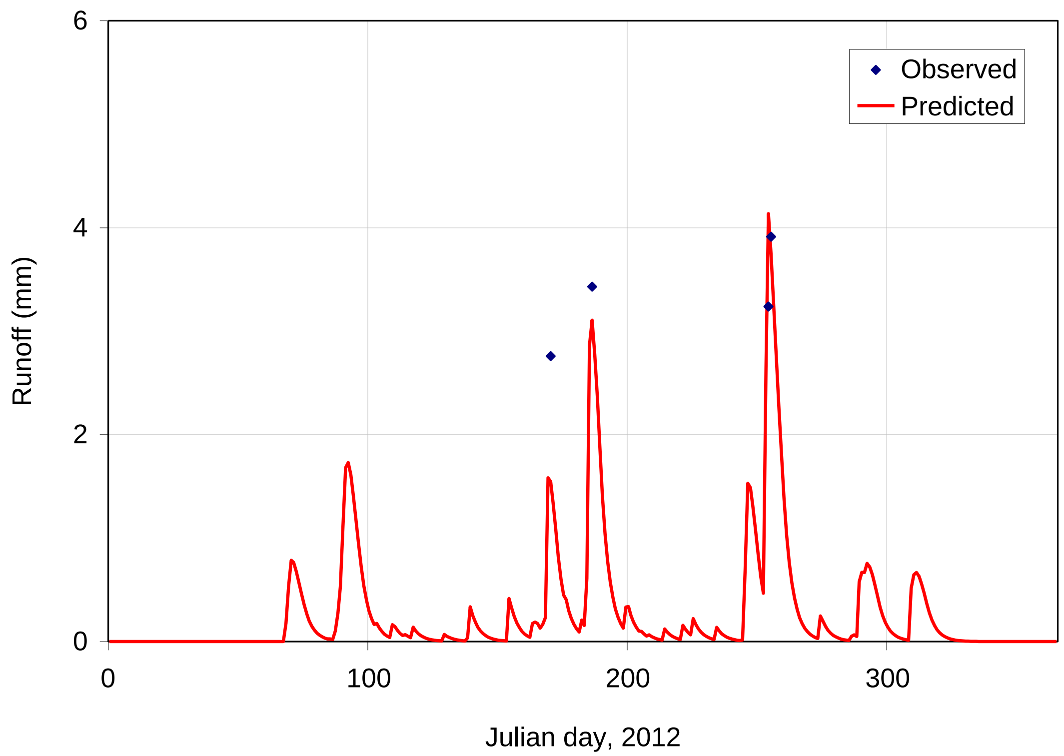

Figure 93. Observed and predicted daily runoff from Wapisiw Lookout watershed for CP2.

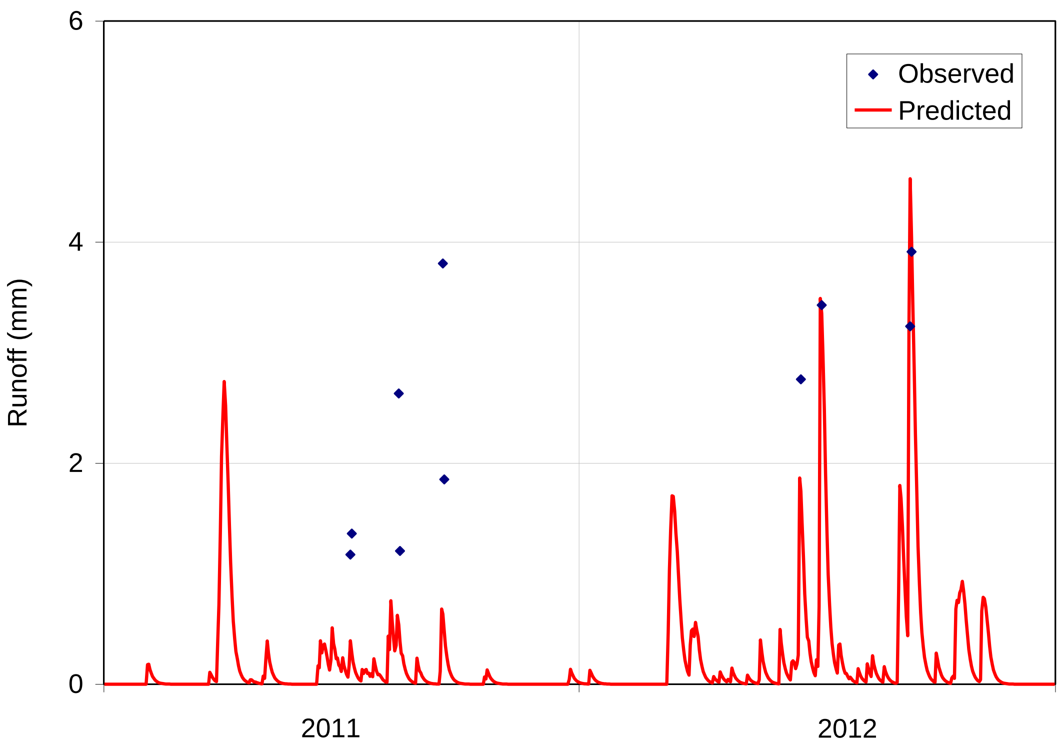

Figure 94. Observed and predicted daily runoff from Wapisiw Lookout watershed for CP3.

The values of NSE_D obtained from the application of $SWAT_{BF}$ to the Wapisiw Lookout watershed for the three calibration periods are presented in Table 30. Although the NSE_D values for calibration periods 2 and 3 are indicative of a poor model performance, the model did achieve a good performance rating for calibration period 1.

Table 30. Values of NSE_D for the three calibration periods.

Calibration period	NSE_D
1	0.64
2	-2.52
3	-1.09

7.5 Discussion

Several studies have been reported in the literature whose objective was to determine the impact of utilizing limited streamflow data on the performance of a hydrological model (Perrin et al. 2007, Rojas-Serna et al. 2006, Seibert and Beven 2009). Perrin et al. (2007) randomly selected 10, 50, 100, 250, 350, 400, 500, 750 and 1,000 runoff observations from a large record containing 14,245 runoff observations. They found that approximately 350 observations were required to obtain robust estimates of model parameters. Seibert and Beven (2009) randomly selected 0, 1, 2, 4, 8, 16, 32, 64, 128 and 256 runoff observations from a 10-year period. Figures 1, 3 and 5 in Seibert and Beven (2009) appear to indicate that more observations lead to better model performance but there is a point beyond which model performance does not significantly improve. This also appears to be the case with the results presented in Perrin et al. (2007). Seibert and Beven (2009) pointed out that "results may differ significantly between catchments and also depend on the days chosen for taking the measurements." The implications of this statement are very important and should be taken into consideration when only a small number of runoff observations are available to calibrate a hydrological model. Therefore, further studies are required before hydrologists and engineers can better understand how a limited number of runoff observations will influence model performance.

