HYDROLOGICAL MODELING OF ALBERTA USING SWAT MODEL

A preliminary Report

Karim C. Abbaspour
abbaspour@eawag.ch
EAWAG, Swiss Federal Institute of Aquatic Scienec and Technology

Monireh Faramarzi
monireh.faramarzi@cc.iut.ac.ir
Departement of Natural Resources, Isfahan University of Technology, Iran

Elham Rouholahnejad
EAWAG, Swiss Federal Institute of Aquatic Scienec and Technology
elham.rouholahnejad@eawagh.ch

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Content

1. Summary

Water is Alberta's most important renewable natural resource. It is reported that it has a good supply of surface water. However, spatial and temporal variation of the climate and hydrologic cycle has caused regions of water scarcity in this province. Numerous factors contribute to the complexity of water management in Alberta. These include: conflict over water resources; inadequacy of knowledge about existing programs, water uses, and water availability; and the nature and extent of stakeholder participation.

An exact knowledge of internal renewable water resources of Alberta is needed to lay a strong basis for a systematic analysis of water use-water availability for its long-term planning of the water and food security. The main objective of this project is the quantification of Alberta's water resources including all components of the water balance at the subbasin spatial and monthly temporal scale. This includes blue water flow (river discharge plus deep aquifer recharge), green water flow (evapotranspiration), green water storage (soil moisture), and aquifer recharge.

In this study we used the program Soil and Water Assessment Tool (SWAT) in combination with the Sequential Uncertainty Fitting program (SUFI-2) to calibrate and validate a hydrologic model of Alberta based on river discharges. Uncertainty analyses were also performed to assess the model performance. The results were not very satisfactory by using the observed climate data, but more reasonable results were obtained through the use of CRU (Climate Research Unit, http://www.cru.uea.ac.uk/) gridded climate data. The study period modeled was 1985–2006 for calibration (1991-2006) and validation (1985-1990). We quantified all components of the water balance including blue water flow (water yield plus deep aquifer recharge),

green water flow (actual and potential evapotranspiration) and green water storage (soil moisture) at sub-basin level with monthly time-steps. The spatially aggregated water resources components were used to predict sub-provincial blue and green water resources availability. Using the 2.5 arcmin population map available from the Center for International Earth Science Information Network in 2005, 20015, and 2015 (CIESIN, http://sedac.ciesin.columbia.edu/gpw), the water scarcity indicator, was obtained and presented as per-capita blue water availability per year at subbasin level. The results show that the lack of information on the dam operation, water diversion, and consumptive water use causes a large uncertainty in the areas concerned, hence we do not show this graph until more accurate information is used. Pertaining to the staple food crops in the province, the vulnerable situation of water resources availability has serious implications for the province's food security, and the looming impact of climate change could only worsen the situation. This study provides a strong basis for further studies concerning the water and food security and the water resources management strategies in the province and a good basis for the analysis of impact of climate change on blue and green water resources in Alberta.

2. Introduction

2.1 Climate

Alberta, as the fourth largest province in Canada, has an area of 661,185 km^2. It is located between 45-65°N and 105-125 ° E. The altitude varies from 170 m in the Wood Buffalo National Park in the northeast to 3747 m in the Rocky Mountains along the southwestern border. This variation as well as the variation in sea surface temperature of the Pacific Ocean has a pronounced influence on the diversity of the climate. Although most parts of Alberta could be classified as semi-arid, it has a wide range of climatic conditions. The average annual precipitation is 510 mm yr^{-1}. The leeward side of the Canadian Rocky Mountains, part of which is known as the Foothills, is relatively wet, with an average annual precipitation of 600 mm or more, while that of northern Alberta ranges from about 400 mm (northeast) to over 500 mm on the northwest, and that of southern Alberta from less than 350 mm (southeast) to about 450 mm [Mwale et al., 2009]. Arctic air masses in the winter produce extreme minimum temperatures varying from −54 °C in northern Alberta to −46 °C in southern Alberta. In the summer, continental air masses produce maximum temperatures from 32 °C in the mountains to 40 °C in southern Alberta.

2.2 Water availability

Although Alberta is abundant in terms of fresh water, but the spatial and temporal variation of this resource has caused regions of scarcity. Northern regions of Alberta are the wettest. The majority of Alberta's water is generated in the Peace River system and flows northward through the Slave River. In contrast, in the south, where water use is highest, the least amount is available. There are three main reasons of variation in stream flow: i) The size of drainage basin (e.g., the Peace River Basin encompasses nearly 44% of total area of Alberta); ii) The location of headwater systems (the mountains and foothills receive more precipitation than do the plains); iii) The variation in climate (temperature is higher and evaporation greater in southeastern Alberta than in northern and western regions). Based on the hydrologic deviation by Alberta Environment (http://www.environment.alberta.ca/apps/basins/default.aspx?Basin=12), there are ten River Basins (RB) or River Sub-basins (RSB) in Alberta (Figure 1). These include:

Hay River Basin: the Hay River is located in the northwest portion of the province and originates in British Columbia's Rocky Mountains. It flows from the Hay River eventually meet Arctic Ocean. The basin has a drainage area of 47,900 km^2 at the Alberta-Northwest Territories border. The mean annual discharge at the border is 3,630 million m^3.

Peace River Basin: the Peace River begins in the mountains of British Columbia, and flows to Alberta. The W.A.C. Bennett Dam is located

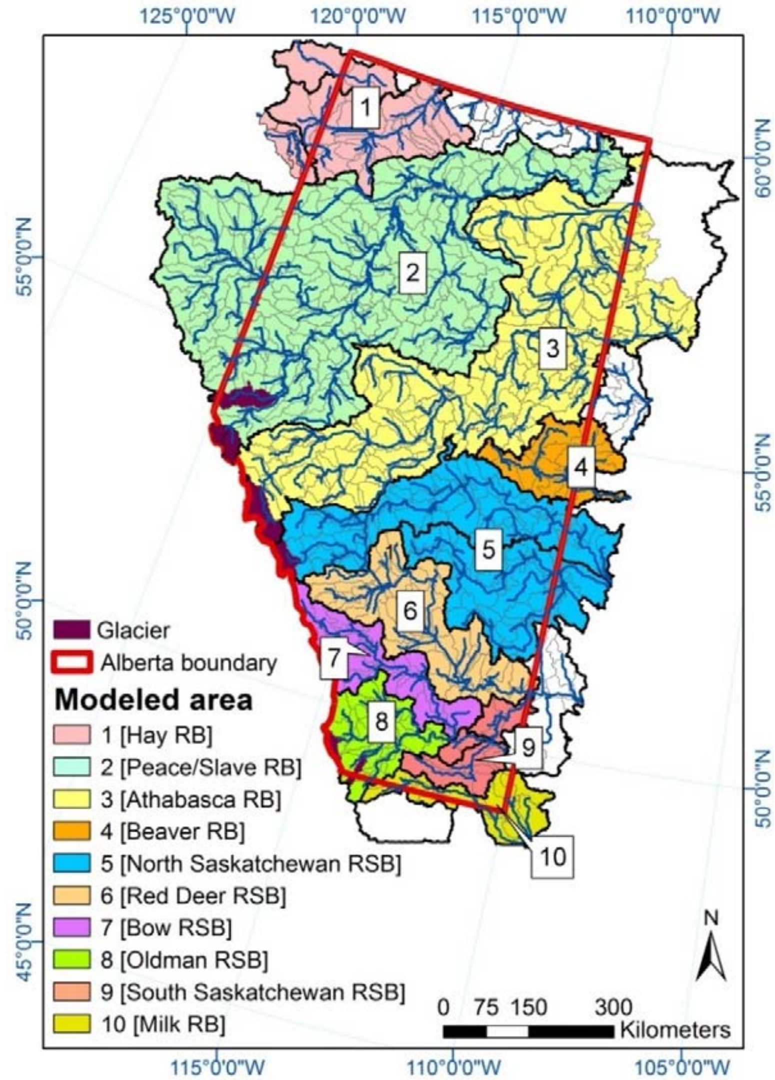


Figure 1. The modeled region of Alberta including main river basins/subbasins. The white area is the modeled subbasins which are not located within Alberta boundary.

on the Peace River in British and influences the stream flow in downstream.

The river flows northeast across the province, through the town of Peace River and empties into the Slave River. At Peace Point the Peace River has a mean annual discharge of 68,200 million m^3 and a drainage area of 293,000 km^2. The Peace/Slave River Basin includes the Wapiti, Smoky, Little Smoky and Wabasca rivers.

Athabasca River Basin: the Athabasca River originates in the Rocky Mountains of Alberta. The river flows northeast through the province, past the urban centers of Jasper, Hinton, Whitecourt, Athabasca and Fort McMurray prior to emptying into Lake Athabasca. Flows from the basin eventually make their way to the Arctic Ocean. At Jasper, Athabasca and Fort McMurray the mean annual discharge is 2,790 million m^3, 13,600 million m^3 and 20,860 million m^3, respectively. The drainage areas at Jasper, Athabasca and Fort McMurray are 3,880 km^2, 74,600 km^2 and 133,000 km^2 respectively. The Athabasca River Basin includes the McLeod, Pembina and Clearwater rivers.

Beaver River Basin: the Beaver River is one of the smaller basins within the province with a catchment area of about 14,500 km^2. The basin and river extend east, across the provinces of Saskatchewan and Manitoba, emptying into Hudson's Bay. The Beaver River begins at Beaver Lake, and then flows through urban centres of Bonnyville, Cold Lake and Grand Centre. The mean annual discharge of the Beaver River at the Alberta-Saskatchewan border is 653 million m^3. The Cold Lake Area Weapons Range comprises the majority of the northern part of the basin. The basin is characterized by many meandering streams and rivers which drain such lakes as Cold, Moose, Muriel, Ethel and Wolf Lake.

North Saskatchewan River Basin: covers about 80,000 km^2 of the province.

The basin begins in the ice fields of Banff and Jasper National Parks and generally flows in an eastward direction to the Alberta-Saskatchewan border. The Brazeau, Nordegg, Ram, Clearwater, Sturgeon and Vermilion rivers flow into the North Saskatchewan River within Alberta. The Battle River also forms part of the North Saskatchewan Basin and joins with the North Saskatchewan River in Saskatchewan. There are two large dams located in the basin. The Big Horn Dam on the North Saskatchewan River creates Lake Abraham. The Brazeau Reservoir is created by the Brazeau Dam, located on the Brazeau River. Major centres within the basin include Drayton Valley, Edmonton, Fort Saskatchewan and the Saddle Lake Indian Reserve. The mean annual discharge from the basin in Alberta into Saskatchewan is over seven billion m^3.

