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CLIMATE CHANGE IMPACTS ON HYDROLOGICAL PROCESSES IN SILVER BOW CREEK WATERSHED

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CLIMATE CHANGE IMPACTS ON HYDROLOGICAL PROCESSES IN SILVER BOW CREEK WATERSHED

by

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requirements for the degree of

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Abstract

Climate change is expected to alter temperature and precipitation regimes across the globe and have varying effects on localized hydrological processes. For Silver Bow Creek (SBC), a headwater to the Clark Fork River in western Montana, the magnitude, duration, and frequency of spring runoff and summer base flow are dependent on the processes of snow accumulation and melt. Headwater hydrology and mountain streams will likely experience earlier snowmelt, increased spring flows, and decreased summer flows due to climate change.

A process-based hydrological model the Soil and Water Assessment Tool (SWAT) was used to evaluate the effects of climate change on SBC spring runoff and summer base flows. SWAT is a continuous simulation model that allows the user to predict surface water discharge, sediment loading, and stream nutrient content from user specified meteorological forcing functions. The SBC model was developed using 1/3 arc second DEM, SSURGO soil database, Montana land cover framework, and observed climatic data and was calibrated between the years 2008-2009 and validated between the years 2010-2011 to daily USGS flow data. Projected future downscaled climate change from CMIP5 emission scenarios RCP 2.6, 4.5, 6.0, and 8.5 were used as temperature and precipitation for the modeling period. A calibrated and validated baseline model was used for comparison against the four CMIP5 scenarios. Results were then used to make qualitative inferences about changes in surface water quality due to climate change. Model simulations indicate the timing of spring melt off to be earlier, the duration shorter, and volume to be less than the baseline scenario. One of the limitations to this study was the inability to satisfactorily calibrate and validate daily values.

Keywords: SWAT, Climate Change, Silver Bow Creek Watershed, Snowpack, Snowmelt, Hydrology

Dedication

Per aspera ad Astra.

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Glossary of Terms

Term	Definition
GCM	Global Circulation Models
CMIP5	Coupled Model Intercomparison Project
RCP	Representative Concentrated Pathways
SWAT	Soil and Water Assessment Tool
GIS	Geographical Information Systems
HRU	Hydrologic Response Unit
SBC	Silver Bow Creek
USGS	United States Geological Survey
SBC WWTP	Silver Bow Creek Waste Water Treatment Plant
SFTMP	Snow Fall Temperature
SWE	Snow Water Equivalent
WCRP	World Climate Research Program
BCCAv2	Bias Corrected Constructed Analogue

1. Introduction

1.1. Climate Change

Earth has gone through roughly seven major climatic changes throughout the last 650,000 years, where a retreat and advancement of ice caps is marked at the beginning and end of each cycle. Ebbs and flows of global temperatures are deduced from measuring the amount of CO_2 trapped in ice caps (NASA: Global Climate Change 2018a) and warmer and cooler periods are the result of two phenomena (IPCC 2014). The first is that the earth's rotation around the sun isn't set, there are eccentricities to it. Over a period of about 100,000 years, the earth's rotation around the sun fluctuates from being a perfect circle to more of an ellipse. As the earths annulus turns more elliptical, it increases the distance of the earth from the sun during certain times of the year, reducing the amount of solar radiation reaching the planet. Currently, the earth's orbit is closer to a circular orbit. The second phenomenon is that the earth's axis rotates. On about a 40,000 year cycle the earth's axial tilt ranges from 22.1 to 24.5 degrees. This tilt causes more extremity of the seasons by increasing the distance of the hemispheres from the sun. Currently the tilt is in the middle of its phase.

In the latest Intergovernmental Panel on Climate Changes report, 95% of scientist agree that the current trend of climate warming is outside the natural variance (IPCC 2014). This warming trend is believed to be the direct cause of anthropogenic influence, mainly the burning of fossil fuels and the subsequent release of greenhouse gasses into the atmosphere. Most of the earth's heat is the result of atmospheric gases reflecting the suns solar radiation back on earth. The main gasses that contribute to the greenhouse effect are: water vapor (H_2O), nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). As these gas concentrations increase so does trapped solar radiation, resulting in warming of the planet. In the last 150 years, atmospheric

CO_2 concentrations have increased from 280 ppm to just over 400 ppm, outside a range we have ever seen before (IPCC 2014). Additionally, since the late 1800s there has been a global increase in temperature of 0.9°C, a previously unprecedented event (Mann and Bradley 1999) (Figure 1).

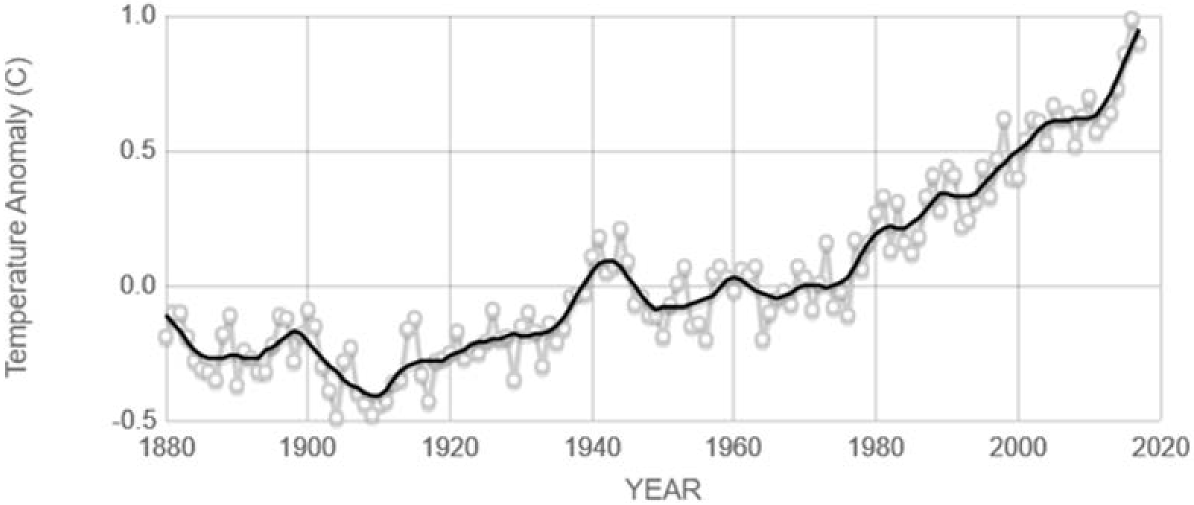

Figure 1: Global increase in temperature since 1880 (NASA: Global Climate Change 2018b)

1.2. Montana Climate Change

Due to Montana's size and topography its climate varies from east to west. The east is marked by relatively flat topography, warmer summers, colder winters, less overall precipitation, and the majority of rainfall occurring in late spring and summer. The west is marked by mountainous topography, relatively cooler summers, relatively warmer winters, more precipitation than the east, and a more evenly distributed precipitation throughout the year. Overall, the state receives very little precipitation and is in a semi-arid climate (Desert Research Institute and Western Regional Climate Center 2016). Because of Montana's relatively arid climate, winter snow pack plays an integral role in annual hydrology. Snowpack, and the capture of spring runoff, drive late summer baseflow in streams and overall hydrology in the state.

Montana has already seen an increase in temperature of 1.1-1.7°C across the state from 1950-2015. Most of this warming has been during the spring months with average increase of 2.2°C. Additionally, the state has more warmer days on average throughout the year, with a lengthening of the growing season by 12 days. Montana's climate is projected to get warmer; 2.5-3.3°C by 2050, and 3.1-5.4°C by 2100 (Figure 2) (Silverman et al. 2017).

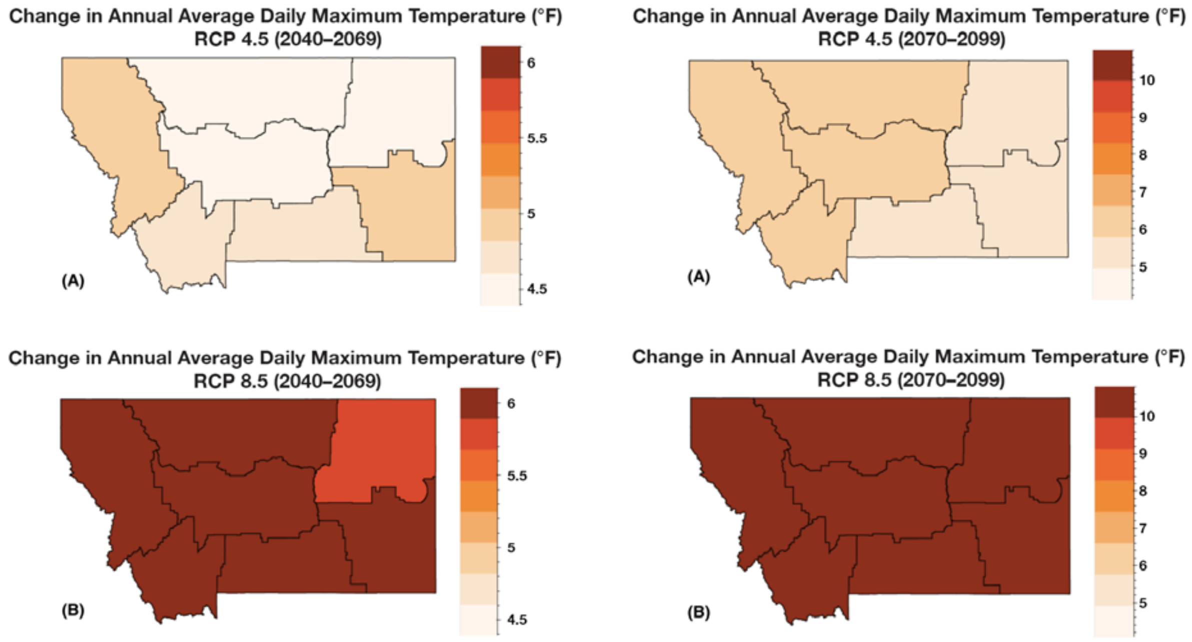

Figure 2: Change in temperature across the state for two climate scenarios a) RCP 4.5 and b) 8.5 (Silverman et al. 2017)

Overall, peak runoff from snowmelt has occurred earlier in the spring (Stewart et al. 2005) and is only expected to shift more with projected climate scenarios (Stewart et al. 2004). The Rockies specifically have seen a decrease in April 1st snow water equivalent between 15-30% between the years 1950-1997 (Glawe and Dugan 2006). As snow pack continues to decrease, it will mean earlier peak runoff and more stressed water days in late summer. This could lead to prolonged drought, stressed environments for aquatic species, more extreme fire season, and impact towards municipal water supply.

1.3. Silver Bow Creek Hydrological Processes

Silver Bow Creek is a 26-mile-long creek originating near the continental divide in Silver Bow County, Montana. Silver bow creek is a headwater to the Clark Fork River, which eventually drains into the Columbia River Basin. The watershed is in a semi-arid climate and receives a relative small amount of precipitation over the year and is heavily dependent snow pack that drives early spring runoff and late summer base flows. Snowpack is an integral part to the hydrological processes in SBC. As snowpack increases throughout the winter, it is stored and then released later in the year when the watershed is water limited (Figure 3). When snowpack starts to melt in the spring it recharges shallow and deep aquifers, supplies overland flow to SBC, and supplies water to wetlands and ponds. Both wetland and aquifer recharge are important once the initial surge of surface flows retreat from snow pack runoff as it supplies additional flow to SBC.

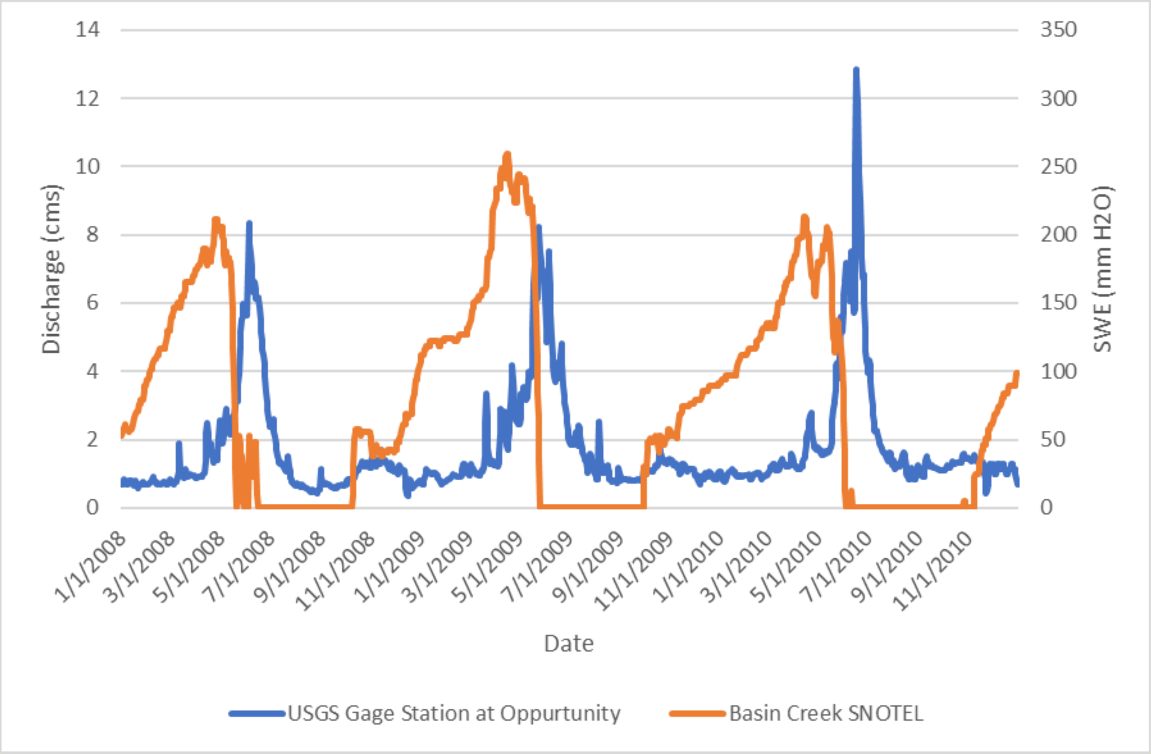

Figure 3: Snowmelt Vs Discharge in SBC Watershed

As snowpack plays such an integral role in hydrological processes for SBC, increased temperature associated with climate change could have devastating effect on the watershed. Increased temperatures may cause more precipitation falling as rain rather than snow and less snowpack accumulation throughout the winter. From a hydrological perspective, this would mean earlier snowmelt, increased spring flows, and decreased summer flows.

1.4. Hydrologic Models and Their Utility for Evaluating Climate Change

Hydrological models are effective tools for understanding basin wide implications to hydrological processes (Gassman, et al., 2014) and models have utility in predicting water quantity in scenarios where empirical data is unattainable, such as modeling stream hydrology with projected climate change data. One model in particular, the Soil and Water Assessment Tool (SWAT), has been used in a number of instances to model hydrological processes and climate change (Jin and Sridhar 2012) (Watershed et al. 2008). Through use of soil type, land use, weather data, and topographical data while using geographical information systems (GIS) in tandem as a user interface (Arnold et al, 1998). SWAT is a continuous time simulation model that allows the user to predict the impacts on sediment loading, stream nutrient content, and surface water discharge. SWATs GIS interface, ArcSWAT, allows the modeler a platform for visual representation and an interface for file management. SWAT uses a digital elevation models (DEM) and stream network to divide basins into smaller watersheds based upon topographical and river location information. SWAT then further divides the basin into smaller units, called HRUs (hydrologic response units) which are the fundamental computational unit of the model. HRUs are determined by a common factor of land use, land cover, soil type, and management type. After sub watershed and HRUs are discretized the model is forced with observed climate data. The model requires precipitation, temperature, solar radiation, and wind speed. Following calibration and validation, coupling SWAT with future projected climate change data can be an effective way to understand the effects of changing climate can have on small head water streams in Montana, such as Silver Bow Creek (SBC).

