Chapter 3

INTEGRATED MODELING OF THE ATHABASCA RIVER BASIN USING SWAT

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Abstract: The Athabasca River Basin significantly contributes to the provincial economy. There are various sectors such as agriculture, coal mines, oil sands, pulp mills and urbanization. These sectors abstract water and discharge effluent into the basin. The effluents contain excessive nutrients, heavy metals, and organic chemicals that may have adverse environmental and human health risks. In addition, the abstraction of water negatively impacts the environment during the low-flow seasons. An insight into hydrologic processes, contaminant pathways, and mitigation measures through a basin-scale modeling is imperative for sustainable development of the basin. This paper presents database preparation and hydrological modeling of the Athabasca River Basin. The Soil and Water Assessment Tool (SWAT), which is semi-distributed process-based model, was applied to simulate the hydrology process. Digital Elevation Model (DEM), land cover, soil, and climate data were collected and organized into geodatabases using geographical information system (GIS). The geodatabases are extracted with GIS interface and input files to SWAT prepared. Sensitivity parameters were identified and those parameters were calibrated using the observed flow data. The model then validated using separate data to verify its performance. The result shows that the simulated flow matches the observed flow as confirmed by statistical techniques.

Key words: Integrated modelling, Hydrology, Geodatabase, SWAT, Simulations, GIS

1. INTRODUCTION

The Athabasca River Basin, which begins from the Columbia Glacier and drains into Lake Athabasca, significantly contributes to the provincial economy (Athabasca Watershed Council 2011). The main activities that are going in the basin include agriculture, pulp mills, municipal water-treatment plants (WTTP), coal mining, and oil sands mining. Each activity abstracts water and discharges effluent into the basin. The effluents from agriculture, pulp mills, and WTTP contain excessive nutrients such as nitrogen, phosphorus, and organic carbon (Government of Canada, Alberta 2005). The effluents from coal and oil sands mining contain heavy metals and organic chemicals (Government of Canada, Alberta 2005). Excessive amount of nutrients, inorganic, and organic contaminants may have adverse environmental and human health risks. The abstraction of water for purpose of productions also negatively impacts the environment during the low-flow seasons. An insight into hydrologic processes, contaminant pathways, and mitigation measures through a basin-scale modeling is imperative for sustainable development of the basin(Betrie et al. 2011).

Integrated river basin modeling helps decision-makers to understand the basin-scale environmental problems (e.g., point and diffused sources of pollution) by considering the upstream-downstream interdependencies (Betrie et al. 2011). The literature review shows that this approach is widely used to support policy making, particularly in the European Water Framework Directive (WFD) (Grizzetti et al. 2008; Hesse et al. 2008; Volk et al. 2009). Grizzetti et al. (2008) applied the GREEN model to estimate the nitrogen pressures on surface water quality at medium and European scale using readily available data. The results identified the sources and quantity of the diffuse nitrogen emission at the European scale. Hesse et al. (2008) applied SWIM model to identify nutrient pollution, assess the impact of land use and climate changes on water quality and quantity, and evaluate mitigation measures at the Rhine River Basin. The results showed that nitrogen pollution were caused by diffuse sources and could be reduced by application of agricultural measures, whereas phosphorus were caused by point sources and could be reduced by the reduction of point source emissions. Volk et al. (2008) used the SWAT model to evaluate land use and land management scenarios to reduce the total nitrogen concentration in rivers to meet the WFD requirements at the Upper Ems River Basin. The results showed that in order to achieve the requirements of WFD there is a need to reduce arable land, increase pasture and reforestation.

The literature review shows that there is a paucity of research on the impact of the various economic activities have on water quality and quantity of the Athabasca River Basin. Squires et al. (2009) quantified the spatial and temporal changes of water quantity and quality of the basin between periods 1966-1976 and 1996-2006 using statistical techniques. The results show both the water quality and quantity have changed significantly between the periods. Kelly et al. (2010) conducted field study at the lower part of the basin and reported some heavy metals from oil sands development were exceeded regulatory values near or downstream of development.