The Red Deer, Oldman and Bow River Subbasins: are part of South Saskatchewan River Basin; begin in the Rocky Mountains, generally flowing eastward through foothills and prairie. The combined watershed of the basins is 121,095 km^2, of which 41% is from the Red Deer sub-basin. The mean annual discharge from the combined basin into Saskatchewan is 9,280 million m^3.

Milk River Basin: is the smallest of the province's major river basins encompassing an area of about 6,500 km^2. The river is a northern part of the Missouri-Mississippi River Basin. The Milk River enters Alberta from Montana, flows eastward through the southern portion of the province prior to looping back to Montana. Mean annual flows entering Alberta are 106 million m^3 and leaving Alberta are 167 million m^3.

The annual variation of water resources causes critical water supply licensing problems in the areas where water users have already been licensed to withdraw a certain amount of the estimated mean annual flow volume. Total annual runoff from the high mountain regions varies little from year to year. The variation is large for Bow River from about 900 million m^3 in 1949 to 160 million m3 in 1954. In contrast, total annual flow variation in the Battle River at Ponoka, a central plain stream, has ranged from 15 million m^3 in 1976 to 260 million m^3 in 1927. Located midway between these two, the Red Deer River, at Red Deer, which rises on the eastern slopes of the Rocky Mountains, has experienced a variation in total annual flow volume from less than 700 million m^3 in 1949 to almost 4000 million m^3 in 1915.

Seasonal variations also affect water supply. Spring melts and summer rains produce the great volumes of flow while drier fall weather and temporary storage of water in snow and ice during winter are reflected in low runoff patterns. This seasonal change in surface water flow varies across the province. Mountain-fed streams such as the Bow River generally experience greatest flows in June or July during the mountain snow melting period, while streams located in the plains usually peak in April. The Battle River is an example of the latter. The West Arrow wood and Sounding creeks respond almost entirely to an early spring melt.

2.3 Water use and water management

Aside from hydro power production (a very significant but non-consumptive use) there are five main water withdrawal (consumptive) uses in Alberta: agricultural, thermal power, municipal, industrial and water injection. In addition there are instream uses other than hydro, which include fisheries, recreation and effluent dilution. The total amount of water withdrawn by users is not fully consumed; some, such as sewage effluent, irrigation return flow and thermal cooling water is returned to the natural drainage system. For example, the total amount of surface water withdrawn by major water users in Alberta in 1989 was approximately 4700 million m^3, while the total volume consumed was 2600 million m^3. The irrigation is the largest water user so far.

In addition to the sources of surface water, groundwater is an important component of Alberta's water resource. Practically every part of the province has groundwater, but aquifer depths, yields, and water potability vary. Aquifer discharge establishes the base flow of many rivers and streams, sustaining them during winter and other dry periods. Of all the water currently withdrawn in Alberta, only about 3% comes from the groundwater system. However, this relatively small volume is of vital importance, since a great many Albertans depend upon groundwater for their domestic water supply. Currently there are approximately 500,000 domestic wells in the province and about 7,000 are added each year. Figure 2 shows the percent of natural water flow which is allocated in each river basin. It is shown that in the central and southern part of Alberta water use is high and in some areas it is fully allocated for different sectors of uses.

Irrigation for agriculture is the largest user of water in Alberta, accounting for 60 to 65 per cent of all water consumed on average. In 2007, irrigation - including small, private irrigators - accounted for nearly 43% of allocated surface water, or more than 4.1 billion m^3. It represents almost 73% of all water allocated in the South Saskatchewan River Basin. Thirteen organized irrigation districts collectively represent the largest amount of water allocated for a specific purpose in Alberta at over 3.5 billion m^3 (Figure 3). The four largest districts account for 83% of total diversions.

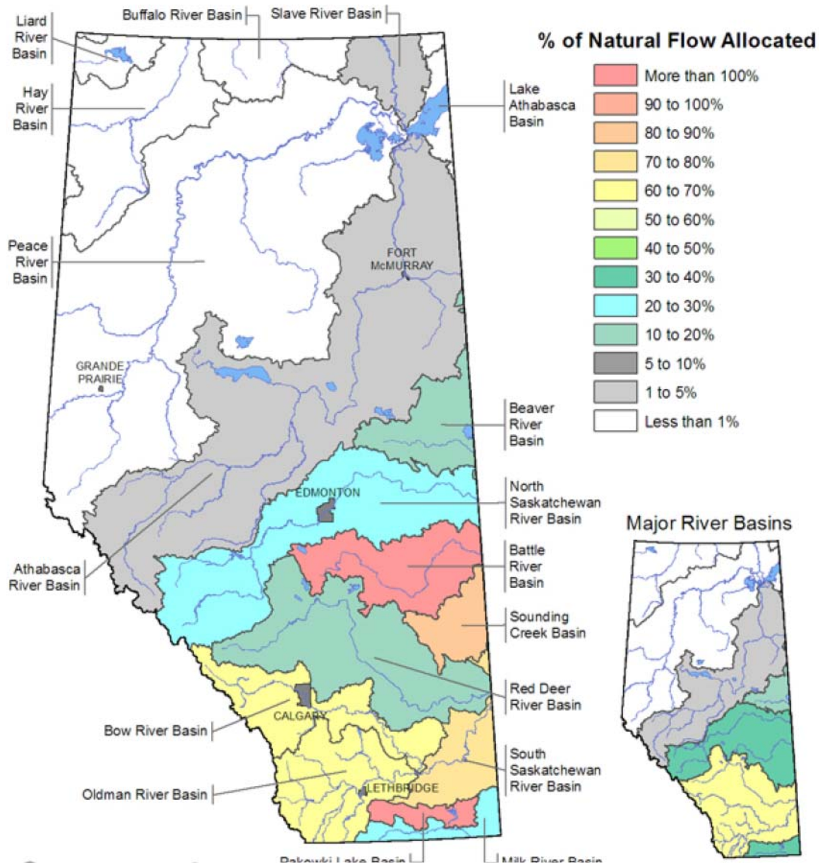


Figure 2. Water allocations in 2008 by river basins compared to average natural flow [Government of Alberta, Environment].

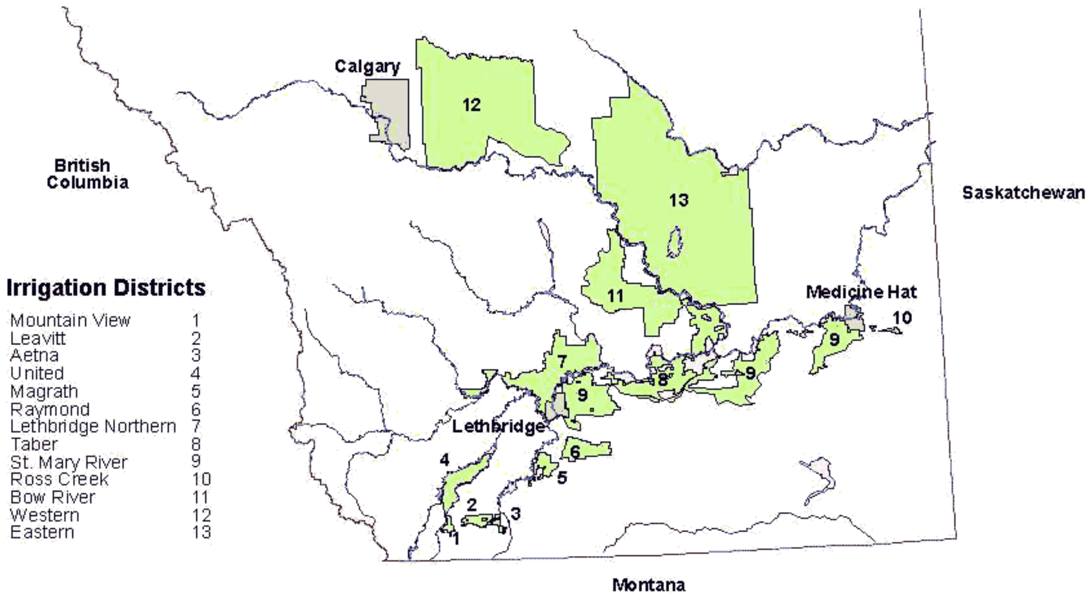


Figure 3. Thirteen organized irrigation districts in Alberta

Nearly all uses of water result in some water that is not returned back to the ecosystem from which it was derived. With irrigation, the majority of water applied to crops is taken up by plants for growth, or evapo-transpires into the atmosphere. Additionally, a small amount of water is never used for irrigation itself; however, it is required to maintain the minimum depth of water in canals and reservoirs in order to transport irrigation water through the system. Therefore, some of this water ends up as return flow back into other creeks and/or rivers, though seepage and evaporation losses in canals and reservoirs can occur.

In much of southern Alberta, there is not enough rainfall and moisture to naturally sustain agricultural crops. However, there is abundant sunshine and heat that can contribute to growing many different crops if water were not a limiting factor. Early in the settlement of Alberta, it was recognized that agriculture would not be successful in the southern region without an abundant and assured supply of water to irrigate fields. Irrigation Districts were organized and granted water licenses to divert large quantities of water from the tributaries of the South Saskatchewan River, primarily the Oldman (St. Mary, Waterton and Belly) and Bow Rivers [Alberta Water Portal, http://www.albertawater.com/index.php?option=com_content&view=article&id=84].