1.5. Climate Change Data

General circulation models (GCMs) are used to predict worldwide changes in weather patterns based upon atmospheric CO_2 concentrations and they consider interactions between greenhouse gas concentration a trapped solar radiation of the entire globe and output daily temperature and precipitation data. They forecast potential climate scenarios for possible futures. Generally, GCMs create data that is too large for regional use and downscaling must be performed before used in a local environment. Downscaling is a statistical technique or the refining of large scale climate data to a local environment. GCMs generally make data output on a scale that is appropriate for an area larger than 100 km^2, so it doesn't account for small scale geography that plays an important role in local weather. So, when downscaling climate data local geography and weather conditions are considered for a more refined climate projection.

The Coupled Model Intercomparison Project (CMIP5) is a framework of atmospheric-oceanic driven GCMs, comprised of about 30 coupled GCMs. The CMIP5 uses an anthropogenic class system to categorize emission scenarios called Representative Concentrated Pathways (RCPs) (Braconnot et al. 2011). RCP emission pathways are split into four different groups: 2.6, 4.5, 6.0, and 8.5. These different scenarios are grouped based upon hypothetical future anthropogenic influence on atmospheric greenhouse gas concentrations. Factors such as economic growth, urbanization, and technological growth and innovation are considered. Each scenario has a corresponding greenhouse gas emission and a resulting radiative forcing (W/m^2) that guide the projected effect on temperature and precipitation (Bjørnæs 1992).

- RCP 2.6 - Lowest emission path scenario; peak radiative forcing peak at 3.1 W/m^2 and then decline to 2.1 W/m^2 by 2100. Emissions peak in 2020 and reduced and becoming negative by 2100. Peak CO_2 concentration at 490 ppm (van Vuuren et al. 2011).
- RCP 4.5 – Moderate emission path; radiative forcing stabilizes after 2100 at 4.5 W/m^2, peaking at 2040. Peak CO_2 concentration at 650 ppm (Clarke et al. 2007)(Thomson et al. 2011).
- RCP 6.0 – Moderate emission path; 6.0 is also a stabilization pathway but has a stabilization at 6 W/m^2 by 2100 with a peak at 2080. Peak CO_2 concentration at 850 ppm (Fujino J, Nair R, Kainuma M 2016) (Masui et al. 2011).

- RCP 8.5 – Highest emission path; this is the rising scenario, with peak radiative forcing at 8.5 W/m^2 in 2100. Peak CO_2 concentration at 1370 ppm (Riahi et al. 2011).

There is a wide range of variability across the globe for projected climate change scenarios, on average though, temperature is expected to rise, and precipitation is expected to increase (Figure 4 Figure 5). These meteorological changes are expected to have cascading global effects on human and ecological health including: ocean acidification, mass species extinction, threatened food security, coastal flooding, drought, landslides, air pollution, water scarcity, reduction in snow pack, and more severe storms (Ernmenta and Nel 2014).

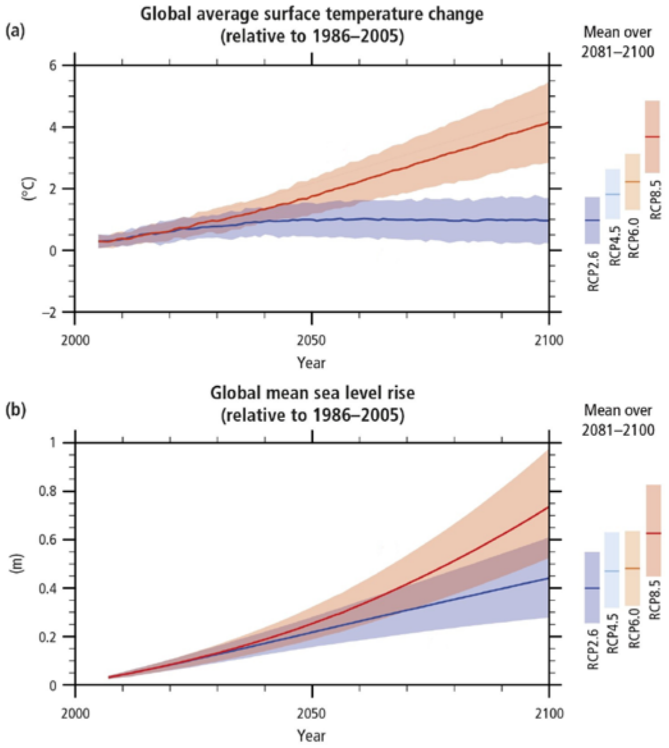

Figure 4: a) IPCC projection for global average increase in temperature for different climate emission scenarios b) IPCC projection for global mean sea level rise for different climate emission scenarios (Ernmenta and Nel 2014)

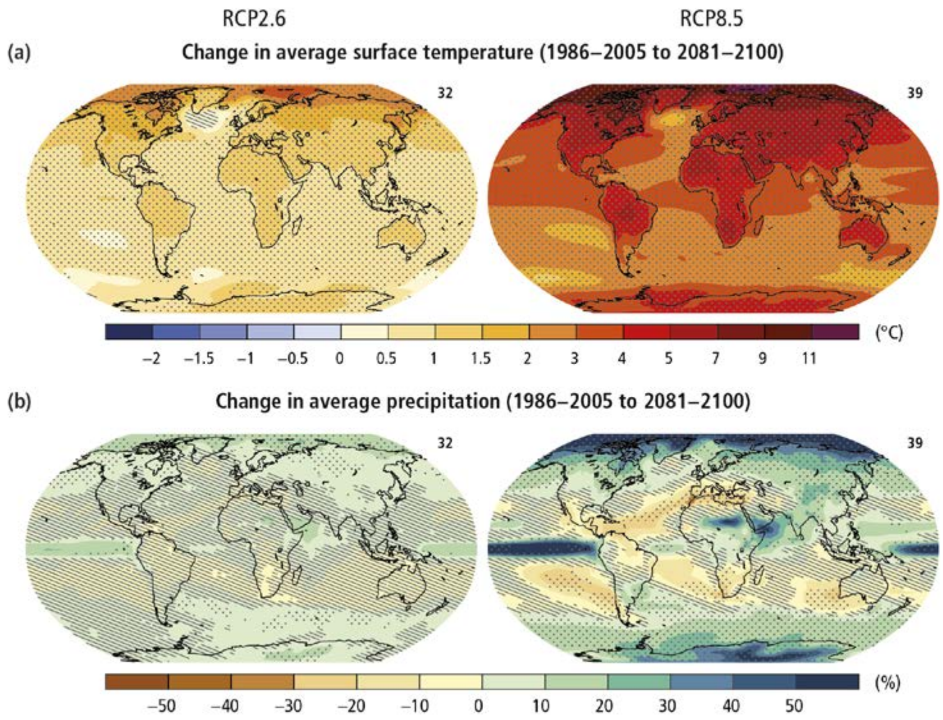

Figure 5: a) IPCC projection for average change in global surface temperature under RCP 2.6 and 8.5 emission scenarios for decadal average from 1986-2005 and 2081-2100 b) IPCC projection for average change in global precipitation under RCP 2.6 and 8.5 emission scenarios for decadal average from 1986-2005 and 2081-2100 (Ernmenta and Nel 2014)

1.6. Objectives

The goal of this study is to assess the effects of climate change on hydrological process in the Silver Bow Creek Watershed.

Specific objectives of this study are:

- Develop a Soil and Water Assessment Tool (SWAT) model of the study area
- Calibrate and validate the model within a statistically acceptable range of corresponding real-world data
- Conduct scenario analysis in the model with climate change data
- Investigate the effects of climate change on peak and base flows as well as the impact to snow pack.

2. Methods

2.1. Study Area

The study area is in southwestern Montana and is a 26-mile-long stretch of SBC, beginning at the confluence of Little Basin and Blacktail creeks and extending to USGS Opportunity gage station located just west of Opportunity MT, where it becomes the Clark Fork River (Figure 6). The area surrounding and containing the Berkeley Pit (west of Butte) is omitted from the watershed boundary, as it is hydrologically separated from the greater watershed.

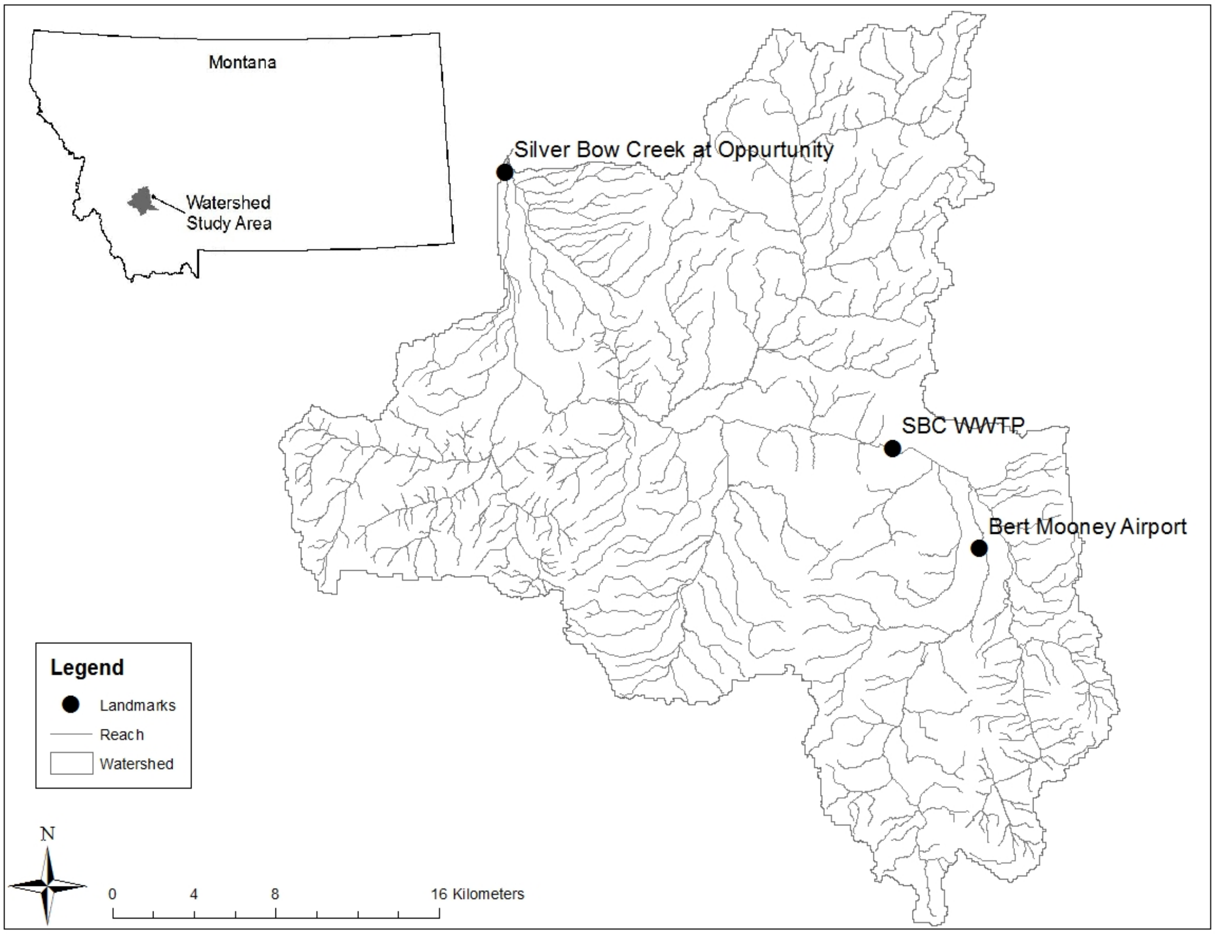

Figure 6: SBC Watershed

2.2. Model Development

2.2.1. Basic Model Overview

Figure seven outlines the basic process for model development. The model is built for the study area and then calibrated and validated to predetermined statistical standards. Following calibration and validation, the base line model's weather data is replaced with RCP 2.6, 4.5, 6.0, and 8.5 scaled CMIP5 weather data and compared to the baseline SWAT model.

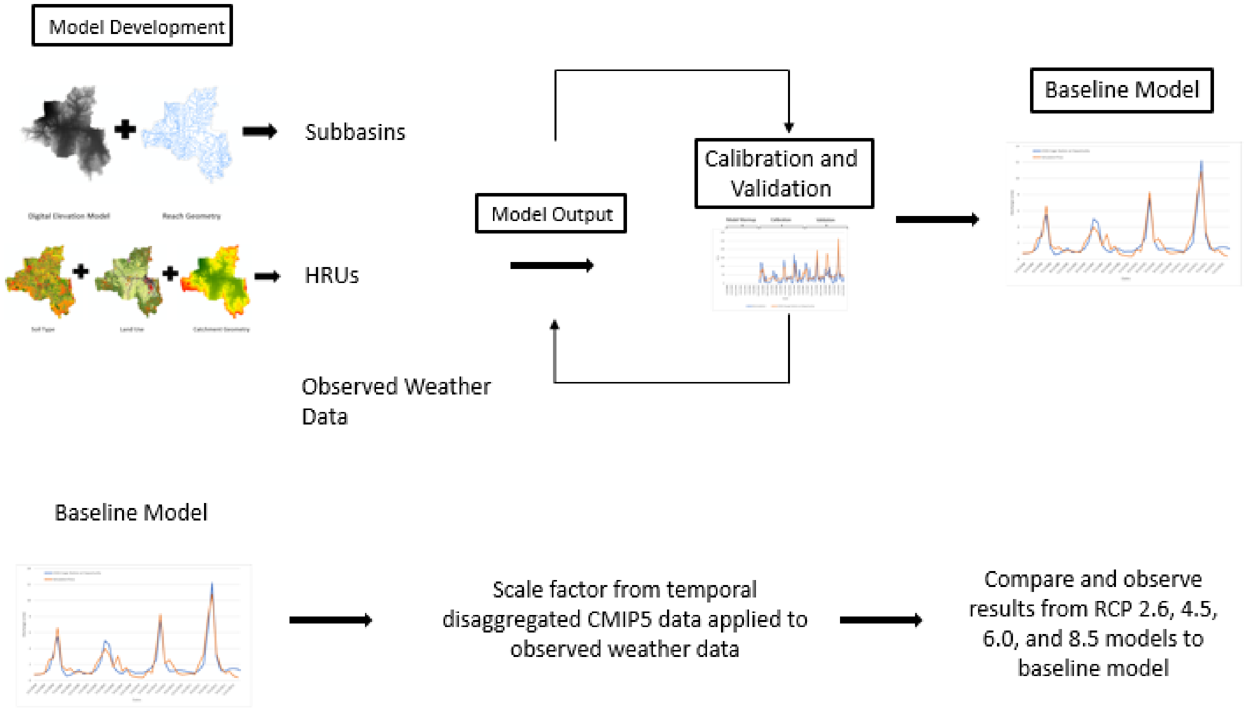

Figure 7: Conceptual flow diagram for model development

2.2.2. Watershed Delineation

The first step in SWAT's basin wide modeling is to divide the greater watershed into smaller units called subbasins. These subbasins are further divided into HRU's, which make up the basis for subbasin hydrologic process prediction.

The watershed was delineated using a 64-meter digital elevation model for Montana, downloaded from the Defense Mapping Agency's 3-arc second 1x1 degree 1: 250,000 scale Digital Elevation Models database (Defense Mapping Agency 1970). A mask was created with the U.S. Department of Agriculture's complete digital hydrologic unit boundary layer of sub-watersheds for Montana (U.S. Department of Agriculture, Natural Resources Conservation Service 2014). The watershed outlet was chosen at Opportunity, MT due to the availability of USGS stream gage data. Additionally, the USGS National Hydrography Dataset (U.S. Department of Agriculture, Natural Resources Conservation Service 2014) was used to burn in the stream network to increase accuracy.