The objective of our research team is to develop an integrated modeling framework that can simulate hydrological and biogeochemical processes in the Athabasca River Basin. This framework will enable decision-makers to understand sources and pathways of contaminants and implement best management practices in order to reduce the impact of contaminants in the environment. To this end, this paper presents preliminary results of database development and hydrological modeling of the Athabasca River basin.

2. METHODOLOGY

2.1 Model

Soil and Water Assessment Tool (SWAT) is a semi-distributed model that simulates continuous-time landscape processes at catchment scale (Arnold et al. 1998). The catchment is divided into hydrological response units (HRUs) based on soil type, land use, and slope classes that allows a high level of spatial detail simulation. The major model components include hydrology, weather, soil erosion, nutrients, soil temperature, crop growth, agricultural management, and stream routing.

The model predicts the hydrology at each HRU using the water balance equation, which includes daily precipitation, runoff, evapotranspiration, percolation, and return flow components. The surface runoff is estimated in the model using the Natural Resources Conservation Service Curve Number (CN) method and the Green and Ampt method. The percolation through each soil layer is predicted using storage routing techniques combined with crack-flow model. The evapotranspiration is estimated in SWAT using the Priestley-Taylor, Penman-Monteith and Hargreaves methods.

The SWAT model uses the Modified Universal Soil Loss Equations to compute soil erosion at an HRU level. It uses runoff energy to detach and transport sediment. The sediment routing in the channel consists of channel degradation using stream power and deposition in channel using fall velocity. Channel degradation is adjusted using USLE soil erodibility and channel cover factors.

The amount of nitrogen and phosphorous in water is estimated using load and partitioning concepts (Arnold et al. 1998), respectively. The simulation of nitrogen and phosphorous cycles are shown in Figure 1. To simulate these nutrients, SWAT takes inputs such as point sources (e.g., industrial effluents) and diffused sources (e.g., fertilizers from agricultural fields). The agriculture management simulates practices like tillage, irrigation, pesticides and fertilizations.

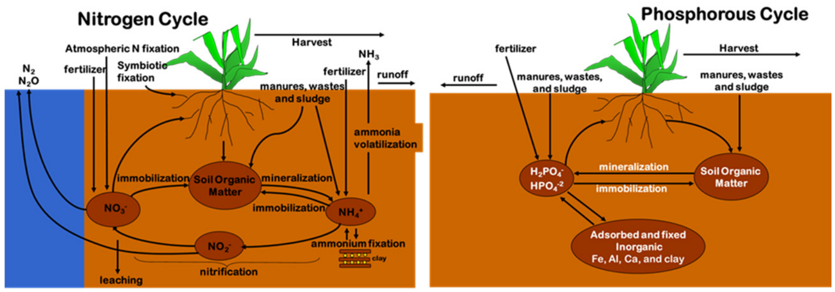

Figure 1: The nitrogen and phosphorous cycles in SWAT (after Arnold et al. 1998)

2.2 Database

The SWAT model requires various inputs that reflect the physiography of a given river basin, which include digital elevation model (DEM), land cover, soil, and weather data. DEM is used to delineate the basin and to extract topographic parameters (e.g., slope and elevation). The delineation process discretizes the basin into hydrologically connected watersheds. The DEM was obtained from the CGIAR-CSI GeoPortal that provides DEM data with 90m spatial resolution and in an ASCII format for the entire world (CGIAR-CSI 2015). A total of six tiles that covers the entire province of Alberta were downloaded. Each DEM was converted into a raster format and combined to form a single map using ArcGIS 10.2 software.

A land cover map is required to identify land covers and estimate their parameters as inputs to the SWAT model. The land cover map was obtained from the GeoGratis portal (GeoGratis 2013). This land cover map has a spatial resolution of 250 m and contains 45 classes that represent vegetative and non-vegetative covers of Canada. A total of 1000 tiles of map were downloaded in a vector format. These maps were combined, converted into raster format, and projected into NAD 183Transverse Mercator using Arc GIS 10.2 software. Then the land cover map of Alberta was extracted from the combined map. A database that stores parameters (e.g., temperature responses, leaf area development, residue decomposition, and others) of each land cover was built based on the available SWAT crop database.

