Development of a Snowmelt Runoff Model for the Lower Smoky River

Centre for Hydrology Report No. 13

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Executive Summary

The Smoky River tributary of the Peace River has an ungauged (in real-time) basin area of 23,769 km^2, corresponding to 46% of its basin area of 51,839 km^2. The purpose of this study was to develop a model to simulate the daily spring ungauged flows of the Smoky River and its main tributary, the Little Smoky River for recent periods using measured meteorological data and forecast periods using the outputs of a numerical weather forecast model.

A physically-based model of the ungauged local flows contributing to the Smoky River at Watino and the Little Smoky River at Guy, the Lower Smoky River Model (LSRM), was developed using the CRHM platform. The model was deployed to 26 ungauged sub-basins, from which discharges were routed and accumulated to produce the ungauged discharges at Guy and Watino. The modelled sub-basins were regionalised into characteristic ecoregion types, mountain, boreal forest, boreal-agriculture transition and agricultural, for purposes of delineating model structure, interpretation of land cover classifications and parameterisation. Parameters were estimated from GIS databases of vegetation type, topography and soil texture, a site visit, literature review and to better fit the hydrographs of four test sub-basins

A significant challenge in operating the model is missing meteorological data and the low density of meteorological stations over much of the basin. A flexible system for interpolating from existing observations to infill missing data was developed to compensate for this, but it was found that when substantial precipitation was not measured, the model was incapable of estimating discharge correctly. This was most evident in the Little Smoky River in 2007.

The LSRM modelled discharge was evaluated to estimate the discharge of the Smoky River and Little Smoky River in an operational setting with measured meteorological observations. Results from this comparison were very good with a high degree of hydrograph predictability, small bias in flow estimation, and very good prediction of peak daily discharge and excellent prediction of the timing of peak daily discharge. The results were somewhat better for the Smoky River than for the Little Smoky River, showing the effect of increasing basin size in compensating for inadequate precipitation observation density and/or errors in model structure or parameterisation.

For operation in real time, the CRHM LSRM was interfaced with WISKI by creating the LSRM Data Management System (LSRM-DSM). The LSRM-DSM system brings in updated observational data from nine stations and forecast data for 384 hours in the future on a daily basis to run LSRM and then output the LSRM modelled discharges for use by AESRD in forecasting. Missing observational data are infilled by interpolation from other weather stations in the same manner as was used in the evaluation runs. It should be noted that if no observational or forecast weather data is available for a substantial period of time (>3 hours), then the model cannot be run reliably and so automated QA/QC of weather station data and forecasts before input to LSRM by AESRD staff during forecasting periods is highly recommended. The model has not yet been tested in an operational setting during a spring snowmelt event and its full capabilities and usefulness cannot be assessed until it has been tested in such a setting.

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List of Acronyms

AARD	Alberta Agriculture and Rural Development
ABMI	Alberta Biodiversity Monitoring Institute
AESRD	Alberta Environment and Sustainable Resource Development
AGCM	Agricultural Climate Monitoring
AGDM	Agricultural Drought Monitoring
API	Application Programming Interface
AWK	Aho, Weinberger and Kernighan
Bash	Bourne Again SHell
BEAV	Beaverlodge RCS
CRHM	Cold Regions Hydrological Model platform
DEM	digital elevation model
EAGL	Eaglesham AGCM
fallstat	fall soil saturation (%)
F.O.S.S.	free open source software
Gawk	Gnu AWK
GDAL	geospatial data abstraction library
GIS	geographic information system
GLAC	La Glace AGCM
GPL	GNU Public Licence
GUI	Graphical User Interface
gw_{max}	water storage capacity for groundwater layer (mm)
HEND	Hendrickson Creek
HRU	hydrological response unit
IDW	inverse distance weighted