According to (Jha et al. 2004) subbasin size has a significant influence on the model's accuracy to represent sediment loading and water quality, but not stream flow. The optimal size of the subbasin relative to the greater watershed was between 3-5% for sediment loading and water quality. The watershed in this study was created with 29 subbasin (Figure 8), with each subbasin on average accounting for 3% of the greater watershed area.

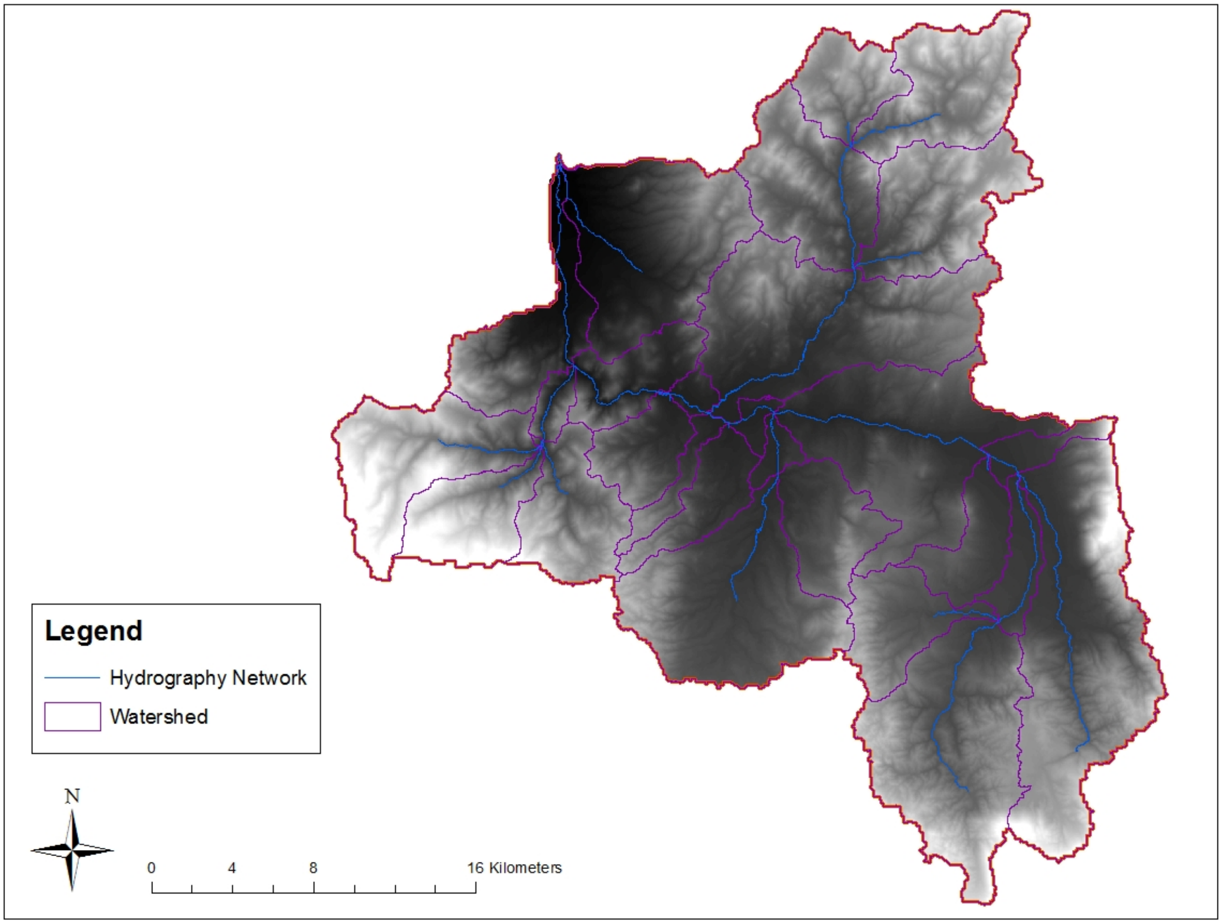

Figure 8:Subbasins

2.2.3. HRU Definition

After the watershed is discretized into smaller subbasins, it is further divided fundamental computational units called HRUs. HRUs are the smallest component of the model and are grouped based on homogenous land use, soil, catchment geometry, and slope to represent areas within the subbasin that respond similarly hydrologically (Figure 9). SWAT allows the user to define a specific HRU at multiple location across a subbasin. If a HRU is replicated throughout the subbasin it means that it's response to meteorological data will be the same. HRUs can further be classified upon the modeler's specifications to group certain land types together, omitting or including specific classes, or have certain land types play a larger role in the overall model.

With concern to model output, each unique HRU within a subbasin calculates independent yields for discharge, sediment, stream quality. HRU yields are then summed for a total yield of the subbasin (Shekhar and Xiong 2008).

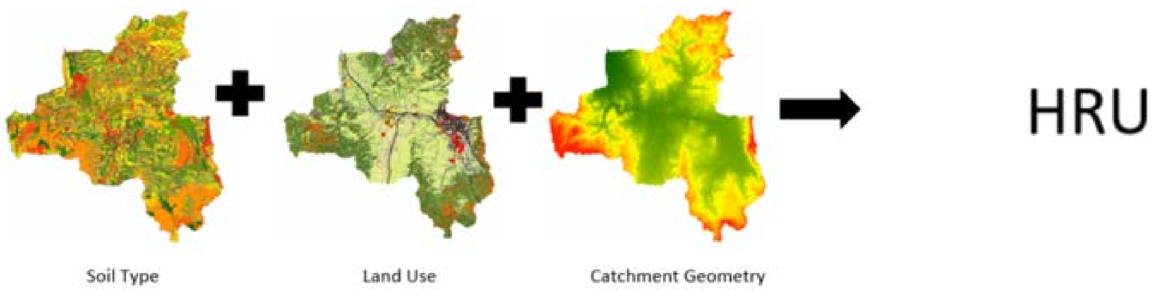

Figure 9: HRU Development

2.2.3.1. Land Use

SWAT uses a land use and cover raster set to determine the spatial extent of each class. For this study the Montana Land Cover Framework published by the Montana Natural Heritage program was used (Montana Natural Heritage Program 2016). This is a statewide raster set of land use and vegetation coverage for the state of Montana. SWAT requires land use classes in a specific format that is different from the Montana Land Cover Framework, so, a “.txt” file was created to translate land use designations from the Montana Land Cover Framework to SWAT appropriate land classes. Table I presents the land classes and corresponding percentages that were used in this study.

Table I: SWAT Land Use Classifications

Land Use	SWAT Code	Area (Ha)	% of Total Area
Commercial	UCOM	2173.55	2.45
Residential-Low Density	URLD	1125.78	1.27
Transportation	UTRN	4359.09	4.92
Forest-Evergreen	FRSE	42207.67	47.59
Range-Brush	RNGB	8510.36	9.60
Range-Grasses	RNGE	29109.49	32.82
Wetlands-Non-Forested	WETN	4.79	0.01
Industrial	UIDU	990.47	1.12
Residential-High Density	URHD	152.69	0.17
Agricultural Land-Generic	AGRL	52.86	0.06

2.2.3.2. Soil Data

The second step in HRU classification is the interpretation of soils data for the study area. This study used the Soil Survey Geographic (SSURGO) database published by the U.S. Department of Agriculture, Natural Resources Conservation Service (U.S. Department of Agriculture and Natural Resources Conservation Service 2017).

2.2.3.3. Slope

The third and final step in HRU classification is slope classification (Table II). For this study, five slope classes were created. These slope classes were chosen using an approach similar to (Moriasi et al. 2015).

Table II: Slope Classification

Class	Lower Limit	Upper Limit
1	0	10
2	10	20
3	20	30
4	40	50
5	50	9999

2.2.3.4. Elevation Bands

SWAT was originally developed to model agricultural basins where the main form of precipitation falls as rain and the basins are relatively flat (Arnold et al. 1998). Elevation bands were created for SWAT to account for the effect of orography on precipitation and temperature in mountain landscape watershed, particularly in snow melt driven system (Fontaine et al. 2002).

SWAT simulates precipitation as snow or rain based upon the average daily temperature, ‘SFTMP’, which is defined by the user. If the average air temperature falls below ‘SFTMP’ precipitation falls as snow rather than rain. As the elevation range in SBC watershed is significant, elevation bands were used within this study.

For each subbasin, SWAT determines modelled temperature and precipitation daily values based on proximity to input weather stations, and uses daily values provided by those stations. Elevation bands help to more accurately account for the effect of orography on temperature and precipitation with the use of empirically calculated lapse rates.

Initially, the model was run with the number of elevation bands in the range of 3-10. Using the model results, it was found that specifying five elevation bands is optimal on calibration and validation statistics. The model results were insensitive when the number of bands was greater than five. So, five elevation bands were used within the model for improving the calibration and validation statistics and computational efficiency.

2.2.4. Weather Stations

SWAT uses meteorological data to simulate precipitation across a study areas basin, including daily precipitation, daily maximum and minimum temperatures, solar radiation, wind speed, and relative humidity. If any observed meteorological data are not present for a subbasin, SWAT's simulated data is available for use. This study used four meteorological stations located across the basin (Figure 10) (

Table III) (NOAA and National Centers For Environmental Information 2017).

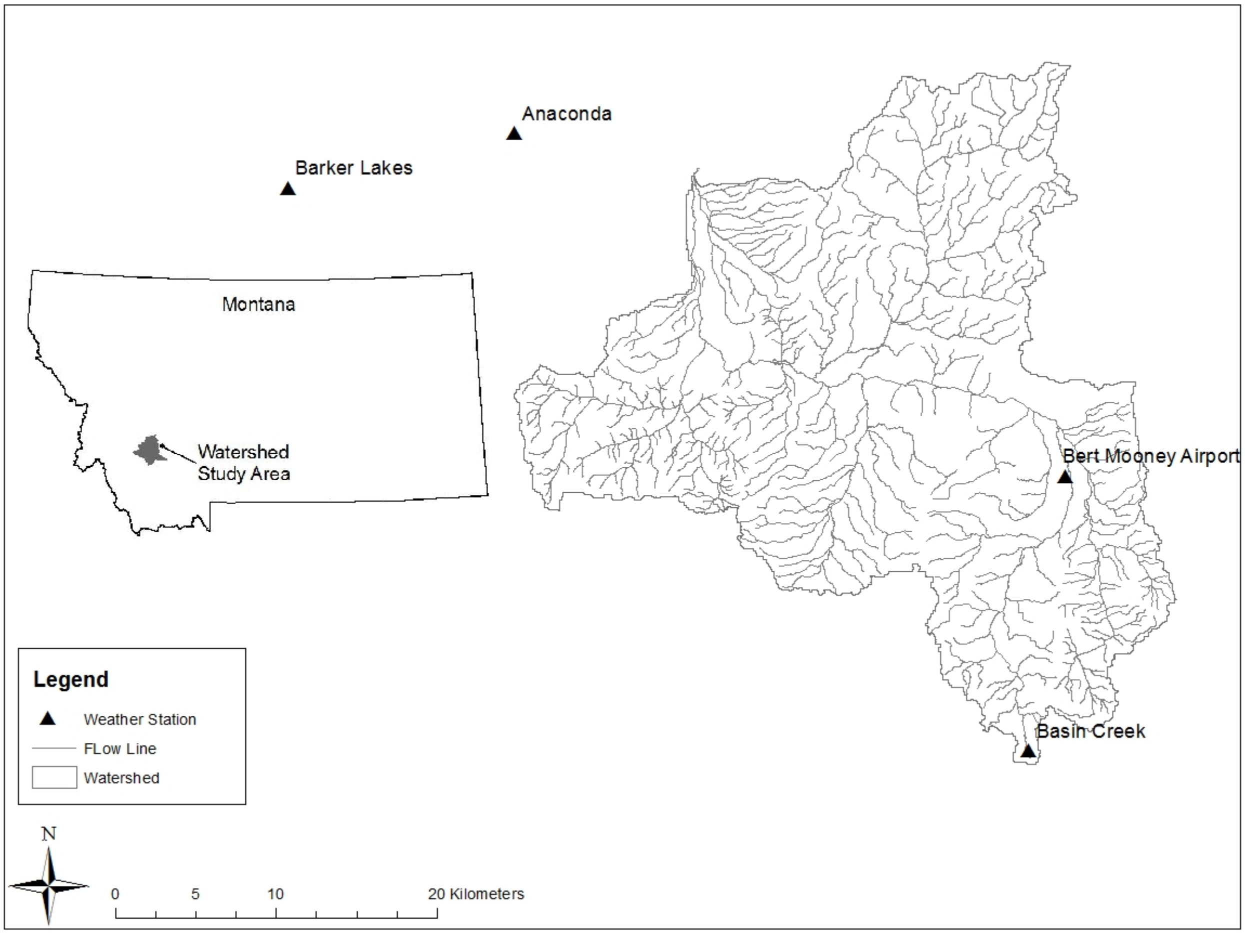

Figure 10: Weather Stations

Table III: Weather Stations

Name	Type	Elevation (km)	Latitude	Longitude
Bert Mooney Airport	Meteorological	1.67	45.95	-112.49
Anaconda	Meteorological	1.59	46.13	-112.95
Basin Cr.	SNOTEL	2.18	45.80	-112.51
Barker Lakes	SNOTEL	2.55	46.09	-113.13

Weather data from the four meteorological stations was compiled from 2004 – 2011. The Anaconda meteorological station went offline in the latter half of 2012 so, the simulation was only completed from 2004 through 2011 (NRCS 2018).

A continuous set of measured data for relative humidity, solar radiation, and wind speed were not available, so, simulated data was used. For the simulated data the CFSR World weather database was used (NCAR and UCAR 2017).

Two of the weather stations used in this study were SNOTEL site. SNOTEL sites are weather observation sites located in remote areas to monitor snow accumulation and melt. They are usually comprised of a snow pillow, snow depth sensor, solar radiation sensor, and precipitation gage.

2.2.5. Database Updates

2.2.5.1. Butte Silver Bow Waste Water Treatment Plant (SBC WWTP)

SWAT allows the user to create point source inputs into the model. The user can either upload a table or manually select a spot in the ArcSWAT interface. This is important for SBC watershed as SBC receives a significant daily discharge from the Silver Bow County Waste Water Treatment Plant. Average monthly values of year 2015 were formatted and used for all the simulated years of the model.

2.2.5.2. Temperature Lapse Rates

The introduction of elevation bands allows SWAT to lapse temperature theryby compensate for adiabatic cooling or heating. SWAT allows the user to define specific temperature lapse rates based upon observed data. This is especially important for areas that have large elevation differences and where temperature plays a key role in the formation, duration, and abundance of snow on the watershed, like SBC.

The watershed was divided into two regions based on data availability and perceived watershed configuration. The first region represented the eastern part of the watershed and used Bert Mooney Airport meteorological site to Basin Creek SNOTEL site. The second region, representing the western part of the watershed, included Anaconda meteorological station to Barker Lakes SNOTEL site for the western portion of the watershed (Figure 10). Temperature lapse rates were calculated by calculating the difference of the mean temperatures in each station (ΔT) (2004-2011) and dividing it by the difference in elevation between stations (Δkm) (1).

$$TLAPS = \Delta T / \Delta km \qquad (1)$$

Temperature lapse rates for Bert Mooney Airport to Basin Creek SNOWTEL and Anaconda meteorological stations to basin creek SNOTEL were calculated to be -1.37ºC/km and -5.1ºC/km, respectively (Table IV).

