

Using SWAT to simulate the effects of forest fires on water yield in forested watershed: A Case Study of Bonaparte Watershed, Central Interior of British Columbia, Canada

Submitted by

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Abstract

Climate change has impacted the forested watersheds of British Columbia by bringing extremely high temperatures and beetle infestations, thus coinciding with increasing amounts of forest fires. On average, it is estimated that about 10,000 fires occur every year in Canada, burning about 2 Million ha of the 400 million ha forested landscape. One of the areas that was most affected by the forest fires in 2017 was the Cariboo Regional District in the central interior of British Columbia. Wildfire burns away the ground cover of the landscape, exposing soils to erosion under heavy storms. The major objective of this study was to simulate the changes in water yield in the forested watershed during pre- and post-wildfire periods, using Bonaparte watershed as the study area. The SWAT model was used for water yield simulations, in order to evaluate the hydrological response of the watersheds to forest fires. ArcMap was used as the visual interface of the SWAT model for simulation and SWAT-CUP was used for parameter sensitivity, model calibration and validation. The model was calibrated between 1999-2004 and validation 2005-2017 using naturalised streamflow. The most sensitive parameters during model calibration with 95% significance were 6 parameters: Soil Evaporation Compensation Factor (ESCO), Ground water delay (GW_DELAY), Baseflow alpha factor (ALPHA_BF), Maximum canopy storage (CANMX), Surface runoff lag time (SURLAG) and SCS runoff curve number (CN2) respectively. The model was considered satisfactory with statistical criteria since $NSE > 0.5$ and $R^2 > 0.5$ and $PBIAS \pm 25\%$. The highest water yield from heavily burned sub-basins varied from 30 to 58%. This is an indicator of an increase in stream discharge and sediment transport from high erosion, causing a deterioration of water quality and an increased stream discharge in the forested watershed. Sub-basins with high burn had more total runoff volumes generated than sub-basins with medium or low burns. Large sub-basins had high runoff increase despite the fact of having smaller total burn areas. It is important to note out that there are some challenges in using SWAT, such as accessibility of the required data as well as data preparation, which is time consuming. The SWAT model can sometimes also over-predict or under-predict the naturalised stream discharge, which might cause uncertainties in most sensitive parameters selection and in calibration and validation of the model. The obtained results while using the model might contain some inaccuracy, because certain physical processes, such as snow melt in the watershed, cannot be simulated in SWAT. There is also uncertainty in the simulation because of the assumption that the land use/land cover has been the same since 2010, before the occurrence of the forest fires. This is not the case, since there is rapid land use change dynamics due to logging and pine beetle infestation, before the onset of fires. Land use/land cover changes (logging and pine beetle infestation) within the actual landscape also contribute to uncertainty in the results.

Key words: Climate Change, forested watershed, forest fires, water yield, SWAT

List of Abbreviations

- SWAT - Soil and Water Assessment Tool
- LULC - Land Use and Land Cover
- HRUs - Hydrological Response Units
- CN - Curve Number

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CHAPTER ONE: INTRODUCTION

1.1 Background

A healthy watershed provides ecosystem services by ensuring clean water supply, maintaining stream health and protecting aquatic life. However, this may be hampered due to damages done to the landscape from both natural and human-induced activities. Seasonal variation in the climate has impacted the mountainous and forested watersheds of British Columbia with beetle infestations and more frequent forest fires (Funk et al., 2014 & Safranyik et al., 2001). Extremely high temperatures and dry conditions have led to the expansion of wildfires, one of the worst consequences of climate change in this part of the world (Schipani, 2017). It is presumed by experts that severe forest fires will continue to manifest, if the increasing outbreaks of bark pine beetle incidences are not controlled (News Scientist, 2017), but there is no conclusive evidence for this claim. Generally, the beetles kill a large amount of trees, which later fall and act as fuel for a burning fire, increasing the spread and intensity of subsequent fires over a larger area (Schoennagel et al., 2012). For example, more fires have happened in forests with lodgepole pine trees than other forest types such as Ponderosa spruce, Boreal forest and Douglas fir, due to high infestations with mountain pine beetles (Jenkins et al., 2013). This has created a considerable amount of dead wood lying on the ground. Additionally, coniferous trees, such as pine, have sap which burn quickly and also tend to grow closer to each other (Alberta Government, 2012). They also create duff layers from decomposition of pine needles, twigs and other organic debris especially with ponderosa pine (Colorado State Forest Fire Service, 2012). Most forests in central British Columbia are known to be dominated by lodgepole pine trees (Natural Resources Canada, 2018). Pine beetles continue to spread during warm winter conditions, which is likely one of the reasons that it might be influencing the rampant and frequent forest fires seen lately (Schoennagel et al., 2012). With less annual dying rates and greater breeding rates, the beetle population has been able to increase rapidly to the extent that the BC foresters cannot cope well with the infestation. The largest areas which initially had long tree standings have now been left with patches as most trees are being killed and falling off, which has greatly increased a high wildfire threat to communities.

On average, it is estimated that about 10,000 fires occur every year in Canada, burning about 2 Million ha of the 400 million ha forested landscape (BC Ministry of Forests and Range Wildlife Management Branch, 2009). In British Columbia, the worst recorded fire incidence on basis of fire history was in 2017, which left over 1.2 Million hectares without forest cover and 65,000 people evacuated to be protected from the fires (Donnelly, 2017). One of the areas that were hit most by the forest fires in 2017 was the central interior BC, in the Cariboo regional district (Environment and Climate Change Canada, 2017). The general population was mainly worried about deterioration in air quality from smoke and ash, but little did they know that the water being consumed at their homes was also affected, and might later influence flooding downstream during heavy storms. The volume, timing and quality of water depends on the state of the landscape. Landscape that is severely affected by wildfires has a low ability to capture, filter and regulate rainfall to the stream (Bryant & Saksa, 2017). The existence of wildfires has a serious impact on the water flow and quality downstream in a forested watershed. Sediment and ash transport, along with other pollutants into streams during active burning for months and years after fire, cause decline in water quality. Ash produced from active burning settles on lakes and reservoirs used for drinking water supply. The fire retardant chemicals used in wildfire fighting also eventually end in water reservoirs, as they are transported by runoff and sediments. Additionally, sediments cause siltation reducing the storage capacity of reservoir thus attracting more investment in reservoir maintenance, increased costs in treatment and water supply. Potential impacts of wildfires depend on so many factors such as extent and intensity of the wildfire, post-wildfire precipitation, watershed topography and local ecology (USGS, 2018).

Wildfire seriously destructs the natural forest ecosystem, since the land is left bare with no vegetation, which increases the risk of soil erosion, causing water pollution in streams and other alterations in hydrologic characteristics. Wildfire burns away the ground cover of the landscape, exposing soils to erosion under heavy storms. Fires can also create hydrophobicity (water repellence) in forest soils, due to vaporization and condensation of aliphatic hydrocarbons from litter and humus. This forms a coating on soil particles, hindering infiltration and after causing excessive overland runoff flow (Huffman et al., 2001). Riparian buffers are destroyed, exposing the stream to contamination from affected landscape. There are different pathways by which nutrients end up in streams, either by adsorbing on the sediments or produced by ash that is wind-blown or transported by runoff. High nutrient concentration therefore contributes to reduced water quality, which affects the aquatic ecosystem (USGS, 2013; Hou et al., 2013). Nutrient levels during the post-fire period depend on several factors such as intensive soil burning, topography and weather variables (wind and precipitation). The first flush rains from the burnt landscape carry a lot of debris that accumulates in streams, impacting aquatic species and also creating challenges for hydropower and water utilities. The most endangered aquatic species includes fish, which utilize streams to lay their eggs in the streambeds every winter. The debris transported into creeks occupy spawning grounds of salmon fish species such as Steel-head trout, Coho and Chinook salmon (Bland, 2017).

The major difficulty with wildfire is that it destroys the forest ecosystem to the extent of not being able to function normally or offer benefits to human and aquatic life. However, there is limited information in BC concerning forest fire impacts on hydrology and long-term effects to human and aquatic life. Different models have been used to predict the influence of forest fire severity on streamflow regimes and sediment generation patterns driven by post-fire soil erosion such as SWAT and WEPP (Putz et al., 2003). SWAT has been widely used in different mountainous regions worldwide to evaluate watershed hydrology, which increases its credibility as useful model. Regions that have used SWAT include Little River Watershed, Tennessee (Zhu and Li, 2011), Himalayan drainages of Nepal (Neupane et al., 2015) and Upper Cache La Poudre Watershed, Colorado (Havel et al., 2018). The SWAT model is designed to simulate the effects of changes in the watershed management practices on surface water and groundwater hydrology, diffuse pollution and sediment erosion (Welde & Gebremariam, 2017). Predicting soil erosion is very important to manage available reservoirs and ensuring proper environmental management (Gould et al., 2016). Vulnerability of water sources to water quality deterioration is determined by spatial and temporal analysis of fire disturbances, rainfall events and exposure of hill slopes to erosion (Langhans et al., 2015). Hence, the purpose of this project is to understand fluctuations in water yield of the watershed and its impact on stream discharge and water quality. Understanding the effects of forest fires on runoff and erosion is very essential to proper management practices of the watershed.

1.2 Project Objectives

1.2.1 Major Objective

- To simulate changes in water yield in the forested watershed due to wildfires using SWAT Hydrological modelling

1.2.2 Specific objectives

- To quantify changes in runoff volumes during before and after wildfire to explain the effects of forest fires on water yield
- To understand how runoff generation varies under different burn severity ranges in a forested watershed

1.3 Description of study area

The considered study area was Bonaparte watershed, which starts from the Silwhoiakun Plateau. Many creeks discharge water into Bonaparte Lake. The Bonaparte River travels from the Bonaparte Lake to Thompson River for approximately 140 km. The watershed has a number of creeks, including Machete creek drained by Machete Lake, Hat creek, Clinton creek, Loon creek and Cache creek. Rayfield River joins the Bonaparte River while originating from Bridge Lake area. The river winds around the Elephant hill with its outlet at the point it connects with Thompson River about 2.3km northeast of Ashcroft. Bonaparte watershed is part of the sub-watersheds that forms Thompson watershed as shown in figure 1.1 A and B (https://www.fraserbasin.bc.ca/Thompson_Watershed_Risk_Assessment.html).

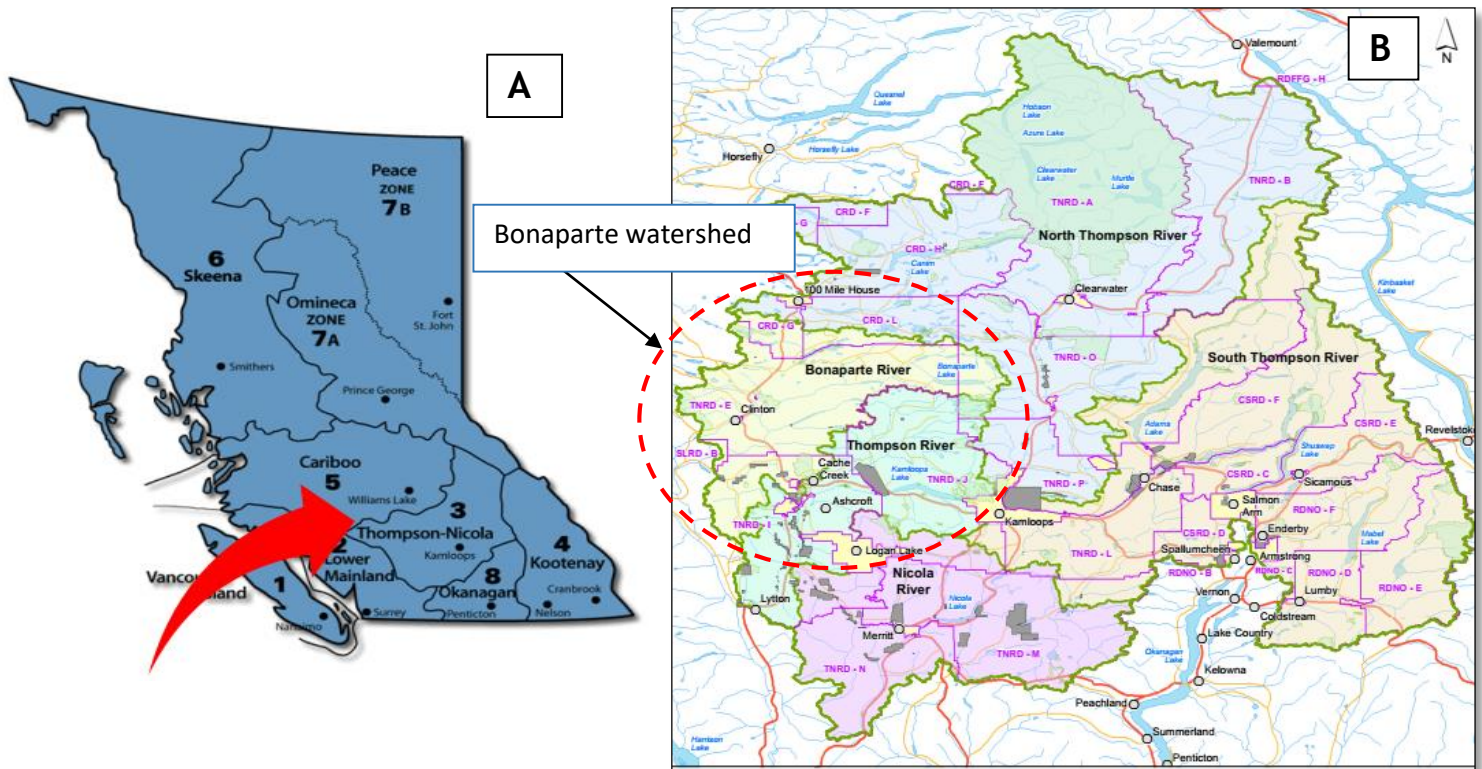


Figure 1.1: Bonaparte watershed; A) Watershed located at Cariboo Region in Central Interior, BC and B) Thompson watershed and its sub-watersheds

1.4 Model Concept

This study considered the effects of the catastrophic wildfires that occurred in the summer of 2017 in the Cariboo region. One of the most affected areas was Bonaparte River basin. The hydrologic response of the watershed to the wildfires was evaluated by considering potential of runoff generation from the landscape into the stream (Bonaparte River) which drains to the Thompson River, and finally to Fraser River. The Soil and Water Assessment Tool (SWAT) was used to determine variability of water yield with changes in land cover/land use before forest fires. Theoretical information about SWAT can be found in **Appendix B** in the Literature Review Section. The model is capable of representing the effect of watershed characteristics, climate and Land Use Land Cover (LULC) changes in water fluxes and water balances. The wildfire effects were accounted for in the model by modifying the land use/land cover inputs and corresponding parameters during simulations.