A soil map is required to identify various soil types and parametrize their physical and chemical characteristics as inputs to the model. The soil data was obtained from Agriculture and Agri-Food Canada (Agriculture and Agri-Food Canada 2013). The data consists of polygon attribute table (PAT), soil name table (SNT), and soil layer table (SLT). The PAT contains attributes such as polygon area, perimeter and their polygon id. The SNT describes the physical and chemical parameters of soils that are stored in in the PAT. It also describes the soil order and groups. The SLT contains information which varies in a vertical direction for each soil stored in the PAT. The collected data in a shapefile format are imported to ArcGIS 10.2, their attribute tables joined, and converted into raster format, and its spatial reference corrected to Transverse Mercator. The final soil map covers the entire province of Alberta, has 2153 soil types, and a spatial resolution of 1 Km. A database that stores all soil types and their associated physical and chemical characteristics was built based on the available SWAT database. The physical properties (e.g., hydrologic group, texture, available water holding capacity, soil erodability constant, bulk density and other) of the soil govern the movement of water and air the profile. On the other hand, the chemical properties (e.g., anion exchange capacity, organic carbon content, pH, EC and other) are used to setup initial amount various chemical in the soil.

Climate data such as precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity are required in order to simulate the hydrological processes. Daily climate data were collected from 126 stations that are located in the river basin. The data was obtained from Environment Canada portal (Environment Canada 2015). These stations do have solar radiation data, relative humidity and have many missing values. Precipitation and temperature inputs for SWAT were prepared for 50 climate stations out of 126 stations. The missing values in precipitation and temperature data were filled using a spatial interpolation technique. The other climate variables were estimated from global weather database that was obtained from NCEP climate forecast system reanalysis (Saha et al. 2010).

2.3 Model Setup

The ArcGIS interface (Winchell et al. 2013) was used to delineate the basin and prepare input files for the SWAT model. The basin was divided into 9 watersheds by defining a threshold area of 600,000 ha, which is the minimum upstream drainage area required to define the beginning of a stream. Figure 2 shows the Athabasca river basin, its watersheds, and the river and its tributaries. In this model, the nine watersheds are shown as polygons. For each watershed, its slope, elevation, area and geographical location are estimated and stored in topographic database. The blue points in the map are the outlets of each watershed and the basin.