IP3	Improved Processes and Parameterization for Prediction in Cold Regions
K_{s_gw}	saturated hydraulic conductivity in the groundwater layer (m s^{-1})
K_{s_lower}	saturated hydraulic conductivity in the lower of soil layer (m s^{-1})
K_{s_upper}	saturated hydraulic conductivity in the upper of soil layer (m s^{-1})
LAI	leaf area index
LSRM	Lower Smoky River Model
LSRM-DMS	Lower Smoky River Model Data Management System
m.a.s.l.	metres above sea level
MB	model bias
MCRB	Marmot Creek Research Basin
NAEFS	North America Ensemble Forecast System
OBS	observation
PEOR	Peoria AGDM
PFRA	Prairie Farm Rehabilitation Administration
ppt	daily precipitation (mm)
RCUTGPR	Cutbank River near Grande Prairie
rh	relative humidity (%)
RKAKGPR	Kakwa River at Highway No. 40
RLSMOGUY	Little Smoky River near Guy
RMUSKGCA	Muskeg River near Grande Cache
RSIMGOOD	Simonette River near Goodwin
RSMOHELL	Smoky River above Hells Creek
RSMOWATI	Smoky River at Watino
RWAPGPR	Wapiti River near Grande Prairie
RWASKMOU	Waskahigan River near the mouth

SAGA	System for Automated Geoscientific Analyses
Sbar	maximum canopy snow interception capacity per unit of leaf area (kg m^{-2})
sd_{rechr_max}	depressional storage capacity (mm)
SnoMIP2	snow model intercomparison project 2
$soil_{moist\_max}$	water storage capacity for the both recharge and lower soil layers (mm)
$soil_{rechr\_max}$	water storage capacity for the recharge soil layer (mm)
SSARR	Streamflow Synthesis and Reservoir Regulation model
ssrKstorage	subsurface flow travel time (day)
SWE	snow water equivalent (mm)
t	air temperature (°C)
TEEP	Teepee Creek AGDM
TOPAZ	TOpographic PArameteriZation
u	wind speed (m/s)
VALL	Valleyview AGDM
YQU	Grande Prairie Airport
λ	pore size distribution index

1. Introduction

1.1 Overview of the Study and Objectives

The intent of this study is to document and demonstrate a "system" able to provide forecasts of spring snowmelt runoff contributions to local inflows to the lower reaches of the Smoky River, Alberta. The "system" consists of several hydrological modelling components, as well as data acquisition components to support the model and pre- and post-processing of the model data. This provides Alberta Environment and Sustainable Resource Development (AESRD), River Forecast Section with a physically-based computer model that can predict the timing and magnitude of snowmelt runoff from ungauged streams to the lower Smoky River basin. An assessment of the initial snowmelt runoff peak from the lower basin is a major factor in spring breakup forecasting for the Smoky and Peace Rivers. Field observations by AESRD have shown that the majority of the initial snowmelt runoff originates in the lower portion of the basin, which is mainly agricultural and lies roughly north of 54° 45'.

Utilizing the near-real time meteorological and hydrometric data, the model is designed to function in an operational environment and to be run on a daily basis using one of i) forecasted meteorological conditions, ii) meteorological scenarios or iii) historic meteorological data. The model is not designed to predict river ice breakup or to estimate ice jam, surge or under-ice flows, but to provide short to medium range forecasts (3 to 7 days out) of local inflows within and their contribution to flows at the exit of the basin. This can be used for breakup forecasting and mitigation in the Peace River.

The specific objective of the study contained in this report is to utilize the meteorological, soil moisture, hydrometric and snow data available to the AESRD River Forecast Centre to produce a calibrated, physically based computer model to calculate snowmelt runoff within the lower Smoky River basin, suitable for use within a setting where forecasts are produced daily to guide time-sensitive water management decisions. The Lower Smoky River Model calculates the contribution of local ungauged flows to daily discharge at the following gauging locations;

1) Smoky River at Watino (07GJ001, RSMOWATI), and

2) Little Smoky River near Guy (07GH002, RLSMOGUY).

This enables the determination of the timing and peak discharge from snowmelt runoff within the lower Smoky River basin.