The paired watershed approach was implemented, which assumes that two compared watersheds were similar before burning and this helps in making general comparisons (Ryan et al., 2011). Two models were developed; Scenario 1 being land cover without fires, and Scenario 2 being land cover with forest fires. Both scenarios helped in determining the hydrological changes of the watershed during pre- and post-forest fires periods respectively. Scenario 1 was used for model calibration and validation, using observed stream data measured before the fires happened. Afterwards, the calibrated SWAT model was used to estimate runoff volumes during post-wildfire period using land use map with burned areas. A testing framework in accordance to Batelis & Nalbantis (2014) was followed with steps;

1. SWAT model calibrated and validated using collected hydrological data,
2. Forest fires were formulated based on what could be the fire characteristics in the study watershed,
3. SWAT model application to simulate runoff in post-fire hydrological conditions by changing the key model parameters: Curve Numbers (CNs) and
4. Comparison between pre- and post-fires of runoff generated volumes.

1.5 Model Setup

Different modelling interfaces were used in the execution of the simulation of forest fires impacts as summarized in **Table 1.1** and the steps followed are shown in **Figure 1.2**. ArcSWAT version 2012 was used, which is an extension to ArcGIS and displayed within the ArcGIS interface as a toolbar. This tool helps with modeling processes such as SWAT project setup, Watershed delineator, HRU Analysis, Write Input table, Edit SWAT Input and also SWAT Simulation procedures. The SWAT Input files were generated using the same interface to be able to run the model. Map layers for both scenarios were used during simulation by overlaying different maps for key factors such as soils, topography/slope, land use and land cover (LULC) and burn severity.

The digital land use/land cover data was obtained having different classes representing the dominant land uses/cover in study area. Land cover for scenario 2 was developed from the original land use/land cover map for scenario 1 by combining it with the burn thematic map for year 2017. The Land Cover map created for scenario 2 had burned areas categorised as low, medium and high burn severity. For example, if “Evergreen forest” land cover class had a low burn area, it was reclassified into new created class as “Evergreen Forest Low Burn” classification. SWAT Model database and SWAT LULC lookup table were edited to represent independently pre- and post-wildfires conditions (**See Table 2 and 3, Appendix B**). To simulate the post-wildfire conditions for the increase in runoff generation, the Curve Numbers (CNs) were adjusted accordance to Havel et al. (2018), by adding 5, 10 and 15 to pre-wildfire CNs for low, moderate and high burn severity areas respectively.

A digitized soil map was used to provide physical and chemical characteristics of the soils bounded by the watershed, and this helped to understand the movement of water within each HRUs (Welde & Gebremariam, 2017). Hydrologic Soil Group A has small runoff potential compared to D with highest potential. The properties derived by SWAT for each soil type include the depth of the soil layer, soil texture, hydraulic conductivity, bulk density, and organic carbon content.

The slope or topography of the area was determined by using the Digital Elevation Model (30m DEM). The same DEM was used to locate the main stream of the watershed and spatial analyst functions helped further to establish flow direction and accumulation of the drainage patterns of the watershed. The first key step is to define the watershed boundaries and its drainage patterns a process called watershed delineation.

Table 1.1: Model interfaces used in SWAT modelling

Interface type	Purpose	Source
ArcMap	<ul style="list-style-type: none"> GIS map processing and SWAT simulation interface 	ESRI
ArcSWAT	<ul style="list-style-type: none"> Finding land use/land cover/soil and slope combination to produce HRUs and Sub-basins of the watershed Model Simulation using the 2 scenarios 	Texas A&M University (https://swat.tamu.edu)
SWAT-CUP	<ul style="list-style-type: none"> Parameter Sensitivity Analysis, Simulated discharge output, Model Calibration and Validation 	https://swat.tamu.edu/software/

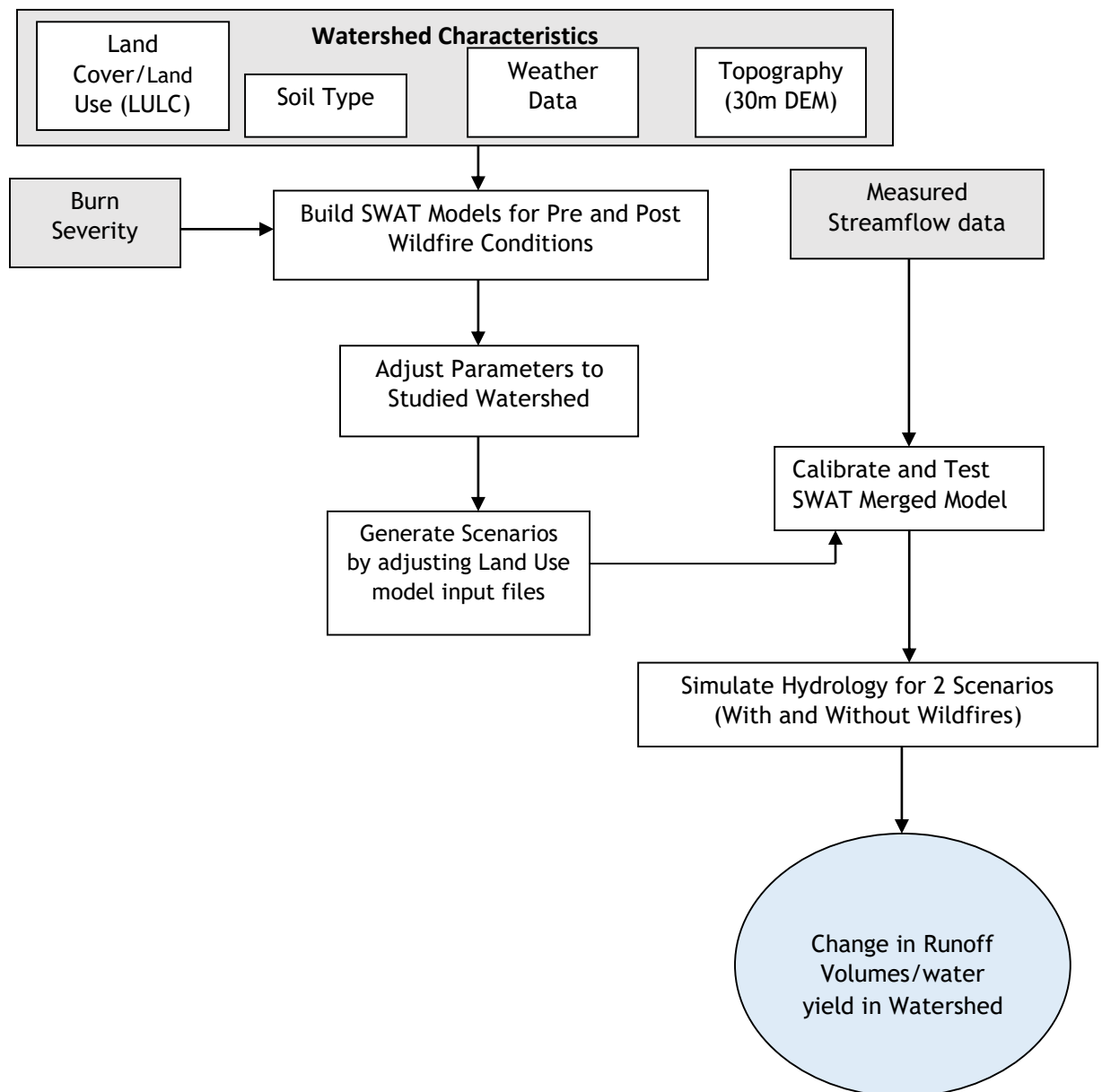


Figure 1.2: SWAT model concept used for SWAT simulation of forest fires impact on water yield

CHAPTER TWO: SWAT METHODOLOGY

This section explains the input datasets which were used to run the model. Data preparation as SWAT input data followed by simulation steps and lastly analysis of obtained simulated data with SWAT.

2.1 Required Data for hydrological modelling in SWAT

Two types of data were used for modeling, spatial and temporal data, as summarised in Table 2.1. Spatial data included Digital Elevation Model (DEM), land-use map and soil map (Welde & Gebremariam, 2017). The land use map contained different land use and land cover classifications, whereas the soil map showed the different soil types found in the watershed. Conversely, the temporal data considered were climate data (precipitation and temperature, solar radiation, relative humidity and wind speed) and hydrological data (stream discharge). Daily naturalised streamflow was obtained from the nearby hydrometric station known as “Bonaparte River below Cache Creek”, station number 08LF002. Weather data for 21 years (1997 - 2017) with only daily precipitation and minimum and maximum temperature was obtained using nearby Climate Station data in Kamloops Pratt Road, BC with climate ID 116C8P0 at latitude 50.38°, longitude 120.1° and elevation of 729m.

2.2 Preparing SWAT input data to run the model

The spatial datasets were converted into Universal Transverse Mercator (UTM) Zone projection (WGS198_UTM_Zone10) using ESRI’s Geographical Information System mapping software, ArcMap. The obtained maps were processed in ArcMap using spatial analyst tools, and or other ArcTool Box tools to organise them into meaningful spatial datasets in a format readable by ArcSWAT. Precipitation and temperature were also modified into the “WGEN user” readable in SWAT by using the “WGEN editor” downloaded from the SWAT model website. SWAT in-built modified WGEN weather generator model was used to also simulate variables that are not measured in chosen meteorological station such as wind speed, relative humidity and solar radiation. Both weather and stream flow data of the past 21 years (1997-2017) were arranged in text file and imported in SWAT database.

Table 2.1: SWAT Model Input Data

Parameters	Source	Reference
Digital Elevation Model (DEM)	<ul style="list-style-type: none"> Geogratis, Natural Resource Canada 	<ul style="list-style-type: none"> http://www.nrcan.gc.ca/earth-sciences/geography/topographic-information/free-data-geogratis/11042
Soil map	<ul style="list-style-type: none"> BC Data Catalogue (Soil Survey)(BC-Soils) 	<ul style="list-style-type: none"> https://catalogue.data.gov.bc.ca/dataset/soil-survey-spatial-view
Land Use Map	<ul style="list-style-type: none"> Commission for Environmental Cooperation - land cover 2010, North America 	<ul style="list-style-type: none"> http://www.cec.org/tools-and-resources/north-american-environmental-atlas/map-files
Burn Thematic Map for 2017	<ul style="list-style-type: none"> Forest Analysis and Inventory, Province of British Columbia 	<ul style="list-style-type: none"> ftp://ftp.geobc.gov.bc.ca/publish/Regional/WilliamsLake/forest/burn_severity_2017

Stream discharge data (daily)	<ul style="list-style-type: none"> Historical Hydrometric Data at Environmental and Natural Resources, Canada https://wateroffice.ec.gc.ca
Weather data (daily)	<ul style="list-style-type: none"> Historical Weather Data at Environmental and Natural Resources, Canada http://climate.weather.gc.ca

2.3 Steps to conduct hydrological modelling with ArcSWAT

2.3.1 Watershed Delineation

The ArcSWAT automatic watershed delineator tool was used to create a stream network, define sub-basin outlet locations, delineate the watershed and calculate the sub-basins using the DEM as illustrated in **Figure 2.1**. The flow direction and accumulation of the watershed were used to create a stream network, after setting a threshold for stream initiation at 1,000 hectares. The selected threshold value provided a more detailed stream network and also avoided oversimplification of the stream network (Havel et al., 2018). The tool automatically identifies the outlets of each creeks of the main stream at every point where the tributaries joins the stream. The outlet of the main stream was indicated manually at its mouth where it drains into the water reservoir known as Thompson River.

2.3.2 Hydrologic Response Units (HRUs) definition

Hydrological Response Units (HRUs) were created from sub-basins with land use/soil/slope combinations after overlaying map layers of land use and land cover (LULC), soil and slope as illustrated in **Figure 2.1**. A single slope class was used in the slope map layer in order to have a small number of HRUs to ease model computation. The “Multiple HRUs” option was selected to generate multiple HRUs over each sub-basin of the watershed. Threshold levels for each of the factors were applied to get rid of small HRUs which have no or little influence on the model results. For example, applying a threshold of 20% to the LULCs to each sub-basin means that all land uses covering less than 20% of a sub-basin can’t be considered, and this area is reallocated to the rest of the remaining land uses. Hence, the selected thresholds were 10% for land use, 5% for soils and slope with 5% in order to have adequate information about HRUs (Havel et al., 2018).

2.3.3 Defining Model Options in SWAT

Most studies have adapted the United States Soil Conservation Service Curve Number procedure to simulate the effects of land use/land cover changes on surface runoff in the watershed due to forest fires (Havel et al., 2018; Batelis & Nalbantis, 2014). In addition, the used scenarios in this study are quite similar to those reported in past SWAT modelling studies that used Curve Number procedure. SWAT simulated runoff for both pre- and post-hydrological conditions by changing the estimated values of Curve Numbers (see **Table 2 and 3 APPENDIX B**) similar to what was done by Batelis & Nalbantis (2014) and Havel et al. (2018). This study implemented a concept of paired watershed to compare changes in hydrological response in two watershed land use/land cover conditions. Penman-Monteith method option was selected to estimate potential evapotranspiration based on energy balance components, whereas, channel routing was determined by Muskingum River Routing method similarly used by Havel et al. (2018). More information about model options are found in the SWAT Theoretical Documentation, Version 2009 (Neitsch et al., 2011).

2.3.4 Model Sensitivity Analysis, Calibration and Validation

Parameter sensitivity analysis indicates the most likely parameters to affect the variation on the output (Welde & Gebremariam, 2017). First, sensitivity analysis was performed, followed by model calibration and lastly validation. The model was run considering daily-time step of naturalised stream discharge for 21 years (1997-2017) as shown in **Table 2.2**. The selection of the period for the data to

be used was based upon the data availability and less change in land use/land covers (Betrie et al., 2011). Sensitivity analysis identifies sensitive parameters for model calibration using Global sensitivity, an automatic tool which is common in SWAT-CUP (Betrie et al., 2011). Only streamflow sensitivity was conducted for only land uses/covers before forest fires. Sensitivity analysis facilitated model calibration by identifying and ranking parameters that are most influential to model outputs (Quintanilla, 2016). Therefore, parameters with 95% probability significance in influencing the variation within the model output were retained for calibration. Calibration and validation were performed automatically with runs shown in **Table 2.2** using SWAT-CUP by comparing model outputs and inputs of stream discharge. The initial parameters that were found sensitive were then modified in the calibration step (Das and Perera, 2013), using the Sequential Uncertainty Fitting (SUFI-2) algorithm in the SWAT-CUP (Betrie et al., 2011).