Table IV: Station Temperatures/Elevations

Location	Elevation (km)	Average Temperature (ºC)	Lapse Rates (°C/km)
Bert Mooney Airport	1.67	4.50	-1.37
Basin Creek SNOTEL	2.18	3.80	
Barker Lakes SNOTEL	2.55	2.00	-5.10
Anaconda	1.59	6.90	

2.2.5.3. Precipitation Lapse Rates

Another important component in modeling SWAT in areas with large elevations gains is precipitation lapse rates. Orographic precipitation is the result of moist air gaining elevation, and due to adiabatic cooling, condensing and precipitating. Precipitation lapse rates were calculated in the same manner as temperature lapse rates but replacing average temperature with average annual precipitation (ΔP) (2).

$$PLAPS = \Delta P / \Delta km \quad (2)$$

The precipitation lapse rate for the Bert Mooney Airport to Basin Creek SNOTEL site is 739.84 mm/km and 46.81 mm/km for Anaconda to Barker Lakes SNOTEL site (Table V).

Table V: Station Precipitation/Elevations

Location	Elevation	Average Precipitation (mm)	Lapse Rate (mm/km)
Bert Mooney Airport	1.67	246.50	739.84
Basin Creek SNOTEL	2.18	625.00	
Barker Lakes SNOTEL	2.55	437.00	46.81
Anaconda	1.59	392.50	

2.3. Calibration

SWAT is a complex model that simulates basin wide hydrological processes based upon empirical data. Because the model is complex, calibration and validation are required to understand whether the model is simulating real world scenarios accurately (Srinivasan et al. 2012). This is done by statistically comparing model output with the measured data. A split sample approach to calibration and validation was used for model performance evaluation. The model simulations were completed from 2004–2011, with 2004-2007 as warm up years, 2008-2009 as the calibration period, and 2010-2011 as the validation period.

The first step in calibration is sensitivity analysis, which helps to identify the parameters that directly affect the model outputs and the suitable range that they fall within (White and Chaubey 2005). A sensitivity analysis was performed for both the SWE and discharge parameters using a local approach of adjusted single parameters individually. Following sensitivity analysis, calibration was performed using the data from Basin Creek SNOTEL and

USGS Gage Station Silver Bow Creek at Opportunity for discharge of the greater SBC watershed model.

2.3.1. Snowpack Calibration

Because snowpack plays an integral role in surface water flows for the study area, calibration of snow pack was performed prior to surface water calibration. Snowpack is represented in SWAT as snow water equivalent (SWE), which is calculated using a mass balance approach, where a previous time step SWE (SWE_1) is added to current snowfall (P_{sb}) and evapotranspiration (E_s) and release of meltwater (M) is subtracted (3).

$$SWE_2=SWE_1+P_{sb}-M-E_s \tag{3}$$

A sensitivity analysis, as well as a meta-analysis of similar projects (Fontaine et al. 2002) Ahl, Woods, and Zuuring 2008)(Arnold et al. 2012), identified input parameters that have the largest effect on SWE (Table VI).

Table VI: Snowmelt Parameters

Parameter Name	Description	Units
SFTMP	Snow fall temperature; temperature at which precipitation falls as snow	ºC
SMTMP	Snow melt base temperature; temperature at which snow pack melts	ºC
TIMP	Snow pack temperature lag factor: influence of the previous days snow pack temp on current day	Unitless
SNO50COV	Fraction of snow volume represented by SNOCOVMX that corresponds to 50% snow cover	Unitless
SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover	Unitless
SMFMX	Melt factor for snow in June 21	mm/C/day
SMFMN	Melt factor for snow on December 21	mm/C/day

To calibrate the SWE, a unit source SWAT model was created using the subbasin that contained the SNOTEL site for the sake of reducing computational time and ensuring the site was at the exactly correct elevation (Figure 11). Once the smaller SWE SWAT model was calibrated, the snow melt parameter values were used to help guide snow melt in the larger SWAT project as discussed in later sections.

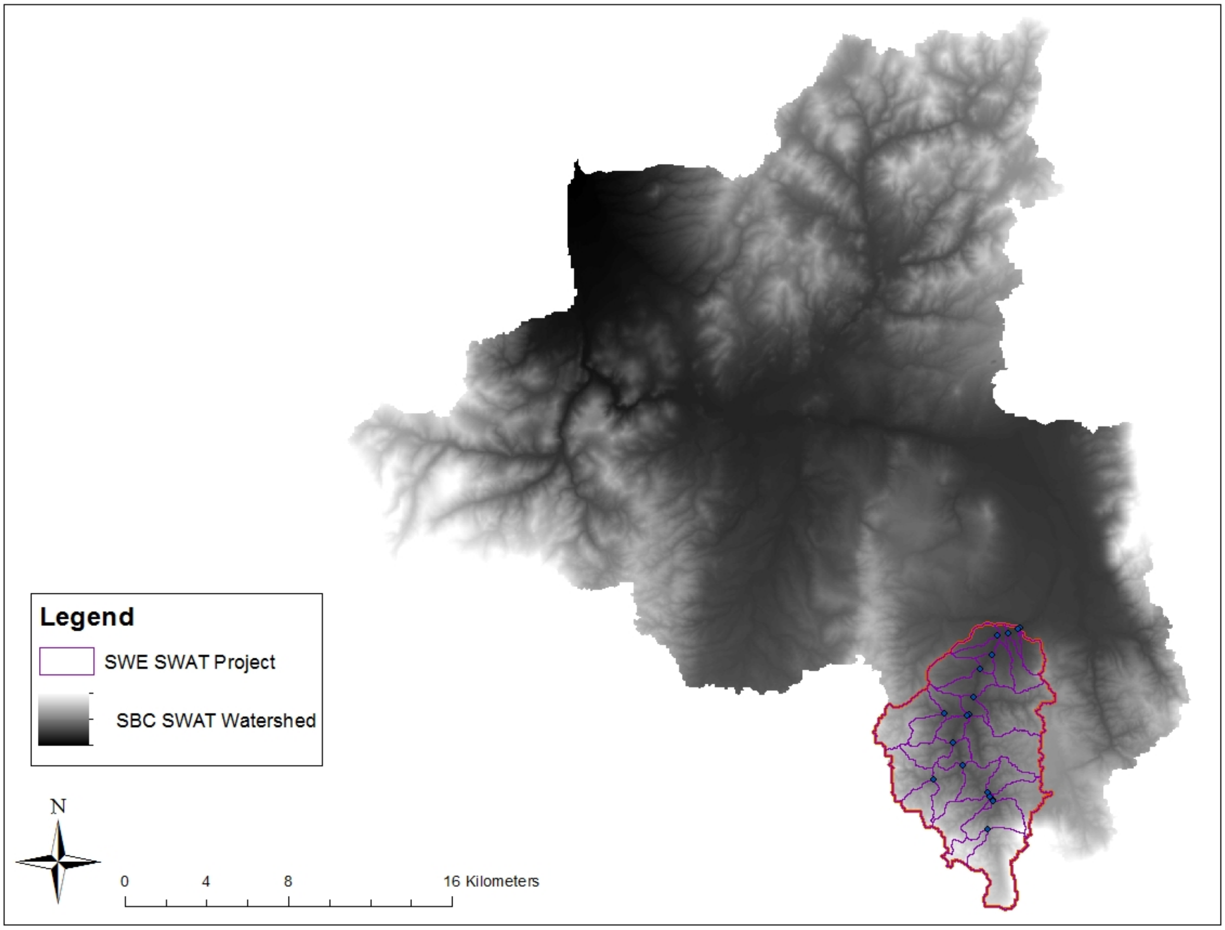

Figure 11: SWE SWAT Model

2.3.2. Streamflow Calibration

A sensitivity analysis, as well as an meta-analysis of similar projects (Arnold et al. 2012)(Flynn and Van Liew 2011)(Fontaine et al. 2002)(Watershed et al. 2008) (Ahl et al. 2008), cumulated a table of parameters to target for calibration of surface water discharge (Table VII).

Table VII: Surface Discharge Parameters

Process	Parameters	Description	Units
Surface Runoff	CN2	Initial SCS runoff curve number	Unitless
	SOL_AWC	Available water capacity of the soil layer	mm H_2o/mm soil
	ESCO	Soil evaporation compensation factor	Unitless
	EPCO	Plant uptake compensation factor	Unitless
	SURLAG	Surface runoff lag coefficient	Unitless
	OV_N	Mannings N value for overland flow	
Base flow	ALPHA_BF	Groundwater flow response to changes in recharge	1/days
	GW_Revap	Groundwater "revap" coefficient	Unitless
	GW_Delay	Groundwater Delay	Unitless
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur.	mm H_2o
	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur	mm H_2o
	RCHARG_DP	Deep aquifer percolation fraction	Unitless

Three USGS Gage Stations were located within the study area (Figure 12). This study originally planned on using a split calibration approach: calibrating Silver Bow Creek Below Blacktail then loading calibrated discharge downstream and then calibrate at Silver Bow Creek at Opportunity. Given time constraints, daily and monthly data from USGS Gage Station Silver Bow Creek at Opportunity were used to calibrate and validate the model(U.S. Geological Survey 2000).

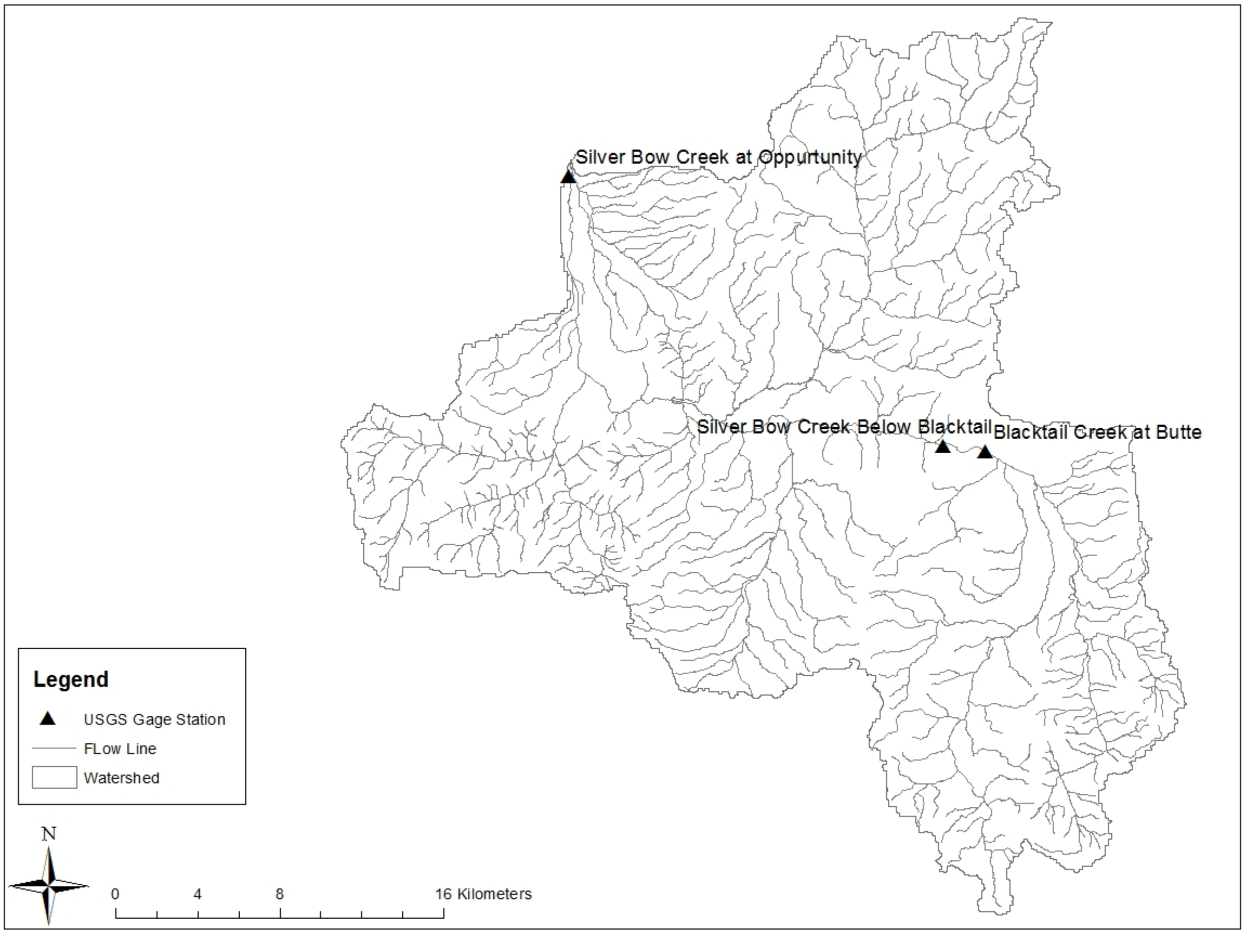

Figure 12: USGS Gage Stations

2.3.3. Calibration Statistics

Streamflow was calibrated manually by adjusting input parameters. Two calibration statistics, Nash-Sutcliffe efficiency (NSE) (4) and percent bias (PBIAS), were used to evaluate the model based on the goals of the study (D. N. Moriasi et al. 2007).

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right] \tag{4}$$

where Y_i^{obs} is the observed value, Y_i^{sim} is the simulated values from SWAT, and Y^{mean} is the mean value of the observed values for the period of simulation. PBIAS is calculated using equation (5):

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) * (100)}{\sum_{i=1}^{n} \left(Y_i^{obs} \right)} \right] \tag{5}$$

where Y_i^{obs} is the observed values over the course of simulation, and Y_i^{sim} is simulated values over the course of the simulation.

A meta-analysis of hydraulic models was used to identify common statistical performance measures and evaluation standards for SWAT (Moriasi et al. 2015). The evaluation standards to evaluate the success of this study are reported in Table VIII.

Table VIII: NSE and PBIAS Performance Standards (per Moriasi et al.)

Measure	**Temporal Scale**	**Very Good**	**Good**	**Satisfactory**	**Not Satisfactory**
PBIAS	Annual	≤±2.5	±2.5≤ PBIAS ≤ ±15	±2.5≤ PBIAS ≤ ±15	≥ 60
	Monthly	≤±3.0	±3.0≤ PBIAS ≤ ±10	±10≤ PBIAS ≤ ±15	≥ 15
	Daily	≤±10	±10≤ PBIAS ≤ ±15	±15≤ PBIAS ≤ ±45	≥ 45
NSE	Annual	>.75	.60 ≤ NSE ≤ .75	.50 ≤ NSE ≤ .60	≤ .50
	Monthly	>.85	.70 ≤ NSE ≤ .85	.55 ≤ NSE≤ .70	≤ .55
	Daily	>.80	.70 ≤ NSE ≤ .80	.50 ≤ NSE ≤ .70	≤ .50

2.4. Climate Change Data

Following a satisfactory calibration and validation of the model (Table VIII), the model's daily min and max temperatures and precipitation were scaled from the downed CMIP5 climate change data. Scale factors were calculated using averages from 1990-2010 and 2050-2070 as described below.

2.4.1. Projected Climate Change Data Sources

This study used the World Climate Research Programme's (WCRP's) fifth phase of the couple model intercomparison project (CMIP5) multi-model ensemble (Brekke et al. 2013). The data consisted of 132 daily bias-correction constructed analogues (BCCAv2) models that were downloaded in a rectangular extent around the watershed area (46.2672 Latitude/-113.2196 Longitude; 45.9301 Latitude/-112.4686 Longitude) to a 1/8th degree resolution. Monthly values for precipitation rate (mm/day), minimum surface air temperature (ºC), and maximum surface air temperature (ºC) were used for this study. This rectangular grid was further refined to only select points that fell within the watershed area (Figure 13).