Numerous factors contribute to the complexity of water management, including conflict over water resources; adequacy of knowledge about existing programs, water uses, and water availability; and the nature and extent of stakeholder participation. The manmade changes on natural water systems have a significant impact, both spatially and temporally, on hydrological water balance of the region [Faramarzi et al., 2009]. Figure 4 shows the Alberta water management infrastructure and projects

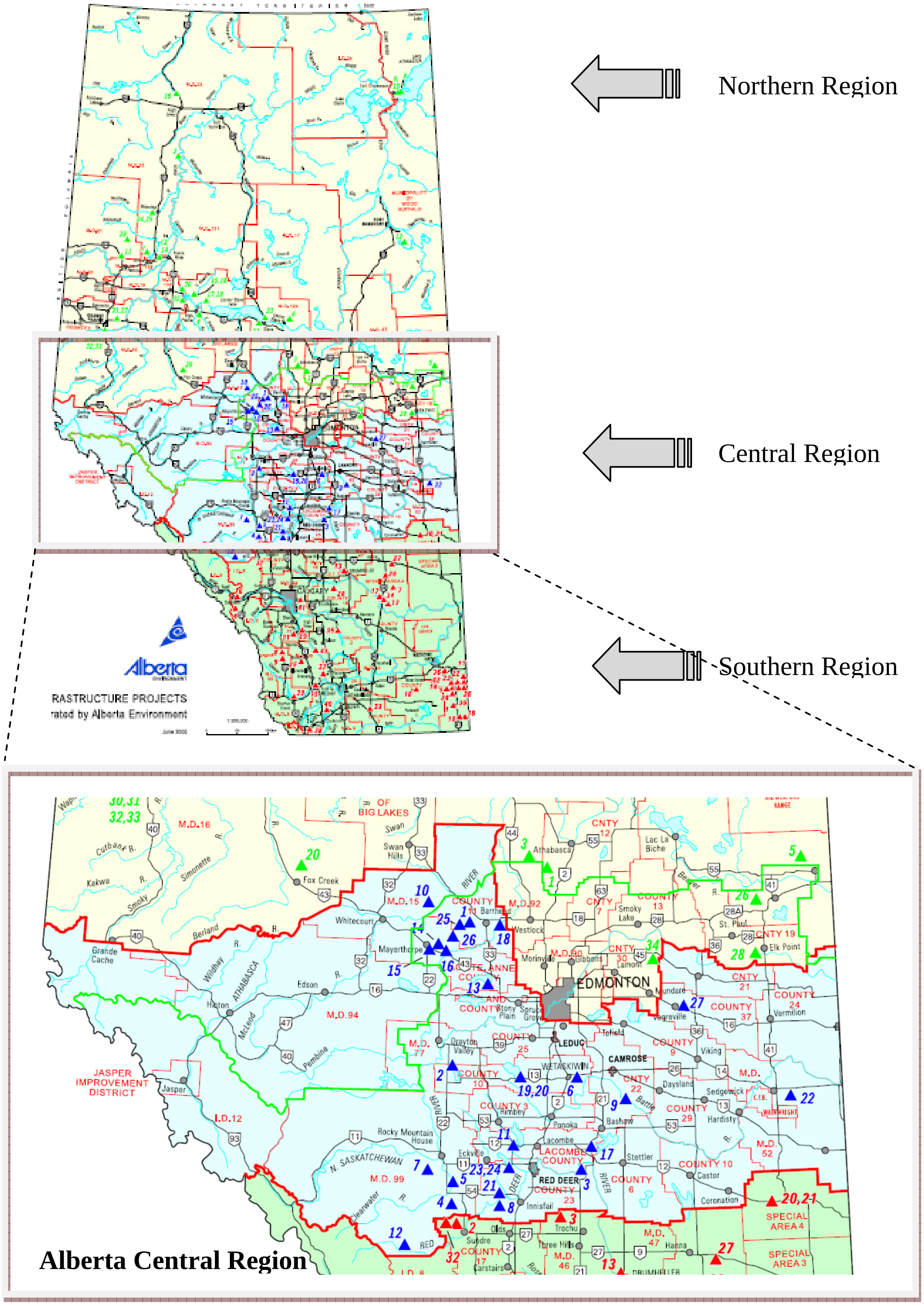


Figure 4. Major water management infrastructure projects in Alberta [owned and operated by Alberta Environment, 2005].

[http://www3.gov.ab.ca/env/water/wmo/resources/maps.html]. Table 1 shows the projects operating in Central Region of Alberta.

Table 1. List of the water projects which are operated by Alberta Environment within the Central Region
http://www3.gov.ab.ca/env/water/wmo/resources/maps.html

CENTRAL REGION		
LOCATION NUMBER	PROJECT NAME	TYPE OF STRUCTURE
1	Barrhead Water Supply	Weir
2	Buck Lake	Weir
3	Buffalo Lake Pumphouse / Pipeline	Pumphouse
4	Burntstick Lake	Weir
5	Clearwater River	Dykes
6	Coal Lake	Dam
7	Cow Lake Stabilization	Weir
8	Dickson Dam	Dam
9	Driedmeat Lake	Weir
10	Goose Lake	Weir
11	Gull Lake Pumphouse / Pipeline	Pumphouse
12	Klein Lake	Dam
13	Lac Ste. Anne	Weir
14	Little Paddle Dykes	Dykes
15	Paddle River Dam	Dam
16	Paddle River Dykes	Dykes
17	Parlby Cr. / Spotted L. / Alix L. Structure	Multiple
18	Pembina River Dykes	Dykes
19	Pigeon Lake - Creek	Ditch
20	Pigeon Lake - Weir	Weir
21	Red Deer River Erosion	Groynes
22	Ribstone Lake	Dam
23	Sylvan Lake Creek	Channel Improvement
24	Sylvan Lake Retaining Wall	Erosion Protection
25	Thunder Lake	Weir
26	Twin Lakes	3Backflood
27	Vermilion River – All Phases including Dam	Channel Improvement, Dam

2.4 Future climate change impact

It is reported that all dry regions of the world show an overall net negative impact of climate change on water resources and freshwater ecosystems. Decrease of runoff will likely result in reduction in the value of the services provided by water resources and the increase of annual runoff in other areas are likely to be tempered in some areas by negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality and flood risks (IPCC, 2007). Increases in temperature can affect the amount and duration of snow cover which, in turn, can affect timing of streamflow. Glaciers are expected to continue retreating, and many small glaciers may disappear entirely. Peak streamflow may move from late spring to early spring/late winter in those areas where snowpack is important in determining water availability. Changes in streamflow have important implications for water and flood management, irrigation, and planning. If supplies are reduced, off-stream users of water such as irrigated agriculture and in-stream users such as hydropower, fisheries, recreation and navigation could be most directly affected. Canada, with a wide range of climate conditions is expected to face changes on both water quantity and quality. The earlier stream peak flow in spring [Whitefield and Cannon, 2000], Drought conditions in Prairie Provinces [Nyirfa and Harron, 2001], saltwater intrusion into estuarine groundwater [Forbes et al., 1997] are repoted in Canada to be evidence of global climate change. It is of strategic importance for Canadian provinces to assess the impact of climate change on freshwater resources availability with a high spatial and temporal resolution model such as the one created here.

2.5 Project objectives

Numerous factors contribute to the complexity of water management, including conflict over water resources; inadequacy of knowledge about existing programs, water uses, and water availability; and the nature and extent of stakeholder participation.

The main objective of this project is the quantification of Alberta's water resources including all components of the water balance at the subbasin spatial and monthly temporal scale. This includes blue water flow (river discharge plus deep aquifer recharge), green water flow (evapotranspiration), green water storage (soil moisture), and aquifer recharge as shown in Figure 5.

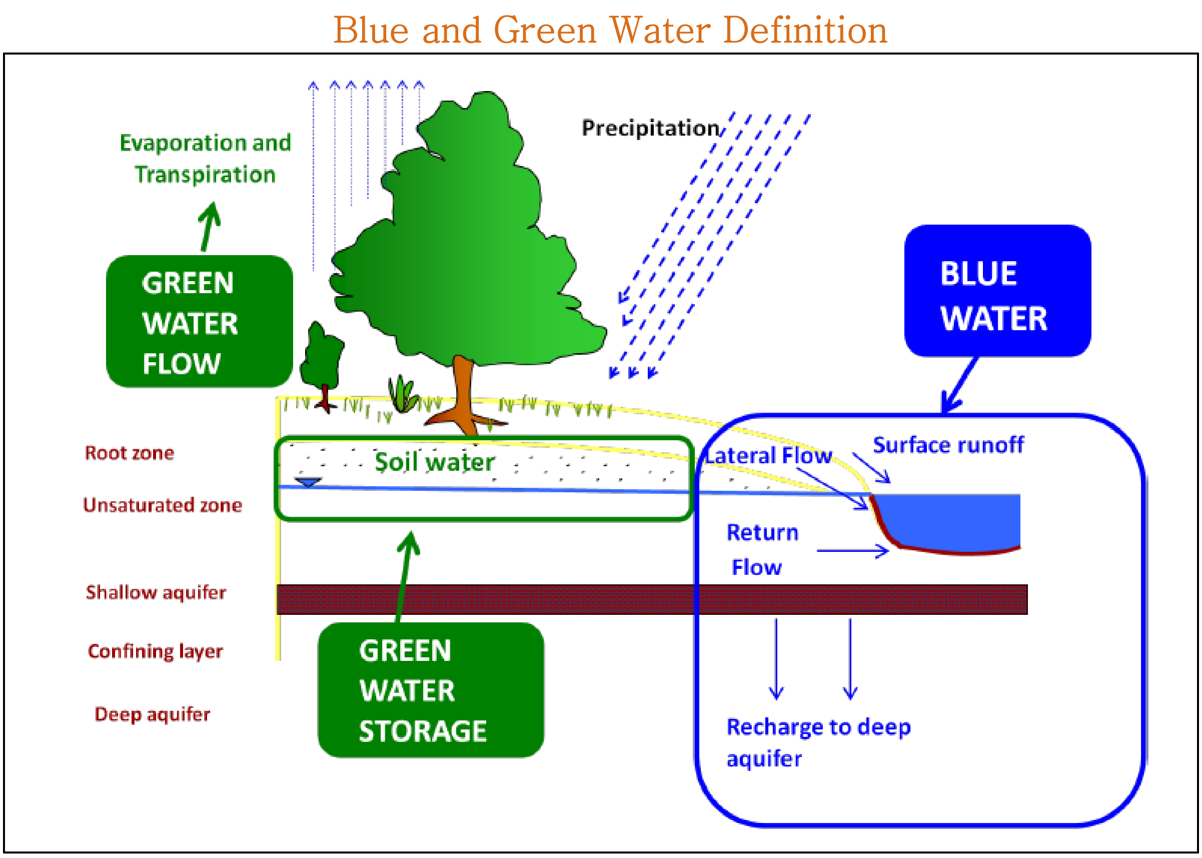


Figure 5. Definition of water balance components including blue water flow, green water flow, and green water storage.

3. Methodology

To model Alberta's water resources we used the hydrologic model Soil and Water Assessment Tool (SWAT) [Arnold et al., 1998] in combination with the Sequential Uncertainty Fitting program (SUFI-2) [Abbaspour 2007, Abbaspour et al., 2007] to calibrate, validate, and perform uncertainty analysis based on the available measured river discharge data. The modeled region of Alberta is shown in Figure 1.

3.1 The SWAT simulator

SWAT is a computationally efficient simulator of hydrology and water quality at various scales. It is a mechanistic time-continuous model that can handle very large watersheds in a data efficient manner. The model is already used in the "Hydrologic Unit Model for the United States" (HUMUS) [Arnold et al., 1999; Srinivasan et al., 1998], where the entire U.S. was simulated with good results for river discharges at around 6000 gauging stations. This study is now extended within the national assessment of the USDA Conservation Effects Assessment Project (CEAP, http://www.nrcs.usda.gov/Technical/nri/ceap/ceapgeneralfact.pdf). A more recent large scale SWAT application included the work of Gosain et al., [2006] where twelve large river basins in India were modelled with the purpose of quantifying the climate change impact on hydrology. SWAT is recognized by the U.S. Environmental Protection Agency (EPA) and has been incorporated into the EPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) [Di Luzio et al., 2002]. We used SWAT to model the whole of Africa [Schuol et al., 2008a,b], and the country of Iran [Faramarzi et al., 2009] as well as smaller watershed in Switzerland [Abbaspour et al., 2007] and China [Yang et al., 2008].