Table 2.2: Summary of model runs for 21 years (1997-2014)

Activities	Stream flow periods
Spin-Up/Model warm-up	1997 - 1998 (2 years)
Calibration	1999 - 2004 (5 years)
Validation	2005 - 2014 (9 years)

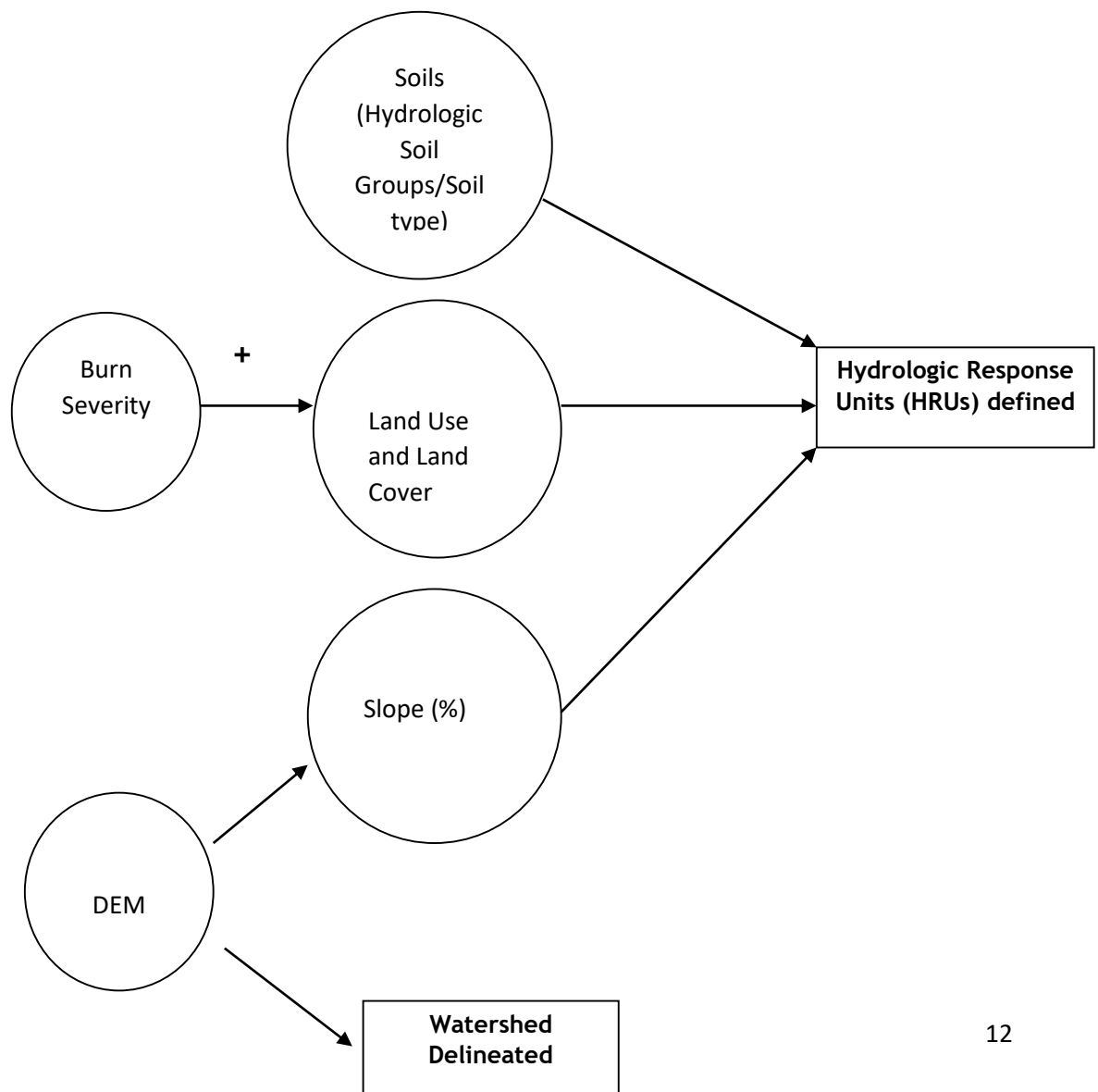


Figure 2.1: Summary of watershed delineation and Hydrologic Response Units (HRUs) definition

2.3.5 Model performance evaluation

The model performance was evaluated at watershed scale for streamflow using statistics described in **Equations 2.1, 2.2 and 2.3**. These are three quantitative criteria; coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) (Moriassi et al., 2007). The error statistics are used to determine how well the model simulations match the observations at the mouth of the considered stream. NSE is the ratio of residual variance to measured data variances (Gebremicael et al., 2013). It is a normalised statistic that describes the relative magnitude of the residual variance as compared to the observed and demonstrates how well the plot of observed versus simulated value fits the 1:1 line (Welde & Gebremariam, 2017; Moriassi et al 2007). PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Betrie et al., 2011). R^2 explains the proportion of the total variance in the observed data that can be explained by the model (Gebremicael et al., 2013), with higher value indicating less error variance. Generally, model simulation can be taken as satisfactory when $NSE > 0.4$, $R^2 > 0.5$ and $PBIAS \pm 25\%$ for streamflow (Welde & Gebremariam, 2017). However, according to Moriassi et al., (2007), model performance is accepted as satisfactory if $NSE > 0.5$ and $R^2 > 0.5$ for streamflow.

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2} \quad (2.1)$$

$$PBIAS = \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})}{\sum_{i=1}^n Y_i^{obs}} \right] \times 100 \quad (2.2)$$

$$R^2 = \frac{\sum_{i=1}^n (Y_{obs} - \overline{Y_{obs}})(Y_{sim} - \overline{Y_{sim}})}{\sqrt{\sum_{i=1}^n (Y_{obs} - \overline{Y_{obs}})^2} \sqrt{\sum_{i=1}^n (Y_{sim} - \overline{Y_{sim}})^2}} \quad (2.3)$$

Where; Y_i^{obs} is observed streamflow, Y_i^{sim} is the simulated streamflow, and Y_i^{mean} is the mean of observed streamflow (Moriassi et al., 2007).

2.3.6 Evaluating changes in water yield for pre and post-forest fires periods

The new land classes and modified curve number to depict forest fires are summarized in **Table 3 Appendix B**. The obtained runoff depths for two scenarios were analysed and graphs were plotted. A relationship between both observed and simulated discharge was determined using the linear regression, same to the runoff depths for the two scenarios. The change in the total runoff volumes for

each of the sub-basins regardless of the fire occurrence was also visualised by developing a graph between the sub-basin areas and the increase in the total runoff generation. To estimate the change in the runoff increase from the burned sub-basins under different fires severity, a plot of fire severity presented as burned area for each of the fire ranges (high/medium/low) and the runoff increase was produced.

CHAPTER THREE: RESULTS AND DISCUSSION

3.1 Land use/Land cover and Soils in Bonaparte watershed

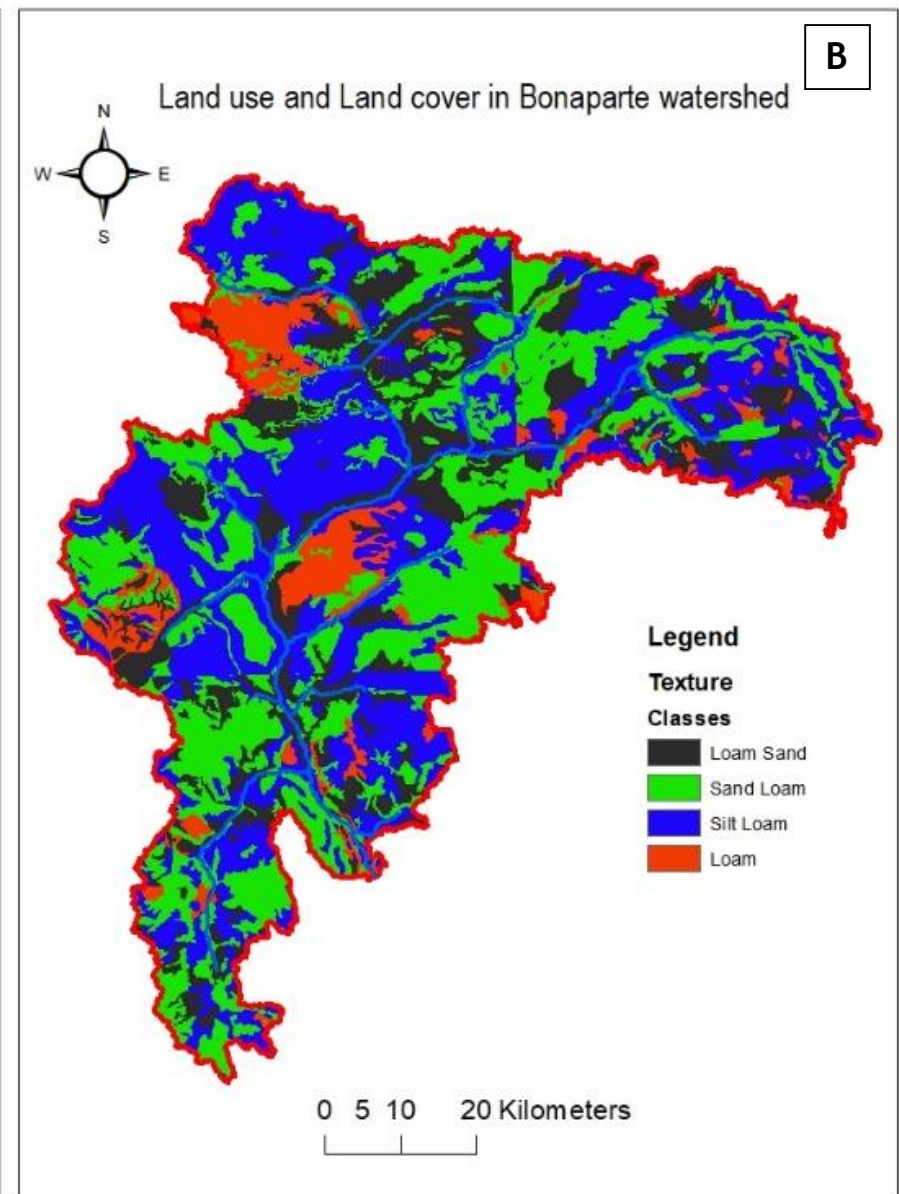
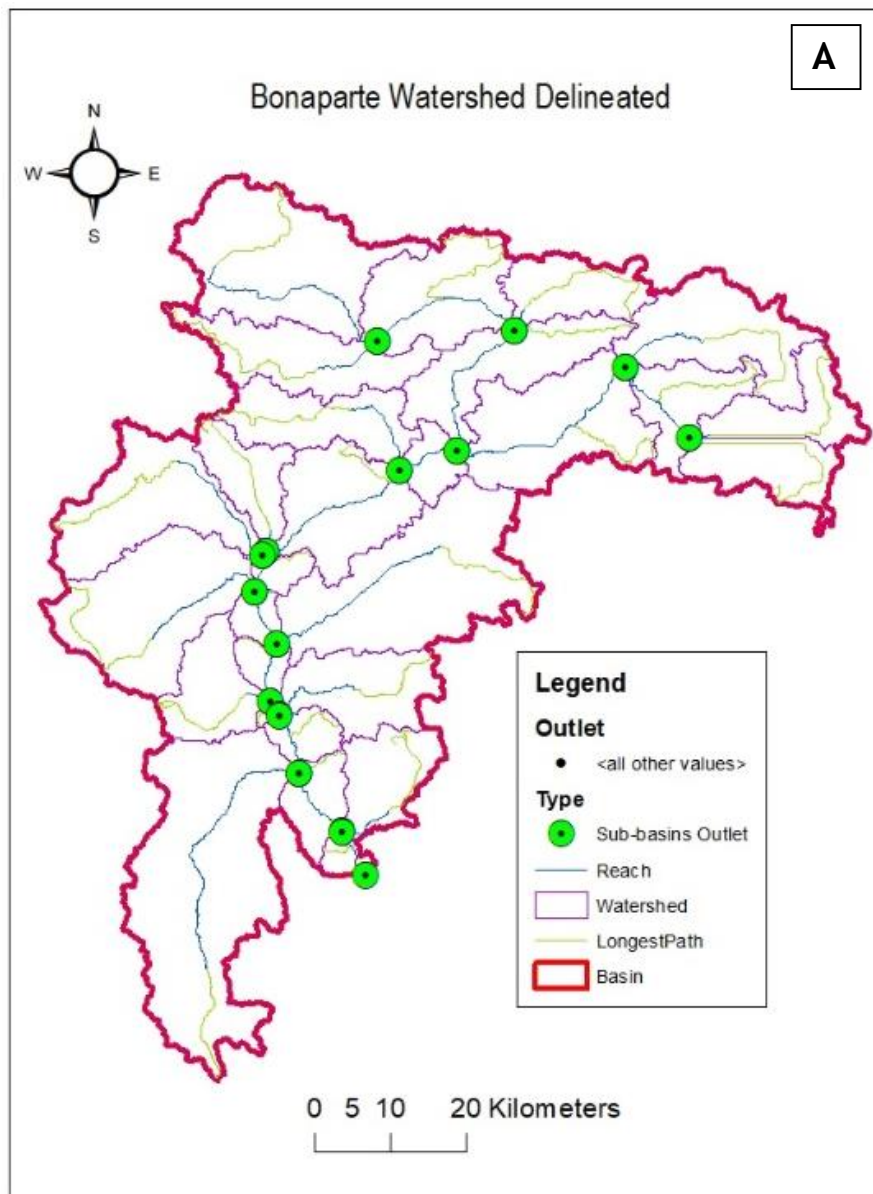
The areal extent of the Bonaparte watershed was automatically delineated using ArcSWAT from the DEM with raster size of 30x30 m (see **Figure 3.1A**). The approximated area of the watershed after delineating was 5285 km². From **Figure 3.1C**, the dominant land use/land cover included deciduous forest (FRSD), which covers 0.05% of the total area of the watershed, Evergreen forest (FRSE) covering the largest area standing at 87.54%, 0.82% mixed forest (FRST), Shrub land (RNGB), Grassland (RNGE), Agriculture (AGRL), Open water (WATR), all covering 4.46-, 2.88-, 0.07-, and 4.23% of the total area respectively. Loam sand, silt loam and loam are the dominant soil types in the Bonaparte watershed as shown in **Figure 3.1B**. The soils helped in estimating the runoff of each of the sub-basins by modifying the soils to the soil types within the “user soil” database with similar hydrological soil groups (A-D) and soil texture. Hydrological soil group A has the lowest runoff potential followed by B with moderate runoff potential. Soils in these categories have high infiltration capacities with texture like sand, loam sand or sand loam. Soil Group D has the highest runoff potential but with very low infiltration capacities and such soils have a clay texture. However, in this study area, all the soils belonged to soil group A and B, that were used in runoff estimations before and after forest fires happened.