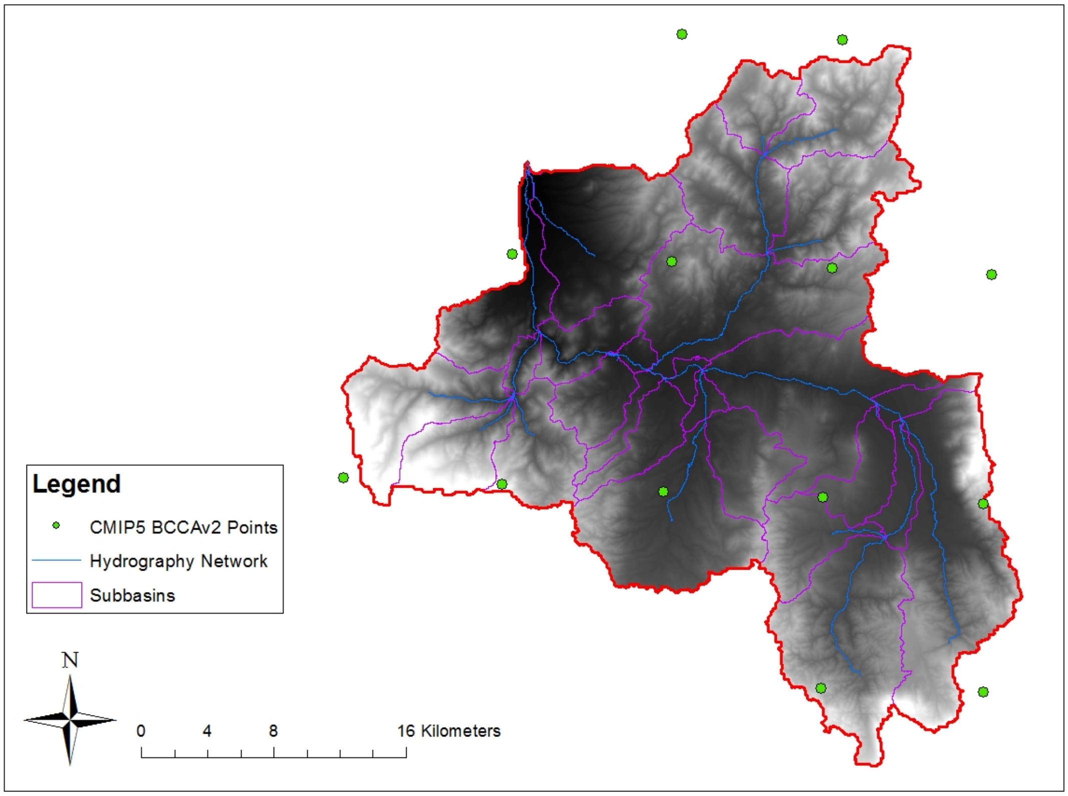

Figure 13: CMIP5 BCCAv2 Climate Data Points

2.4.2. Scenarios

Four different emission scenarios where used in this study (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) to evaluate the effects of climate change on SBC watershed. RCP 2.6 is characterized as a low emission scenario, RCP 4.5 is characterized by an intermediate emissions scenario, RCP 6.0 is characterized by a slightly higher intermediate emissions scenario, and RCP 8.5 is characterized by a high emissions scenario.

2.4.3. Temporal Disaggregation

To avoid capturing any yearly climate anomalies, decadal averages were used in developing scaling factors for the observed meteorological data (Krysanova and Srinivasan 2014) (Johnson et al. 2015). Average precipitation and temperature for individual months were calculated over twenty-year periods, 1990-2010 and 2050-2070, and compared. Mean differences in temperature for each month, between the two periods, were added to historical daily data for the corresponding month (Table IX). Precipitation ratios between the two decadal averages were used as a multiplier for the corresponding months (Table X).

Table IX: Scaling factors for temperature

	RCP 2.6 Monthly Averages (°C)			**RCP 4.5 Monthly Averages (°C)**			**RCP 6.0 Monthly Averages (°C)**			**RCP 8.5 Monthly Averages (°C)**		
	1990-2010	2050-2070	RCP 2.6	1990-2010	2050-2070	RC9 4.5	1990-2010	2050-2070	RCP 6.0	1990-2010	2050-2070	RCP 8.5
January	-7.54	-7.13	**0.41**	-11.37	-9.72	**1.65**	-10.03	-8.14	**1.89**	-8.21	-5.80	**2.41**
February	-5.72	-4.00	**1.72**	-9.39	-6.52	**2.87**	-8.90	-7.30	**1.60**	-6.15	-2.87	**3.28**
March	-2.62	-0.45	**2.17**	-5.97	-2.11	**3.86**	-5.86	-3.38	**2.48**	-3.17	0.50	**3.67**
April	2.83	3.40	**0.57**	-0.42	2.60	**3.02**	0.11	1.59	**1.49**	1.95	5.36	**3.41**
May	7.34	8.35	**1.01**	5.01	7.17	**2.15**	4.90	6.85	**1.95**	7.55	10.01	**2.46**
June	11.86	13.18	**1.33**	9.39	11.70	**2.32**	9.66	11.36	**1.70**	11.94	15.65	**3.71**
July	15.40	17.03	**1.62**	13.66	17.17	**3.52**	12.82	15.32	**2.51**	16.11	21.91	**5.80**
August	14.52	16.42	**1.90**	11.83	15.93	**4.11**	12.09	14.12	**2.03**	14.77	20.22	**5.45**
September	9.39	10.65	**1.26**	7.07	9.88	**2.82**	6.90	9.49	**2.60**	9.39	14.35	**4.96**
October	3.82	5.64	**1.82**	1.66	3.90	**2.25**	1.59	3.87	**2.27**	3.97	6.96	**2.99**
November	-2.34	-0.69	**1.65**	-5.33	-2.59	**2.73**	-4.73	-2.63	**2.09**	-3.13	0.01	**3.14**
December	-7.02	-6.05	**0.96**	-11.18	-8.70	**2.48**	-9.93	-7.57	**2.36**	-8.17	-3.77	**4.41**

Table X: Scaling factors for precipitation

	RCP 2.6 Monthly Averages (mm H_2O)			**RCP 4.5 Monthly Averages (mm H_2O)**			**RCP 6.0 Monthly Averages (mm H_2O)**			**RCP 8.5 Monthly Averages (mm H_2O)**		
	1990-2010	2050-2070	RCP 2.6	1990-2010	2050-2070	RCP 4.5	1990-2010	2050-2070	RCP 6.0	1990-2010	2050-2070	RCP 8.5
January	1.24	1.10	**0.88**	1.15	1.21	**1.04**	1.33	1.59	**1.19**	1.16	1.01	**0.87**
February	1.04	1.04	**0.99**	0.98	1.20	**1.23**	1.16	1.04	**0.90**	1.06	0.94	**0.88**
March	1.41	1.83	**1.29**	1.67	1.80	**1.07**	1.42	1.81	**1.27**	1.66	2.06	**1.24**
April	2.10	2.39	**1.13**	1.67	2.43	**1.45**	2.24	2.53	**1.12**	1.56	2.44	**1.55**
May	2.19	2.50	**1.14**	2.48	2.28	**0.91**	2.23	2.85	**1.27**	2.41	2.55	**1.05**
June	2.37	2.44	**1.02**	2.40	2.18	**0.90**	2.40	2.15	**0.89**	2.32	1.73	**0.74**
July	1.55	1.30	**0.83**	1.10	0.96	**0.87**	1.61	0.97	**0.60**	0.97	0.52	**0.54**
August	1.07	0.76	**0.71**	1.21	0.90	**0.74**	1.10	1.24	**1.12**	1.19	0.96	**0.80**
September	1.44	1.33	**0.92**	1.33	1.13	**0.85**	1.39	1.19	**0.86**	1.20	0.98	**0.81**
October	1.08	0.98	**0.90**	1.12	1.19	**1.05**	1.12	1.10	**0.97**	1.01	1.20	**1.18**
November	1.11	1.27	**1.14**	1.14	0.96	**0.84**	1.05	1.14	**1.09**	1.19	1.40	**1.17**
December	1.09	1.33	**1.22**	0.94	1.05	**1.11**	1.03	1.50	**1.45**	0.88	1.00	**1.13**

3. Results and Discussion

3.1. Pre-calibration Model

Before calibration, the preliminary model's performance was compared to USGS gage station data to help identify parameters that need further investigation (Figure 14).

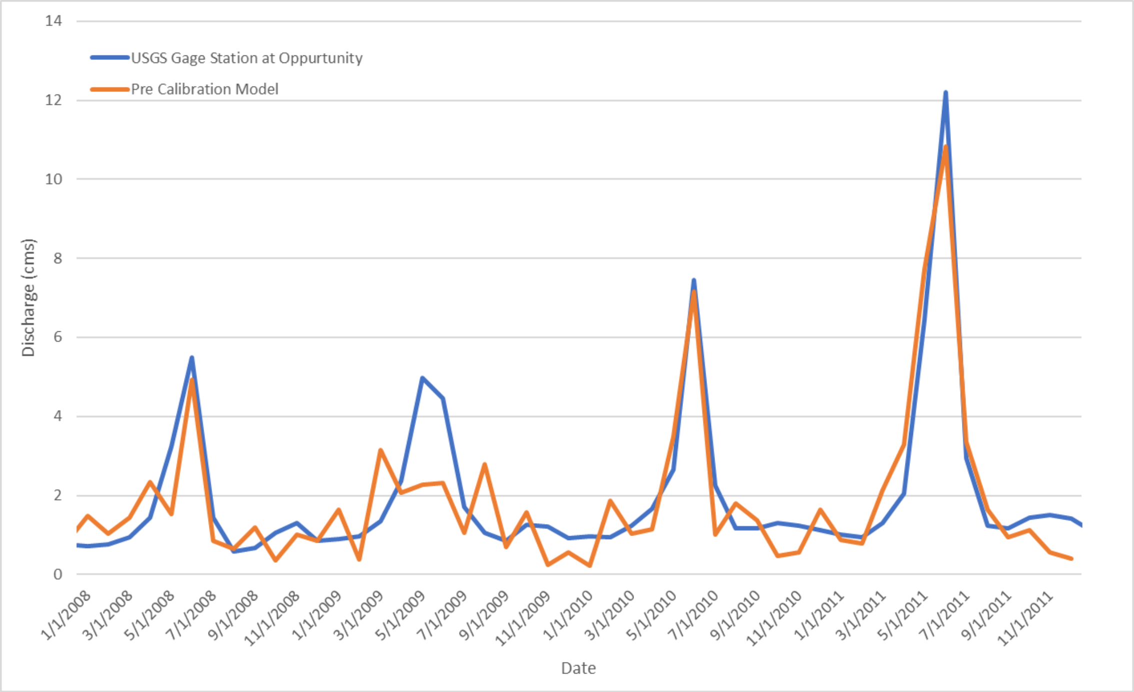

Figure 14: Pre-calibration Monthly Discharge

The model's calibration period had a monthly NSE values of .45 and PBIAS value of 10.1; the validation period had a NSE value of .91 and a PBIAS value of 2.5 (Table VIII: NSE and PBIAS Performance Standards). The preliminary model predicted the flow rates reasonably well, however, the prediction can be improved by systematic calibration and validation. Several areas were identified to target during calibration: systematic underestimation of base flow, failure to simulate some high peak flows, and secondary peaks.

3.2. Snowpack Calibration

As the snow pack plays a significant role in discharge, snow water equivalent was calibrated prior to discharge to help guide parameter selection (Figure 10). A final calibration resulted in a calibrated daily NSE of .91, PBIAS of 7.58, and a validated value for NSE of .93, and PBIAS of 7.69 (Figure 15)(Table XI).

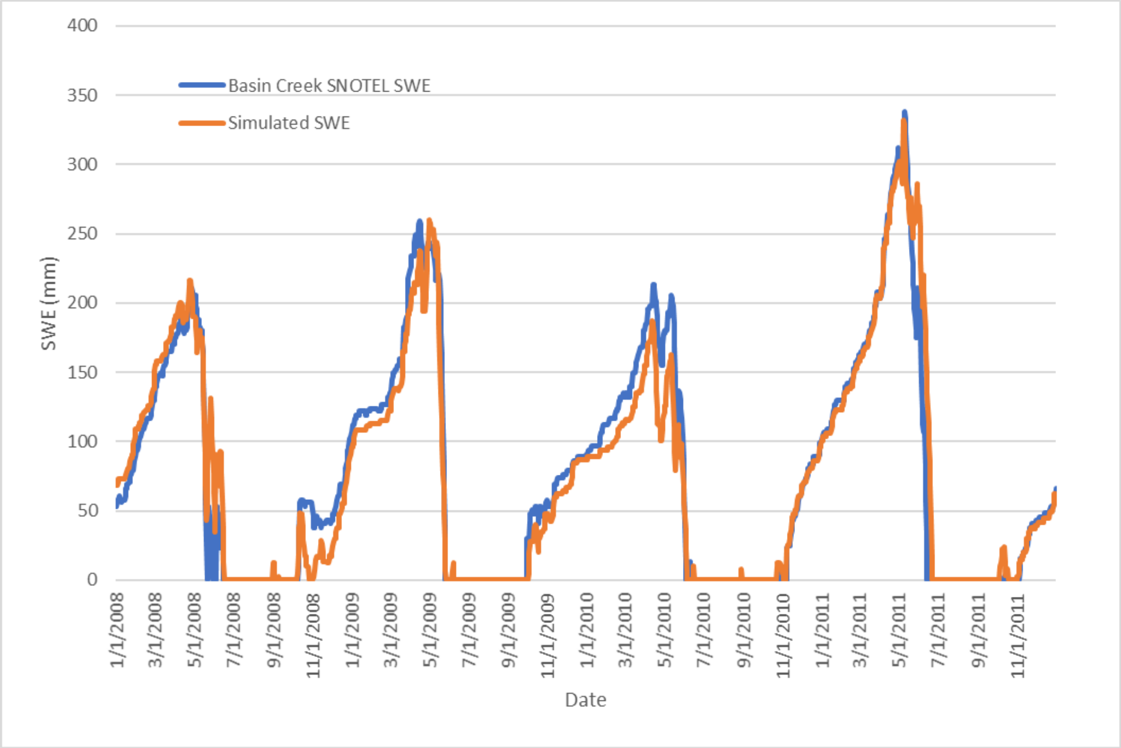

Figure 15: Calibrate SWE

Calibrated SWE values were used for guidance in the main SWAT model. The original and calibrated model parameters are presented in Table IX.

Table XI: Calibrated SWE Values

Parameter	**Description**	**SWAT Recommended Range/Units**	**Original Value**	**Calibrated Value**
SFTMP	Snow fall temperature	-5/5 (ºC)	1	5
SMTMP	Snow melt base temperature	-5/5 (ºC)	.5	2.5
TIMP	Snow pack temperature lag factor	0-1	1	.1
SMFMX	Melt factor for June 21	0-10 (mm/C/day)	4.5	2.5
SMFMN	Melt factor for December 21	0-10 (mm/C/day)	4.5	2.5

3.3. Discharge Calibration

3.3.1. Daily

Satisfactorily daily calibration and validation statistics could not be achieved for the simulated discharge values. This is one of the major limitations of this study. Daily flow values simulate micro surges of water occurring on the landscape, sometimes ten times as much as the observed runoff values. Even though there is a gross discrepancy between the daily simulation and the observed values, these over simulated daily values seem to be “washed out” during the monthly calibration and validation because satisfactory monthly calibration and validation statistics were achieved.

An inspection into the source of the simulated extra water revealed that it was all coming from snow melt. Most likely SWAT is simulating these flash melts of snow and not directing them correctly, either from groundwater delay or overland flow.