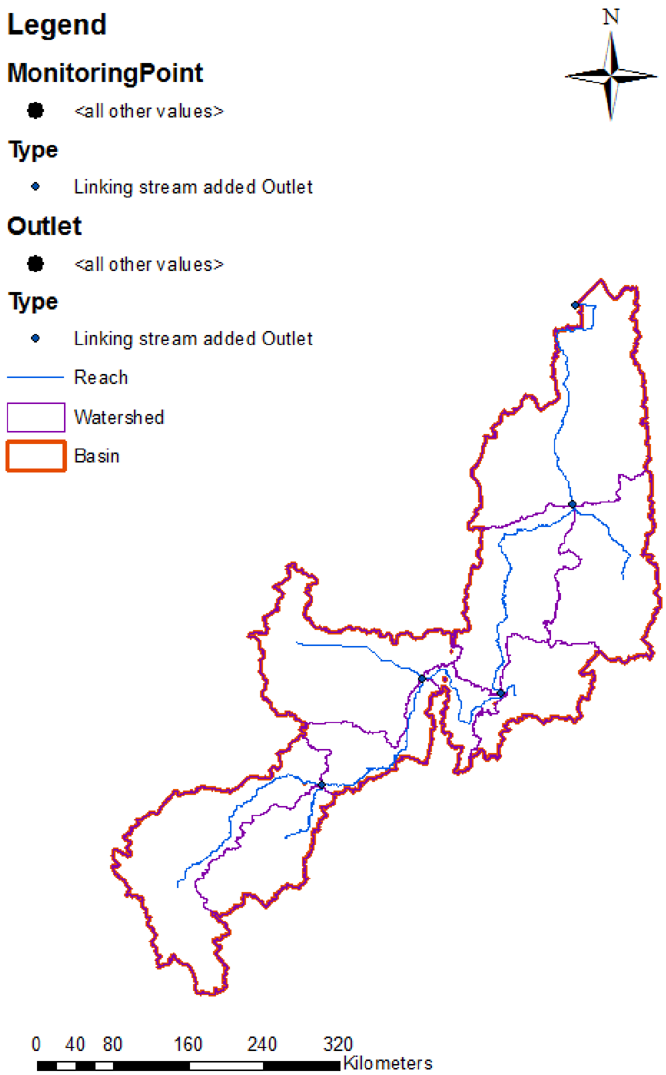

Figure 2: The Athabasca River Basin and its watersheds

Figure 3 depicts the land cover and soil classes for the Athabasca River Basin. The model estimated 11 cover classes from the provided land cover map. These cover classes are water, barren land, shrub land, forested wetlands, non-forested wetland, herbaceous land, range land, agriculture land, pasture land, evergreen forest, and mixed forest. In addition, the model estimated 119 different soil types from the provided soil map. The dominant soil types at the upper, central, and lower parts of the basin are Hubalta, Kinosis, and Fire Bag, respectively.

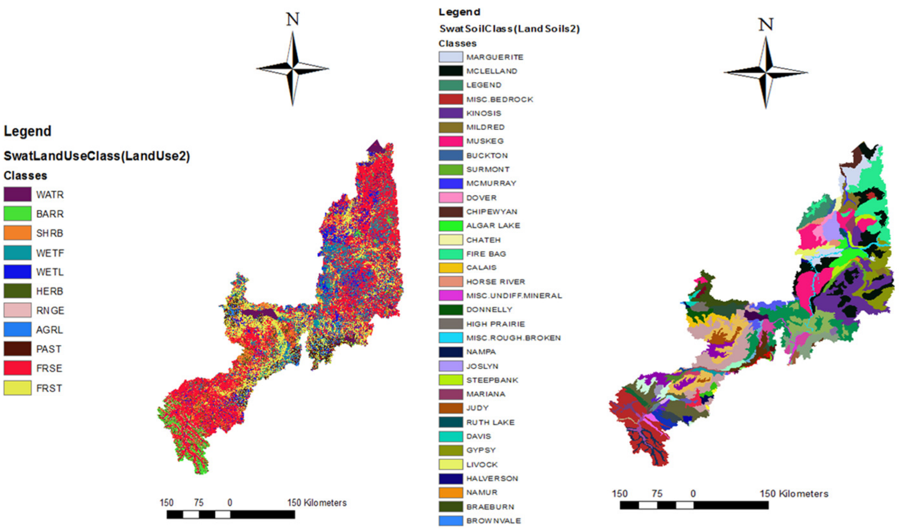

Figure 3: Land cover (left) and soil (right) classes of the Athabasca River Basin

Figure 4 shows the slope classes of the Athabasca River Basin. The slopes are computed from the provided DEM. In this model, five slopes classes are computed, which are 0-5%, 5-15%, 15-30%, 30-50%, and greater than 50%. The upper part of the basin is characterized by greater than 30% slope. The central part of the basin is characterized with slope between 5-15%. The lower part is characterized with slope less than 5%.

The land cover, soil, and slope maps were overlaid to derive 1362 dominant HRUs. HRU is a unique combination of soil, land cover, and slope class. These HRUs are used by the model to simulate hydrological and water quality processes in the basin. The model was run for 15 years from 1990 to 2004. The first three years were used to warmup the model, while the periods 1993 to 1998 and 1999 to 2004 were used to calibrate and validate the model, respectively. SWAT has over 300 parameters, but a few parameters must be selected for simulation to reduce the model complexity. Thus, sensitivity analysis was conducted to identify most sensitive parameters for model calibration using the One-factor-At-a-Time algorithm (van Griensven et al. 2006). The sensitive parameters were calibrated using Sequential Uncertainty Fitting algorithm (Abbaspour et al. 2007). The performance of the SWAT simulation was measured using statistical techniques, which are R2 and Nash-Sutcliffe efficiency (NSE).