SWAT is developed to quantify the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land uses, and management conditions over long periods of time. The main components of SWAT are hydrology, climate, nutrient cycling, soil temperature, sediment movement, crop growth, agricultural management, and pesticide dynamics. In this study, we used Arc-SWAT [Olivera et al., 2006], where ArcGIS (ver. 9.3) environment is used for project development.

Spatial parameterization of the SWAT model is performed by dividing the watershed into subbasins based on topography. These are further subdivided into a series of hydrologic response units (HRU), based on unique elevation, soil, landuse, and slope characteristics. The responses of each HRU in terms of water and nutrient transformations and losses are determined individually, aggregated at the subbasin level and routed to the associated reach and catchment outlet through the channel network. SWAT represents the local water balance through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m). The soil water balance equation is the basis of hydrological modeling. The simulated processes include surface runoff, infiltration, evaporation, plant water uptake, lateral flow, and percolation to shallow and deep aquifers. Surface runoff is estimated by SCS curve number equation using daily precipitation data based on soil hydrologic group, land use/land cover characteristics and antecedent soil moisture.

In this study, potential evapotranspiration (PET) was simulated using Hargreaves method (Hargreaves et al., 1985). Actual evapotranspiration (AET) was predicted based on the methodology developed by Ritchie [1972]. The daily value of the leaf area index (LAI) was used to partition the PET into potential soil evaporation and potential plant transpiration. LAI and root development were simulated using the "crop growth" component of SWAT. This component represents the interrelation between vegetation and hydrologic balance. A more detailed description of the model is given by Neitsch et al. [2002].

3.2 The calibration program SUFI-2

The program SUFI-2 [Abbaspour 2007; Abbaspour et al., 2007; Abbaspour et al., 2004] was used for a combined calibration and uncertainty analysis. In any (hydrological) modeling work there are uncertainties in input (e.g., rainfall), in conceptual model (e.g., by process simplification or by ignoring important processes), in model parameters (non-uniqueness) and in the measured data (e.g., discharge used for calibration). SUFI-2 maps the aggregated uncertainties to the parameters and aims to obtain the smallest parameter uncertainty (ranges). The parameter uncertainty leads to uncertainty in the output which is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% (L95PPU) and the 97.5% (U95PPU) levels of the cumulative distribution obtained through Latin hypercube sampling. Starting with large but physically meaningful parameter ranges that bracket 'most' of the measured data within the 95PPU, SUFI-2 decreases the parameter uncertainties iteratively. After each iteration, new and narrower parameter uncertainties are calculated [see Abbaspour 2007] where the more sensitive parameters find a larger uncertainty reduction than the less sensitive parameters. In deterministic simulations, output (i.e., river discharge) is a signal and can be compared to a measured signal using indices such as R^2, root mean square error, or Nash-Sutcliffe, *NS*. In stochastic simulations where predicted output is given by a prediction uncertainty band instead of a signal, we devised two different indices to compare measurement to simulation: the *P-factor* and the *R-factor*

[Abbaspour 2007; Abbaspour et al., 2004]. These indices were used to gauge the strength of calibration and uncertainty measures. The *P-factor* is the percentage of measured data bracketed by the 95PPU. As all correct processes and model inputs are reflected in the observations, the degree to which they are bracketed in the 95PPU indicates the degree to which the model uncertainties are being accounted for. The maximum value for the *P-factor* is 100%, and ideally we would like to bracket all measured data, except the outliers, in the 95PPU band. The *R-factor* is calculated as the ratio between the average thickness of the 95PPU band and the standard deviation of the measured data. It represents the width of the uncertainty interval and should be as small as possible. *R-factor* indicates the strength of the calibration and should be close to or smaller than a practical value of 1. As a larger *P-factor* can be found at the expense of a larger *R-factor*, often a tradeoff between the two must be sought.

3.3 The calibration setup and analysis

Sensitivity, calibration, validation, and uncertainty analysis were performed for the hydrology using river discharge. As SWAT model involve a large number of parameters, a sensitivity analysis was essential to identify the key parameters across different hydrologic regions. For the sensitivity analysis, 22 parameters integrally related to stream flow [Liu et al., 2008; Levesque et al., 2008; Holvoet et al., 2005; White and Chaubey, 2005; Abbaspour et al., 2007a, Faramarzi et al., 2009] were initially selected (Table 2). We refer to these as the 'global' parameters. In a second step, these global parameters were further differentiated by main river basins in order to account for spatial variation in climate and management conditions (i.e., SCS curve number CN2 of agricultural areas was assigned differently in Beaver River Basin from that of Milk River Basin areas). This resulted in 102 scaled parameters.

As different calibration procedures produce different parameter sets (Abbaspour et al., 1999; Abbaspour et al., 2007a; Schuol et al., 2008b; Yang et al., 2008), we used two different approaches here for comparison of observed and simulated discharge data to provide more confidence in the results. These include: (i) the "global approach", where all discharge gauges from all river basins were calibrated within a single calibration framework, (ii) the "regional approach", where discharge gauges were separately calibrated for different water regions. Based on the deviation presented in Figure 1, we considered six major water regions for the regional calibration and did not consider the "River Sub Basins (RSB)" as a single water region. The six calibrated water regions were:

- RB1 and RB2 (for RB 1 we did not have any discharge data)
- RB 3
- RB 4
- RB 5
- RB 6, 7, 8, and 9
- RB 10

4. Input data

SWAT can run on different ranges of data availability. Clearly, the more the input data the better will be the output results. Table 3 summarizes a list of essential and optional SWAT data requirement. The status of data availability is also indicated in Table 3. The preliminary results are based on the data indicated in the Table. Figures 6 to 10 show spatial distribution of the land use classes, soil types, climate stations, river discharge stations and CRU raster climate points used in this study.

Table 2. Sensitive input parameters in the calibration processes

Parameter Name	**Definition**
SURLAG.bsn	Surface runoff lag time (days)
SMTMP.bsn	Snow melt base temperature (ºC)
SFTMP.bsn	Snowfall temperature (ºC)
SMFMN.bsn	Minimum melt rate for snow during the year (mm/ºC-day)
TIMP.bsn	Snow pack temperature lag factor
CN2.mgt	SCS runoff curve number for moisture condition II
ALPHA_BF.gw	Base flow alpha factor (days)
REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)
GW_DELAY.gw	Groundwater delay time (days)
GW_REVAP.gw	Groundwater revap. coefficient
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
RCHRG_DP.gw	Deep aquifer percolation fraction
ESCO.hru	Soil evaporation compensation factor
SOL_AWC.sol	Soil available water storage capacity (mm H2O/mm soil)
SOL_K.sol	Soil conductivity (mm/hr)
SOL_BD.sol	Soil bulk density (g/cm3)
SMFMX.bsn	Maximum melt rate for snow during the year (mm/ºC-day)
EPCO.hru	Plant uptake compensation factor
OV_N.hrul	Manning's n value for overland flow
SOL_ALB.sol	Moist soil albedo
CH_N2.rte	Manning's n value for main channel
CH_K2.rte	Effective hydraulic conductivity in the main channel (mm/hr)

Table 3. Data requirement of SWAT

Data name	Required information
DEM	- we are using 90m x 90m resolution data from: ESRI Global Digital Elevation Model (SRTM)
Landuse	- we are using 250 m resolution data from: Natural Resources Canada - NRCan's EOSD data - Earth Observation for Sustainable Development. This is augmented for areas surrounding Alberta with 1000 m resolution data from global database
Soil	- we are using the data from Agriculture Canada or CANSIS - Canadian Soils Inventory System and some data from Agriculture Canada found under the Canadian Geography Networks Arc Voyager's ArcIMS site. The spatial resolution is 1:250000. For the Alberta surrounding area we used the FAO global soil map. We have created as associated database containing the following variables needed for SWAT simulations: - Two soil layers (0-30 cm, 30-100 cm) - Soil Hydrologic group (A, B, C, or D) - Maximum rooting depth (mm) - Textural class of first soil layer - Depth from soil surface to bottom of each layer (mm) - Moist bulk density (g/cm^3) - Available water capacity (mm H2O/mm soil) - Saturated hydraulic conductivity (mm/hr) - Organic carbon content (% soil weight) - Clay content (% soil weight) - Silt content (% soil weight) - Sand content (% soil weight) - Rock fragment content (% total weight) - Moist soil albedo - Soil erodibility factor, K, in USLE equation
Stream network map	- missing We would like to have a river map with river names
Climate data	1- we bought a CD from: http:\\climate.weatheroffice.ec.gc.ca\prodos_servs\documentation_index_e.html The database in sparse in northern Alberta The data base includes: - Daily precipitation (mm) for the period of 1985 to 2007

	- Dail Max temperature (degree C.) for the period of 1985 to 2007 - Dail Min temperature (degree C.) for the period of 1985 to 2007 - Location (lat, long, elevation) of the climate stations 2. we downloaded the raster data from http://www.cru.uea.ac.uk/cru/data These are gridded climate database (0.5 degree) CRU TS3.0 and include: - Daily precipitation (mm) for the period of 1985 to 2006 - Dail Max temperature (degree C.) for the period of 1985 to 2006 - Dail Min temperature (degree C.) for the period of 1985 to 2006 - Location (lat, long, elevation) of the climate stations
Reservoir operation information	- missing We would need information on the location of dams and reservoirs and their operations as follows: - Month the reservoir became operational (0-12) - Reservoir surface area when the reservoir is filled to the emergency spillway (ha) - Volume of water needed to fill the reservoir to the emergency spillway (10^4 m3) - Reservoir surface area when the reservoir is filled to the principal spillway (ha) - Volume of water needed to fill the reservoir to the principal spillway (10^4 m3) - Initial reservoir volume. - Initial sediment concentration in the reservoir (mg/L) - Equilibrium sediment concentration in the reservoir (mg/L) - Hydraulic conductivity of the reservoir bottom (mm/hr) - Daily reservoir outflow (m^3/s).
Inlet	- missing - Lat and long for any inlet to the watershed is required - daily data for any inlet (optional)
Agricultural management data	- missing - Planting and harvest dates - Fertilization information (when, where, how much) - Tillage operation (method, date) - Irrigation (source, date, amount) - Grazing - Tile drains (exits or not, if yes, at what depth) - Pesticide application - Crop rotation