The initial conditions established within the model at the beginning of the calibration period could also potentially influence model performance. However, it is difficult to achieve accurate initial conditions using precipitation records that have been obtained from a meteorological station located some distance from the watershed in question. This is because the precipitation measured at that station may not be representative of the precipitation that fell on the watershed for the same period. Long-term precipitation records measured at the watershed itself will help overcome this problem.

The estimates of runoff derived in this study from the observed change of water level in the wetland are considerably less accurate than measurements of runoff that would be calculated from the stage of a river or creek. Therefore, it is recommended that a weir be established on the main swale of the Wapisiw Lookout watershed so that the stage can be measured accurately. This would allow a continuous accurate record of streamflow from the watershed to be calculated.

7.6 Summary

This study represents the first attempt to predict runoff from a reclaimed watershed in the oil sands geographic area using $SWAT_{BF}$. Although comprehensive data sets for the Wapisiw Lookout watershed are not currently available, it was still possible to setup and calibrate $SWAT_{BF}$ for three different periods to determine how model performance might vary depending on the period. When $SWAT_{BF}$ was calibrated for the year 2011 a good performance rating was achieved in terms of the value of NSE_D. However, calibrating the model for the year 2012 and the period 2011 to 2012 resulted in a poor performance rating being achieved in both cases. Achieving a value of 0.64 for NSE_D in 2011 is an encouraging result that warrants further applications of $SWAT_{BF}$ be undertaken to evaluate the performance of the model.

Unfortunately, the application of $SWAT_{BF}$ in this study does not permit major conclusions to be drawn regarding the suitability of the model for predicting runoff from reclaimed watersheds in the oil sands geographic area because of the limited data sets available. However, this situation should be rectified in the next few years with the FORWARD project commencing its monitoring program in 2013.

8 CONCLUSIONS

There are few high quality data sets available for reclaimed watersheds in the oil sands geographic area that can be used to set up and operate $SWAT_{BF}$. This is because very few watersheds have been reconstructed in the oil sands geographic area to date. Furthermore, the level of instrumentation varies considerably between watersheds. In fact, very few reconstructed watersheds have long-term data sets that would be considered adequate for stringently testing the performance of hydrological models. However, it is likely that this situation will change in the near future as the importance of acquiring long-term meteorological and hydrological data sets for scientific research becomes more appreciated. It is well established that watersheds are extremely complex natural systems. The key to better understanding these systems is to collect high quality data sets that support detailed scientific and engineering studies.

$SWAT_{BF}$ was applied to five regional watersheds in the oil sands geographic area: Beaver River, Hangingstone River, Joslyn Creek, MacKay River and Muskeg River. Most of the data sets (DEM, land use and soils) used to set up $SWAT_{BF}$ for these watersheds were acquired from WaterBase. Although these data sets are not the most comprehensive for the oil sands geographic area, they offer a very important advantage: they can be easily imported into the MWSWAT GIS interface without the need to manipulate the GIS layers. Furthermore, they are compatible with the vegetation and soils databases that are utilized by the MWSWAT GIS interface to create the necessary input files. This reduces the set up time considerably.

The overall performance of $SWAT_{BF}$ for predicting runoff from the five regional watersheds was deemed to be satisfactory. It is important to remember that this study represents the first attempt to predict the water yield from regional watersheds in the oil sands geographic area using $SWAT_{BF}$. Once more comprehensive data sets become available, it is expected that the performance of $SWAT_{BF}$ would improve. The results achieved in this study are extremely encouraging and warrant further research be conducted to further test and develop the model.

$SWAT_{BF}$ was applied to the Wapisiw Lookout watershed which was constructed by Suncor Energy Inc. Runoff from the Wapisiw Lookout watershed into Wapisiw wetland is not directly measured at the present time. A V-notch weir has been installed on one of the smaller swales but the streamflow data were not available for this study. Therefore, a LIDAR topographic survey and the change in water levels of Wapisiw wetland were used to derive runoff estimates. Due to significant noise in the water level measurements, only 10 daily runoff observations could be determined with certainty. $SWAT_{BF}$ was calibrated for three different periods for the Wapisiw Lookout watershed: 2011, 2012 and 2011 to 2012. Although model performance was poor for the 2012 and 2011 to 2012 calibration periods, the performance of $SWAT_{BF}$ for the 2011 calibration period was good. Although it is not currently possible to stringently test model performance for Wapisiw Lookout watershed, the result achieved for the 2011 calibration period is extremely encouraging and indicates that there is a need to conduct further testing of $SWAT_{BF}$ using higher quality data sets once they have been collected.

The FORWARD project is planning to commence its monitoring program for Wapisiw Lookout watershed in 2013. It will take at least 2 to 3 years to collect and compile the necessary data sets needed to carry out a more stringent evaluation of $SWAT_{BF}$. The need for good quality data sets to test hydrological models is critical. The statement of Whittemore and Lebo (2000) draws attention to the need for good quality data sets:

> "The availability of reliable monitoring data for calibration is essential to defensible model development."

In the meantime, however, it would be an extremely useful investigation to apply $SWAT_{BF}$ to another reclaimed watershed that has more comprehensive data sets available. Application of the model at another location would allow the developers of $SWAT_{BF}$ to gain further insights into how the model performs for reclaimed watersheds.

9 RECOMMENDATIONS

The overall performance of $SWAT_{BF}$ in this study was deemed to be satisfactory and would indicate that $SWAT_{BF}$ has good potential to be utilized as a practical tool for predicting runoff from watersheds in the oil sands geographic area. The results of this study were very encouraging given that the data sets utilized in this initial application of $SWAT_{BF}$ had a fairly coarse resolution. Therefore, it is highly recommended that further research be undertaken to more stringently test the capabilities of $SWAT_{BF}$ for the oil sands geographic area. Further testing of the model is obviously contingent on more comprehensive data sets being made available in the future. Given that one high quality data set is currently available for a reclaimed watershed in the oil sands geographic area, namely SW30 dump, it may be possible to implement the above recommendation in the short term.

Several other recommendations are made below regarding how to implement the findings of this report. The recommendations listed below are the opinions of the authors and not those of OSRIN or any other sponsoring/funding agencies.

1. Valuable data sets are scattered across many agencies. Gaining access and compiling the necessary data sets to parameterize $SWAT_{BF}$ is a time consuming and expensive task. The data sets are often in formats that are not supported by the GIS interfaces that can be used to set up $SWAT_{BF}$. Furthermore, all of the GIS data sets do not use the same projection. Processing the data sets so that they are in the same format and projection is a labour intensive task. It is recommended that the data sets required by $SWAT_{BF}$ be acquired from the various agencies and companies, processed to achieve consistency and then stored in a data repository that can be easily accessed via the Internet. It remains to be seen who would take responsibility for this initiative.