3.2 Developing Burn Severity Map

Modified land use depicting the occurrence of forest fires in 2017 Summer in the Bonaparte watershed was developed by combining the original land use/land cover map and the burn severity thematic map (see **Figure 3.1D**). The map shows that almost all of the area around the main channel and its creeks were burnt under different burn severity ranges; high, medium and finally low burn. However, the larger area was burnt under high and medium burn severity ranges and smaller areas burnt with less severe fires.

3.3 Defining the Hydrological Response Units for each scenario

HRUs were determined after combining the soil, land use and slope maps, whereby the slope of the area was assumed to have one range (0-99%) in order to reduce the number of HRUs with land/soils/slope combinations for easy simulation. The maps had to have same projection (WGS_UTM 1989_Zone 10) and same areal extent as the DEM used for watershed delineation. The watershed had a total of twenty-nine (29) sub-basins and one hundred and forty (140) Hydrological Response Units (HRUs). Each sub-basin has unique land use/soils/slope combinations that are homogeneous or similar within each of the entire HRUs.



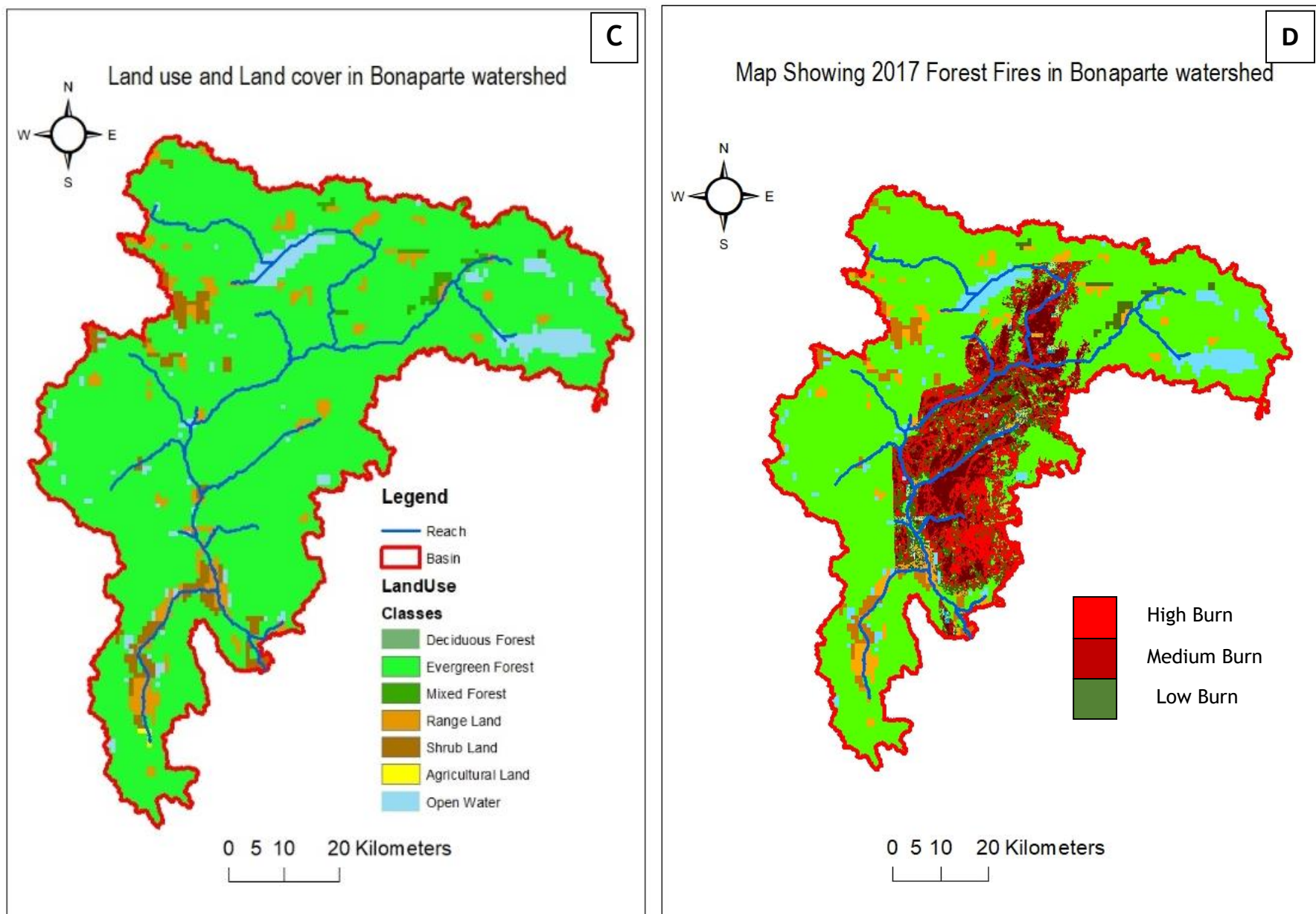


Figure 3.1: Developed maps in ArcSWAT; A) delineated watershed, B) land use/land cover map, C) soil map and D) 2017 forest fires in Bonaparte basin

3.4 Sensitivity Analysis, Model Calibration and Validation

3.4.1 Parameters Sensitivity

Sensitivity analysis was conducted, to get sensitive parameters to the model calibration using global sensitivity in SWAT-CUP with 500 number of simulations. Parameters used for sensitivity analysis and later used for calibration included those related to the hydrological processes in regards to soil, groundwater, overland flow and routing in the stream. The parameters used are summarized in **Table 3, Appendix B**. According to Abbaspour et al. (2017), not all SWAT parameters are relevant to all sub-basins and most parameters cannot be used together to calibrate the model. Because rainfall is a driving variable to the stream flow, it was not used to fit other parameters during calibration of the SWAT model. Canopy storage and snowmelt parameters as well may contribute to errors because both help in producing the water that later ends in the stream that contributes to the stream discharge (Abbaspour et al. 2017). There were 28 parameters selected for sensitivity analysis at both HRU and the sub-basin scale, including factors from land use, slope, and soil characteristics of the watershed. The most sensitive parameters for predicting the stream flow using Global sensitivity after iteration with $p > 0.8$ were: Soil Evaporation Compensation Factor (ESCO), Threshold depth of water in the shallow aquifer for “revap” to occur (REVAPMN), Ground water delay (GW_DELAY), Effective hydraulic conductivity in tributary channel alluvium (CH_K1), Baseflow alpha factor (ALPHA_BF), Average slope of the main channel (CH_S2), Snow water equivalent that corresponds to 50% snow cover (SNOCOV MX), Groundwater “revap” coefficient (GW_REVAP), Maximum canopy storage (CANMX), Surface runoff lag time (SURLAG), SCS runoff curve number (CN2), Mannings “n” value for overland flow (OV_N), Manning’s “n” value for the main channel (CH_N2), Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) and Plant uptake compensation factor (EPCO) (see **Table 4 Appendix B**). The most sensitive parameters during model calibration with $p > 0.95$ significance were; Soil Evaporation Compensation Factor (ESCO), Ground water delay (GW_DELAY), Baseflow alpha factor (ALPHA_BF), Maximum canopy storage (CANMX), Surface runoff lag time (SURLAG) and SCS runoff curve number (CN2) respectively. Only these parameters were used to calibrate the model by using the observed discharge compared to the simulated discharge by the model. The selected sensitive parameters to the model output all ranged between $0.2 < RS < 1$ ($RS = 0.7$), implying that they have high sensitivity to the model output. Normally, sensitivity parameters are categorized into classes; small ($0 < RS < 0.05$), medium ($0.05 < RS < 0.2$), high ($0.2 < RS < 1$) and very high ($RS > 0.1$) (Welde & Gebremariam, 2017).

3.4.2 Model Calibration and Performance

Auto-calibration with SWAT-CUP was performed using Sequential Uncertainty Fitting (SUFI-2) algorithm or estimation (Rusli et al., 2016; Betrie et al., 2011). Model performance was evaluated, using monthly time-step discharge data analysed with statistical equations and visual inspection using scatter plot. The model performance was examined with use of observed and simulated streamflow for the period starting 1999 to 2014. The stream discharge for 2015 to 2017 was lacking at the chosen hydrometric station and therefore not considered for the model simulation. Three statistical criteria were used, including coefficient of determination (R^2), the Nash-Sutcliffe model efficiency (NSE) and the percent bias (PBIAS) using equations 3.3, 3.1 and 3.2 respectively. These criteria were used to find out whether the SWAT model were able to replicate the temporal trends in the observed natural hydrological processes in the watershed (Ahn & Kim, 2017). NSE is the ratio of residual variance to measured data variance (Gebremicael et al., 2013). It is a normalised statistic that describes the relative magnitude of the residual variance as compared to the observed, and demonstrates how well the plot of observed versus simulated value fits the 1:1 line (Welde & Gebremariam, 2017; Moriasi et al 2007). PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. R^2 explains the proportion of the total variance in the observed data that can be

explained by the model and with higher value indicating less error variance (Gebremicael et al., 2013). The statistical results for calibration were $R^2=0.82$, $NSE=0.75$ and $PBIAS \pm 25\%$ and validation were $R^2=0.78$, $NSE=0.65$ and $PBIAS \pm 23\%$ and this confirms that the model simulation is regarded satisfactory since $NSE>0.5$ and $R^2>0.5$ and $PBIAS \pm 25\%$ for the naturalised streamflow (Moriasi et al. 2007). The obtained higher R^2 shows that there is less variance between the two stream discharges (Welde & Gebremariam, 2017). The visual inspection using the scatter plot shown in Figure 4.2 show that the simulated and observed discharge for monthly time-steps almost follow similar trends, however, there are discrepancies in a few months for the years 1999, 2002 and 2014 where the model underestimates the stream discharge. This is probably because of the high peak of precipitation received in the watershed, and also because the model doesn't consider the influence of the snow melt to the stream discharge (Havel et al., 2018).

This analysis explains that SWAT model is able to represent the hydrological processes of the watershed and it can be used to show the effects of forest fires on the water yield into the main stream. However, there is some uncertainty in the simulation, because of the assumption that the land use/land cover has been the same since 2010 before the occurrence of the forest fires. This is not the case, since there are rapid land use change dynamics due to logging and pine beetle infestation before the onset of fires.

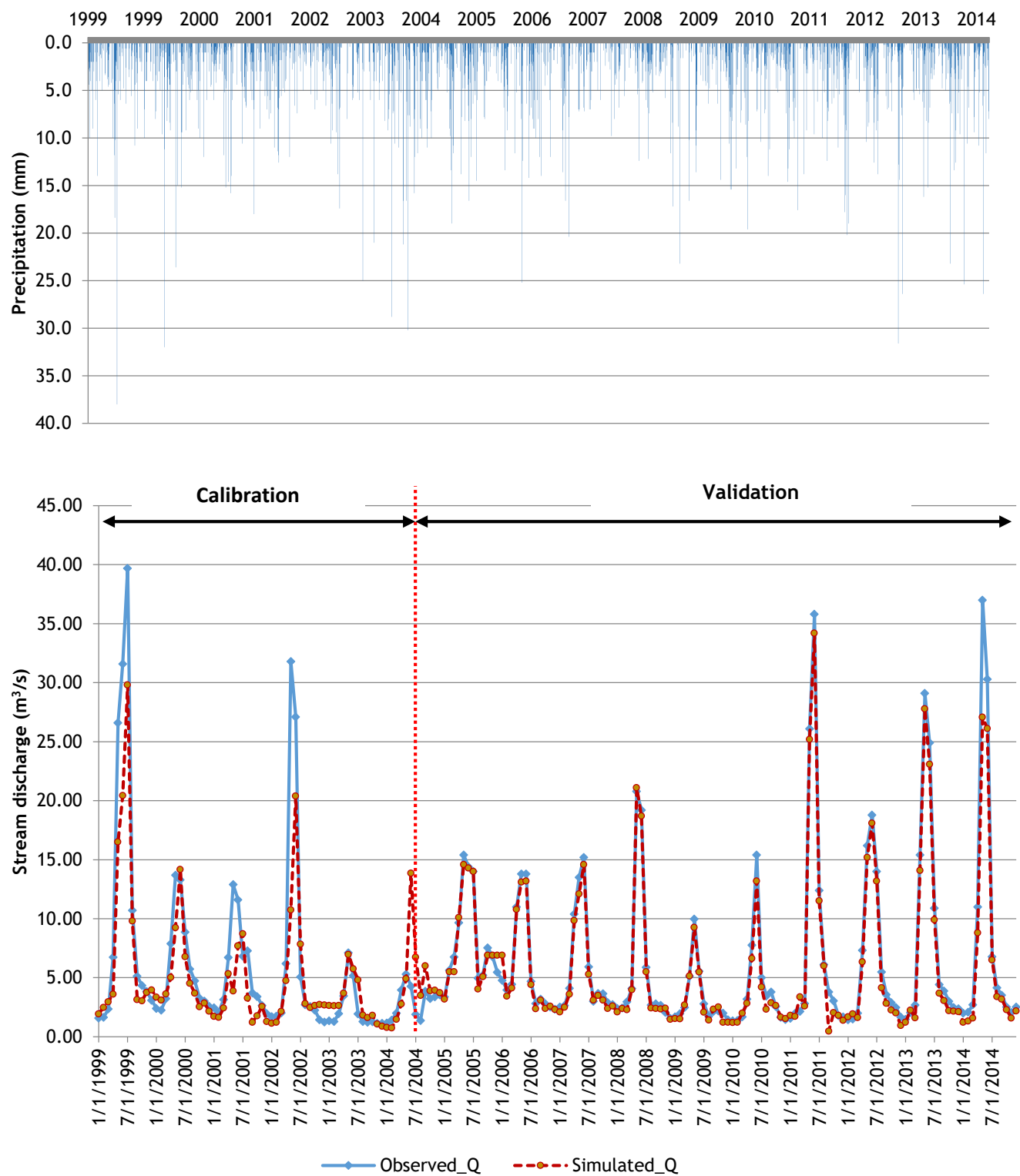


Figure 3.2: Graphical representation between Observed and Simulated discharge of Bonaparte River

3.4.3 Model Performance using observed and simulated discharge of Bonaparte River

The measured monthly discharge of the stream was used in model calibration and validation, and one of the outputs in the SWATCUP was the simulated monthly discharge as shown in **Figure 3.2**. The use of the linear regression in **Figure 3.3** shows that the model represents the natural hydrological processes of the forested watershed reasonably well. This is because the observed discharge correlates positively well with the simulated discharge with the high coefficient, ($R^2 > 0.5$) implying a strong correlation between the assumed and observed discharge. Therefore, the SWAT model could be a good estimating tool that is useful in representing the hydrological responses to the land use change in forested watershed (Batelis & Nalbantis, 2014).