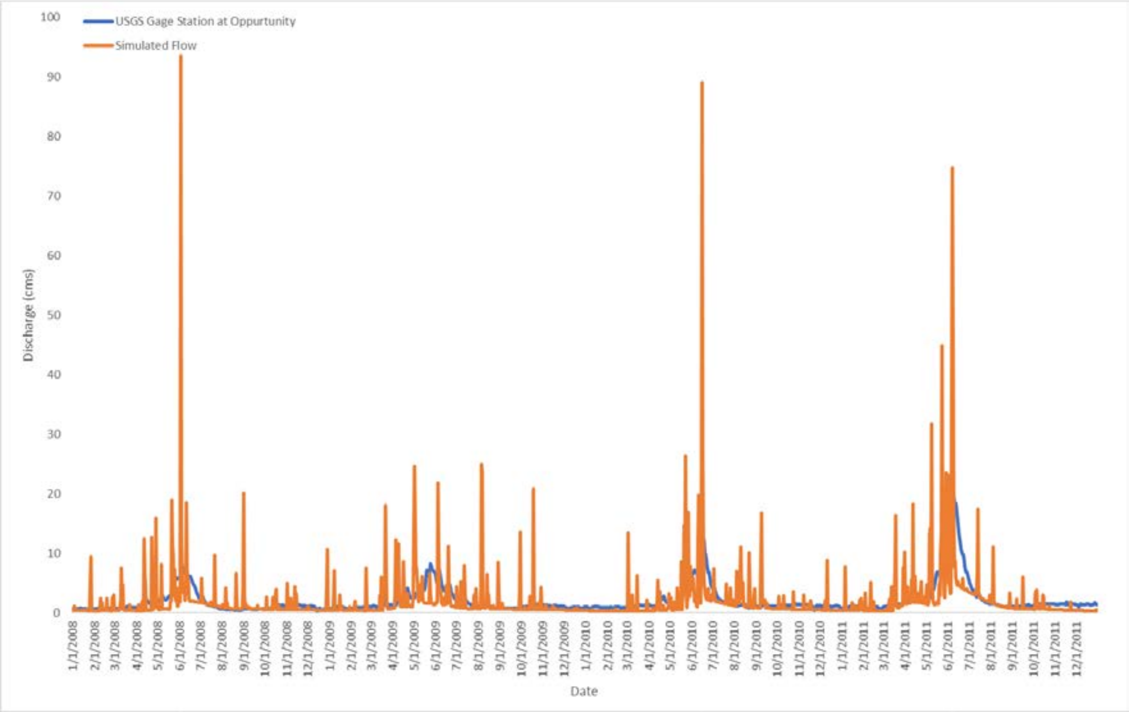

Figure 16: Simulated Daily Discharge vs Observed at Opportunity Gage Station

3.3.2. Monthly

The model performance statiscs for the monthly calibration period are .72 NSE and -10.3 PBIAS, and.91 NSE and -1.51 PBIAS for the validation period (Table VIII). The model's outputs had an overall good fit to the measured data. The model has reasonably predicted peak runoff and late summer base flows. It systematically predicted the peak runoff very well as well as the late summer baseflow. In general, the model performed better in the validation period than the calibration period. Overall, the model represented real world discharge well and was found suitable for use in climate change scenario analysis. The existing conditions presented below in Figure 17 form the baseline for the climate change evaluations.

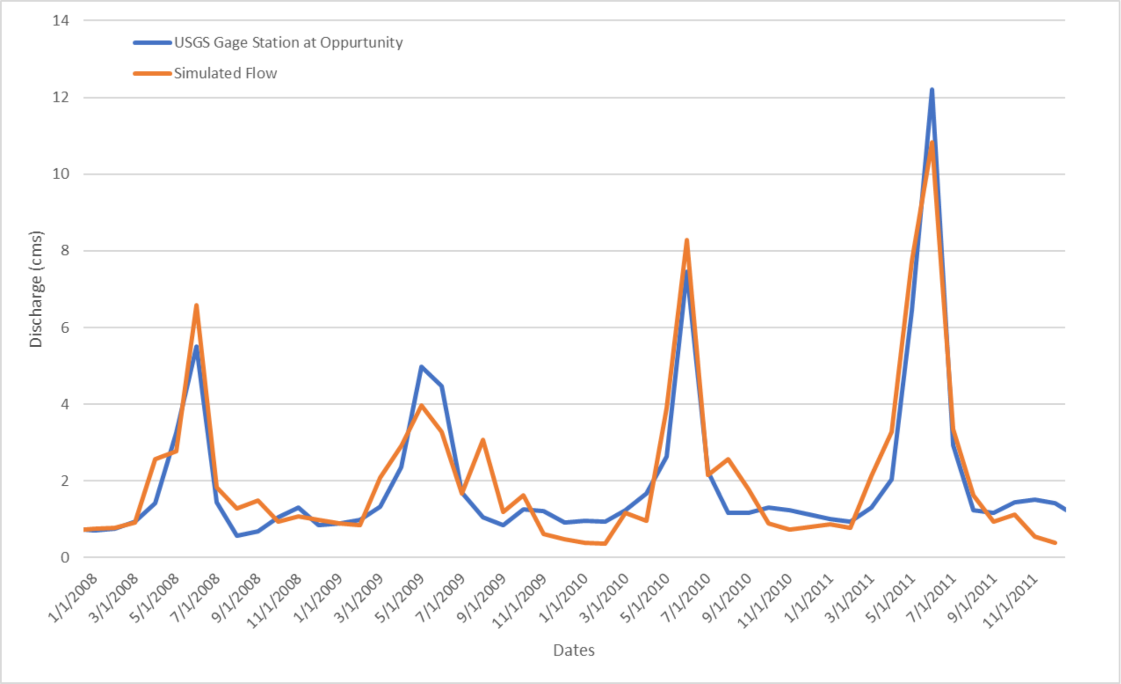

Figure 17: Calibrated and validated Monthly Discharge

3.4. Climate Change Data – Temperature

Decadal averages for1990-2010 and 2050-2070 were computed for RCP 2.6, 4.5, 6.0, and 8.5 and indicate an increase of temperature across the watershed with the largest increases seen in the spring and summer (Figure 18). Each scenario projects a relative higher temperature across the watershed, due to global increase in radiative forcing (van Vuuren et al. 2011), omitting RCP 4.5, which is higher than RCP 6.0. Scenario RCP 4.5 is a peak and stabilizing scenario, with peak radiative forcing occurring around mid-century then stabilizing to 4.5 W/m^2 at the end of the century (Thomson et al. 2011), whereas, RCP 6.0 is a stabilization scenario with a gradual increase of 6.0 W/m^2. Due to this peak radiative forcing occurring in RCP 4.5 mid-century receives a higher radiative forcing for RCP 4.5 than 6.0.

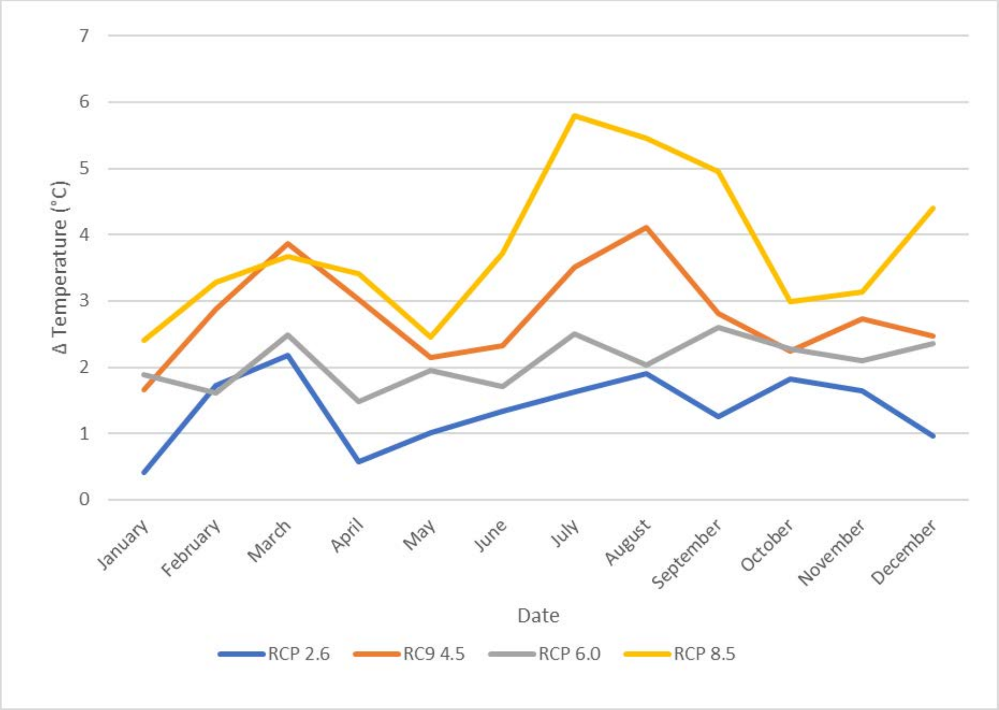

Figure 18: Δ Temperature of GCM data: 1990-2010 vs. 2050-2070

3.5. Climate Change Effects on Precipitation

All RCP scenarios predicted an increase in overall basin wide precipitation in early spring and late summer and a decrease during summer and winter (Figure 19). Both the findings for the temperature as well as the precipitation are consistent with other climatic studies for Montana (Silverman et al. 2017).

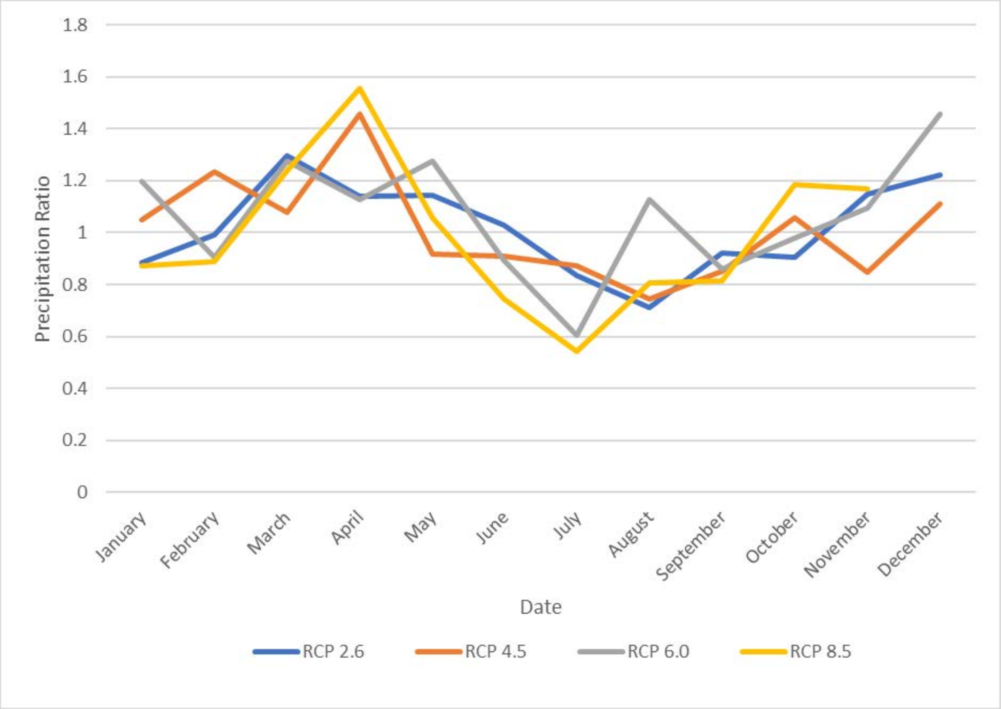

Figure 19: Precipitation Ratio of GCM data: 1990-2010 vs. 2050-2070

3.6. Climate Change Effects on Snowpack

As simulated in SWAT, an incremental decrease of SWE can be seen with each consecutive scenario, excluding RCP 6.0, which has a larger SWE content than RCP 4.5 due to the higher radiative forcing during mid-century (2050). The increased precipitation in the spring modeled some years with an earlier accumulation of snowpack, specifically 2008, but generally all scenarios predict less snow fall later in the season and melting sooner. Average April SWE values for the historical data was computed and compared to all four scenarios: RCP 2.6 SWE decreased by 23%, RCP 4.5 SWE decreased by 58%, RCP 6.0 SWE decreased by 31%, and RCP 8.5 SWE decreased by 65%.