2. There is a considerable amount of literature held in the Alberta Government library that is related to the oil sands geographic area. The first author of this study spent several days searching this library. Scattered throughout this vast collection of literature are good quality data sets that could be used to support hydrologic modelling studies in the oil sands geographic area. It would be worthwhile to fund a project aimed at extracting useful data sets from the literature held in the Alberta

Government library and store them in a data repository that can be accessed by researchers. Such a project would likely require about 1 to 2 years to be completed successfully and would need the full support of the Alberta Government. Furthermore, a project of this type could only succeed if the individual (or even a small group) responsible for collecting and compiling the data sets is based in Edmonton.

3. One of the most valuable sources of data sets for the oil sands geographic area is the EIAs that have been submitted to the Alberta Government. Vast amounts of good quality data were collected by the consulting companies who produced these EIAs on behalf of the oil companies. Since the consulting companies own many of the data sets, they are virtually inaccessible to researchers at the present time. It is our recommendation that oil companies be encouraged to purchase the data sets from the consulting companies and then make them available to researchers.

4. Several parties have collected and compiled high quality data sets from reclaimed watersheds in the oil sands geographic area. All parties involved in monitoring reclaimed watersheds should be strongly encouraged to make their data sets available to other researchers working in the oil sands geographic area.

5. The oil companies should be encouraged to increase the level of monitoring for reclaimed watersheds. Furthermore, they should be encouraged to collaborate closely with scientists and engineers so that the critical data sets are collected. The potential benefits of implementing more comprehensive data collection programs to the science and engineering of restoring disturbed landscapes to a state similar to pre-disturbed conditions would be immense.

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11 GLOSSARY

11.1 Terms

The following terms have been sourced from Beven (2012), Lørup and Styczen (1996) and State of Nevada Division of Water Resources (n.d.).

A-Horizon

The uppermost zone in the soil profile.

Actual Evapotranspiration

The rate of evapotranspiration from a surface or vegetation canopy to the atmosphere under the prevailing meteorological conditions and water availability.

B-Horizon

A mineral horizon in the soil profile, below the A-horizon.

Bankfull Discharge

A flow condition where the stream flow completely fills the stream channel up to the top of the bank before overflowing onto the floodplain.

Baseflow

The fair-weather or sustained flow of streams; that part of stream discharge not attributable to direct runoff from precipitation, snowmelt, or a spring. Discharge entering streams channels as effluent from the groundwater reservoir.

Calibration

The process of adjusting parameter values of a model to obtain a better fit between observed and predicted variables.

Canopy

The overhanging cover formed by leaves, needles, and branches of vegetation.

Channel

A natural or artificial watercourse with definite bed and banks to confine and conduct flowing water. River, creek, branch, and tributary are some of the terms used to describe natural channels.

Datum

Any numerical or geometric quantity or set of such quantities that may serve as a reference or base for other, comparable quantities.

Discretization

The process of subdividing a watershed into smaller units such as subwatersheds or grid cells.

Flow Duration Curve

A cumulative frequency curve that shows the percentage of time that specified discharges are equalled or exceeded.

Hydraulic Conductivity

A coefficient of proportionality describing the rate at which water can move through an aquifer or other permeable medium.

Hydrograph

A graph showing stage, flow, velocity, or other hydraulic properties of water with respect to time for a particular point on a stream.

Hydrologic Cycle

The circuit of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes such as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transportation.

Hydrologic Model

Mathematical formulations that simulate hydrologic phenomenon considered as processes or as systems.

Hydrologic Response Unit (HRU)

A parcel of the land surface defined in terms of its soil, vegetation and topographic characteristics.

Infiltration

The rate of movement of water from the atmosphere into the soil. That portion of rainfall, irrigation or surface runoff that moves downward into the subsurface rock and soil profile.

Lateral Flow

Runoff due to that part of the precipitation which infiltrates the surface soil (but not to the water table) and moves laterally through the upper soil horizons toward the stream channels. Also referred to as interflow.

Litter

The vegetative material on the surface of the soil.

Objective Function

A measure of how well a simulation fits the available observations.

Parameterization

The process of defining structures of parameter variations.

Potential Evapotranspiration

The maximum quantity of water capable of being evaporated from the soil and transpired from the vegetation of a specified region in a given time interval under existing climatic conditions, expressed as depth of water.

Reach

Most generally, any specified length of a stream, channel, or conveyance.

Root Zone

The subsurface zone from the land surface to the depth interwoven by plant roots.

Routing

A technique used to compute the effect of channel storage and translation on the shape and movement of a flood wave through a river reach.

Runoff

That portion of precipitation that moves from the land to surface water bodies. Can also be defined as the depth to which a drainage area would be covered if all of the runoff for a given period of time were uniformly distributed over it.

Saturated Soils

Soils that have absorbed, to the maximum extent possible, water from rainfall or snowmelt. Any further precipitation on saturated soils will result in surface runoff.

Soil Profile

The arrangement of soil horizons or layers below the ground surface.

Stage

The height of a water surface above some established reference point or datum at a given location. Also referred to as gage height.

Streamflow

The discharge that occurs in a natural channel. Although the term "discharge" can be applied to the flow of a canal, the word streamflow uniquely describes the discharge in a surface stream course. Streamflow is a more general term than "runoff" as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

Subwatershed

A unit into which a watershed is subdivided for hydrologic study purposes.

Surface Runoff

That part of the runoff which travels over the soil surface to the nearest stream channel.

Temperature-Index Method (Degree-Day Method)

A method for predicting snowmelt as proportional to the difference between mean daily temperature and a threshold value.

Time of Concentration

The time required for water to flow from the farthest point on the watershed to the gauging station, culvert, or other point of interest.

Transpiration

The quantity of water absorbed, transpired, and used directly in the building of plant tissue during a specified time period. It does not include soil evaporation.

Validation

A process of evaluation of models to confirm that they are acceptable representations of a system.

Watershed

An area that, because of topographic slope, contributes water to a specified surface water drainage system, such as a stream or river. An area confined by topographic divides that drains a given stream or river.