1.2 Snowmelt Runoff in the Lower Smoky River Basin

Important hydrological characteristics of the Peace River District, including the Lower Smoky River Basin are long periods of winter (usually five months) and a snowcover modified by wind redistribution and sublimation of blowing snow (Pomeroy and Gray, 1995). The blowing snow process is affected by the interaction of local topography and surficial vegetation cover with regional wind flow patterns (Pomeroy et al., 1993; Fang and Pomeroy, 2009). High surface runoff derives from spring snowmelt, which is 80% or more of annual local surface runoff in the Prairies (Gray and Landine, 1988), and occurs as a result of frozen mineral soils at the time of melt and a relatively rapid release of water from melting snowpacks (Gray et al., 1985). Snowmelt timing and meltrate are primarily controlled by the net inputs of solar radiation, thermal radiation, energy advected from rainfall, turbulent transfer of sensible and latent heat. These net inputs are controlled by the storage of internal energy in the snowpack and the snow surface albedo, both of which change rapidly in the pre-melt and melt period. Meltwater infiltration into frozen soils can be restricted, limited, or unlimited depending on soil infiltrability (Gray et al., 1985; Zhao and Gray, 1997). Frozen mineral soils usually have limited infiltration characteristics, which mean that the infiltrability is controlled by the degree of saturation of the soil pores with water and ice. The degree of saturation can be estimated from the soil porosity and the volumetric moisture content of the preceding fall if overwinter soil moisture changes are minimal. Substantial mid-winter melts or rain events can cause restricted infiltration where most snowmelt goes directly to runoff (Gray et al., 2001). Heavy clay soils can crack when frozen, resulting in close to unlimited infiltration and so little to no runoff generation (Pomeroy et al., 1990). Deep prairie soils are characterized by good water-retaining capacity and high unfrozen infiltration rates (Elliott and Efetha, 1999). Most rainfall occurs in spring and early summer from large frontal systems and the most intense rainfall in summer is associated with convective storms over small areas (Gray, 1970). During summer, most rainfall is consumed by evapotranspiration associated with the growth of crops and perennial grasses (Armstrong et al., 2008). Evapotranspiration occurs quickly from wet surfaces such as water bodies, wetted plant canopies and wet soil surfaces and relatively slowly from unsaturated surfaces such as bare soils and plant stomata (Granger and Gray, 1989). Any snowmelt runoff model for this region must correctly address these hydrological processes.

1.3 CRHM Modelling

The Lower Smoky River Model will be developed using the Cold Regions Hydrological Model platform (CRHM) described by Pomeroy et al., (2007), which is a physically-based, distributed, modular, object-oriented model development system. The component modules have been developed based on the results of 50 years of research by the University of Saskatchewan and Environment Canada in prairie, boreal, mountain and northern environments. The system is very flexible and creates 'purpose-built' models for particular basins, environments and predictive needs. CRHM is unique in being physically-based and in reproducing all of the important hydrological processes of cold regions.

CRHM is a modular modelling system that permits appropriate hydrological processes for the basin, selected from a library of process modules, to be linked to simulate the hydrological cycle as a purpose-built model (Pomeroy et al., 2007). From its inception, CRHM has focused on the incorporation of physically based descriptions of cold regions hydrological processes, which make models developed using this platform particularly appropriate to application in the very continental climate of Western Canada. Recent developments include options for treeline forest effects from alpine blowing snow (MacDonald et al., 2010), improved soil moisture accounting and fill-and-spill depressional storage (Fang et al., 2010) and enhanced forest canopy interception and radiation modules (Ellis et al., 2010). CRHM has a wide range of processes that can be relevant for snow hydrology studies such as calculation of solar radiation using diurnal temperature ranges, direct and diffuse radiation to slopes, longwave radiation in complex terrain, intercepted snow, blowing snow, sub-canopy turbulent and radiative transfer, sublimation, energy balance snowmelt, infiltration to frozen and unfrozen soils, rainfall interception, combination-type evapotranspiration, sub-surface flow, depressional storage fill and spill, saturation excess overland flow and routing of surface, sub-surface and streamflow. CRHM uses an object-oriented structure to develop, support and apply dynamic model routines. Existing algorithms can be modified or new algorithms can be developed and added to the module library, which are coupled to create a purpose-built model, suited for the specific application. The model operates on the spatial unit of the hydrological response unit (HRU) which has been found optimal for modelling in basins where there is a good conceptual understanding of hydrological behaviour, but incomplete detailed information to permit a fully distributed fine scale modelling approach (Dornes et al., 2008). The level of disaggregation into HRU is guided not only by the spatial variability of biophysical attributes and drainage conditions in the basin, but by the available information to describe these attributes as parameters. CRHM was evaluated in the recent SnoMIP2 snow model intercomparison and performed relatively quite well in modelling forest snowmelt at sites in Switzerland, USA, Canada, Finland and Japan (Rutter et al., 2009). The model has been applied for small basin hydrological cycle prediction in the IP3 Cold Regions Hydrology network at basins in Alberta, Saskatchewan, Yukon, and NWT and was used to evaluate forest harvesting impacts on streamflow in central BC. The model was used to determine hydrological drought across the Prairies in the DRI Network and is being used to design best management practices for agricultural runoff in South Tobacco Creek, Manitoba. It is currently being used in snowmelt runoff prediction studies in the mountains of Spain (Lopez-Moreno et al., 2012), western China, Germany and Chile through collaborations with the governments of Spain and China and the University of Chile, Santiago and Ludwig-Maxmillians University, Munich.