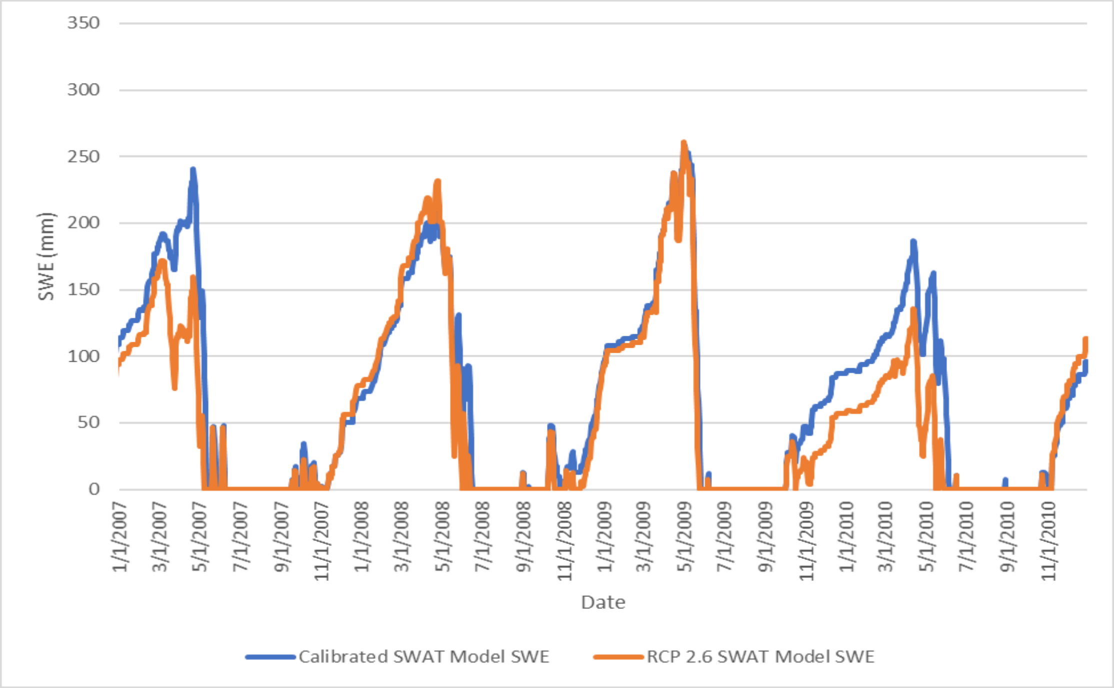

Figure 20: RCP 2.6 Basin Creek SNOTEL SWE Simulation

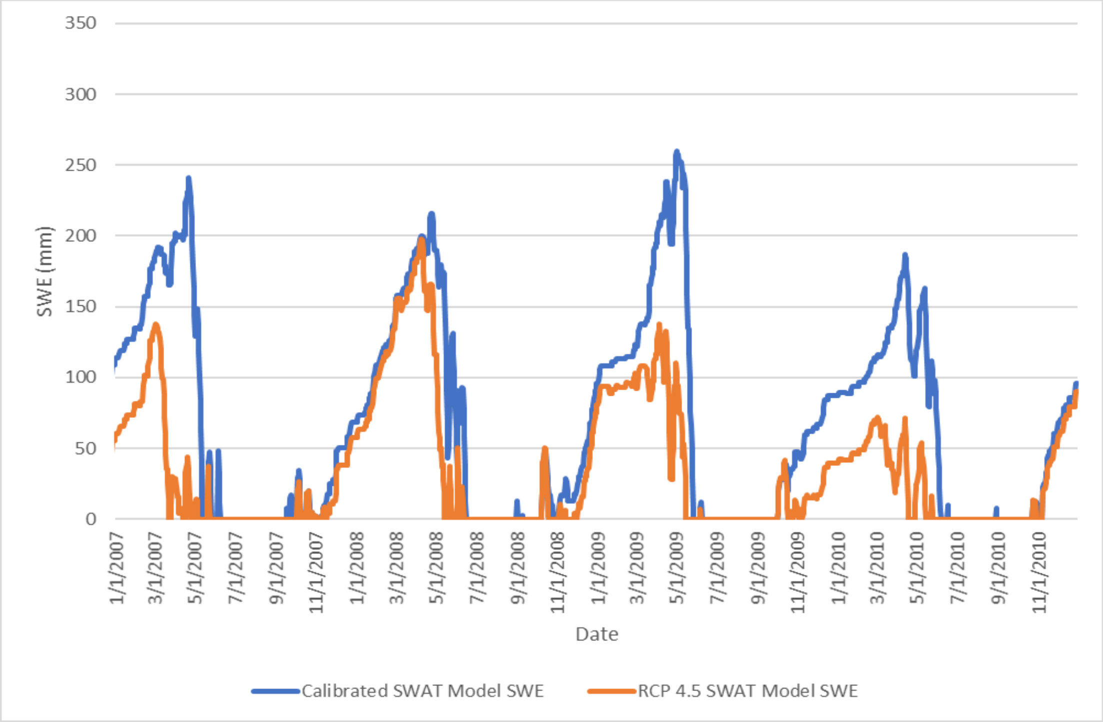

Figure 21: RCP 4.5 Basin Creek SNOTEL SWE Simulation

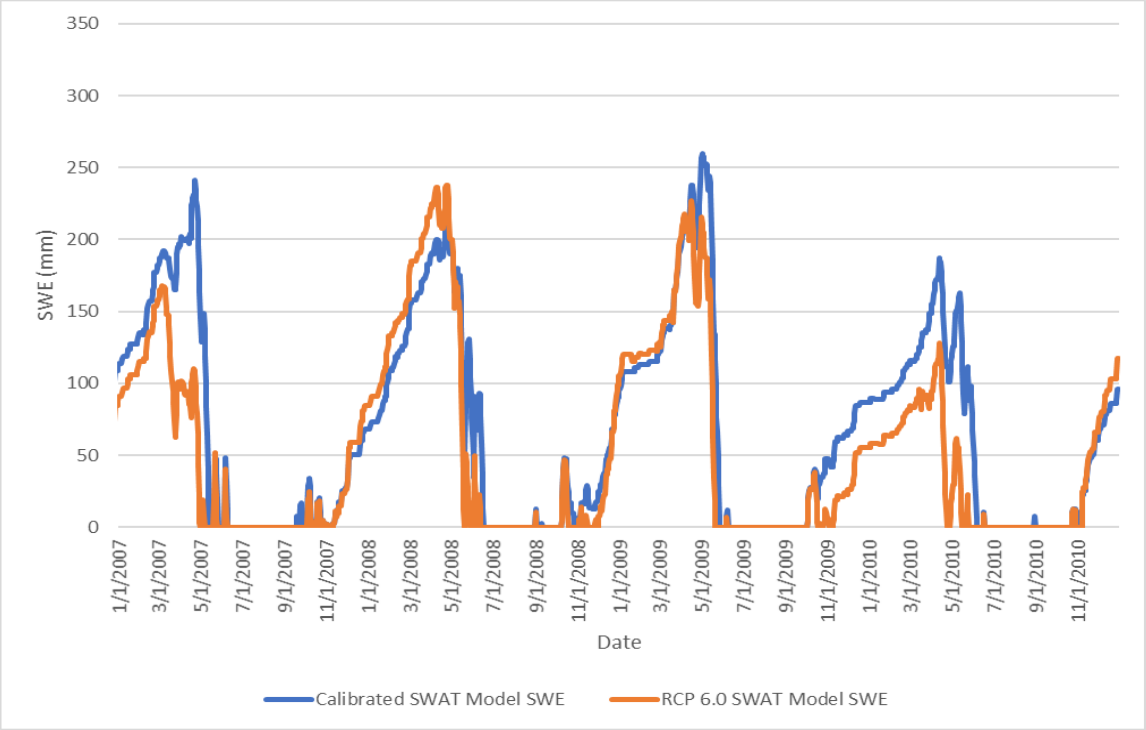

Figure 22: RCP 6.0 Basin Creek SNOTEL SWE Simulation

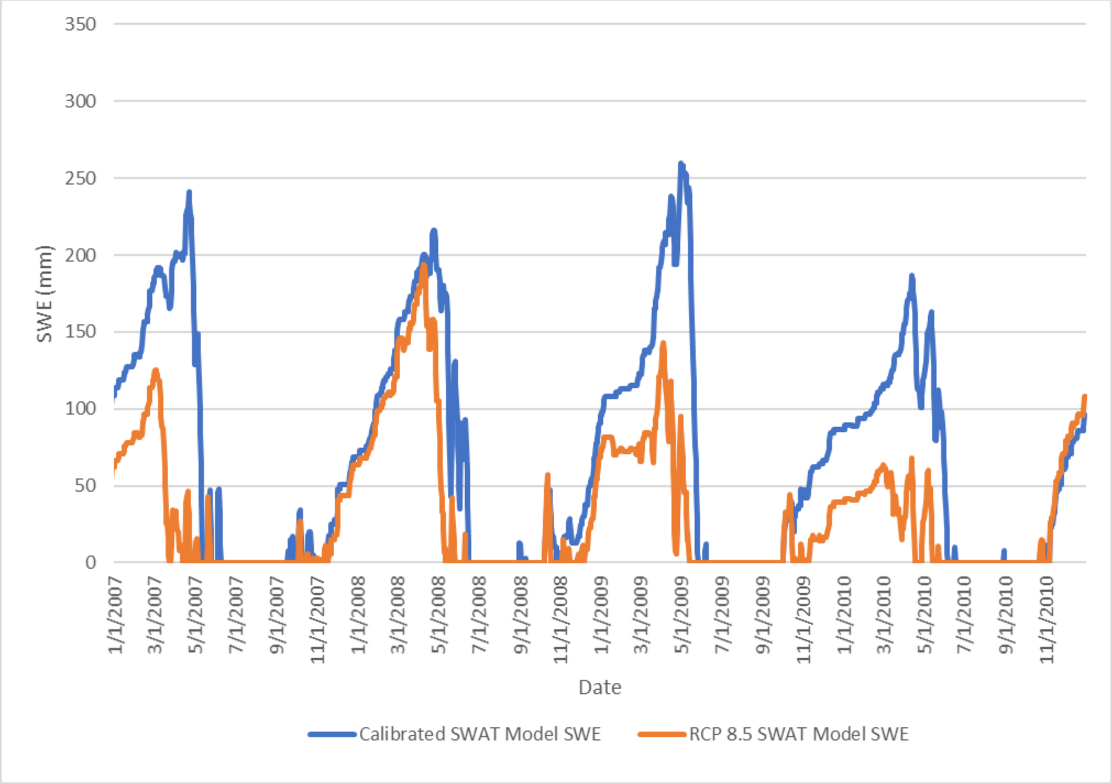

Figure 23: RCP 8.5 Basin Creek SNOTEL SWE Simulation

3.7. Climate Change Effect on SBC Discharge

3.7.1. Monthly flowrates

All the scenarios projected decrease in the overall amount of water in SBC over baseline conditions, except for RCP 2.6. This is most likely due to increased precipitation and relatively small increase of radiative forcing in this scenario. But in general, all the scenarios are marked by a smaller hydrograph peak and occurring somewhat sooner in the season. RCP 8.5 is the most dramatic with peak flows being almost half of observed. Additionally, RCP 8.5 projects peak flows occurring earlier in the year and having less water during late summer/early winter base flows. The false peak aforementioned between July and August 2009 can be seen to be particularly exaggerated in the RCP 6.0 discharge simulation.