11.2 Acronyms

3-PG	Physiological Principles in Predicting Growth
ALMANAC	Agricultural Land Management Alternatives with Numerical Assessment Criteria
AOSERP	Alberta Oil Sands Environmental Research Program
ASCII	American Standard Code for Information Interchange
BAW	Beach Above Water Tailings
BL	Bill’s Lake
CDED	Canadian Digital Elevation Data
CFS	Canadian Forest Service
CNRL	Canadian Natural Resources Limited
CP1	Calibration Period 1
CP2	Calibration Period 2
CP3	Calibration Period 3
CR	Confidence region
CRCCH	Cooperative Research Centre for Catchment Hydrology
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
DT	Densified Tailings Sand
EIA	Environmental Impact Assessment
EOSD	Earth Observation for Sustainable Development of Forests

EPIC	Erosion-Productivity Impact Calculator
FA	Flyash
FAO	Food and Agriculture Organization
FDR	Frequency Domain Reflectometry
FORWARD	Forest Watershed and Riparian Disturbance Project
GCL	Geosynthetic Clay Liner
GIS	Geographic Information System
GLCC	Global Cover Characterization
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems
HBV	Hydrologiska Byråns Vattenbalansavdelning
HPD	High Probability Density
HRU	Hydrologic Response Unit
INCA	Integrated Catchment Model
LAI	Leaf Area Index
LASCAM	Large Scale Catchment Model
LH-OAT	Latin-Hypercube One-factor-At-a-Time
LIDAR	Light Detection and Ranging
MFT	Mature Fine Tailings
MODIS	Moderate Resolution Imaging Spectroradiometer
MUSLE	Modified Universal Soil Loss Equation
NRCan	Natural Resources Canada
OSRIN	Oil Sands Research and Information Network
P4	Plant 4 Tailings
Parasol	Parameter Solutions
RAMP	Regional Aquatic Monitoring Program
ROTO	Routing Outputs to Outlet
SB	Sand Berm
SCE-UA	Shuffled Complex Evolution – University of Arizona
SCS	Soil Conservation Service
SEE	School of Energy and the Environment

SHE	Système Hydrologique Européen
SRTM	Shuttle Radar Topographic Mission
SSQ	Sum of the squares of the residuals
SSQR	Sum of the squares of the difference of the measured and simulated values after ranking
SW30	Southwest 30
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WBEA	Wood Buffalo Environmental Association
WSC	Water Survey of Canada

APPENDIX 1: Environmental Impact Assessments (EIAs)

A list of EIAs held in the Alberta Government Library (Great West Life Suite, Edmonton, Alberta) at the time of writing that potentially contain data sets for setting up and applying $SWAT_{BF}$ to watersheds in the oil sands geographic area is provided below.

Title:	Application for Approval of the BlackGold Expansion Project
Call number:	TD 195 O38 B628 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Environmental Impact Assessment ○ Section 7 – Hydrology ○ Section 8 – Surface Water Quality ○ Section 10 – Soils and Terrain ○ Section 11 – Vegetation ○ Section 14 – Land & Resource Use • Volume 3 – Environmental Impact Assessment Appendices ○ Appendix D – Surface Water Quality ○ Appendix E – Soils & Terrain ○ Appendix F – Vegetation • Volume 4 – EIA Addendum ○ Section 8 – Water Quality ○ Section 10 – Soils & Terrain • Volume 5 – EIA Addendum Appendices ○ Appendix D – Surface Water Quality

Title:	Application for Approval of the Black Pearl Resources Inc. Blackrod Commercial SAGD Project
Call number:	TD 195 O38 B631 EIA

Volumes with potential data sets for $SWAT_{BF}$:	• Volume 3
	  ○ Section 1 – Hydrology
	  ○ Section 3 – Surface Water Quality
	• Volume 4
	  ○ Section 1 – Vegetation
	  ○ Section 4 – Terrain & Soils
	• Volume 5
	  ○ Section 10 – Section 1 – Land Use & Management

Title:	CNRL Primrose and Wolf Lake Expansion 2000
Call number:	TD 195 O38 C212 EIA

Volumes with potential data sets for $SWAT_{BF}$:	• Volume V – Water
	  ○ Section 4 – Surface Water Hydrology
	  ○ Section 5 – Surface Water Quality
	• Volume V – Water (Appendices)
	  ○ Appendix D – Climate and Hydrology
	  ○ Appendix E – Surface Water Quality
	• Volume VI – Land
	  ○ Section 3 – Soil and Terrain
	  ○ Section 4 – Vegetation and Wildlife
	  ○ Appendix A – Soil and Terrain
	  ○ Appendix B – Vegetation and Wildlife
	  ○ Appendix C – Forestry
	• Volume 7 – Maps
	• Volume 8 – Additional Supplementary Information
	  ○ Appendix V – Water Quality Table Updates

Title:	Firebag In-Situ Oil Sands Project Application
Call number:	TD 195 O38 F523 EIA

Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2a – Introduction, Air, Aquatic Resources
	  ○ Section C3 – Hydrology
	  ○ Section C4 – Water Quality
	• Volume 2B – Terrestrial Resources
	  ○ Section D2 – Soil and Terrain
	  ○ Section D3 – Vegetation & Wetlands
	• Volume 4A – Appendices
	  ○ Appendix V – Hydrology
	  ○ Appendix VI – Water Quality
	  ○ Appendix VIII – Soil and Terrain
	  ○ Appendix IX – Vegetation and Wetlands
	  ○ Appendix X – Forestry and AVI
	• Volume 7 – Part I. Level 11 Soil Survey. Firebag Revised Local Study Area
	• Volume 8 – Part II. Impact Assessment Update of the Firebag Projects to Soil and Terrain

Title:	Fort Hills Oil Sands Project
Call number:	TD 195 O38 F736 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Environmental Baseline Study ○ Section 5 – Surface Water Hydrology ○ Section 6 – Water Quality ○ Section 8 – Soils and Terrain ○ Section 9 – Vegetation and Wetlands ○ Section 12 – Resource Use • Volume 3A – Environmental Impact Assessment ○ Section 5 – Surface Water Hydrology ○ Section 6 – Water Quality • Volume 3B – Environmental Impact Assessment ○ Section 8 – Soils and Terrain ○ Section 9 – Vegetation and Wetlands ○ Section 12 – Resource Use • Volume 5B – Supporting Technical Information ○ Section 5 – Surface Water and Hydrology ○ Section 6 – Water Quality ○ Section 8 – Soils and Terrain ○ Section 9 – Vegetation and Wetlands • Volume 6A – Supplemental Information Part 1 ○ Section 2 ○ Section 3 • Volume 7 – Supplemental Information Part 2 ○ Section 8 – Soils and Terrain ○ Section 9 – Vegetation and Wetlands

Title:	Frontier Oil Sands Mine Project
Call number:	TD 195 O38 F935 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Baseline ○ Section 2 – Climate ○ Section 4 – Hydrology ○ Section 5 – Surface Water Quality ○ Section 7 – Terrain and Soils ○ Section 8 – Vegetation ○ Section 12 – Resource Use • Volume 5 – Water ○ Section 3 – Hydrology ○ Section 4 – Surface Water Quality • Volume 6 – Terrestrial ○ Section 2 – Terrain and Soils ○ Section 3 – Vegetation • Volume 8 – People and Places ○ Section 4 – Resource Use