CRHM can be run using a graphical interface or from a command line. In both cases the model's data requirements are identical. The command-line operation of CRHM allows the Lower Smoky River Model to be run routinely, or to be called by a WISKI model. The graphical interface allows CRHM to be run interactively for detailed investigation of the model operation and non-standard outputs. Being physically-based, CRHM models do not require calibration against gauged flows and therefore are suitable for parameterisation in ungauged basins. Input parameters can be entered and edited directly in the user interface, or obtained from GIS files and other formats such as ASCII. Parameters are typically selected *a priori* from soil/land cover characteristics, vegetation cover, drainage networks and other basin information. Some unmeasured parameter values can be transferred from hydrologically similar basins. Calibration of unknown parameters against gauged flows is possible using trial and error methods. CRHM can be executed with a wide range of time steps, but the hourly time step is preferred for most applications as this most closely approximates the time step assumptions of certain key algorithms.

2. Meteorological and Hydrometric Data Collection

2.1 Meteorological Data

Running CRHM requires observation files that contain continuous daily or hourly precipitation and hourly air temperature, humidity (relative humidity or dew point), and wind speed data. CRHM can also make use of, but does not require, hourly solar radiation data or daily observations of sunshine hours. Where reliable radiation data is not available CRHM estimates radiation using calculated clear-sky solar radiation derived from the day of year, latitude, and elevation, adjusted for cloud cover using the daily temperature range (Shook and Pomeroy, 2012). Continuous data means that there must be an observation for each time interval (daily or hourly) without gaps or substantial errors. Since all meteorological observations have gaps, then these gaps must be filled by temporal or spatial interpolation. For gaps of three hours or less, temporal interpolation is used for infilling, whilst for longer gaps spatial interpolation from adjacent stations is used. Other meteorological data, snowpack and soil moisture data can be used to diagnose and evaluate CRHM simulations.

Air temperature, relative humidity, wind speed, wind direction, precipitation, radiation, soil moisture, and soil temperature were acquired from Alberta Environment and Sustainable Resource Development for 22 stations within or near to the Smoky River Basin. Not all of these variables were available for every station. The stations that are within or near the edge of the Smoky River Basin are shown in Figure 1. These data have variable periods of record, ranging from 1 to 40 years; coverage of radiation is very sporadic, and observations of soil moisture/temperature are only available for a few stations, starting in April 2010: Fairview AARD, High Prairie Airport AARD, and Peoria AGDM. Many of these stations are located outside of the Smoky River Basin and well outside of the lower basin where the data is needed to run CRHM. It was decided that radiation would be estimated by CRHM rather than use the incomplete records available in the basin and that hourly records of air temperature (t, °C), relative humidity (rh, %) and wind speed (u, m/s) along with daily precipitation (ppt, mm) would be used to create observation files for CRHM. Relatively clean records of these variables were downloaded from Environment Canada's National Climate Data and Information Archive (http://climate.weatheroffice.gc.ca/climateData/canada_e.html) for nine stations located in or near the Smoky River Basin (Figure 1). These stations include Beaverlodge RCS (BEAV), Grande Prairie Airport (YQU), Hendrickson Creek (HEND), Peoria AGDM (PEOR), and Valleyview AGDM (VALL); these stations have longest record amongst the stations existing in and near the basin, ranging from October 2001 to July 2012. Data from an additional three stations: Eaglesham AGCM (EAGL), La Glace AGCM (GLAC), and Jean Cote AGCM (Jean Cote) were acquired from July 2007 to July 2012, and data from Teepee Creek AGDM (TEEP) station were acquired from September 2008 to July 2012. Station information is summarized in Table 1.