Water management	- missing - Water transfer information, water use from shallow and deep aquifer, river, and ponds
River discharge data at hydrometric stations	- have daily river discharge (m^3/s) data for 167 stations. However, some are given in terms of water height rather than discharge; some are controlled by dams and reservoirs, and some by glaciers. Need to know this information but we currently don't have them. Source: http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm
Crop yield data	- missing Need: - Annual yield for major crops in the region
Water quality at hydrometric stations (if water quality is required)	- missing This data would be needed for water quality studies. Needed data are some or all of the following depending on the objectives: - Sediment load transported by the river (daily, or monthly) (tn), or - River sediment concentration (mg/l) - Nitrate load transported by the river (kg N) - Phosphorus load transported by the river (Kg P) - Dissolved oxygen transported by the river (kg O_2) - Algal biomass transported by river (kg) - Other chemicals such as: NH4, NO2, Mineral P, organic P, Organic N, CBOD are also considered by SWAT
Point sources	- missing - Input from water treatment plants (quantity and quality of water) - Lat-Lon location - Springs (quantity and quality, and also Lat-Long location)

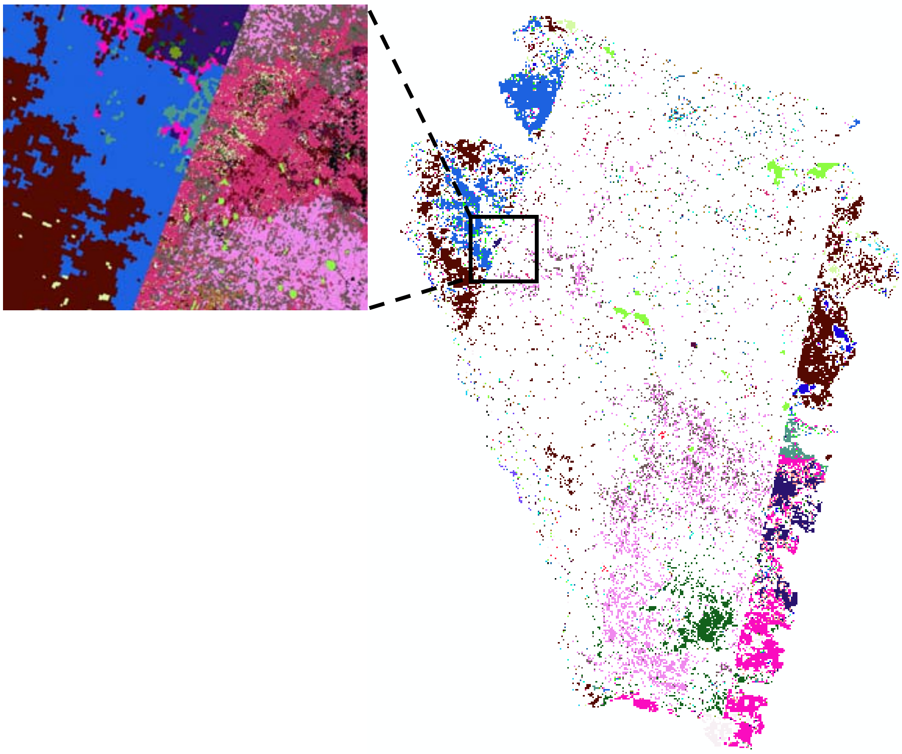


Figure 6. Landuse map of Alberta (250 m resolution) and surrounding areas (1000 m resolution).

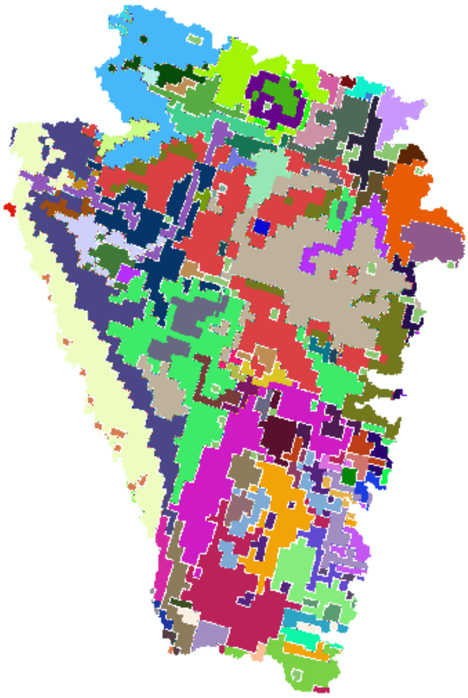


Figure 7. Soil map of Alberta (1000 m resolution).

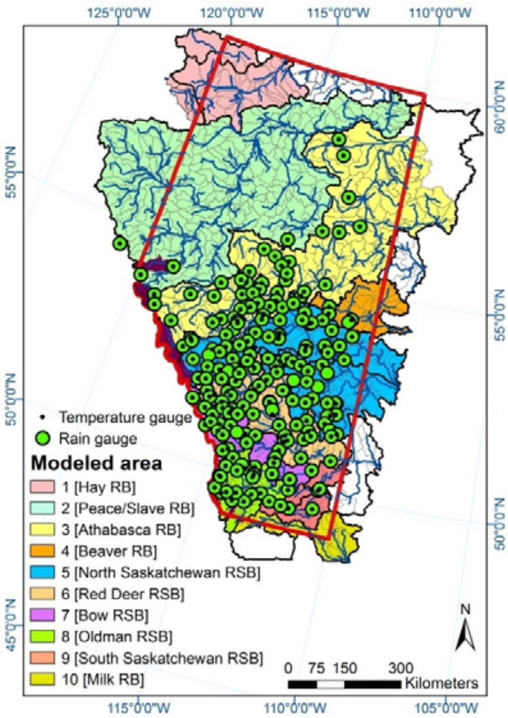


Figure 8. Distribution of observed temperature and precipitation stations.

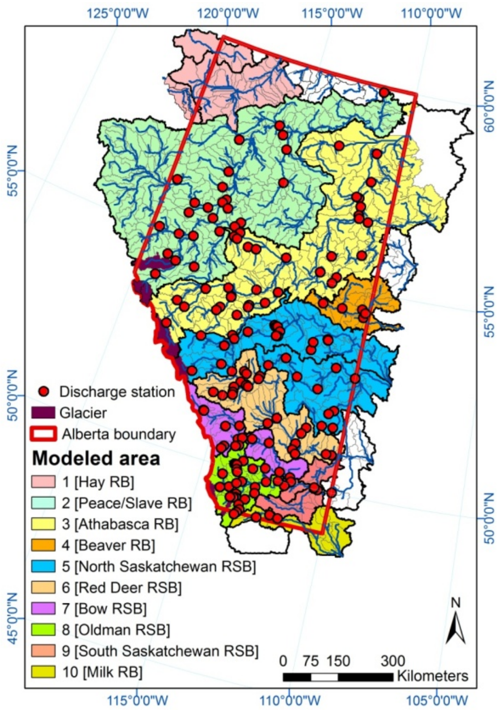


Figure 9. Distribution of the 167 outlets used in the initial run.

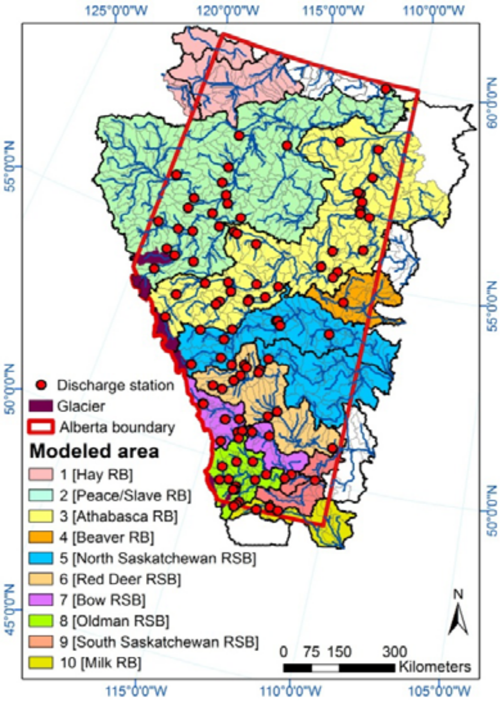


Figure 10. Distribution of the 101 outlets used in the initial run

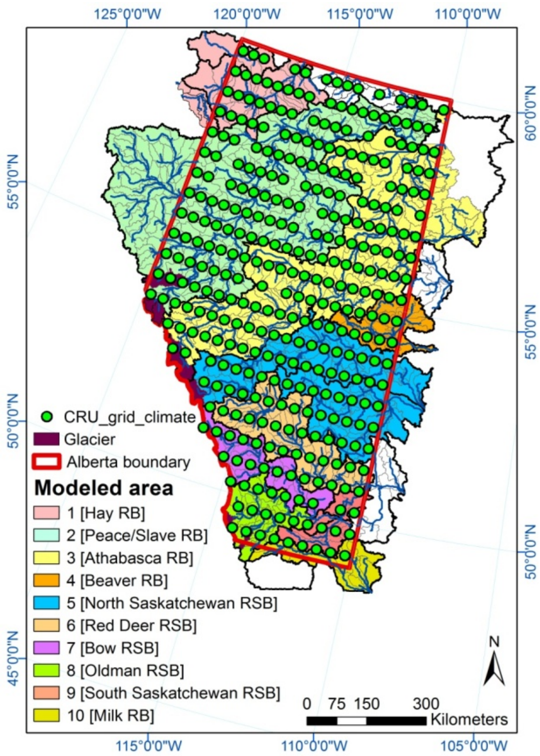


Figure 11. Distribution of the gridded climate points with 0.5 degree resolution from CRU providing daily precipitation and maximum and minimum daily temperature data for the entire Alberta.

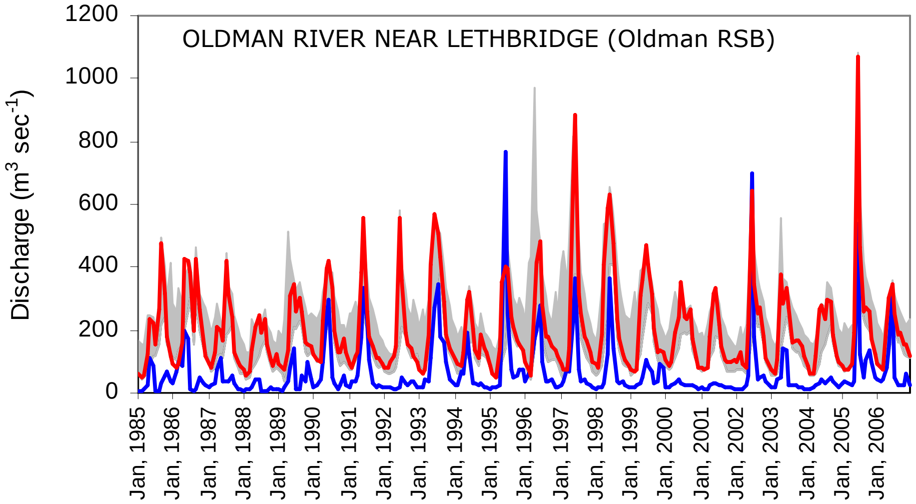
5. Preliminary results

To calibrate and validate the hydrologic model, we started with one first run to get an indication of the model performance and observed discharge stations to be used for calibration. The results show that many stations are:

- small creeks
- under the influence of reservoirs, dams and glaciers,
- some stations are not properly placed on the correct river or stream (a river map with river names would be useful to identify these stations), and
- some have only reported water heights and no discharge numbers

After identifying and properly accounting for this, we calibrated in the next step using the discharge data of 101 stations (Figure 10) rather than 167 (Figure 9). Examples of discharge stations under the influence of dam, reservoir, Glacier, consumptive water use, water transfer, or wrong data (water height instead of discharge) are presented in Figures 12 to 14. Figure 15 shows a station located downstream of a dam, Figure 16 shows a station located in a small creek. To calibrate the former we need to know dam's operation while the data from the small creek is not reliable. Performance of these stations cannot be improved by calibration unless we know the exact nature of the observed discharge.