Title:	Application for Approval of the Germain Project Expansion
Call number:	TD 195 O38 G372 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 1 – Project Expansion ○ Part D.6 – Hydrology ○ Part D.9 – Soils Resources ○ Part D.10 – Vegetation ○ Part D.13 – Land Use and Management ○ Part E.3 – Initial Development, Soil Salvage and Storage Program ○ Part E.4 – Soil Conservation Operations ○ Part E.5 – Reclamation and Soil Replacement Program ○ Part E.6 – Revegetation ○ Part E.7 – Reclamation Monitoring Program

Title:	Horizon Oil Sands Project Application for Approval
Call number:	TD 195 O38 H80 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 3 – People o Section 4 – Resource Use o Appendix 3B – Resource Use Baseline • Volume 5a – Water o Section 3 – Hydrology o Section 5 – Water Quality • Volume 5b – Water Appendices o Appendix 5A – Hydrology Baseline o Appendix 5C – Water Quality Appendix • Volume 6a – Land o Section 3 – Soil and Terrain o Section 4 – Vegetation, Wetlands and Forest o Appendix 6A – Soil and Terrain Baseline • Volume 6b – Land Appendices o Appendix 6B – Vegetation, Wetlands and Forest Baseline o Appendix 6G – Forestry Baseline • Volume 7 – Environmental Health o Section 8 – Effects of Terrestrial Systems and Biota • Volume 10 – Supplemental Information. Volume 1b Appendices o Appendix A Section 10 – Closure and Reclamation o Appendix B Section 3.1 – Hydrology Section 3.3 – Water Quality Section 4 – Land

Title:	Application for Approval of the Jackpine Mine Phase 1
Call number:	TD 195 O38 J12 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 3 – Introduction and Aquatic Resources, Part 1 ○ Section 5 – Surface Water Hydrology Assessment ○ Section 6 – Surface Water Quality Assessment • Volume 3 – Introduction and Aquatic Resources, Part 2 ○ Appendix VIII – Surface Water Hydrology Changes for the Planned Development (CEA) Case • Volume 4 – Terrestrial Resources and Wetlands ○ Section 4 – Soil and Terrain Assessment ○ Section 5 – Terrestrial Vegetation, Wetlands and Forest Resources Assessment • Volume 6 – Cultural Evaluation ○ Section 3 – Resource Use Assessment • Volume 8 – Aquatic Resources Environmental Setting for Jackpine Mine – Phase 1 • Volume 11 – Closure Drainage Plan for Jackpine Mine – Phase 1 • Volume 13 – Forestry Environmental Setting for Jackpine – Phase 1 • Volume 17 – Soil and Terrain Environmental Setting Report for Jackpine Mine – Phase 1 • Volume 18 – Surface Water Hydrology Environmental Setting for Jackpine – Phase 1 • Volume 19 – Terrestrial Vegetation and Wetlands Environmental Setting Report for Jackpine – Phase 1 • Volume 21 – Water Quality Environmental Setting Report for Jackpine Mine – Phase 1 • Volume 24 – Surface Water Quality and Human /aquatic Biota and Wildlife Health ○ Section 2 – Surface Water Quality • Volume 26 – Supplemental Information ○ Section 10 – Aquatic Resources • Volume 27 – Supplemental Information and Consultation Update

Title:	Jackpine Mine Expansion Project & Pierre River Mine Project
Call number:	TD 195 O38 J122 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 4A – Aquatic Resources ○ Section 6.4 – Hydrology ○ Section 6.5 Water Quality • Volume 4B – Aquatic Resources Appendices ○ Appendix 4-3 – JEMA Closure Drainage Plan ○ Appendix 4-4 – PRMA Closure Drainage Plan ○ Appendix 4-6 – Conceptual Compensation Plan ○ Appendix 4-9 – Aquatics Monitoring Program • Volume 5 – Terrestrial Resources and Human Environment ○ Section 8.4 – Resource Use ○ Appendix 5-1 – JEMA Closure, Conservation and Reclamation Plan ○ Appendix 5-2 – PRMA Closure, Conservation and Reclamation Plan • Volume 6 – Aquatics ○ Section 2 – Hydrology ○ Section 3 – Water Quality • Volume 9 – Terrestrial ○ Section 2 – Soils and Terrain ○ Section 3 – Terrestrial Vegetation, Wetlands and Forest Resources ○ Section 4 – Forestry • Volume 10 ○ Appendix I – Closure Drainage Plan for JME ○ Appendix II – Closure, Conservation and Reclamation Plan ○ for JME • Volume 17 – Fort MacKay Specific Assessment ○ Section 4 – Surface Water Hydrology ○ Section 5 – Water Quality and Fisheries Resources ○ Section 7 – Vegetation

Title:	Application for Approval to the Energy Resources Conservation Board and Alberta Environment. Japan Canada Oil Sands Limited. JACOS Hangingstone Expansion Project.
Call number:	TD 195 O38 J21 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – EIA Part A ○ Section 8 – Hydrology • Volume 2 – EIA Part B ○ Section 9 – Surface Water Quality ○ Section 11 – Terrain and Soils ○ Section 12 – Vegetation and Wetlands • Volume 2 – EIA Part C ○ Section 15 – Land and Resource Use

Title:	Joslyn North Mine Project. Alberta Energy and Utilities Board. Alberta Environment Integrated Application.
Call number:	TD 195 O38 J81 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 4 – Consultants Reports o CR#7 – Hydrology o CR#10 – Soils and Terrain • Volume 5 – Consultant Reports o CR#11 – Surface Water Quality o CR#13 – Vegetation and Wetlands

Title:	Joslyn SAGD Project. Phase IIIA AEUB. Alberta Environment Integrated Application.
Call number:	TD 195 O38 J83 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Phase IIIA ○ CR#7 – Hydrology ○ CR#10 – Soils ○ CR#11 – Surface Water ○ CR#13 – Vegetation

Title:	Kearl Oil Sands Project – Mine Development
Call number:	TD 195 O38 K24 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 3 – Baseline Reports ○ Section 2 – Climate ○ Section 4 – Surface Water Quantity ○ Section 5 – Surface Water Quality ○ Section 7 – Soils and Terrain ○ Section 8 – Vegetation ○ Section 11 – Resource Use • Volume 6 – Water ○ Section 4 – Surface Water Quantity ○ Section 5 – Surface Water Quality • Volume 7 – Land ○ Section 3 – Soils and Terrain ○ Section 4 – Vegetation • Volume 9 – People ○ Section 3 – Resource Use