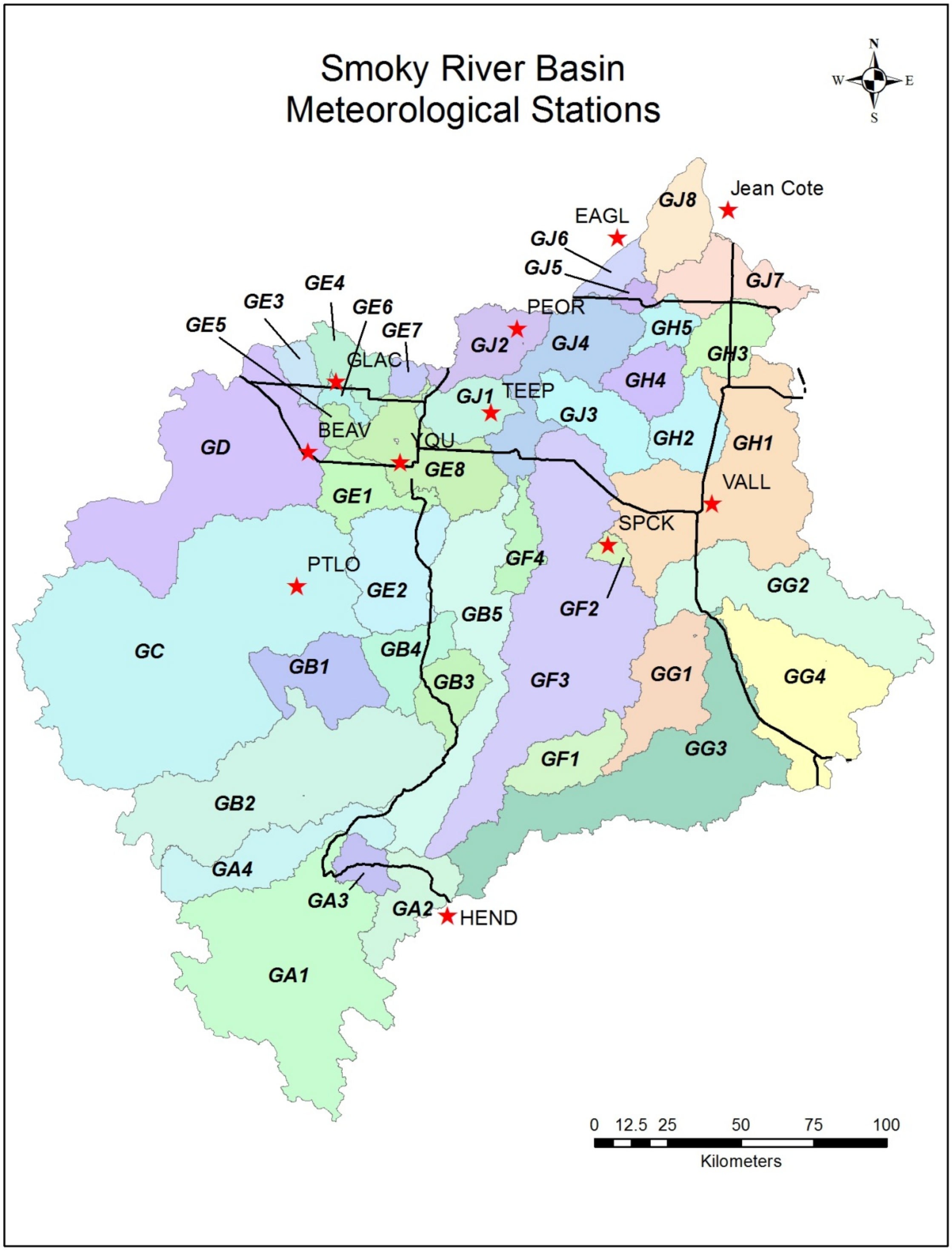


Figure 1. Smoky River sub-basins with meteorological stations having hourly records.