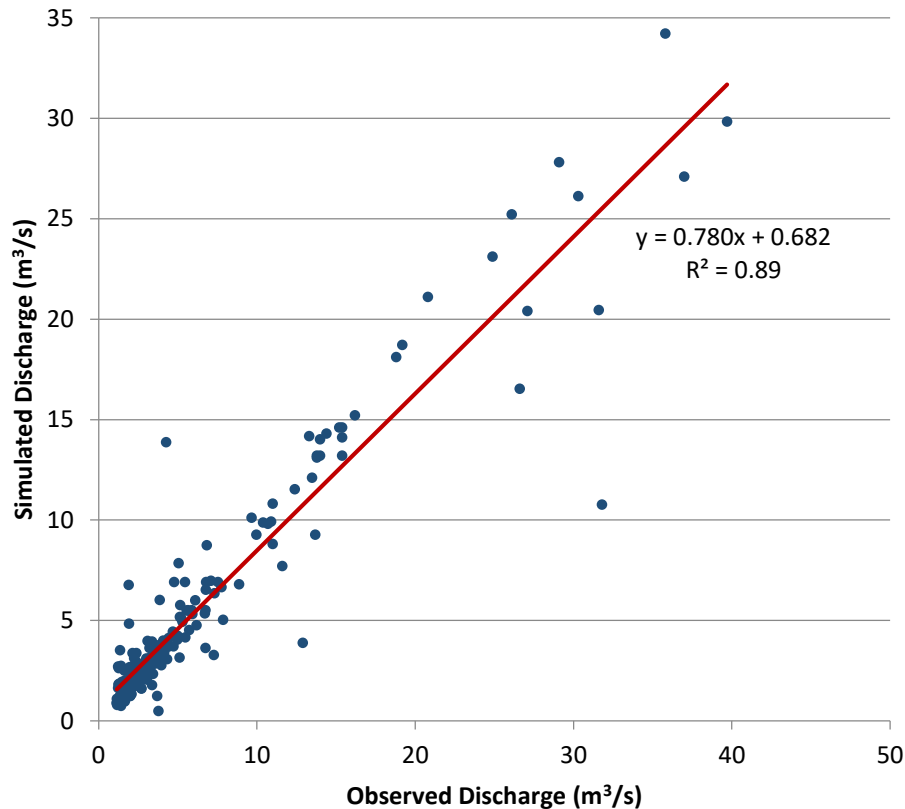


Figure 3.3: Relationship between simulated discharge and observed discharge for both validation and calibration of Bonaparte River

3.5 Runoff prediction for pre- and post-forest fires period

3.5.1 Model performance with produced simulated runoff depths for two scenarios

The selected parameters after calibration were used to estimate the runoff depths for the two scenarios. The SWAT model was applied to simulate the runoff after forest fire (Scenario 2) by adjusting the Curve Numbers for each of the land use class depending on the burned area severity a similar method used by Havel et al. (2018) and Batelis & Nalbantis (2014). A linear regression was used to understand how well the model estimates the runoff generated from each sub-basin for each month of the year, 2017. A plot shown in **Figure 3.4** indicates that the model performed well in estimating the runoff for the two periods with a high coefficient of determination, $R^2 > 0.5$ thus this model is a good estimator for the runoff depths. Generally, there is also a strong correlation between the water yield for each sub-basin from which the runoff is generated in comparison to both scenarios (pre- and

post-forest fires). Sub-basins which initially had high runoff before forest fires, would eventually have much higher runoff volumes after the occurrences of the forest fires. However, it should also be noted that the amount of generated runoff not only depends largely on the area of the sub-basins, but also on the degree of forest fires disturbances (fire intensity), area of the burned forest vegetation, precipitation/climate, geology, soils, watershed aspects and tree species (Havel et al., 2008).

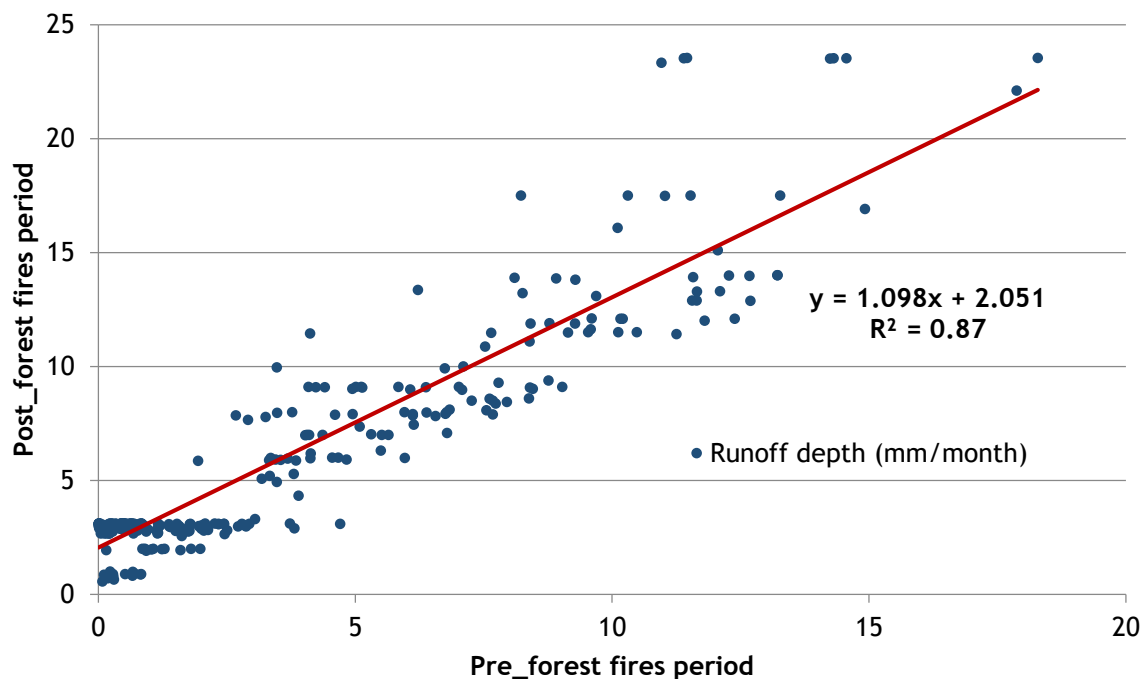


Figure 3.4: Relationship between Model Simulated Runoff depths for pre- and post-forest fires period

3.5.2 Runoff increase in different sub-basins of the Bonaparte after forest fires

As shown in **Figure 3.5**, the largest sub-basin is SUB_29, followed by SUB_20, SUB_2, SUB_18, SUB_10, SUB_14, SUB_4 and SUB_14 respectively. The figure shows in the sub-basins with no or low burn severity of forest fires, there was no or less significant increase in the runoff because the natural land cover was not disrupted and also there was no creation of exposed soil cover by the underlying vegetation. The lower increase in the unburned sub-basins could be attributed to the land use change from timber logging and tree killings from pine infestations. Highest peaks of runoff increase were observed in sub-basins 2, 15, 20 and 29, which confirms that there were forest fires that happened in these areas, whereas sub-basins with low peaks are those which were not affected by forest fires or experienced fires at low severity. Forest fires usually change the physical properties of the soils and burn away the vegetation that controls the hydrological responses of the watershed from the received precipitation and solar radiations. For example, in areas with evergreen forest that were not burned, their natural ecosystem was maintained with enough closed canopy and underlying vegetation. This vegetation and canopy cover intercepted the precipitation and also prolonged precipitation holding time on the soil surface, allowing for it to infiltrate and later percolate to contribute to the base flow within a well performing watershed. According to Havel et al. (2018), at the sub-basin scale after forest fires, the increase in water yields also is a result of reduced evapotranspiration, and it is also one of the important components of the watershed hydrology. Based on another study, another reason for an increase in runoff in the burned areas could be, the presence of soil hydrophobicity or water

repellency that could have increased the runoff potential due to the low infiltration levels shown by the soils found in each of the independent sub-basins (Robichaud et al., 2016; Moody et al., 2013 & Neary et al., 2011). This study therefore modelled the change of the soil surfaces and land cover land use by modifying the Curve Numbers (CNs) for each of the land cover/land use classes with the corresponding soil groups (A and B) as done by the similar studies (Havel et al., 2018; Batelis & Nalbantis, 2014).

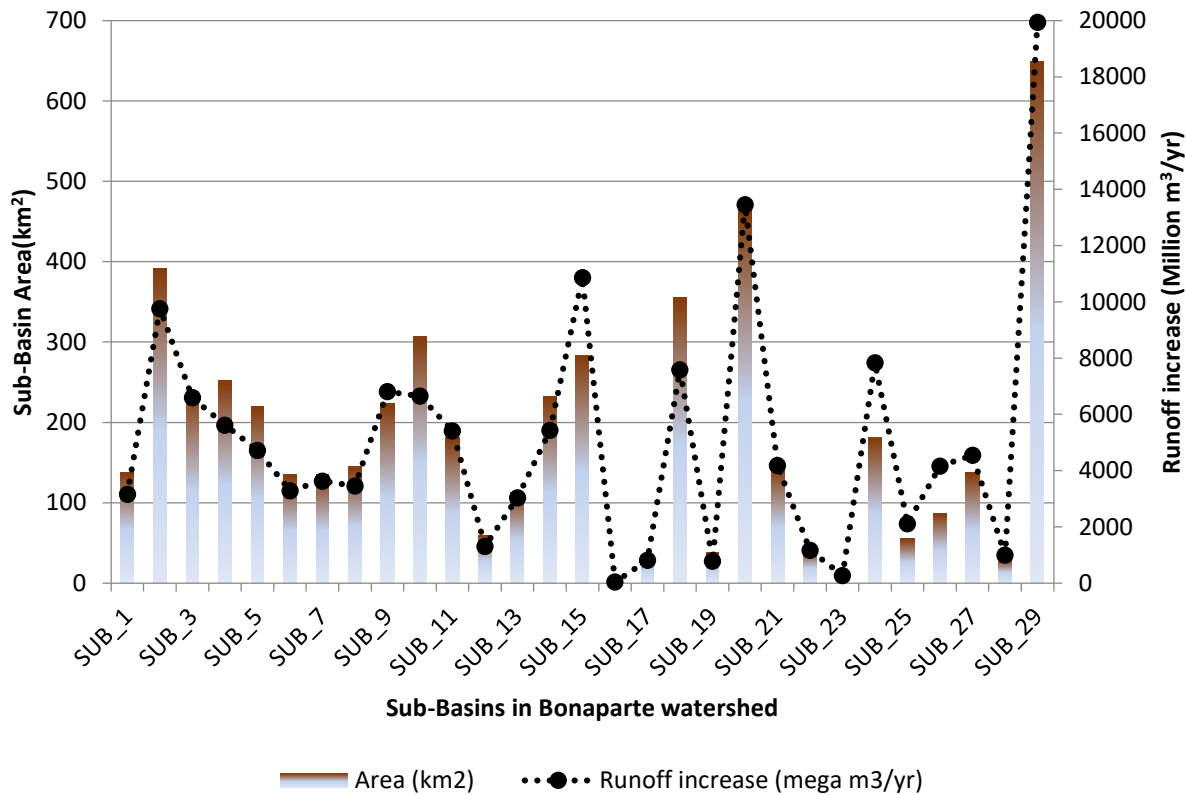


Figure 3.5: Runoff generation comparison between burned and unburned in sub-basins after forest fires in Bonaparte watershed

3.5.3 Change in water yield under different burn severity of forest fires

Forest fires occur under three different burn severity ranges; high, medium and finally low burn. Almost all sub-basins experienced high burn severity, except sub-basins 10 and 27 as shown in **Figure 3.6**. The figure depicts that there is a close relationship between the burn severity to the water yielded from different sub-basins into the main stream. There was an increase in the water yield with high burn severity as well as large area of burn especially in the winter period similar to the findings made by Havel et al. (2018) and Batelis & Nalbantis (2014). In this study, it was found that most of the area of sub-basins 2, 15, 20, 24 and 29 were extremely burnt with high burn severity forest fires (see **figure 3.1D**). These sub-basins have almost the highest change in water yield response because of the destruction of the bigger area of land cover (evergreen/deciduous/mixed forests) and changes in the physical properties of the soils. The highest change in water yield response is seen in Sub-basins 2, 20, 24 and 29 standing at 30-, 43-, 33-, and 58% respectively because of high burn severity of the forest fires. According to the study conducted by Havel et al. (2018), the sub-basins which had received high burn severity fires, almost with burning of 50% of the total areas of the sub-basins, there was a runoff increase of approximately 66 to 75%. The high burn of the landscape contributes to transformation of

biomass and soil organic matter that forms a layer of ash that clogs the soil pores making the soil less porous and thus high runoff potentials (Bodi et al., 2014). Large sub-basins had high runoff increase despite the fact of having smaller total burn areas because of the cumulative effect from a bigger area covered same reason hinted out by Havel et al. (2018).