<table>
<tr><td>Title:</td><td>Long Lake Project. Application for Approval to Alberta Energy and Utilities Board and to Alberta Environment.</td></tr>
<tr><td>Call number:</td><td>TD 195 O38 L848 EIA</td></tr>
<tr><td>Volumes with potential data sets for SWAT$_{BF}$:</td><td>

Volume 2 – EIA Introduction, Air Quality, Aquatic Resources
Section F3 – Hydrology
Section F4 – Water Quality
Volume 3 – Terrestrial Resource, Traditional Land Use, Resource Use, Human Health, Historical Resources, Socio-economics, EIA Summary
Section G2 – Soil and Terrain
Section G3 – Terrestrial Vegetation and Wetlands
Volume 4 – Appendices I to VII
Appendix VII – Hydrology
Volume 5 – Appendices VIII to XI
Appendix VIII – Water Quality
Appendix X – Soil and Terrain
Appendix XI – Terrestrial Vegetation and Wetlands
Volume 6 – Appendices XII to XV
Appendix XII Forestry
Volume 7 – Appendices XVI to XXIII
Appendix XVII – Resource Use
Volume 9 – Supplemental Information
Hydrology
Soil and Terrain
Terrestrial Vegetation and Wetlands
Volume 10 – Supplemental Information
Aquatic Resources
Terrestrial Resources
</td></tr>
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Title:	MacKay River Expansion
Call number:	TD 195 O38 M152 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2B – Water and Aquatic Resources ○ Section 3 – Surface Water Quantity ○ Section 4 – Surface Water Quality ○ Section 5 – Aquatic Resources • Volume 2C – Terrestrial ○ Section 2 – Soils and Terrain ○ Section 3 – Vegetation

<table>
<tr><td>Title:</td><td>Muskeg River Mine Project</td></tr>
<tr><td>Call number:</td><td>TD 195 O38 M987 EIA 1997</td></tr>
<tr><td>Volumes with potential data sets for SWAT$_{BF}$:</td><td>

Volume 2 – Biophysical and Historical Resources – Baseline Conditions

Section D4 – Surface Water Hydrology
Section D5 – Surface Water Quality
Section D8 – Terrain and Soils
Section D9 – Terrestrial Vegetation
Section D10 – Wetlands

Volume 3 – Biophysical and Historical Resources – Part 1. Impact Assessment

Section E4 – Surface Water Hydrology
Section E5 – Surface Water Quality
Section E8 – Terrain and Soils
Section E9 – Terrestrial Vegetation
Section E10 – Wetlands

Volume 3 – Part 2. Supplements

Appendix V – Surface Water Quality

Volume 7 – Aquatic Resources Baseline Study for the Muskeg River Mine Project
Volume 10 – Forestry Baseline Report for the Muskeg River Mine Project
Volume 13 – Lease 13 Surface Hydrology 1997 Winter Data Collection Program
Volume 16 – Terrain and Soil Baseline for the Muskeg River Mine Project
Volume 17 – Terrestrial Vegetation Baseline for the Muskeg Mine Project
Volume 19 – Wetlands Baseline for the Muskeg River Mine Project
Volume 22 – 1997 Summer Data Collection Program and Baseline Hydrologic and Hydraulic Studies for the Muskeg River Mine Project
Volume 26 – Oil Sands Regional Aquatics Monitoring Program (RAMP) 1997

</td></tr>
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Title:	Application for Approval of the Muskeg River Mine Expansion Project
Call number:	TD 195 O38 M988 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 3 – Aquatic Resources ○ Section 5.4 – Hydrology ○ Section 5.5 – Water Quality ○ Appendix 3.2 – Closure Drainage Plan • Volume 4 – Terrestrial Resources and Human Environment ○ Section 7.4 – Resource Use Assessment ○ Section 7.6 – Historical Resources ○ Appendix 4-4 – Closure, Conservation and Reclamation Plan • Volume 5 – Aquatics ○ Appendix A – Muskeg River RAMP Hydrology Stations S1 and S13 ○ Appendix G – Water Quality and Toxicity Summary Tables ○ Appendix H – Sediment Quality and Toxicity Summary Tables ○ Appendix I – Water Quality Profile Data • Volume 9 – Terrestrial ○ Section 2 – Methods – Soils ○ Section 3 – Methods – Vegetation ○ Section 5 – Results – Soils ○ Section 6 – Results – Vegetation • Volume 9a – Terrestrial Appendices ○ Appendix A – Key to Abbreviations Used in Soil Mapping Units and Inspection List ○ Appendix B – Inspection Site List ○ Appendix C – Chemistry of Soil Map Units in the Local Study Area

	○ Appendix E – Upland Ecosite Phase Descriptions ○ Appendix F – Wetland Class Descriptions ○ Appendix I – Cover Classes in the Regional Study Area ○ Appendix J – Vegetation Local Study Area 2004 Baseline Data ○ Appendix K – Vegetation Local Study Area Historical Data ○ Appendix V – Surface Water Quality

Title:	Cenovus FCCL Ltd. Narrows Lake Project
Call number:	TD 195 O38 N234 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 4 – Aquatic Resources ○ Section 4.2 Hydrology ○ Section 4.3 Water Quality • Volume 5 – Terrestrial Resources ○ Section 4.1 – Terrain and Soils ○ Section 4.2 – Terrestrial Vegetation, Wetlands and Forest Resources • Volume 7 – Supplemental Requests (I) ○ Water ○ Terrestrial • Volume 8 – Supplemental Information Requests (II) ○ Terrestrial

Title:	Cenovus Energy Inc. Pelican Lake Grand Rapids Project
Call number:	TD 195 O38 P364 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 4 – Aquatic Resources o Section 4.2 – Hydrology o Section 4.3 – Water Quality o Section 5.2 – Hydrology • Volume 5 – Terrestrial Resources o Section 4.1 – Terrain and Soils o Section 4.2 – Terrestrial Vegetation, Wetlands and Forest Resources

Title:	Project Millennium Application
Call number:	TD 195 O38 P964 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2A – Introduction, Air Quality, Aquatics o C2 – Surface Hydrology and Hydrogeology o C3 – Water Quality • Volume 2B – Terrestrial Resources, Closure Assessment o D2 – Soils and Terrain o D3 – Vegetation and Wetlands • Volume 2D – Appendices o Appendix V – Water Quality Modelling Results and Model Assumptions • Volume 5 – Hydrology Baseline for Project Millennium Report • Volume 7 – Report on Forestry Baseline for Project Millennium • Volume 10 – Report on Oil Sands Regional Aquatics Monitoring Program (RAMP) 1997 • Volume 12 – Report on Soil and Terrain Baseline for Project Millennium • Volume 14 – Report on Terrestrial Vegetation Baseline for Project Millennium • Volume 16 – Report on Wetlands Baseline for Project Millennium • Volume 18 – Report on Winter Aquatics Survey – Steepbank River, Shipyard Lake, and Leases 19, 25 and 29