Table 1. Smoky River Basin main meteorological station information.

Station	Code	Province	Latitude (°)	Longitude (°)	Elevation (m a.s.l)	Period of Record: Hourly t, rh, u	Period of Record: Daily ppt
Beaverlodge RCS	BEAV	AB	55.2	-119.4	745	1 October 2001 - 31 July 2012	1 January 2001 - 18 August 2012
Eaglesham AGCM	EAGL	AB	55.81	-117.89	563	24 July 2007 - 31 July 2012	24 July 2007 - 31 July 2012
Grande Prairie Airport	YQU	AB	55.18	-118.89	669	1 October 2001 - 31 July 2012	1 January 2001 - 18 August 2012
Hendrickson Creek	HEND	AB	53.8	-118.45	1448	1 October 2001 - 31 July 2012 (no u)	1 January 2001 - 18 August 2012
La Glace AGCM	GLAC	AB	55.42	-119.25	760	25 July 2007 - 31 July 2012	25 July 2007 - 31 July 2012
Jean Cote AGCM	Jean Cote	AB	55.91	-117.12	638	4 July 2007 - 31 July 2012	4 July 2007 - 31 July 2012
Peoria AGCM	PEOR	AB	55.62	-118.29	621	4 February 2002 - 31 July 2012	1 February 2001 - 18 August 2012
Teepee Creek AGDM	TEEP	AB	55.35	-118.41	670	1 September 2008 - 31 July 2012	27 July 2007 - 31 July 2012
Valleyview AGDM	VALL	AB	55.1	-117.2	698	9 October 2002 - 31 July 2012	19 December 2002 - 18 August 2012

2.2 Hydrometric Data

Daily discharge data were acquired from the Water Survey of Canada archived hydrometric data website (http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm) for the stations shown in Table 2. These stations are illustrated in Figure 2 for the Smoky River Basin. Note that some gauges located in the upper basin and are operated in real-time and so their discharges can be lagged and used in forecasting streamflow downstream whilst other gauges are non-real time or are located in the lower basin and so their streamflows must be estimated by modelling.

Table 2. Hydrometric stations in Smoky River.

Station Name	Station ID 1	Station ID 2	Real-time	Period of Record
Smoky River at Watino	07GJ001	RSMOWATI	Yes	1 March 2002 - 31 October 2010
Little Smoky River near Guy	07GH002	RLSMOGUY	Yes	1 March 2002 - 31 October 2010
Waskahigan River near the mouth	07GG001	RWASKMOU	Yes	1 March 2002 - 31 October 2010
Simonette River near Goodwin	07GF001	RSIMGOOD	Yes	1 March 2002 - 31 October 2010
Wapiti River near Grande Prairie	07GE001	RWAPGPR	Yes	1 March 2002 - 31 October 2010
Cutbank River near Grande Prairie	07GB001	RCUTGPR	Yes	1 March 2002 - 31 October 2010
Kakwa River at Highway No. 40	07GB003	RKAKGPR	Yes	1 March 2002 - 31 October 2010
Smoky River above Hells Creek	07GA001	RSMOHELL	Yes	1 March 2002 - 31 October 2010
Muskeg River near Grande Cache	07GA002	RMUSKGCA	Yes	1 March 2002 - 31 October 2010
Grande Prairie Creek near Sexsmith	07GE003		No	1 March 2002 - 31 October 2010
Bear River near Valhalla Centre	07GE007		No	1 March 2002 - 31 October 2010
Little Smoky River at Little Smoky	07GG002		No	1 March 2002 - 31 October 2010
Iosegun River near Little Smoky	07GG003		No	1 March 2002 - 31 October 2010

2.3 Snow Survey Data

Archived snow survey data were acquired from Alberta Environment and Sustainable Resource Development for various snow survey courses in the lower Smoky River Basin (Figure 3). Data include snow depth, density, and notes about conditions at the time the snow survey was conducted. Data from five survey courses: Bezanson, Girouxville, Hythe, Little Smoky, and Sexsmith were used to calculate the snow accumulation as mm snow water equivalent (mm SWE) following procedures outlined by Pomeroy and Gray (1995). Measured snow accumulation was not used to drive CRHM, but to diagnose the modelled snow accumulation at the sites with similar land cover to the survey courses.