Figure 17 shows example of stations that can be improved by calibration. Because, the first run shows a rather good prediction in terms of BR^2 and *P-factor* but the *R-factor* (a measure of uncertainty) has to be decreased through parameter optimization in the next calibration iterations.



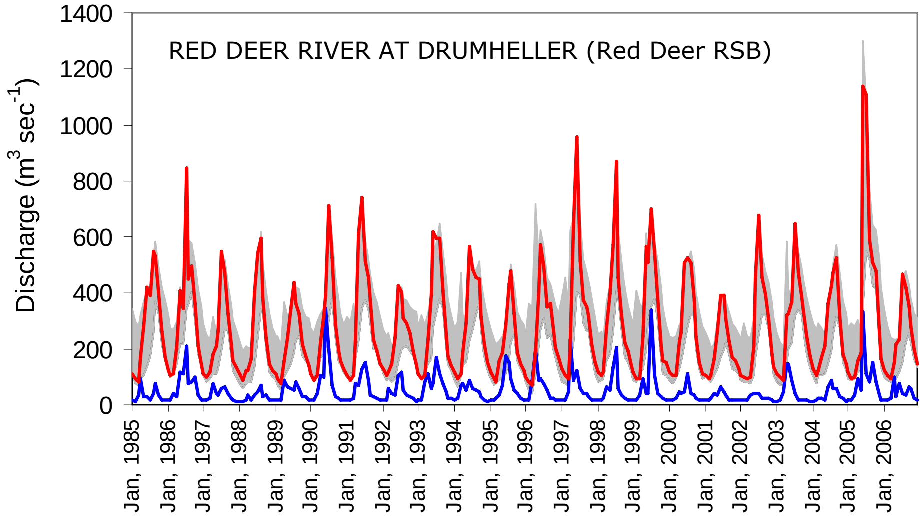


Figure 12. Example of stations that could not benefit from calibration and most likely is affected by a dam or reservoir or water extract from upstream.

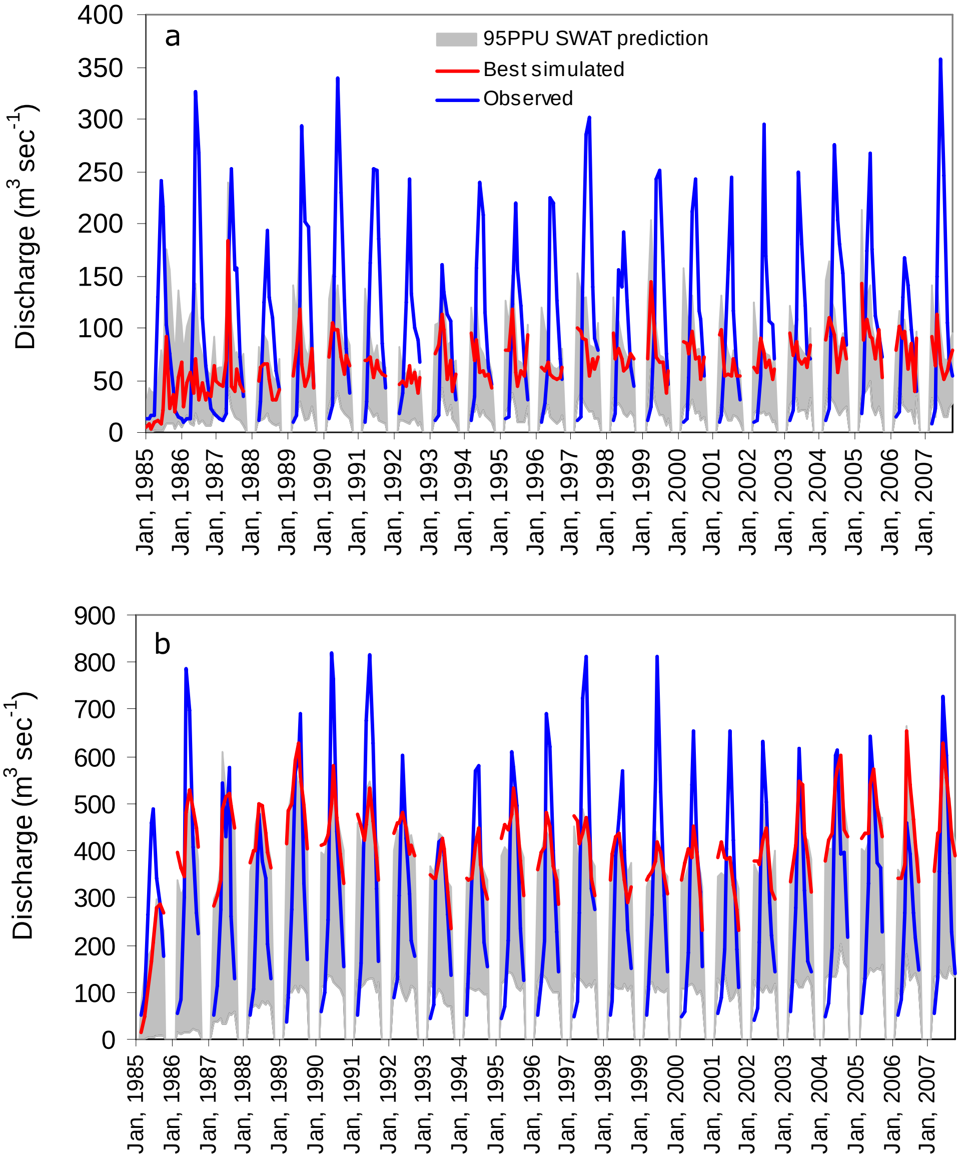


Figure 13. Example of stations that are affected by glaciers at upstream. The glaciers have additional input to the rivers. We modified this in SWAT model.

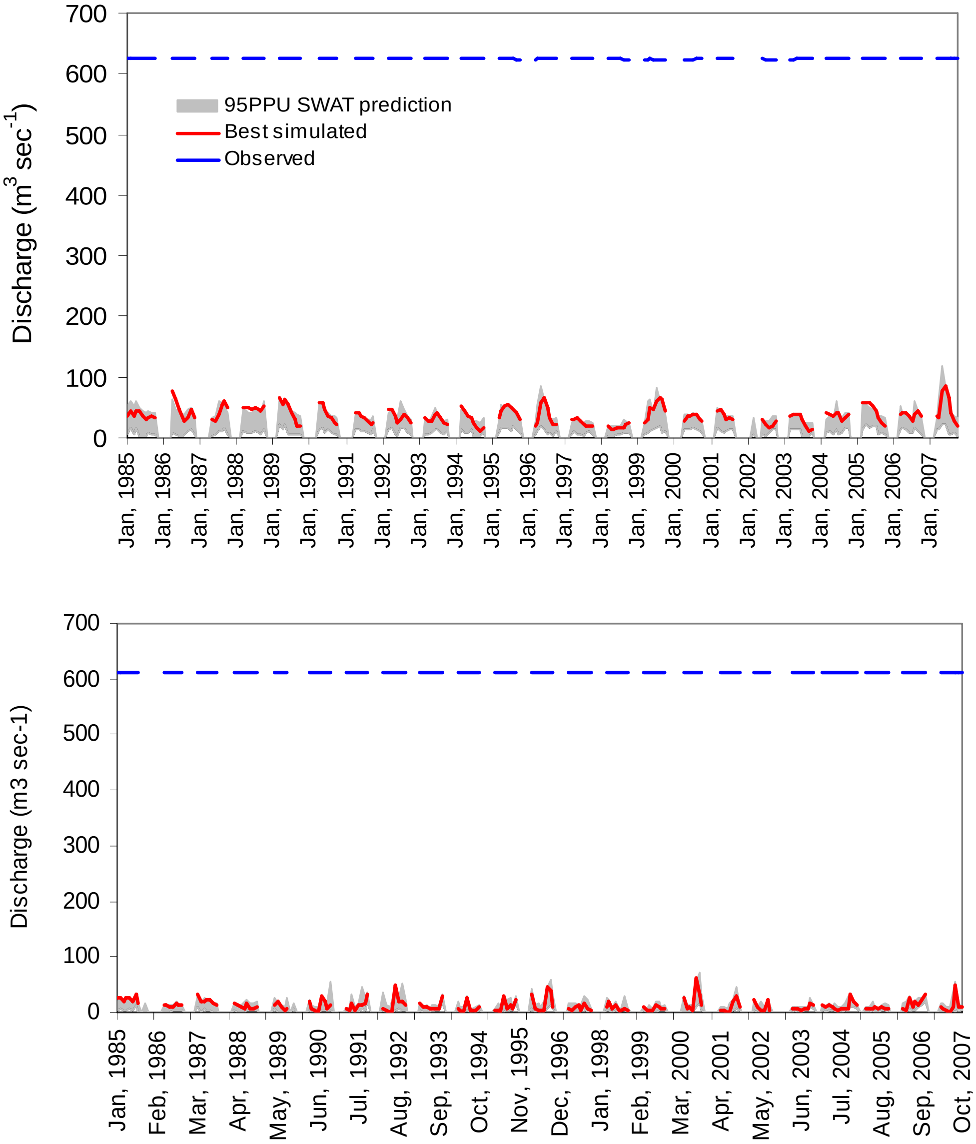


Figure 14. Example of stations where we have water heights instead of discharges. We need to obtain discharges, or remove them from calibration process.