Title:	STP MacKay Thermal Project – Phase 2. Application for Approval
Call number:	TD 195 O38 S727 Ph. 2 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 1 ○ Part D.2 – Aquatic Resources ○ Part D.6 – Hydrology ○ Part D.9 – Soil Resources ○ Part D.10 – Vegetation, Wetlands and Rare Plants ○ Part D.13 – Land and Resource Use • Volume 2 ○ Consultant Report #2 Aquatic Resources • Volume 3 ○ Consultant Report #6 Hydrology ○ Consultant Report #9 Soil and Terrain ○ Consultant Report #10 Vegetation and Wildlife • Volume 4 ○ EPEA and Water Act Application Section 9.2 – Aquatic Resources Section 9.5 – Hydrology Section 9.6 – Soils Section 9.7 – Vegetation Appendix E – Conceptual Conservation and Reclamation Plan • Volume 5 ○ Section 10.2 – Aquatic Resources Assessment ○ Section 10.9 – Soil Resources ○ Section 10.10 – Vegetation Assessment ○ Section 10.13 – Land and Resources Use Assessment

Title:	Steepbank Mine Project Application
Call number:	TD 195 O38 S814 EIA 1996 → TD 195 O38 S814 EIA W32 1996
Volumes with potential data sets for $SWAT_{BF}$:	• Aquatic Baseline Report for the Athabasca, Steepbank and Muskeg Rivers in the Vicinity of the Steepbank and Aurora Mines • Aquatic Baseline Report for the Athabasca, Steepbank and Muskeg Rivers in the Vicinity of the Steepbank and Aurora Mines Appendices • Baseline Soil Survey for the Proposed Suncor Steepbank Mine • Hydrology Baseline Steepbank Oil Sands Mine • Impact Analysis of Aquatic Issues Associated With the Steepbank Mine • Impact Analysis of Terrestrial Resources Associated with the Steepbank Mine • Meteorology Observations in the Athabasca Oil Sands Region • Detailed Conservation and Reclamation Plan for Suncor’s Integrated Mine Plan • Suncor Mine Advance Plan (D&R) and Cumulative Effects Assessment • Suncor Reclamation Landscape Performance Assessment • Terrestrial Baseline Report for the Steepbank Mine

Title:	Suncor South Tailings Pond Project
Call number:	TD 195 O38 S957 EIA

Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Environmental Impact Assessment
	  ○ Section 3 – Aquatic Resources
	  ○ Section 4 – Terrestrial Resources, Wetlands and Biodiversity
	• Volume 5 – Forestry Baseline Report for the South Tailings Pond Project
	• Volume 8 – Hydrology Baseline for the Suncor South Tailings Pond Project
	• Volume 9 – Soil and Terrain Baseline Report for the Suncor South Tailings Pond Project
	• Volume 10 – Terrestrial Vegetation, Wetlands and Forest Resources Baseline Report for the Suncor South Tailings Project

Title:	Sunrise Thermal Project
Call number:	TD 195 O38 S958 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2B – Aquatic Resources ○ Section 7.0 – Surface Water Quantity ○ Section 8.0 – Surface Water Quality • Volume 2C – Terrestrial Resources ○ Section 10.0 – Soil and Terrain ○ Section 11.0 – Vegetation • Volume 3 – Land & Resource Use ○ Section 14.0 – Land and Resource Use • Volume 4 – Supplemental Information ○ Appendix C – Soil SIL1 Survey • Volume 5 – Clarification to Supplemental Information Response ○ Section 2.0 – Water ○ Section 3.0 – Terrestrial

Title:	Application for the Approval of the Surmont In-Situ Oil Sands Project
Call number:	TD 195 O38 S961 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Biophysical and Resource Use Assessment Part 1 ○ Section 4 – Surface Water ○ Section 6 – Soils • Volume 2 – Biophysical and Resource Use Assessment Part 2 ○ Section 7 – Vegetation ○ Section 10 – Resource Use • Technical Appendix 1 – Environmental Baseline Study Part 1 ○ Section 4 – Surface Water • Technical Appendix 1 – Environmental Baseline Study Part 2 ○ Section 6 –Soils ○ Section 7 – Vegetation ○ Section 9 – Resource Use

Title:	Surmont Project
Call number:	TD 195 O38 S963 EIA

Volumes with potential data sets for $\mathrm{SWAT}_{\mathrm{BF}}$:	• Volume 2 – Application to ESRO
	  ○ Section 4.3 – Baseline Soil and Vegetation
	  ○ Section 4.6 – Baseline Watercourses
	• Volume 4 – Aquatic Resources
	  ○ Section 6 – Hydrology
	  ○ Section 7 – Surface Water Quality
	• Volume 5 – Terrestrial Resources
	  ○ Section 9 – Terrain and Soils
	  ○ Section 10 – Vegetation
	• Volume 6 – Human Environment
	  ○ Section 13 – Land Use and Management

Title:	Application for Approval of the Taiga Project
Call number:	TD 195 O38 T129 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 3 – Aquatic Resources ○ Section 6 – Hydrology ○ Section 7 – Surface Water Quality • Volume 4 – Terrestrial Resources ○ Section 9 – Terrain and Soils ○ Section 10 – Vegetation • Volume 5 – Social Aspects ○ Section 13 – Land Use

Title:	Application for Approval of the Tamarack Integrated Oil Sands Project
Call number:	TD 195 O38 T153 EIA

Volumes with potential data sets for $SWAT_{BF}$:	• Volume 1 – Project Description
	  ○ Section 3.2.2 – Soils and Terrain
	• Volume 2 – Environmental Impact Assessment
	  ○ Section 7 – Hydrology
	  ○ Section 8 – Surface Water Quality
	  ○ Section 10 – Soils
	  ○ Section 11 – Vegetation
	  ○ Section 14 – Land/Resource Use
	• Volume 3 – EIA Appendices
	  ○ Appendix D – Surface Water Quality
	  ○ Appendix F – Soils
	  ○ Appendix G – Vegetation

Title:	Telephone Lake Project. Application for Approval
Call number:	TD 195 O38 T268 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Environmental Impact Assessment Sections 1.0 to 9.0 ○ Section 7.0 – Surface Water Quantity ○ Section 8.0 – Surface Water Quality • Volume 2 – Environmental Impact Assessment Sections 10.0 to 17.0 ○ Section 10.0 – Soils ○ Section 11.0 – Vegetation ○ Section 13.0 – Land and Resource Use • Volume 3 – EIA Appendices ○ Appendix E – Surface Water Quality ○ Appendix F – Surface Water Quality ○ Appendix H – Soils ○ Appendix I – Vegetation/Biodiversity