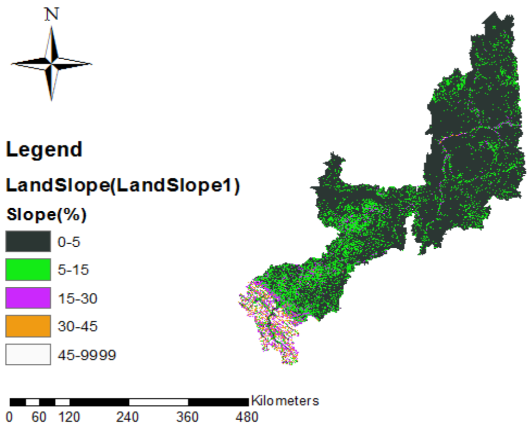

Figure 4: Slope class of the Athabasca River Basin

3. RESULTS

The results of sensitivity analysis are shown in Table 1. The most sensitive parameters are snow melt base temperature (SMTMP), snowfall temperature (SFTMP), maximum melt factor for snow (SMFMX), snowmelt temperature lag factor (TIMP), curve number (CN2), surface runoff lag time (SURLAG), base flow alpha factor (ALPHA_BF), groundwater delay time, (GW_DELAY), recharge to deep aquifer (RCHRG_DP), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), and minimum melt factor for snow (SMFMN). These parameters with their fitted values are used to simulate the hydrology of the Athabasca River Basin.

Table 1. The sensitive parameters, their range and fitted values

Parameter	Description	Minimum value	Maximum value	Fitted value
SMTMP.bsn	Snow melt base temperature	0	5	0.5
SFTMP.bsn	Snowfall temperature	-10	5	3.5
TIMP.bsn	Snowmelt temperature lag factor	0	1	0.7
SMFMX.bsn	Maximum melt factor for snow	0	5	1.5
CN2.mgt	Curve number	0	1	0.3
SURLAG.bsn	Surface runoff lag time	0.05	2	0.245
ALPHA_BF.gw	Base flow alpha factor	0	1	0.9
GW_DELAY.gw	Groundwater delay time	0	1	0.3
RCHRG_DP.gw	Recharge to deep aquifer	0	1	0.9
ESCO.hru	Soil evaporation compensation	1	1	1

	factor			
EPCO.hru	Plant uptake compensation factor	0	3	2.7
SMFMN.bsn	Minimum melt factor for snow	0	3	0.3

The flow simulation of SWAT was calibrated from 1993 to 1998 and the result is shown in Figure 4. The simulated flow matched the observed flow by R2 is equal to 0.61 and NS is equal to 0.32. In both R2 and NSE measurements, the model is acceptable but not that much good. The simulated flow overestimates the observed flow during the peak flow. The model well simulated the low flow except for the years 1997 and 1998. The simulation of the model well captured the rising and falling limbs of the observed hydrograph.