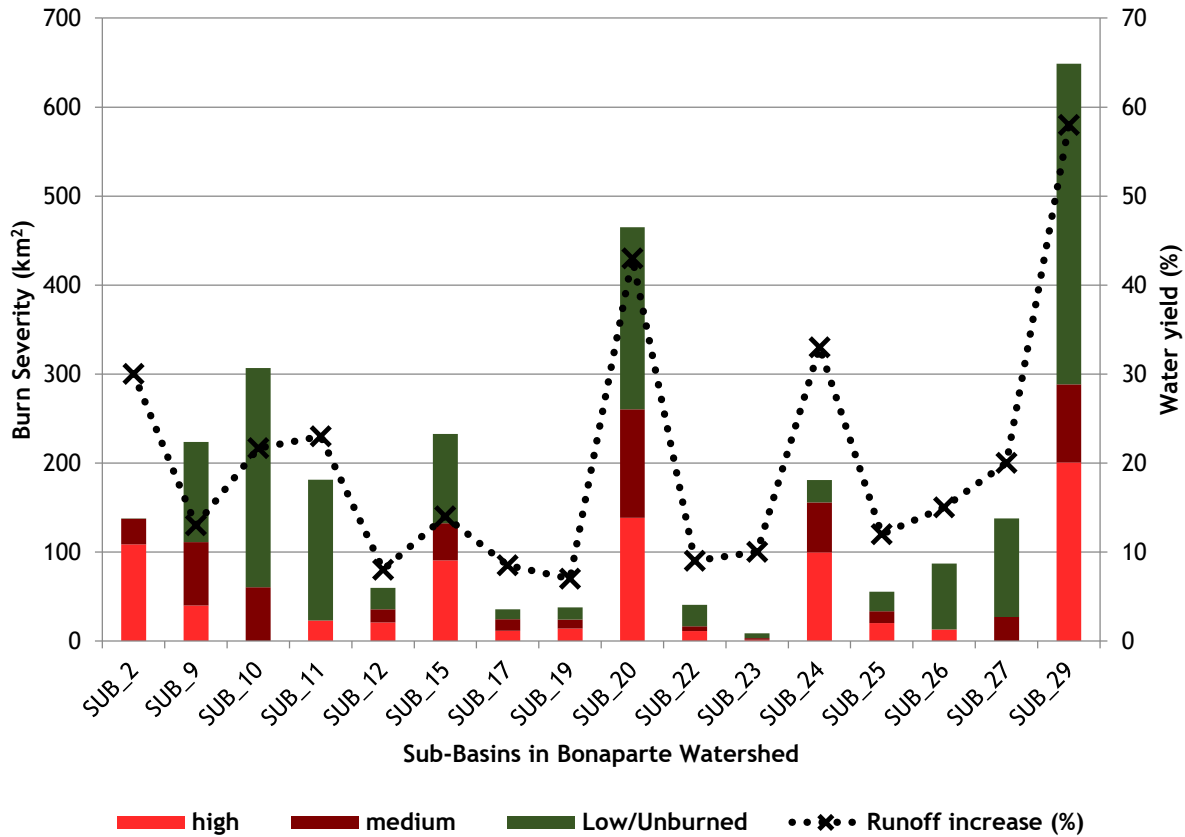


Figure 3.6: Effect of burn severity to water yield in Bonaparte watershed

3.6 SWAT Model Limitations and Challenges

One of the most important aspects in using the SWAT model is the data requirement and data consistency, especially spatial datasets. Maps must be prepared in the required projections and cell sizes for the case of the maps in the raster format. This is because if there are errors in the map, the model will not read the map and the modeller cannot go beyond the simulation process. Modification of land use/land cover to forest fires by adjusting the runoff curve numbers may contribute to the uncertainty in the model estimations, because there is no well-established procedure for estimating post-wildfires as pointed out by Havel et al. (2018). Finding complete climate and discharge data of the watershed under the study was a challenge. In this study, we failed to get the discharge for the full years of study with years for post-forest fires period, particularly data for the year 2017, and as a result the model calibration in that period was not possible, nor was comparing the changes in stream discharge before and after forest fires. The model results might be less accurate because the land use change dynamics in the watershed due to logging and pine infestations before the onset of forest fire. This model sometimes over-predict or under-predict the naturalised stream discharge which might cause uncertainties for the most sensitive parameters selection and in calibration and validation of the model. The obtained results while using the model might be inaccurate because some physical processes cannot be simulated in SWAT (Betrie et al., 2011).

CHAPTER FIVE: CONCLUSION

The 2017 forest fires occurred in the Bonaparte watershed, located in the Cariboo region in the Central interior of British Columbia. Such fires affect the natural hydrological processes of the watershed because of changes in land cover after wildfire, and changes in the soil properties because of the coating of repellents and the ash clogging soil pores. All of which lowers water infiltration. The main objective of this study was to estimate the impact of the forest fires on the water yield from the watershed to the main stream by hydrological modelling using the SWAT model. The findings reveal that once forest fires occur, there is an expected increase in the runoff generated from the sub-basins and the entire watershed. However, the level of increase depends on the burn severity of the area as it was seen in sub-basins with high burn severity.

ArcSWAT, an extension of ArcMap, was used for the graphical user interface to create the SWAT model. ArcSWAT helped in generating SWAT input files especially the geo-referenced and well-prepared maps for DEM for watershed delineation. Additionally, ArcSWAT was used to determine the terrain of the area as well as land use/land cover and soil maps. The SWAT model simulation was used to compare the changes in water yield considering two scenarios: scenario 1 being watershed without forest fires and the scenario 2 being watershed with forest fires. The land use and curve number updating method was used to assess the effects of forest fires in order to mimic the hydrological changes within the watershed caused by the fires. The model was satisfactory, after using three statistical criteria for calibration (Coefficient of determination, $R^2 = 0.62$, Nash-Sutcliffe Efficiency, $NSE = 0.65$) since $NSE > 0.5$ and $R^2 > 0.5$ in simulating the daily naturalized discharge at the mouth of the Bonaparte River. The simulated and observed discharge were compared, and showed that the SWAT model can be used to represent the hydrological processes of the watershed. The obtained runoff depths for both pre- and post-forest fires period strengthened the fact that the model provided a good estimator for the runoff depths with $R^2 > 0.5$. Sub-basins with less burned area had less water yield, different from those that had a high-burned area with high runoff depth. Sub-basins with high burn severity had the highest runoff generated from 20 to 53% runoff increase. The SWAT modeller, however, should be careful of how the maps are prepared in terms of projection and with a good raster cell size. A number of assumptions had to be made, such as land use/land cover changes were not the same in the pre-wildfire period from 2010 to 2017. Also, no discharge data was obtained during the fire to include in the calibration of the model output. This might affect the sensitive parameters for the model calibration. The most sensitive parameters during model calibration with $p > 0.95$ were; Soil Evaporation Compensation Factor (ESCO), Ground water delay (GW_DELAY), Baseflow alpha factor (ALPHA_BF), Maximum canopy storage (CANMX), Surface runoff lag time (SURLAG) and SCS runoff curve number (CN2) respectively.

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**APPENDIX A: UNDERSTANDING TYPES AND SEVERITY OF FOREST FIRES AND ITS EFFECT,
MODELLING AND SWAT THEORY AND SWAT APPLICATION IN DIFFERENT STUDIES**

LITERATURE REVIEW

The increased wildfire occurrences in regions of Canada especially British Columbia, is creating a need to understand the wildfire effects on the hydrologic behaviour of the watersheds. This will help in enhancing the waters resources management and also improving public safety through protections of water sources used for water supply and recreational activities. Understanding the changes in watershed conditions and hydrologic responses induced by fire is important to have successful management of water resources and human population in a post-wildfire environment. Therefore, the effects has to be determined basing on the land use and stream behaviour changes between pre- and post-wildfire periods. SWAT is one of the models that can help in finding out the hydrologic responses of the watershed to wildfires.

Understanding fire severity and ranges as percentage of burnt area in a watershed

Fire severity is the term which describes the magnitude of the disturbance and therefore, reflects the degree of change in the forest ecosystem (Neary et al., 2011). Fire severity is driven by the nature of fuels available for burning, and the combustion characteristics such as type (flaming versus smoldering), duration, location (ground, crown, or both), etc, that characterize a fire.

The criteria of describing the rate of fire severity as according to Neary et al. (2011);

1. Low severity burn- less than 2% of the area is severely burned, less than 15% moderately burned, and the remainder of the area burned at a low severity or unburned. Black ash is used as a visual indicator.
2. Moderately severity burn - less than 10% of the area is severely burned but more than 15% is burned moderately, and the remainder is burned at low severity or unburned. Gray ash is used as a visual indicator.
3. High severity burn - more than 10% of the area has spots that are burned at high severity and more than 80% moderately or severely burned and the remainder is burned at low severity or unburned. White or orange ash is used as a visual indicator.

Wildfires and Hydrologic Conditions of the watershed

Wildfire is a type of forest fires that has potential to drastically change the watershed hydrologic conditions (Neary et al., 2011). Wildfires affect the hydrologic conditions of watershed in many worlds' forest ecosystem depending on fire's severity, duration and frequency (Neary et al., 2011). Basins that have experienced high-burn severity and mostly with steep forested terrain, have flashier hydrographs and can produce peak-flows orders of magnitude greater than pre-fire conditions. This always happens in the short term (1-3 years) due to drastic changes in the hydrology of burnt watersheds. The loss of canopy and forest floor organic horizon that formerly intercepted precipitation, moderated infiltration and protected mineral soil, contributes to reduced evapotranspiration and infiltration and thus increased runoff (Neary et al., 2011).

According to Moody and Martin (2001), wildfires extensively change the land use/land cover (LULC) as well as vegetation in the watershed which eventually change hydrologic regime in the following manner;

- Decrease of canopy interception which increases rainfall conversion into runoff
- Increase base flow because of decrease of water lost by evapotranspiration
- Increase runoff velocities and reduce interception/ storage of rainfall since there is no ground cover, litter, duff and debris

There are first-order impacts of wildfire such as burned vegetation and reduced soil infiltration, and second order impacts such as increased runoff, hillslope erosion, stream sedimentation and alterations of terrestrial and aquatic ecosystems (Ryan et al., 2011). To determine the degree and type of erosion depends on the timing, magnitude, and duration of storms immediately after fire (Ryan et al., 2011). The stream discharge changes soon after the wildfire when there is increase in flow after rainstorms following the early post-fire period. However, snow-dominated regimes, there is streamflows snowmelt is higher following fire and happens during the early summer season (Ryan et al., 2011). As reported by Ryan et al. (2011), extremely high erosion rates happen when severe fire is followed by rainfall (2 - 10 year recurrence frequency) and peak flows occur faster due to water repellency and vegetation loss.

Wildfire Effects on Water Quality and Quantity

Wildfires affect the water quality by increasing nutrient input levels and trace elements which eventually contributes to higher concentration levels above the thresholds reported in the Guidelines (Langhans et al. 2015). Hill slope water erosion is the main process which supports the pollution of reservoirs since it increases the sediment delivery into the stream network feeding water into the reservoir (Langhans et al. 2015). Usually, ash and sediment transport by erosion from hillslopes happens within the first year after the fire (Langhans et al. 2015). Additionally, there can be trace elements, bacteria and nutrients that can attach to sediments whose levels rise in the water when the suspended sediments are deposited in reservoirs and streams. Not only, does suspended sediment increases the turbidity, but also plays a bigger role in transport of other contaminants in sediment due to their high affinity for adsorption on the surface. There is increase in erosion rates after a wildfire because it alters the soil hydraulic properties, generates more sediment and removes vegetation. Severe fires increases water repellency below the surface and thus reduction in the infiltration rates (Langhans et al. 2015). With removal of surface vegetation, overland flow hydraulic resistance is reduced and finally more detachment of the soil.

Influencing factors to high severity of wildfire impacts

Susceptibility of the water sources to inputs of suspended sediment loads are also due to different factors regardless of the fire regimes and this includes, probability of wildfire occurrence, the probability distribution of intense rainfall events, the time interval after fire disturbs soil and vegetation conditions and increases the overall vulnerability of hillslopes and channels to debris flow initiation (Langhans et al. 2015). Wildfire probability can be obtained from historical records and efficiency of ignition suppression mainly depends on weather conditions, as well as, history of planned fires (Langhans et al. 2015).

Timing and magnitude of rainfall during post-wildfire period influences the volumes of sediment input and type of erosion process (Langhans et al. 2015). The first flush of rainfall always fills the ash's pores and loose sediments from surface above the water repellent layer. High intensity rainfall creates dense rill networks that act as channels for sediment transport. Larger debris is deposited in higher order

streams while coarse material is seen in the stream networks (Langhans et al. 2015). Very sudden and large increases in the hillslope erosion happen when the threshold intensities and durations of rainfall is exceeded. Erosion processes starts from low to high event size - diffusive inter-rill erosion with short travel distances to rill erosion dominated by fluvial transport and finally hillslope debris flows which is dominated by overland flow for mass movement to channel debris flows. The rainfall threshold is different for each process and varies with overland flow, mass of non-cohesive material overlying a water repellent and cohesive layer, all influenced by slope gradient, hydraulic roughness and sediment trapping potential (Langhans et al. 2015).

Evaluating changes in hydrologic activities of the watershed in post-wildfire periods

This is done by comparing physical processes or transport rates between burned and unburned areas since adequate data on sediment yield rates and patterns is often limited (Ryan et al., 2011). Therefore, changes in discharge, hillslope and channel erosion, rates of sediment transport and in stream deposition can be evaluated using paired watershed approach. Paired watershed approach makes an assumption that both systems were similar before burning which helps in making general comparisons (Ryan et al., 2011).

Methods used in quantifying the impacts of forest fires in watershed

Models for quantifying erosion after wildfire have been developed in different studies. Starting from calibrating existing hillslope erosion models for burnt conditions (Sidman et al., 2015; Chen et al., 2013; Robichaud et al., 2007 and Canfield et al., 2005), to empirical post-fire models for the probability of debris flow initiation, and volume from large datasets of observed debris flows (Gartner et al., 2014; Cannon et al., 2010). Some models are used to calculate the long-term sediment transport distribution of small catchments considering the wildfire and rainfall probabilities and quantifying various erosion processes (diffusive erosion, gully erosion, landsliding and debris flows), all assume a uniform landscape disturbance by the fire which cannot be applied to large catchments (Langhans et al. 2015). However, as reported by Langhans et al. (2015), models have to incorporate the non-uniformity of fire severity and patterns across a landscape which some models has addressed by representing fire spread mechanisms in terms of fuel burning characteristics, topography and management effects, though used data for considered parameters are regional based.

Modelling hydrologic response of watershed to forest fires

Sometimes watershed managers lack enough tools to quantify overall impacts of forest fires to water quality and quantity. They can now use models to assist them in allocation of resources for source water protection by identifying areas with greatest risk at generating sediments within catchment, in order to develop mitigation efforts towards wildfire risks to water quality (Langhans et al. 2015). Models are important for quantifying the overall impacts of forest fires to water quality since most times watershed managers lack enough tools. Mathematical modelling is very useful in understanding the complex watershed processes (Havel et al., 2018). Different approaches model hydrologic and water quality processes in watersheds, starting from empirical to process-based models (Havel et al., 2018).

Hydrological simulation models use mathematical equations to calculate output variables such as flow rate and total volume of streamflow as a function of input variables and watershed characteristics (parameters) (Putz et al., 2003). The inputs can include, time series data on local precipitation, air temperature, wind, and solar radiation whereas, watershed characteristics include topography, forest cover amount and type, ground surface detention storage and infiltration, subsurface soil

characteristics (hydraulic conductivity versus depth), soil moisture, and stream characteristics. Hydrologic models have to be first calibrated using streamflow data collected at a particular point within the watershed, thereafter the model is used to predict future streamflow conditions as a function of estimated input conditions (Putz et al., 2003).

Water quality models use mathematical equations to estimate the mass concentration of dissolved and suspended constituents in the stream resulting from storm events or maybe from base flow (Putz et al., 2003). Output from the water quality simulation model as noted by Putz et al. (2003);

- Predict total mass of constituent exported from a watershed on a per storm event basis (ie an event-based simulation)
- Describe a time series of constituent concentrations in the streamflow at a specified position within the watershed (ie a continuous simulation).