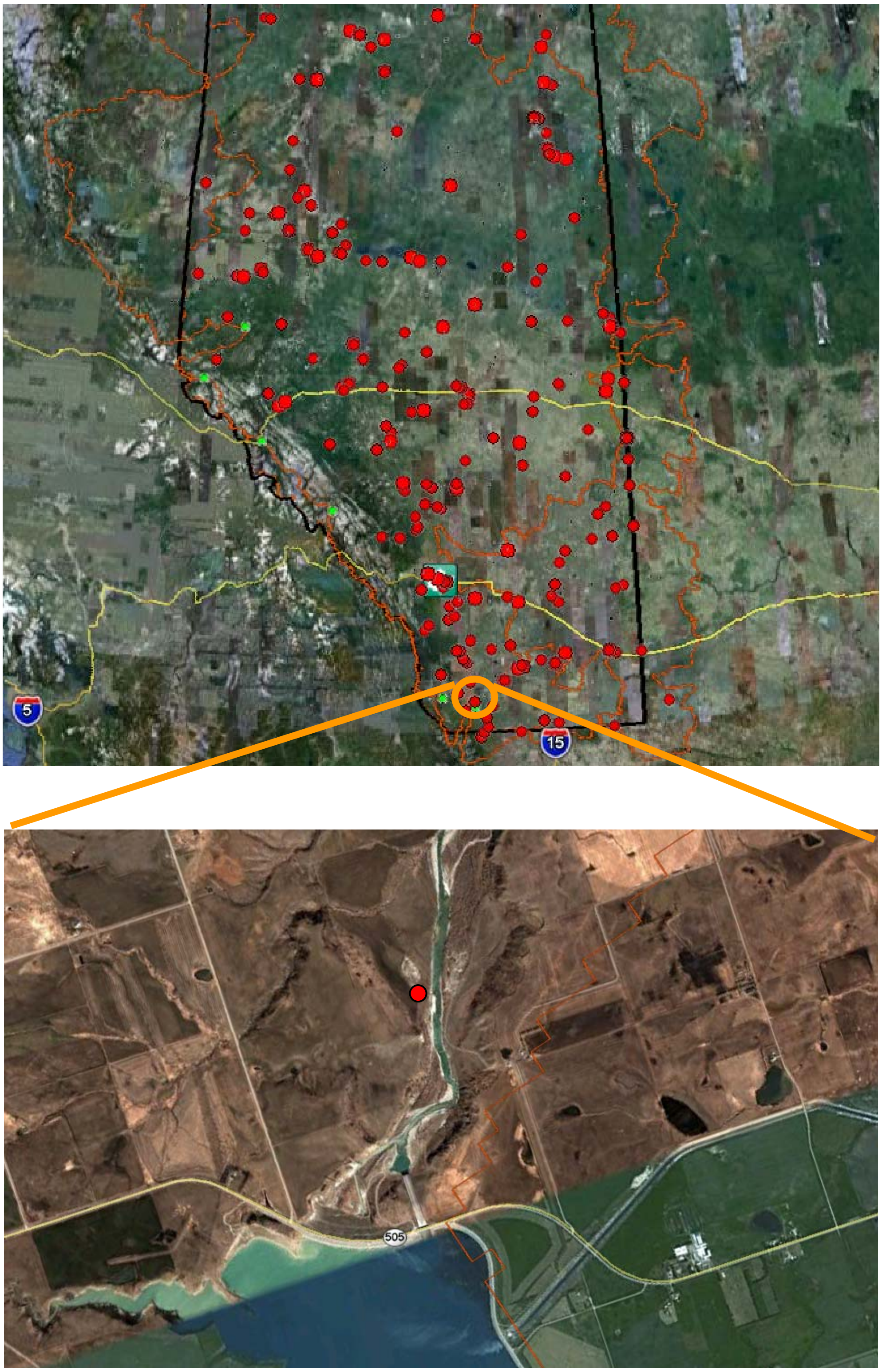
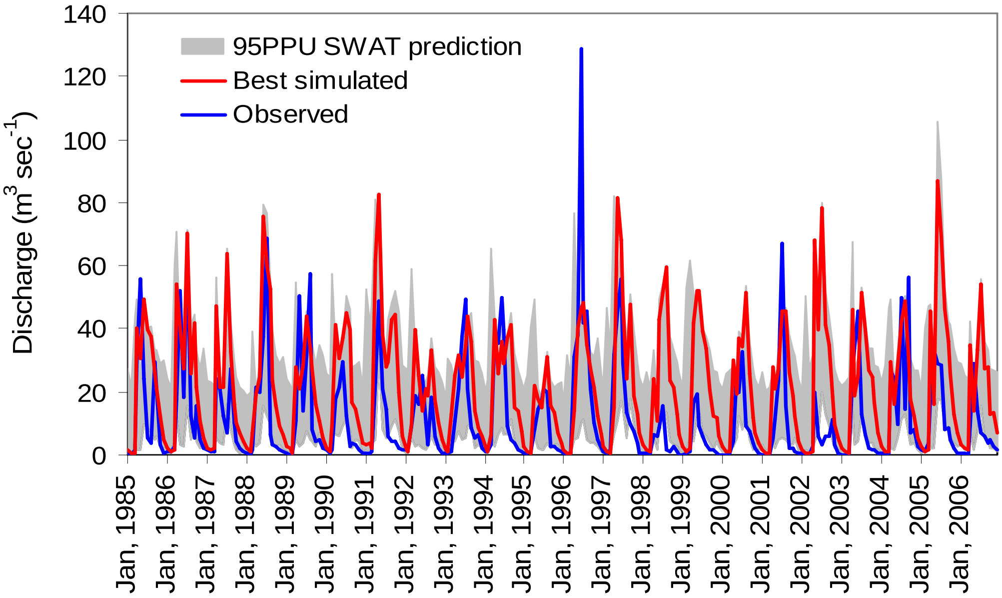


Figure 15. Example of stations located downstream of a dam. To calibrate this station we need to know the dam’s operation

Figure 16. Example of a discharge station located in a small creek. The data from these statioins are not reliable



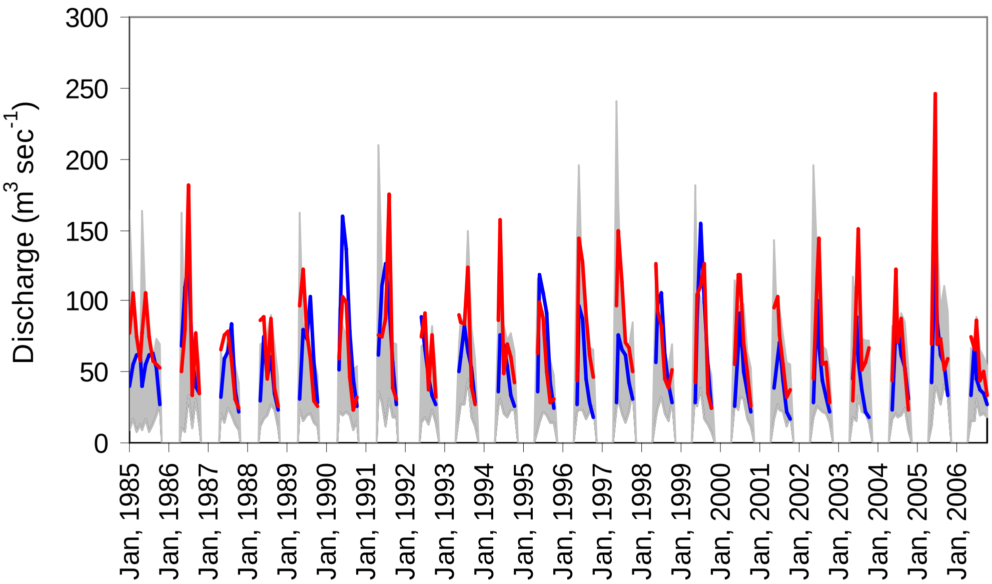


Figure 17. Example of a stations that could be improved with calibration.

6. Final results

6.1 Final results using the observed climate data as input to the SWAT model

Using the observed climate data of 194 rain gauge and 189 temperature gauges as input in the SWAT model (Figure 8), the calibration results for 101 discharge stations produced a poor performance as presented in Table 3. In general, we started with a rather wide initial range of parameter values for each water region and tried to narrow this uncertainty in the next calibration iterations. All water regions performed poor in terms of goal function and R^2. The initial *P-factor* was in general satisfactory but attempt to narrow uncertainty band while improving goal function, resulted in quite small percentage of observed data bracketed within uncertainty band (i.e. in average for the whole Alberta the P-factor was 0.17, at final stage of calibration procedure). To improve the calibration performance in some stations which were likely affected by glaciers, we considered additional water inflow using "inlet" option in the model. Figure 18 shows how the calibration performance was improved in a downstream station of a glacier in the model (namely "Athabasca River near Windfall" station, Figure 19). In this station, the calibration performance was improved from 0.45 to 0.63 for *P-factor*, from 1.47 to 1.43 for *R-factor*, from 0.17 to 0.80 for R^2 and from 0.02 to 0.66 for goal function (bR^2).

Table 3. Calibration performance of different water regions while using observed climate data as input in the SWAT model.

River basin/subbasin	*P-factor*		*R-factor*		R^2		Goal function	
	initial	Final	initial	Final	initial	Final	initial	Final
Hay & Peac/Slave RB	0.46	0.16	4.40	1.70	0.09	0.08	0.07	0.08
Athabasca RB	0.61	0.27	4.46	2.56	0.04	0.06	0.02	0.03
Beaver RB	0.51	0.18	4.62	2.75	0.06	0.07	0.02	0.03
North Sasketchwan RSB	0.37	0.08	19.37	7.38	0.04	0.05	0.03	0.05
Red Deer, Bow, South Sas., Oldman RSB	0.48	0.23	4.93	2.95	0.07	0.11	0.04	0.05
Milk RB	0.20	0.11	79.04	56.73	0.11	0.14	0.09	0.12

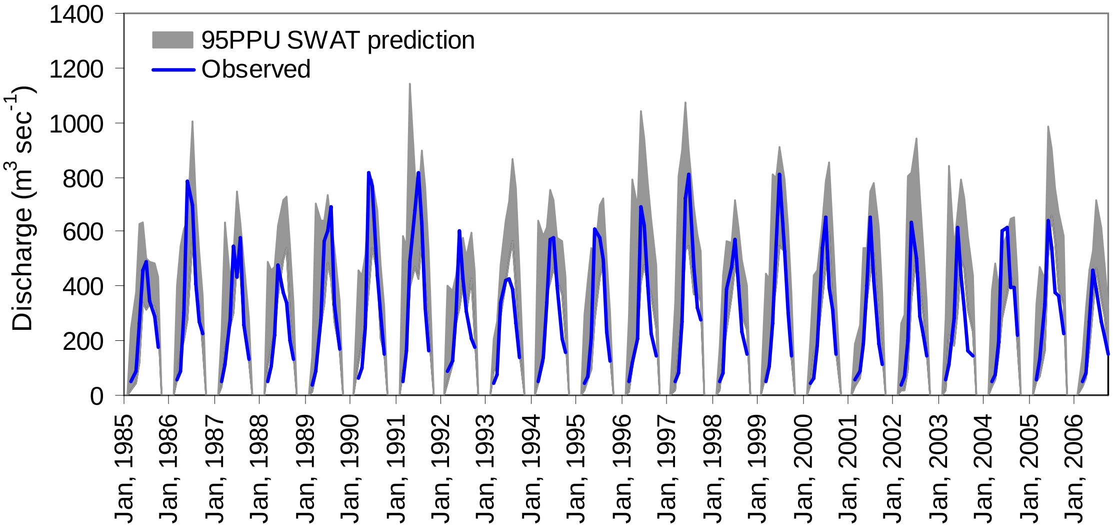


Figure 18. Calibration performance of the "Athabasca River near Windfall" station that was improved compare to its performance with the initial model setup where the effect of glacier did not considered (Figure 13b).