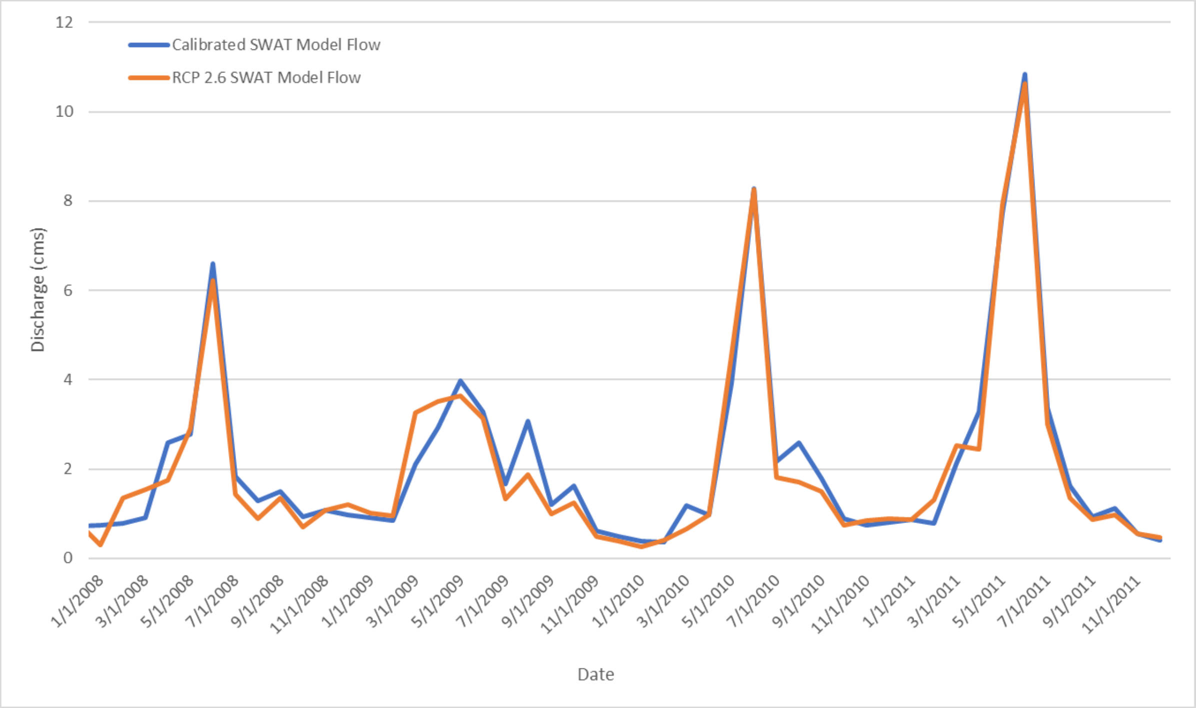

Figure 24: RCP 2.6 Discharge Simulation

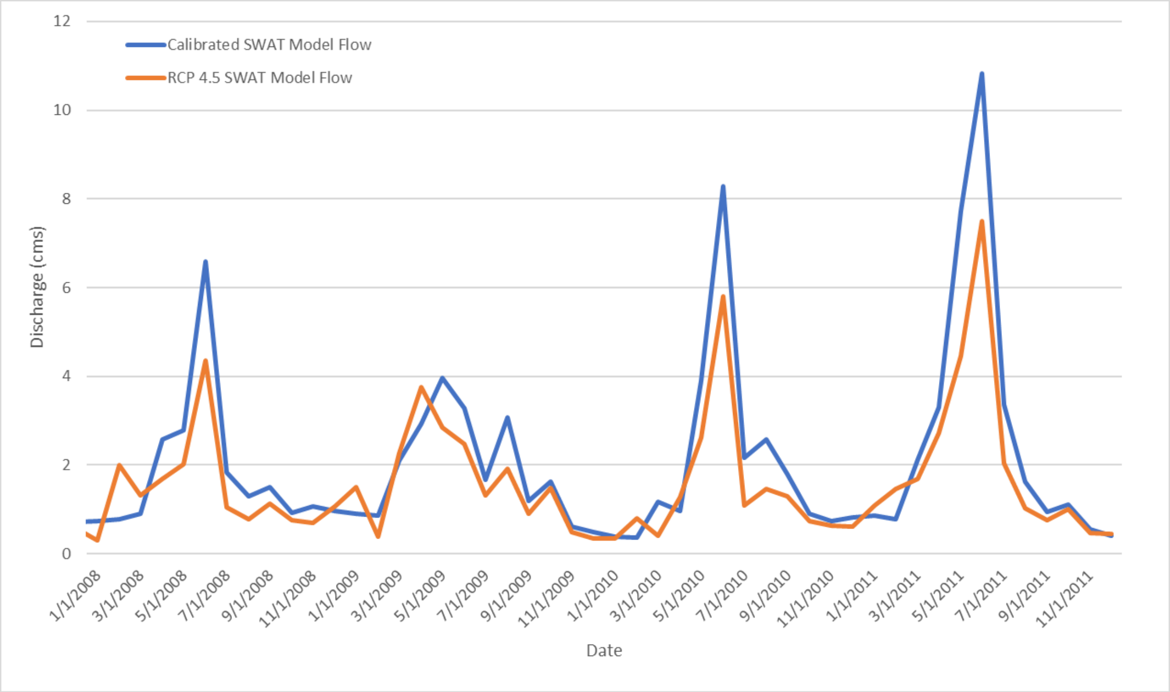

Figure 25: RCP 4.5 Discharge Simulation

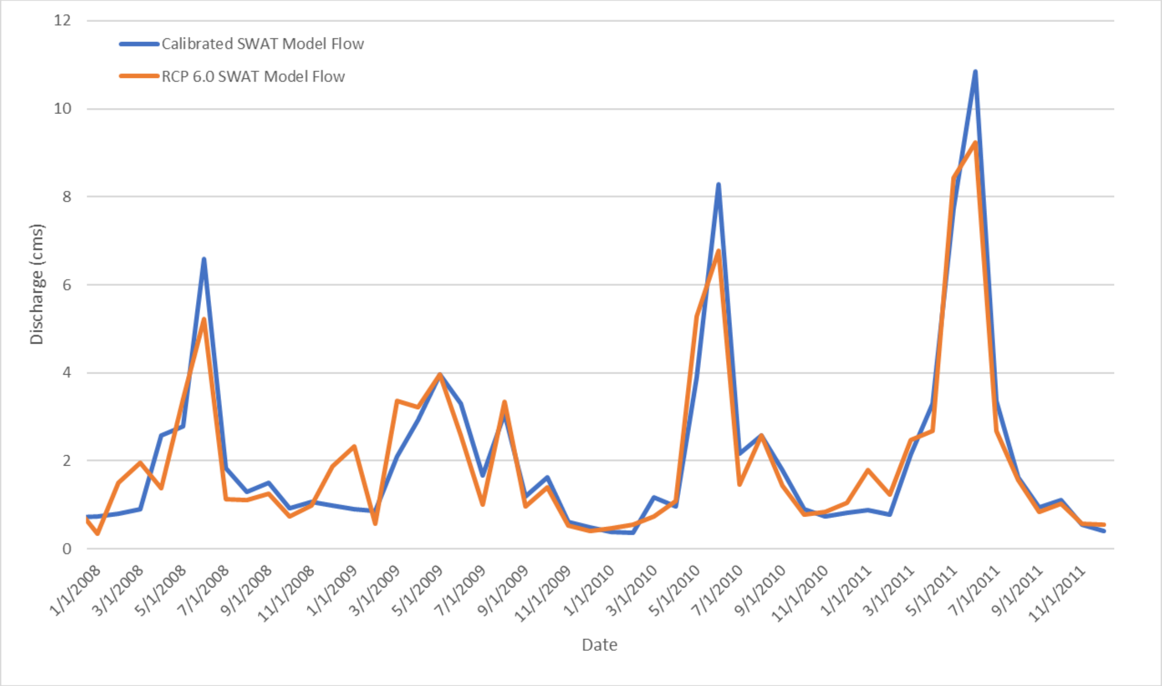

Figure 26: RCP 6.0 Discharge Simulation

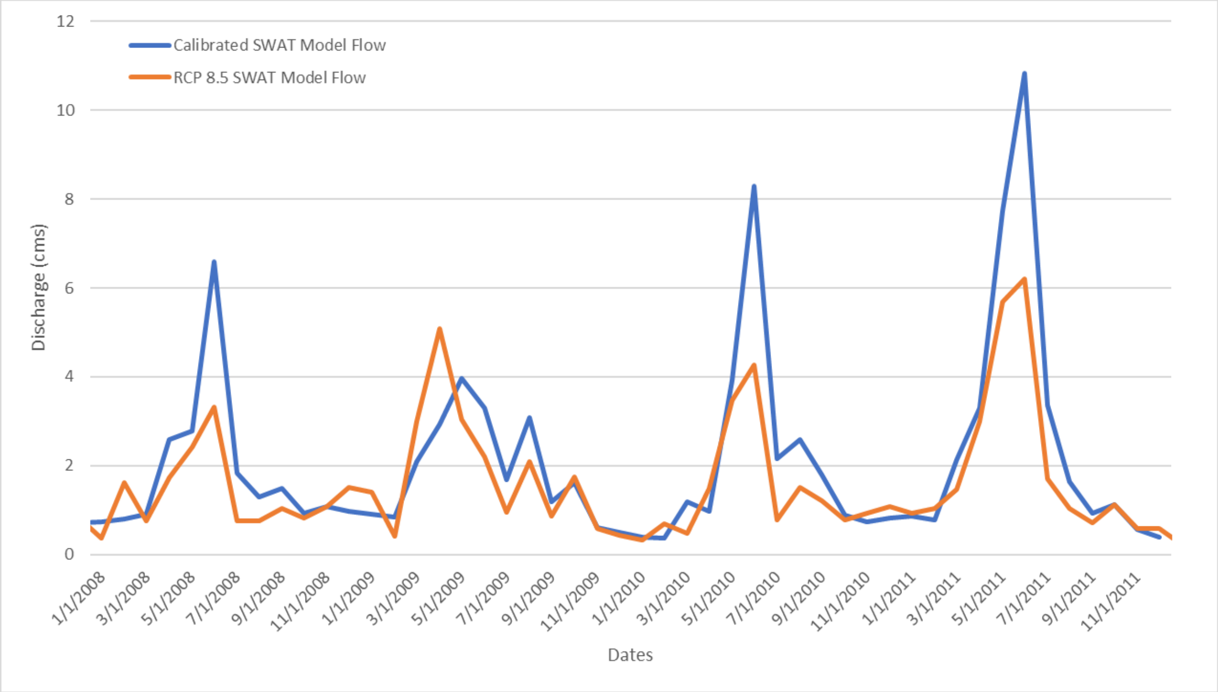

Figure 27: RCP 8.5 Discharge Simulation

4. Conclusions

All the RCP scenarios predict warmer temperatures across the watershed, with the highest increase in the spring and late summer. Additionally, precipitation is projected as having a basin wide increase, with biggest increase in spring and winter. Snowpack was simulated as having a systematic decrease, and this can be seen to be correlated to drop in the intensity and timing of peak spring runoff. Additionally, later summer base flows seem to decrease as well, but not as strong of a correlation can be made between that of snowpack and intensity of spring peak flows. This is most likely due to increased winter precipitation supplementing base flows. These trends are generally true for each RCP and dramatizes with each consecutive scenario, except for RCP 4.5 and 6.0, where radiative forcing is lower and higher, respectively. Even though overall more precipitation falling on the landscape, we see less flow in SBC. This is in part due to the loss of storage on the landscape.

Montana has seen a 15-30% loss of April 1st snowpack between 1950-1997 (Glawe and Dugan 2006) and this study predicts between 20-60% loss of average April snowpack. This loss of snowpack resulted in late summer base flows, most likely from loss of snowmelt feeding springs and reduction in shallow groundwater recharge. All scenarios projected a dramatic decrease in late summer base flow for the years 2008 and 2009. The biggest change can be seen in the reduction of peak flows in the spring as well as a shift in peak timing, mainly in the year 2009 in all scenarios.

This study only considered the effect of precipitation and temperature on hydrologic conditions. Climate change will have cascading ecological effects on the watershed which could possibly dramatize these results further. As snow pack recedes, the melt off period decreases and limits the input to groundwater and overland flow to streams. This will limit the water in perennial streams and could possibly shift perennial streams to ephemeral, reducing spawning habitat for certain species. Additionally, as conditions become drier, the probability of larger, catastrophic fires increase.

Montana is historically a fire dominated landscape, characterized by low-intensity/high-frequency fires (Brown, Ryan, and Andrews 2000). Due to a century of fire suppression, fire intensity and frequency have increased, and some studies suggest an increase in the amount of ignition events due to decreased fuel moisture will occur with climate change (Wotton, Martell, and Logan 2003)(Wotton, Nock, and Flannigan 2010). Overland vegetation plays a key role in the way the water behaves on a landscape; if the intensity, size and frequency are expected to change (Weber and Flannigan 1997) this could play a significant role in the structure and ecological succession of late stage seral forest of Montana, affecting waters behavior as well.

One of the major limitations to this study is lack of a statistically acceptable calibrated and validated daily values.

4.1. Limitations

Hydrological models can be effective tools for understanding basin wide changes when the attainment of empirical data is infeasible. However, they are not predictors of the future, especially when it comes to the use of climate change data. Projected climate change data and model outputs are merely just one possible scenario that could happen. This studies SWAT output was calibrated but it is still a model, and a level of uncertainty exists with it’s credibility to simulate real world scenarios. Coupled with the use of modelled data, the results can become speculative. The results of this study are intended as a guidance tool for water resources managers, an insight to a possible scenario, not a hard truth.

5. References Cited

Ahl, Robert S, Scott W Woods, and Hans R Zuuring. 2008. “Hydrologic Calibration and Validation of Swat in a.” *Journal Of The American Water Resources Association* 44(6): 1411–30. http://doi.wiley.com/10.1111/j.1752-1688.2008.00233.x.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. “Large Area Hydrologic Modeling and Assessment Part I: Model Development.” *Journal of the American Water Resources Association* 34(1): 73–89. http://doi.wiley.com/10.1111/j.1752-1688.1998.tb05961.x.

Arnold, J.G. et al. 2012. “SWAT: Model Use, Calibration, and Validation.” *Transactions of the ASABE* 55(4): 1549–59. http://elibrary.asabe.org/abstract.asp??JID=3&AID=42263&CID=t2012&v=55&i=4&T=1.

Bjørnæs, Christian. 1992. “A Guide to Representative Concentration Pathways.” *CICERO Center*: 5. http://www.sei-international.org/mediamanager/documents/A-guide-to-RCPs.pdf.

Braconnot, Pascale et al. 2011. “The Paleoclimate Modeling Intercomparison Project Contribution to CMIP5.” *CLIVAR Exchanges* 16(56): 15–19.

Brekke, L., B. L. Thrasher, E. P. Maurer, and T. Pruitt. 2013. “Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs.” (May): 104. http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

Brown, P M, M G Ryan, and T G Andrews. 2000. “Historical Surface Fire Frequency in Ponderosa Pine Stands in Research Natural Areas, Central Rocky Mountains and Black Hills, USA.” *Natural Areas Journal* 20(2): 133–39.

Clarke, Leon E et al. 2007. “Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations.” *Program* 2011(July): 164. http://www.ncbi.nlm.nih.gov/pubmed/22275275.

D. N. Moriasi et al. 2007. “Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations.” *Transactions of the ASABE* 50(3): 885–900. http://elibrary.asabe.org/abstract.asp??JID=3&AID=23153&CID=t2007&v=50&i=3&T=1.

Defense Mapping Agency. 1970. “Montana 3-Arc Second 1x1 Degree 1: 250,000 Scale Digital Elevation Model.” http://ftp.geoinfo.msl.mt.gov/Data/Spatial/NonMSDI/Elevation/DEM_64m_1992.zip (January 9, 2017).

Desert Research Institute, and Western Regional Climate Center. 2016. “Climate of Montana.” https://wrcc.dri.edu/narratives/MONTANA.htm.

Ernmenta, Intergov, and L P A Nel. 2014. *Climate Change 2014 Synthesis Report*.

Flynn, K F, and M W Van Liew. 2011. “Evaluation of Swat for Sediment Prediction in a Mountainous Snowmelt-Dominated Catchment.” *Transactions of the ASABE* 54(1): 113–22. http://www.scopus.com/inward/record.url?eid=2-s2.0-79951842553&partnerID=40&md5=c2269f139d910c86214f67fcbbbc9330.

Fontaine, T. A., T. S. Cruickshank, J. G. Arnold, and R. H. Hotchkiss. 2002. “Development of a Snowfall-Snowmelt Routine for Mountainous Terrain for the Soil Water Assessment Tool (SWAT).” *Journal of Hydrology* 262(1–4): 209–23.

Fujino J, Nair R, Kainuma M, et al. 2016. “Multi-Gas Mitigation Analysis on Stabilization Scenarios Using Aim Global Model Author (S): Junichi Fujino , Rajesh Nair , Mikiko Kainuma , Toshihiko Masui and Yuzuru Matsuoka Source : The Energy Journal , Vol . 27 , Special Issue : Multi-Greenhouse Gas." 27(2006): 343–53.

Gassman, Philip W., Ali M. Sadeghi, and Raghavan Srinivasan. 2014. "Applications of the SWAT Model Special Section: Overview and Insights." *Journal of Environment Quality* 43(1): 1. https://www.agronomy.org/publications/jeq/abstracts/43/1/1.

Glawe, Dean A, and Frank M. Dugan. 2006. "Declining Mountain Snowpack In Western North America." *Pacific Northwest Fungi* 1(11): 1–11. http://openjournals.wsu.edu/index.php/pnwfungi/article/view/1026.

IPCC. 2014. "Climate Change 2014 Synthesis Report Summary Chapter for Policymakers." *Ipcc*: 31.

Jha, Manoj et al. 2004. "Effect of Watershed Subdivision on SWAT Flow, Sediment, and Nutrient Predictions." *Journal of the American Water Resources Association* 40(3): 811–25. http://doi.wiley.com/10.1111/j.1752-1688.2004.tb04460.x.

Jin, Xin, and Venkataramana Sridhar. 2012. "Impacts of Climate Change on Hydrology and Water Resources in the Boise and Spokane River Basins." *Journal of the American Water Resources Association* 48(2): 197–220.

Johnson, T. et al. 2015. "Modeling Streamflow and Water Quality Sensitivity to Climate Change and Urban Development in 20 U.S. Watersheds." *Journal of the American Water Resources Association* 51(5): 1321–41.

Krysanova, Valentina, and Raghavan Srinivasan. 2014. "Assessment of Climate and Land Use Change Impacts with SWAT." *Regional Environmental Change* 15(3): 431–34.

Mann, Michael E., and Raymond S. Bradley. 1999. "Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations."

Masui, Toshihiko et al. 2011. "An Emission Pathway for Stabilization at 6 Wm-2radiative

Forcing." *Climatic Change* 109(1): 59–76.

Montana Natural Heritage Program. 2016. "Montana Land Cover Framwork." https://gisservicemt.gov/arcgis/rest/services/MSDI_Framework/LandCoverSPC/MapServer (January 9, 2017).

Moriasi, D N, M W Gitau, N Pai, and P Daggupati. 2015. "Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria." *Transactions of the ASABE* 58(6): 1763–85. http://elibrary.asabe.org/abstract.asp?aid=46548&t=3&dabs=Y&redir=&redirType=.

NASA: Global Climate Change. 2018a. "Climate Change: How Do We Know?" https://climate.nasa.gov/evidence/ (December 1, 2018).

———. 2018b. "Global Land-Ocean Temperature Index." https://climate.nasa.gov/vital-signs/global-temperature/.

NCAR, and UCAR. 2017. "CFSR Global Weather Database." http://swat.tamu.edu/media/99082/cfsr_world.zip (January 9, 2017).

NOAA, and National Centers For Environmental Information. 2017. "Anaconda/Barker Lakes/Bert Mooney Airport/Basin Creek Climate Data." https://www.ncdc.noaa.gov/cdo-web/datatools/findstation (January 9, 2017).

NRCS. 2018. "NRCS and Natural Water and Climate Center." *United States Department of Agriculture*. https://www.wcc.nrcs.usda.gov/webmap/#version=80.1&elements=&networks=!&states=!&counties=!&hucs=&minElevation=&maxElevation=&elementSelectType=all&activeOnly=true&activeForecastPointsOnly=true&hucLabels=false&hucParameterLabels=false&stationLabels=&overl (January 10, 2017).

Riahi, Keywan et al. 2011. “RCP 8.5-A Scenario of Comparatively High Greenhouse Gas Emissions.” *Climatic Change* 109(1): 33–57.

Shekhar, Shashi, and Hui Xiong. 2008. “Soil and Water Assessment Tool ‘SWAT.’” *Encyclopedia of GIS*: 1068–1068. http://link.springer.com/10.1007/978-0-387-35973-1_1231.

Silverman, Nick et al. 2017. “Climate Change in Montana: Chapter Two.” *Montana Climate Assessment*. http://montanaclimate.org/chapter/climate-change (January 2, 2018).

Srinivasan, R, C Santhi, R D Harmel, and A Van Griensven. 2012. “Swat: M.” 55(4): 1491–1508.

Stewart, Iris T., Daniel R. Cayan, and Michael D. Dettinger. 2004. “Changes in Snowmelt Runoff Timing in Western North America under a ‘Business as Usual’ Climate Change Scenario.” *Climatic Change* 62(1–3): 217–32.

———. 2005. “Changes toward Earlier Streamflow Timing across Western North America.” *Journal of Climate* 18(8): 1136–55.

Thomson, Allison M. et al. 2011. “RCP4.5: A Pathway for Stabilization of Radiative Forcing by 2100.” *Climatic Change* 109(1): 77–94.

U.S. Department of Agriculture, Natural Resources Conservation Service, National Geospatial Center of Excellence. 2014. “Watershed Boundary Dataset 12 Digit Hydrologic Units (Subwateshed) For Montana.” http://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/HydrologicUnits/WBDHU12_MT.zip (January 9, 2017).

U.S. Department of Agriculture, and Natural Resources Conservation Service. 2017. “Soil Survey Geographic (SSURGO) Data for Montana.”

http://mslapps.mt.gov/Geographic_Information/Data/NRCS/Soils/Default.aspx (January 9, 2017).

U.S. Geological Survey. 2000. “USGS 12323600 Silver Bow Creek at Oppurtunity, MT.” https://waterdata.usgs.gov/nwis/uv?site_no=12323600 (January 9, 2017).

van Vuuren, Detlef P. et al. 2011. “The Representative Concentration Pathways: An Overview.” *Climatic Change* 109(1): 5–31.

Watershed, Snow-dominated Rocky Mountain, Robert S Ahl, Scott W Woods, and Hans R Zuuring. 2008. “Hydrologic Calibration and Validation of Swat in a.” *Journal Of The American Water Resources Association* 44(6): 1411–30. http://doi.wiley.com/10.1111/j.1752-1688.2008.00233.x.

Weber, M G, and M D Flannigan. 1997. “Canadian Boreal Forest Ecosystem Structure and Function in a Changing Climate: Impact on Fire Regimes.” *Environmental Reviews* 5(3–4): 145–66. http://www.nrcresearchpress.com/doi/abs/10.1139/a97-008.

White, Kati L., and Indrajeet Chaubey. 2005. “Sensitivity Analysis, Calibration, and Validations for a Multisite and Multivariable SWAT Model.” *Journal of the American Water Resources Association* 41(5): 1077–89. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2005.tb03786.x/abstract%5Cnhttp://onlinelibrary.wiley.com/store/10.1111/j.1752-1688.2005.tb03786.x/asset/j.1752-1688.2005.tb03786.x.pdf?v=1&t=ihdj2aeg&s=ad57ee07b37d62c183371343895438382c5e65dd%5Cn%3C.

Wotton, B. M., D. L. Martell, and K. A. Logan. 2003. “Climate Change and People-Caused Forest Fire Occurrence in Ontario.” *Climatic Change* 60(3): 275–95.

Wotton, B. M., C. A. Nock, and M. D. Flannigan. 2010. “Forest Fire Occurrence and Climate

Change in Canada.” *International Journal of Wildland Fire* 19(3): 253–71.

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This is to certify that the thesis prepared by William Howard George entitled "Climate Change Impacts on Hydrological Processes in Silver Bow Creek Watershed" has been examined and approved for acceptance by the Department of Environmental Engineering, Montana Tech of The University of Montana, on this 9th day of April, 2018.

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