Generally, because of limited data, hydrologic models are commonly semi-distributed and hence a watershed is represented as a number of sub-catchments. A lumped model is used to formulate a semi-distributed model which divides the watershed into several smaller sub-catchments or from a distributed model that utilises the groupings of averaged input data (Putz et al., 2003).

1. Mechanistic versus empirical models

A mechanistic model describe a process using a set of scientific principles in addition to using a set of mathematical equations that can be solved, then in principle, a model can be developed as representation of the physical system being simulated. Models that use simplified and empirical components are termed conceptual models (Putz et al., 2003). Empirical model doesn't represent physical principles governing a system but the reality is that it is a mathematical representation of physical processes.

2. Lumped versus distributed models

Lumped models don't consider spatial variations of the catchment but utilize average values of the watershed characteristics and input data. Taking average of parameters and input data influences the processes being represented (Putz et al., 2003). There is often a significant error within the represented hydrologic processes because of averaging of nonlinearity and threshold values.

Common parameters used as input variables for the models

Meteorological data are the primary inputs needed for hydrologic modelling (Putz et al., 2003). Therefore, hydrological models should consider the temporal variability of the meteorological data at the desired time scale - hourly, daily, monthly. The selection of the time step depends on the availability of data and most data is recorded on daily basis using single storm event as an input for simulation of short-term watershed response to the event, watershed characteristics such as forest cover and vegetation type (Putz et al., 2003). However, for long-term continuous simulation, temporal variability of the watershed characteristics has to be accounted for, for example, rate of vegetation re-growth and the succession of plant species after a watershed disturbance.

Most hydrological models can't represent the effects of topography and spatial variability on flow processes without simplifications (Putz et al., 2003). Methods have now been developed to digitally represent terrain in hydrologic models whereby raster digital elevation model (DEM) data is used to delineate and measure properties of drainage networks and drainage basins. Distributed models are good at using GIS database systems in hydrologic modelling process (Putz et al., 2003). Processing of

DEM data for watershed delineation and parameterization is done for overland flow routing between grid cells on which DEM is structured (Putz et al., 2003).

Model Selection Criteria

There are several factors to be considered while selecting a model to use in forest watershed as explained by Putz et al. (2013);

- A model has to represent the forest watershed conditions
- There should be accuracy of the model algorithms while representing hydrologic and water quality processes
- Consider spatial representation of basin characteristics that might be distributed (lumped model not good at representing watershed disturbance effects)
- Model's ability to integrate changes in hydrologic and water quality processes
- The desired output from the model should be known (is it distributed output!)
- Time scale of input data available compared to the required time scale of output data
- Model's capability to conduct long-term continuous simulations over recovery period following the disturbance
- Model's ability to integrate with GIS program or other bridging programs
- Availability of the model from a recognised and reliable scientific Agency (stable, tested versions, documentation, support and training)
- Model's ability to run on the personal computers and popular operating system environments

Sensitivity and uncertainty analysis in modelling

Because hydrologic modelling involves use of different parameters with different combinations of the same parameters, this might output similar predictions. However, the biggest challenge is to find the right combination of parameters and distinguish them among equivalent predictions. The procedure known as GLUE can be used to solve the generalized likelihood uncertainty estimation. GLUE is used for running many runs of model using different combinations of parameter values which are assigned a likelihood of being a simulation of the system. Simulations with a likelihood value greater than zero are retained and re-scaling is conducted such that the sum of the likelihood values is equal to 1. The produced distribution is likelihood function for the parameter combinations which helps to evaluate the goodness of fit of model output of the observed data.

Three sources of error when simulating the model include model error, input error and parameter error. Parameter values that are used as input to models are estimates hence high level of uncertainty. The aggregation of errors is the total or simulation error that brings uncertainty to the model output. Therefore, characterising uncertainty can be classified as first-order uncertainty analysis, sensitivity analysis and Monte Carlo (MC) analysis. MC simulation is a stochastic method used to evaluate possible distribution of output results and thus able to assess the uncertainty of model results. Probability distributions of input parameters to the model have to be first estimated so as to conduct MC simulations. MC method considers random sampling from the input distributions and successive model round until a statistically significant distribution of output results is identified. This way, the model

distinguished between the output results for a given application, for example, comparison of hydrologic and water quality effects of burned watersheds to the unburned watersheds.

Evaluation of model performance

Model performance can be evaluated basing on the quantitative statistics and three quantitative criteria; coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) (Moriassi et al., 2007). NSE is the ratio of residual variance to measured data variance Gebremicael et al., 2013), and it is defined by **equation 1**. It is a normalised statistic which describes the relative magnitude of the residual variance as compared to the observed and demonstrates how well the plot of observed versus simulated value fits the 1:1 line (Welde & Gebremariam, 2017; Moriassi et al 2007). PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts and defined by **equation 2**. R^2 as shown in **equation 3** ranges from 0 to 1 and explains the proportion of the total variance in the observed data that can be explained by the model (Gebremicael et al., 2013), with higher value indicating less error variance. Generally, model simulation can be taken as satisfactory when $NSE > 0.4$, $R^2 > 0.5$ and $PBIAS \pm 25\%$ for streamflow (Welde & Gebremariam, 2017). However, according to Moriassi et al., (2007), model performance is accepted as satisfactory if $NSE > 0.5$ and $R^2 > 0.5$ for streamflow and sediment. The error statistics are used to determine how well the model simulations match the observations at the mouth of the considered stream.

$$NSE = 1 - \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y_i^{mean})^2} \right] \quad (1)$$

$$PBIAS = \left[\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})}{\sum_{i=1}^n Y_i^{obs}} \right] \times 100 \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^n (Y_{obs} - \overline{Y_{obs}})(Y_{sim} - \overline{Y_{sim}})}{\sqrt{\sum_{i=1}^n (Y_{obs} - \overline{Y_{obs}})^2} \sqrt{\sum_{i=1}^n (Y_{sim} - \overline{Y_{sim}})^2}} \quad (3)$$

Where; Y_i^{obs} is observed streamflow, Y_i^{sim} is the simulated streamflow, and Y_i^{mean} is the mean of observed streamflows. The optimal value for NES is 1 and can range between $-\infty$ and 1, with values between 0 and 1 generally regarded as satisfactory levels of performance. Values equal to or smaller than 0 indicate the simulated values are similarly good or a worse predictor than the mean of observed values (Nash and Sutcliffe, 1970).

SWAT as a common mathematical model used in hydrologic modelling

Soil Water Assessment Tool (SWAT) is a process-based distributed parameter watershed model that is used to characterise and quantify the effects of LULC change, climate change, and mitigation strategies on runoff, evapo-transpiration, streamflow, groundwater and other hydrological responses and produces positive outputs (Havel et al., 2018). SWAT is accurate in watershed modelling and better in predicting hydrologic components such as overland flow, subsurface flow and Evapotranspiration

(ET) in agricultural watersheds (Putz et al., 2003). SWAT is at river-basin scale and a continuous-time model which operates on a daily time step (Putz et al., 2003). There is distributed representation of a basin which is subdivided into grid cells or sub-basins. Main components of SWAT include hydrology, weather, sediment yield, nutrients, pesticides, soil temperature, crop growth, tillage and residue, and agricultural management practices. The hydrologic modelling component of SWAT is based on the water balance equation and considers processes such as precipitation, ET, overland flow, return flow and soil water storage. Flow is predicted independently of each of the sub-basin and routed through a channel system to predict the total flow for the basin.

The model simulates flow volume by using the Soil Conservation Service (SCS) curve number technique. The flow volume is predicted from daily rainfall using **equation 4** developed by USDA-SCS (1985).

$$Q = \frac{(R - I_a)^2}{(R + I_a) + S} \quad (4)$$

Where Q is daily flow, R is the daily rainfall, I_a is the initial abstraction and S is the retention parameter. The initial abstraction (I_a) is all losses that happen before runoff which includes depression storage, interception, evaporation, and infiltration. The retention parameter (S) varies in each sub-basin depending on the soil type, land use, management and slope. The retention parameter (S) is related to the curve number (CN) by the SCS equation (USDA-SCS, 1985), and it varies with time because of the antecedent soil water content.

$$S = \frac{1000}{CN} - 10 \quad (5)$$

The SCS technique was adopted in SWAT model and it is an important input and allows comparisons with soil type, land use and management practices.

SWAT model works with GIS database component whereby raster-based GIS is used to extract basin parameters to run the SWAT model to help in the analysis. Recently, SWAT has been linked to basins data management systems and it is an ArcView based GIS interface (Putz et al., 2003). This system allows easy export of data from GIS to the SWAT model with customised menus that help in finding parameter values. It is very important to note that watershed delineation using a DEM is the first step during the pre-processing procedure to determine the slope and flow direction of each cell. There are 3 components of SWAT ArcView system and these include;

1. A pre-processor that generates sub-basin topographic input parameter
2. An input editor and simulation processor
3. A post-processor for viewing graphical and tabular results

Strengths of SWAT Model as according to Putz et al. (2003); 1) it is simple to use though very complex to simulate interactions among weather, vegetation growth and land use management in a river basin for a long period, 2) it integrates with GIS which helps in aggregating input data for large scale applications and 3) it has graphical output and analysis tools which supports visualisation of simulated results.

A continuous time model like SWAT is necessary to find the hydrologic effects of wildfires as it can explore long-term impacts (Havel et al., 2018). This helps to represent a watershed where channel

storage maybe significant and where significant variability exists in land use, soil types and/or topography. SWAT being a distributed-parameter model; it divides a watershed into sub-watersheds, further divided into hydrologic response units (HRUs). HRUs are smallest spatial units in SWAT and are defined as areas within each sub-watershed with unique combinations of land use, soil and slope class. Sub-watersheds can be assigned unique climate and hydrologic properties, which is in combination with unique land use characteristics of HRUs, provides the capability to investigate the effects of land use change scenarios under varying climatic conditions both spatially and temporally (Havel et al., 2018). SWAT was designed for agricultural applications, so it may not be useful enough to simulate forest hydrological processes. But it is able to simulate hydrologic processes and water quality in regions vulnerable to lateral subsurface flow and deep groundwater flow (Putz et al., 2003). This implies that when it is well calibrated, it may eventually be used in accurate estimation of forest hydrologic processes. The main challenge of using this model in evaluating the hydrologic response of a system to wildfire is developing mechanism through which hydrologic effects of wildfires are simulated (Havel et al., 2018). SWAT helps in understanding the forest fire impacts within the watershed to a smaller extent since it doesn't account for some major factors like soil hydrophobicity, or fire severity and intensity.

SWAT MODEL THEORY

SWAT was developed by USDA Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds having variations in soils, land use and management conditions (Neitsch et al., 2011). The model is physically based and requires specific information as input data such as weather, soil properties, topography, vegetation and land management practices of the watershed. It can be used to simulate physical processes associated with water movement, sediment movement, crop growth, nutrient recycling, etc. The advantage of using SWAT approach is that it can model watershed without monitoring data (stream gauge data) and also can evaluate the impact of alternative input data including changes in management practices, climate and vegetation, etc, on water quality and other variable of interest to the user. SWAT can be used for monitoring large basins or different management strategies in the same watershed without using a lot of time and money. Long-term impacts can be determined using the model since it is considered as a continuous time or long-time yield model and not designed for single-event flood routing events, for example, accumulation of pollutants and their impact on the water bodies downstream (Neitsch et al., 2011).

While using SWAT for modelling purposes, a watershed is divided into different sub-watersheds or sub-basins (Neitsch et al., 2011). Normally, sub-basins are important during the simulation because they account for variations in land uses or soils which influence the hydrology. Watershed partitioning into sub-basins helps in spatial referencing of different areas within the watershed to one another. Sub-basins are further divided into Hydrologic response units (HRUs) which refer to land areas comprising of unique land cover, soil and management combinations (Neitsch et al., 2011).

SWAT is developed around the water balance of the watershed (equation 6). The hydrologic cycle simulated by the model should have the actual representation of the hydrologic processes occurring in the watershed in order to produce accurate prediction. Hydrology of the watershed can be simulated by separating it into two major divisions - land and routing phases of the hydrologic cycle. The land phase controls the amount of water, sediment, nutrient and pesticides loadings into the main channel for each sub-basin. Routing phase refers to movement of water and sediments through the channel network of the watershed to the outlet (Neitsch et al., 2011). Watershed subdivision is very important because it helps the model to identify differences in evapotranspiration among various crops and soils, as well as, allowing accurate prediction of total runoff of the watershed because there is separate

determination of runoff for each HRU before it is routed to obtain total runoff. Therefore, watershed division ensures accurate presentation of the physical processes of the water balance (Neitsch et al., 2011).

The land phase of the hydrologic cycle is simulated by SWAT by using water balance equation shown in equation 1.

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (6)$$

Where; SW_t is the final soil water content (mm H₂O), SW_0 is the initial soil water content on day i (mm H₂O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H₂O), Q_{surf} is the amount of surface runoff on day i (mm H₂O), E_a is the amount of evapotranspiration on day i (mm H₂O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H₂O) and Q_{gw} is the amount of return flow/base flow on day i (mm H₂O).

Surface runoff volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972). The curve number decreases when the soil is towards the wilting point and increases to near 100 as the soil approaches its saturation (Neitsch et al., 2011). The curve number method sometimes unable to directly model infiltration since it operates on a daily time-step, otherwise, Green & Ampt infiltration is commonly used method with precipitation data in smaller time increments (Neitsch et al., 2011). Potential evapotranspiration is determined by the Penman-Monteith, and it is rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation with constant of soil water. It requires five parameters (daily precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity). The model predicts lateral flow in each soil layer by using kinematic storage model. Surface runoff that occurs above the soil surface along the slope was simulated by SWAT using daily or sub-daily rainfall amounts to determine surface runoff volumes and peak runoff rates for each HRU. Routing in the main channel can be divided into components such as water, sediments, etc. Flood routing is determined using the Muskingum routing method developed by Williams (1969), as flow is routed through the channel using this variable storage coefficient method. Sediment routing helps to understand transport of sediment in the channel controlled by the simultaneous operation of two processes, deposition and degradation. SWAT uses stream power to estimate deposition/degradation in the channels (Neitsch et al., 2011).

Literature Summary of SWAT Model

SWAT is a comprehensive hydrologic model which is a physically based, continuous, long-term, distributed parameter model used in predicting the effects of land management practices on hydrology and water quality in agricultural watershed under varying soil, land-use and management conditions. The SWAT is based on the concept of hydrologic response units (HRUs) and these are portions of a sub-basin with unique land-use, management and soil attributes. The runoff, sediment and nutrient loadings from each HRU are calculated independently based on the weather, soil properties, topography, vegetation and land management, thereafter summed to find the total loading from the sub-basin. SWAT is based on water balance equation and the physical processes can be divided into two coarse divisions of the hydrologic cycle, the land phase and the routing phase. The two divisions consider processes such as precipitation, surface runoff, evapotranspiration, groundwater flow, snow

melt, and flood routing. The deterministic approach of SWAT Model allows the user to study the relative impact of alternative input data on particular variables of interest.