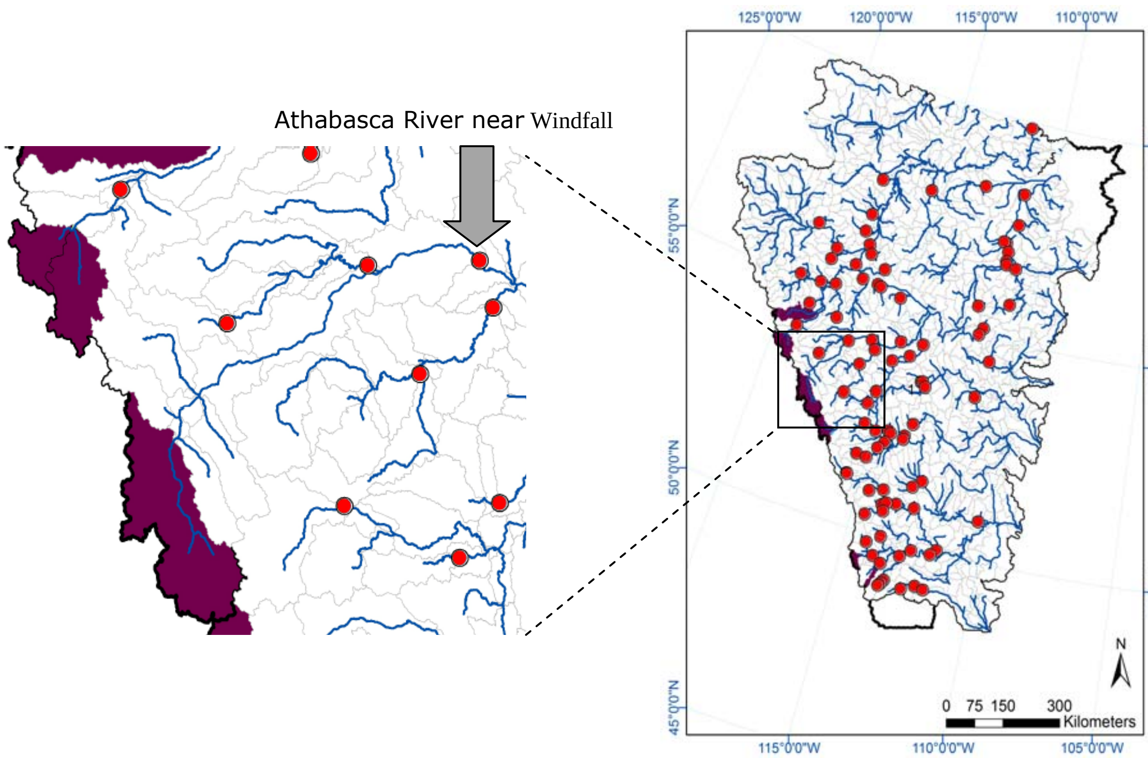


Figure 19. Athabasca River near Windfall station, located at downstream side of a glacier.

Using the optimized parameter ranges we further intended to calculate the long-term average hydrological components at subbasin level to be able to compare the results with improved input data in the next phase. Figures 20 to 24 show different hydrological components of Alberta resulted from this phase of the analysis.

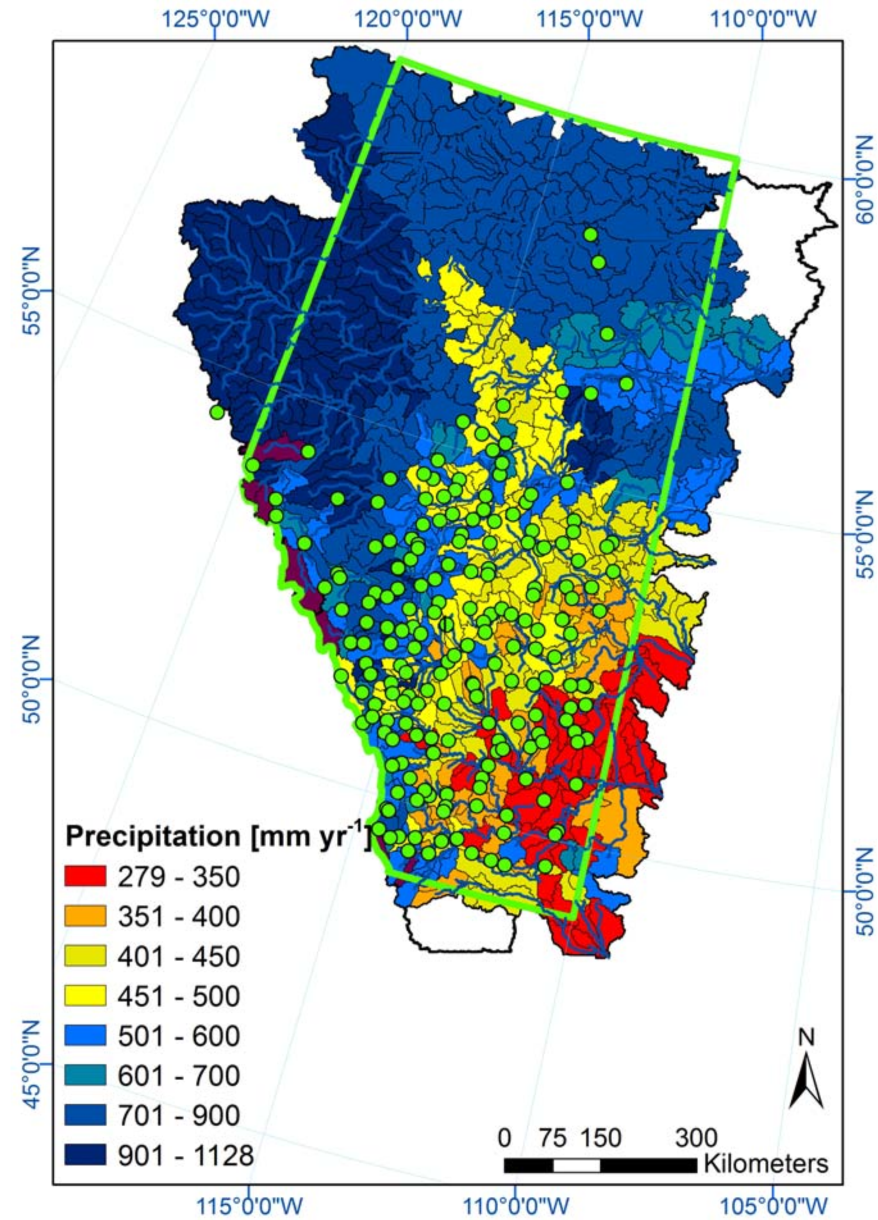


Figure 20. Long term (1985-2007) average distribution of precipitation.

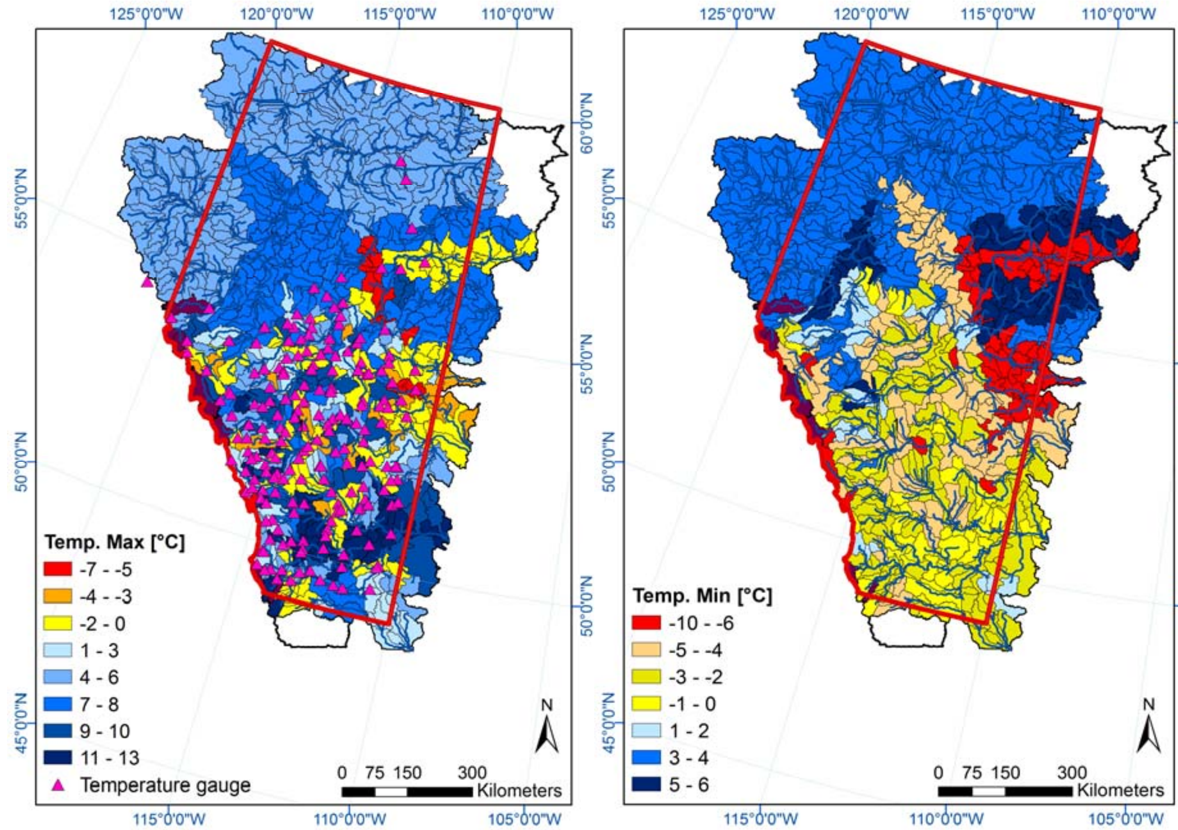


Figure 21. Long term (1985-2007) average distribution of maximum and minimum temperature.