Title:	North Steepbank Extension Project Application
Call number:	TD 195 O38 V975 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – EIA Introduction/EIA Summary ○ Appendix IV – Climate Change in the Oil Sands Region • Volume 4 – Aquatic Resources ○ Section 4.2 – Environmental Setting Summaries ○ Section 4.5 – Evaluation of Effects Pathways (North Steepbank Extension) ○ Section 4.7 – Evaluation of Effects Pathways (Voyageur Upgrader) ○ Appendix I – Operational and Closure Drainage Plans ○ Appendix II – Hydrologic Considerations for the Voyageur Project • Volume 5 – Terrestrial Resources ○ Section 5.2 – Soil and Terrain Assessment ○ Section 5.3 – Terrestrial Vegetation, Wetlands and Forest Resources Assessment • Volume 6 – Human Environment Resources • Volume 9 – Forestry Environmental Setting Report for the Suncor Voyageur Project • Volume 11 – Resource Use Environmental Settings Report for the Suncor Voyageur Project • Volume 12 – Soil and Terrain Environmental Setting Report for the Suncor Voyageur Project • Volume 13 – Surface Water Hydrology Environmental Setting Report for the Suncor Voyageur Project • Volume 14 – Terrestrial Vegetation, Wetlands and Forest Resources Environmental Setting Report for the Suncor Voyageur Project • Volume 16 – Water Quality Environmental Setting Report for the Suncor Voyageur Project

Title:	Voyageur South Project. Project Application
Call number:	TD 195 O38 V977 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 4 – Environmental Impact Assessment ○ Section 7.1 – Terrestrial Resources Scope of Assessment ○ Section 7.2 – Soil and Terrain Assessment ○ Section 7.3 – Terrestrial Vegetation, Wetlands and Forest Resources Assessment ○ Section 8.3 – Resource Use Assessment • Volume 7 – Terrestrial Vegetation and Wetlands Resources Environmental Setting Report for the Suncor Voyageur South Project • Volume 12 – Forestry Environmental Setting Report for the Suncor Voyageur South Project • Volume 13 – Surface Water Hydrology Environmental Setting Report for the Suncor Voyageur South Project • Volume 14 – Soil and Terrain Environmental Setting Report for the Suncor Voyageur South Project • Volume 15 – History of Reclamation and Reclamation Research for the Suncor Oil Sands Projects • Volume 17 – Resource Use Environmental Setting Report for the Suncor Voyageur South Project • Volume 19 – Water Quality and Aquatic Health Environmental Setting Report for the Suncor Voyageur South Project

Title:	MacKay River Project
Call number:	TD 195 P4 M153 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Baseline Environmental Studies ○ Section 4.0 – Surface Water Resources ○ Section 5.0 – Aquatic Resources ○ Section 6.0 – Physiograph, Surficial Geology and Soil ○ Section 7.0 – Vegetation Resources ○ Section 9.0 – Resource Use • Volume 11 – MacKay River Supplemental Baseline Study • Volume 12 – Soil Survey, Reclamation Suitability Evaluation and Soil Handling Recommendations for the MacKay River Project

Title:	Environmental Impact Assessment for the Syncrude Aurora Mine
Call number:	TN 858 S3 E62 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 1 – Environmental Impact Assessment ○ Section 4.2 – Terrain and Geology ○ Section 4.3 – Soils ○ Section 4.4 – Surface Water ○ Section 4.6 – Vegetation ○ Section 4.9 – Resource Land Use ○ Section 5.3 – Surface Water ○ Section 5.5 – Terrain, Geology, Soils and Overburden ○ Section 5.6 – Vegetation ○ Section 5.9 – Resource Use • Volume 6 – Aquatic Baseline Report for the Athabasca, Steepbank and Muskeg Rivers in the Vicinity of the Steepbank and Aurora Mine • Volume 7 – Aurora Mine Project Historical Resources Baseline Study • Volume 9 – Baseline Resource Use in the Aurora Mine Environmental Impact Assessment Regional Study Area • Volume 10 – Baseline Soil Survey, Soil Interpretation and Terrain Analysis of the Aurora Mine Local Study Area • Volume 11 – Baseline Vegetation Inventory and Productivity Assessment for the Syncrude Aurora Mine EIA Local Study Area • Volume 12 – Climate and Surface Water Hydrology Baseline Data for Aurora Mine EIA • Volume 16 – Meteorology Observations in the Athabasca Oil Sands Region • Volume 22 – Vegetation Types and Productivity for the Aurora Mine

Title:	Mildred Lake Upgrader Expansion Environmental Impact Assessment
Call number:	TN 858 S3 M641 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume IIa – Environmental Impact Assessment o Section 4.0 – Surface Water o Section 5.0 – Aquatic Resources o Section 6.0 – Soils • Volume IIb – Environmental Impact Assessment o Section 7.0 – Vegetation o Section 9.0 – Resource Use • Volume III – Appendices o A6 – Soils o A7 – Vegetation

Title:	Application for Approval of the Southwest Sand Storage Conversion Project
Call number:	TN 858 S3 S728 EIA
Volumes with potential data sets for $SWAT_{BF}$:	• Volume 2 – Environmental Impact Assessment o Section 7.0 – Hydrology o Section 8.0 – Surface Water Quality o Section 10.0 – Soils o Section 11.0 – Vegetation o Section 15.0 – LRU (Land and Resource Use) • Volume 3 – EIA Appendices o Appendix D – Hydrology o Appendix E – Surface Water o Appendix G – Soils o Appendix H – Vegetation o Appendix K – Historical Resources

APPENDIX 2: Selected Publications with Relevant Information and Potential Data Sets

A list of publications that contain relevant information to the modelling work undertaken in this study and potentially useful data sets is provided below. The sources for the publications are as follows:

- Cumulative Environmental Management Association (CEMA)
- Alberta Oil Sands Environmental Research Program (AOSERP)
- Oil Sands Research and Information Network (OSRIN)
- Regional Aquatic Monitoring Program (RAMP)
- Miscellaneous

CEMA Reports

Abboud, S.A., L.W. Turchenek and L.A. Halsey, 2004. Critical loads of acid deposition on soils in the Athabasca Oil Sands Region, Alberta. Cumulative Environmental Management Association, Fort McMurray, Alberta. CEMA Contract No. RWG 2000-0002.

Alberta Research Council, 2006. Tailings sand and natural soil quality at the Syncrude Aurora, Albian Sands, CNRL and Suncor mines. Cumulative Environmental Management Association, Fort McMurray, Alberta.

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