Application of SWAT in Hydrological Modelling based on past Studies

- **Data used**

According to Welde & Gebremariam (2017), there are two types of data required by SWAT model, spatial and temporal data. Spatial data includes a digital elevation model (DEM), land use map and soil map. The temporal data includes hydrological data (stream flow and sediment yield) and climatic data (precipitation, temperature, relative humidity, wind speed and solar radiation). From the study done by Gebremicael et al. (2013), DEM was obtained from the Global US Geological Survey site, land use/cover maps were prepared using images from Landsat MSS and ETM imageries and the soil map from the 1995 global soil map of Food and Agriculture Organisation (FAO). Ahn & Kim (2017) obtained digital elevation model (DEM) using 90 m grid-size Shuttle Radar Topography Mission (SRTM). A 2008 Land-cover map of nine classes (coniferous forest, deciduous forest, mixed forest, paddy rice, upland crop, urban, grassland, bare field and water) and a soil map that contained texture, depth and drainage attributes was rasterized to a 90m grid size from a 1: 25,000 scale vector map. Thirty year daily meteorological data (precipitation, maximum and minimum temperature, relative humidity, wind speed and solar radiation) was also collected.

- **DEM**

DEM can be used to delineate the watershed and the drainage pattern of the watershed (Welde & Gebremariam, 2017). DEM is also important in obtaining sub-basin parameters (slope length of the terrain, slope gradient and the stream network characteristics) and stream network characteristics (channel length, slope and width). Hydrological parameters can also be derived from DEM including flow accumulation, direction and stream network.

- **Soil**

Soil map should be in grid format and the soil data about physical and chemical characteristics of the soil, both helps in determining the movement of water and air within the Hydrological Response Units (HRUs). The properties required by SWAT for each layer of each soil type are depth of the soil layer, soil texture, hydraulic conductivity, bulk density and organic carbon content (Welde & Gebremariam, 2017).

- **Land use**

The land use depicts the hydrologic response of the watershed, for example in circumstances when the land is covered by underlying vegetation and forest, there is always less runoff generated. Because rainfall is intercepted and retained for longer time until it infiltrates. In contrast, to change of land use from forest cover to bare open land due to high severe forest fires burning of all trees and vegetation. The landscape eventually has no control of the rainfall received hence more generation of runoff and high sediment transport.

Table 1: SWAT Outlined studies

Purpose	Parameters used	Findings	References
Water quality in terms of sediment yield	Rainfall data, fire severity, ignitions, Burned area, Topography, Soil		Langhans et al. 2015
Hydrologic responses to wildfires at various spatial scales	Land use, land cover, soil and weather, burn severity and streamflow		Havel et al., 2018

Assess the effects of hydrology and water quality on watershed health to analyse the possible long-term changes in watershed	Elevation, land use, soil, weather data	Watershed health decline in terms of hydrology and water quality for the 10-year period	Ahn & Kim (2017)
Land use change impacts on hydrological response (stream flow and sediment yield) of the Tekeze Dam watershed	Land use maps (1986, 2008), climate data, daily stream flow records (1978-2006); and sediment data	Land cover change from shrub land to agricultural land had significant effect on hydrological response. Increasing bare land and agricultural land, increased annual and seasonal stream flow and sediment yield in volumes.	Welde & Gebremariam (2017)
Hydrological effects of forest fires in a Enipeas river basin, a Mediterranean basin	Elevation, land use map, soil and weather data	There is decrease in streamflow under different scenarios of forest fires (low, medium, high).	Batelis & Nalbantis (2014)

Model Calibration, Validation and Sensitivity analysis in past studies

1. Study 1 (Ahn & Kim, 2017)

Ten year data of daily inflow and water quality of 8-day intervals of sediment, Total Nitrogen and Phosphorous was used. Uncertainty analysis for hydrology was done by using daily dam inflow and SUFI-2 method. The method is easy in its applicability in both simple and complex hydrological models and it is widely used in hydrology.

In SUFI-2, parameter uncertainty considers all sources of uncertainty such as input, conceptual model and parameter used. Degree of uncertainty is measured using *P-factor*, which is the percentage of measured data that are within 95% prediction uncertainty (95PPU). Another measure that quantifies the strength of a calibration is *R-factor*, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. A good calibration and prediction uncertainty is based on the closeness of the *P-factor* to 1 and the closeness of the *R-factor* to 0.20 after which sensitive parameters were selected for calibration.

The coefficient of determination (R^2), the Nash and Sutcliffe model efficiency (NSE), the root-mean-square error (RMSE) and the percent bias (PBIAS) were used to evaluate the ability of SWAT model to replicate temporal trends in the observed hydrological and water quality data. The R^2 value of the dam inflow was greater than 0.59, average NSE 0.59-0.87 at different monitoring stations and lastly PBIAS 13.5 - 4.5%. The average R^2 of sediment was 0.54 - 0.90, T-N 0.46-0.82, T-P 0.47-0.80 for each calibration point. It was reported that the calibration results were consistent with the SWAT calibration guidelines ($NSE \geq 0.5$, $PBIAS \leq 28\%$ and $R^2 \geq 0.6$).

2. Study 2 (Welde & Gebremariam, 2017)

Simulation and sensitivity for each land use was performed by dividing the catchment into 47 sub-catchments and assigning HRUs based on multiple HRU definition. After sensitivity analysis followed by calibration and validation, the impact of land use change was evaluated using different land use change maps for years 2008 and 1986.

Parameter sensitivity analysis identified parameters which influence the SWAT output due to input variability (Welde & Gebremariam, 2017). Latin hypercube One-At a Time (LH-OAT) was used in the sensitivity analysis to identify those parameters influencing the model output, but only parameters with 95% probability sensitivity to model output were selected for model calibration. For each reference land uses, stream flow sensitivity analysis was conducted with 12 number of interval within Latin hypercube with total of 27 flow parameters (324 iterations). 240 iterations were done for model sediment parameter sensitisation analysis of the studied watershed. The sensitivity of the parameters were categorized into classes; small ($0 < RS < 0.05$), medium ($0.05 < RS < 0.2$), high ($0.2 < RS < 1$) and very high ($RS > 0.1$). Thereafter, flow and sediment parameters were selected for calibration by considering only those between ranges of very high and medium classes.

Model performance was evaluated before calibration using default parameter values. Monthly time-step against the observations of the discharge and sediment yield loads was recorded for each of the land uses (1986 LULC and 2008 LULC). Model performance was evaluated using quantitative statistics with three statistical criteria, the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and Percent bias (PBIAS). Visual inspection was done with scatter plots with simulation of stream discharge in simulation period. Calibration graphs of observed and simulated discharge for both scenarios were plotted as well as simulated discharge for the two scenarios for one year. The mean annual streamflow and sediment yield of the watershed increased due to land use change by 6.2% and 17.39% respectively

APPENDIX B: SUPPLEMENTARY TABLES FOR SWAT MODELLING

Table 1: Land Class reclassification into SWAT Codes

2010 North America _ Code	2010 North America _ Land class	SWAT Code	SWAT Class	Land use
3	Temperate or Sub-polar Broadleaved Deciduous Forest - Closed Canopy	41	Deciduous Forest	FRSD
4	Temperate or Sub-polar Needleleaved Evergreen Forest - Closed Canopy	42	Evergreen Forest	FRSE
5	Temperate or Sub-polar Needleleaved Evergreen Forest - Open Canopy	42	Evergreen Forest	FRSE
6	Temperate or Sub-polar Needleleaved Mixed Forest - Closed Canopy	43	Mixed Forest	FRST
7	Temperate or Sub-polar Mixed Broadleaved or Needleleaved Forest - Closed Canopy	43	Mixed Forest	FRST
10	Temperate or Subpolar Broadleaved Deciduous Shrubland - Open Canopy	41	Deciduous Forest	FRSD
11	Temperate or Subpolar Needleleaved Evergreen Shrubland - Open Canopy	51	Range Shrubland	RNGB
13	Temperate or Subpolar Grassland	71	Grasslands	RNGE
14	Temperate or Subpolar Grassland with a Sparse Tree Layer	71	Grasslands	RNGE
16	Polar Grassland with a Sparse Shrub Layer	71	Grasslands	RNGE
17	Polar Grassland with a Dwarf-Sparse Shrub Layer	71	Grasslands	RNGE
18	Cropland	85	Agriculture-Generic	AGRL
19	Cropland and Shrubland/woodland	85	Agriculture-Generic	AGRL
20	Subpolar Needleleaved Evergreen Forest Open Canopy - lichen understory	42	Evergreen Forest	FRSE
21	Unconsolidated Material Sparse Vegetation (old burnt or other disturbance)	32	South Western Range + Quarries/Min es	SWRN
22	Urban and Built-up	21	Urban Medium Density	URML

23	Consolidated Rock Sparse Vegetation	31	South Western Range + Bare Rock	SWRN
24	Water bodies	11	Water	WATR
25	Burnt area (resent burnt area)	32	South Western Range + Quarries/Min es	SWRN
26	Snow and Ice	11	Water	WATR
27	Wetlands	91	Woody Wetlands	WETF

Table 2: Pre-wildfire land classes and corresponding Curve Numbers

LULC description	Runoff Curve Numbers			
	A	B	C	D
Pre-Fire Deciduous Forest High/Moderate/Low Burn	-	-	-	-
Pre-Fire Evergreen Forest High/Moderate/Low Burn	25	55	70	77
Pre-Fire Mixed Forest High/Moderate/Low Burn	36	60	73	79
Pre-Fire Shrub land High/Moderate/Low Burn	39	61	74	80
Pre-Fire Grassland High/Moderate/Low Burn	49	69	79	84
Pre-Fire Agriculture High/Moderate/Low Burn	67	77	83	87
Open water	-	-	-	-

Source: Havel *et al.*, 2008

Table 3: Post-wildfire land classes and corresponding Curve Numbers

LULC description	Runoff Curve Numbers			
	A	B	C	D
Post-Fire Evergreen Forest High Burn	40	70	85	92
Post-Fire Mixed Forest High Burn	51	75	88	94
Post-Fire Shrub land High Burn	54	76	89	95
Post-Fire Grassland High Burn	64	84	94	99
Post-Fire Agriculture High Burn	82	92	98	102
Post-Fire Evergreen Forest Moderate Burn	35	65	80	87
Post-Fire Mixed Forest Moderate Burn	46	70	83	89
Post-Fire Shrub land Moderate Burn	49	71	84	90
Post-Fire Grassland Moderate Burn	59	79	89	94
Post-Fire Agriculture Moderate Burn	77	87	93	97
Post-Fire Evergreen Forest Low Burn	30	60	75	82
Post-Fire Mixed Forest Low Burn	41	65	78	84
Post-Fire Shrub land Low Burn	44	66	79	85
Post-Fire Grassland Low Burn	54	74	84	89
Post-Fire Agriculture Low Burn	72	82	88	92

Table 3: SWAT Calibration parameters

No.	Parameter	Description	File	Unit	Min.	Max.
1	GW_DELAY	Ground water delay	.gw	days	0	500
2	ALPHA_BF	Baseflow alpha factor	.gw	days	0	1
3	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	.gw	mm	0	5000
4	GW_REVAP	Groundwater “revap” coefficient	.gw	-	0.02	0.2
5	REVAPM	Threshold depth of water in the shallow aquifer for “revap” to occur	.gw	mm	0	500
6	RCHRG_DP	Deep aquifer percolation fraction	.gw	-	0	1
7	GWHT	Initial groundwater height	.gw	m	0	25
8	GW_SPYLD	Specific yield of the shallow aquifer	.gw	m ³ /m ³	0	0.4
9	REVAPMN	Threshold depth of water in the shallow aquifer for “revap” to occur	.gw	mm	0	500
10	CN2	SCS runoff curve number	.mgt		35	98
11	SOL_AWC	Available water capacity of the soil layer	.sol	mm/mm	0	1
12	SOL_K	Saturated hydraulic conductivity	.sol	mm/hr	0	2000
13	SOL_BD	Bulk density	.sol		0	1
14	CH_N2	Manning’s “n” value for the main channel	.rte	-	-0.01	0.3
15	CH_K2	Effective hydraulic conductivity in main channel alluvium	.rte	-	-0.01	500
16	CH_S2	Average slope of the main channel	.rte	-	-0.001	10
17	OV_N	Mannings “n” value for overland flow	.hru		0.01	30
18	SLSUBBN	Average slope length	.hru		10	150
19	CANMX	Maximum canopy storage	.hru	mm	0	100
20	ESCO	Soil evaporation compensation factor	.hru		0	1
21	EPCO	Plant uptake compensation factor	.hru		0	1
22	SNO_SUB	Initial snow water content	.sub		0	150
23	CH_K1	Effective hydraulic conductivity in tributary channel alluvium	.sub		0	150

24	CH_N1	Mannings “n” value for the tributary channels	.sub		0.01	30
25	SMTMP	Snow melt base temperature	.bsn		-20	20
26	SNOCVMX	Minimum snow water content that corresponds to 100% snow cover	.bsn		0	500
27	SNO50COV	Snow water equivalent that corresponds to 50% snow cover	.bsn		0	1
28	SURLAG	Surface runoff lag time	.bsn		0.05	4

Table 4: SWAT sensitive parameters and their fitted values used for model calibration

Hydrological Processes to Stream discharge	Input parameters	Description	Calibrated values
Surface runoff	CN2 ¹	SCS runoff curve number	51
	ESCO ²	Soil evaporation compensation factor	0.7
	EPCO ³	Plant uptake compensation factor	0.50
	SURLAG ⁴	Surface runoff lag time	16.82
	OV_N ⁵	Mannings “n” value for overland flow	15
	CANMX ⁶	Maximum canopy storage	10.0
	SNOCVMX ⁷	Minimum snow water content that corresponds to 100% snow cover	350.00
Baseflow/Groundwater flow	REVAPM ⁸	Threshold depth of water in the shallow aquifer for “revap” to occur	150.00
	GW_DELAY ⁹	Ground water delay	350.00
	GWQWN ¹⁰	Threshold depth of water in the shallow aquifer required for return flow to occur	3500.00
	GW_REVAP ¹¹	Groundwater “revap” coefficient	0.11
	ALPHA_BF ¹²	Baseflow alpha factor	0.30
Stream channel/Routing	CH_N2 ¹³	Manning’s “n” value for the main channel	0.083
	CH_S2 ¹⁴	Average slope of the main channel	0.99
	CH_K1 ¹⁵	Effective hydraulic conductivity in tributary channel alluvium	270.00