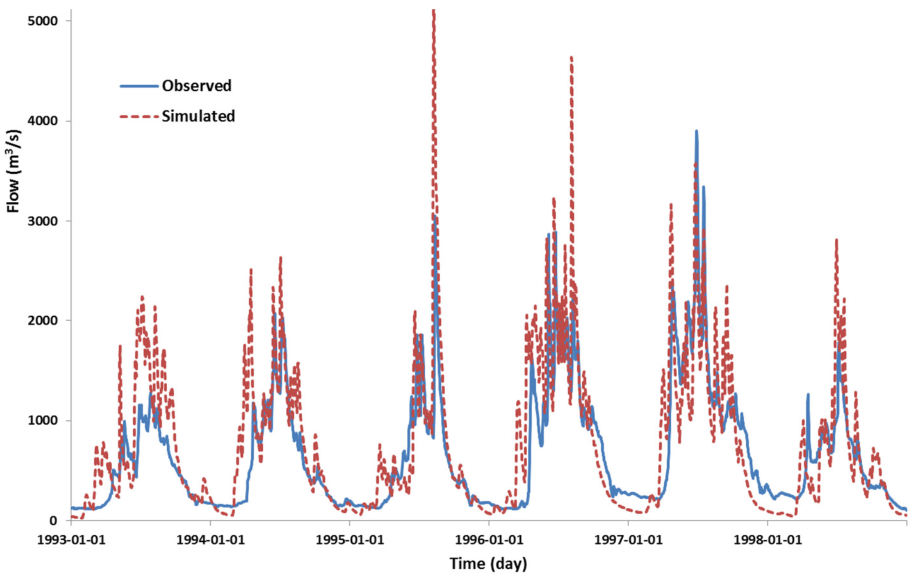

Figure 5: Simulated and observed flows for the calibration period

The flow simulation of SWAT was validated from 1999 to 2004 with the observed dataset that was not used during the calibration period. The result of the flow validation is presented in Figure 6. The simulated flow matched the observed flow by R2 and NSE values are equal to 0.65 and 0.5. This indicates that the model is quite acceptable in both R2 and NSE measurements. SWAT well simulated the observed flow during the peak flow except the summer of 2002. However, the model underestimated the observed flow during the low flow that occurs during winter. In most of the weather stations that are located in the basin, there are no measurements of climatic data. This could be the main reason for the discrepancy between the simulated and observed flow during winter.

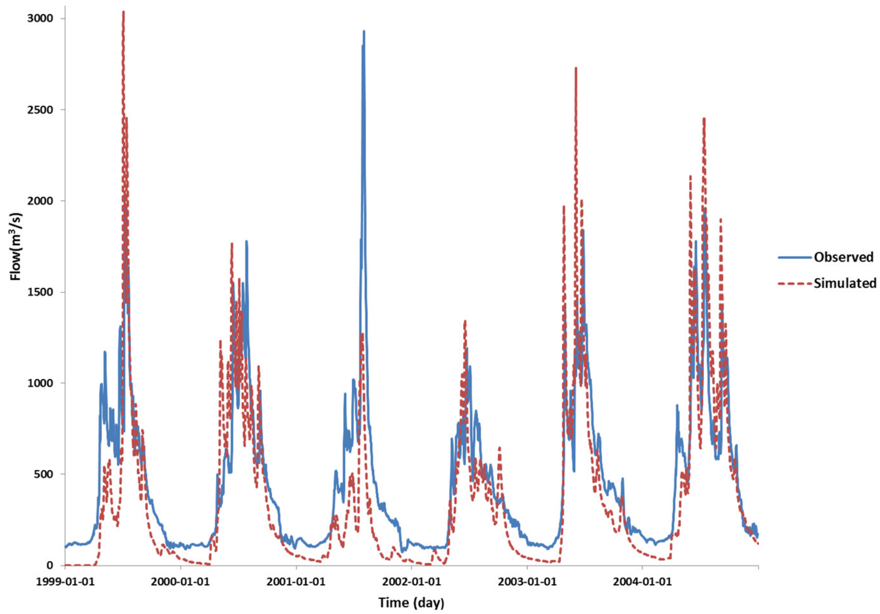

Figure 6: Simulated and observed flows for the validation period

4. CONCLUSION

This paper presents database preparation and hydrological modeling of the Athabasca River Basin. Data such as DEM, land cover, soil and climate data were collected and organized into geodatabases using geographical information system. The prepared databases are used as input to the SWAT model to simulate the hydrology of the basin. Sensitive parameters were identified and calibrated using automatic sensitivity and calibration tools. The performance of the model was evaluated using statistical techniques.

The result of the model validation shows that the simulated flow is comparable to the observed flow. However, the model systematically underestimates and overestimates the low and peak flows, respectively. This is most likely attributed to poor quality of climatic data used as an input to the model, which have huge missing values. Further work is being done to improve the limitation of this model. In conclusion, the preliminary result indicates that SWAT can be applied to understand the hydrological processes of the Athabasca River Basin.

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ACKNOWLEDGEMENTS

The authors gratefully acknowlede the support provided for this research by the Campus of Alberta Innovates Research Chair RCP-12-001-BCAIP.