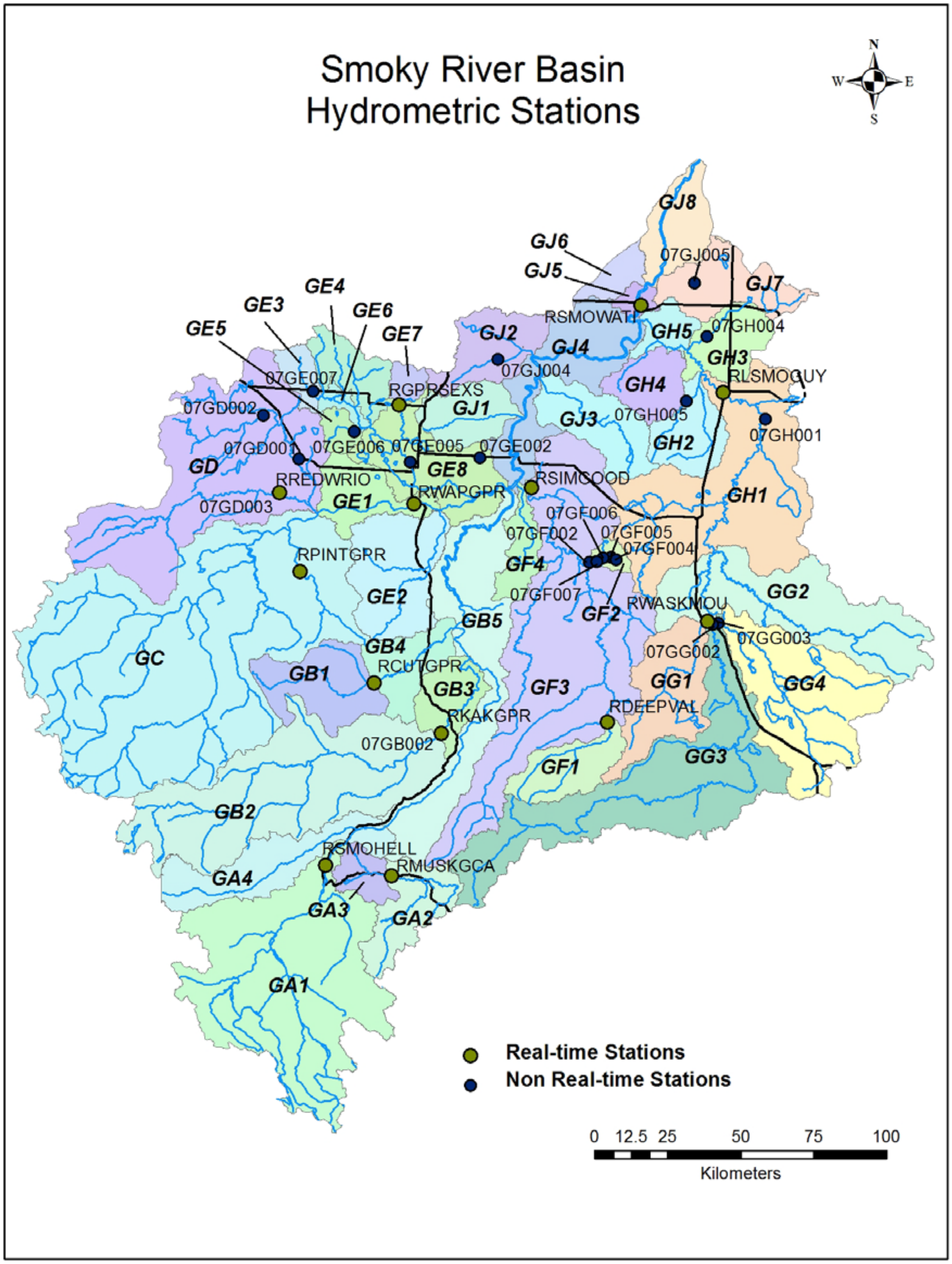


Figure 2. Smoky River sub-basins with Water Survey of Canada hydrometric station locations.

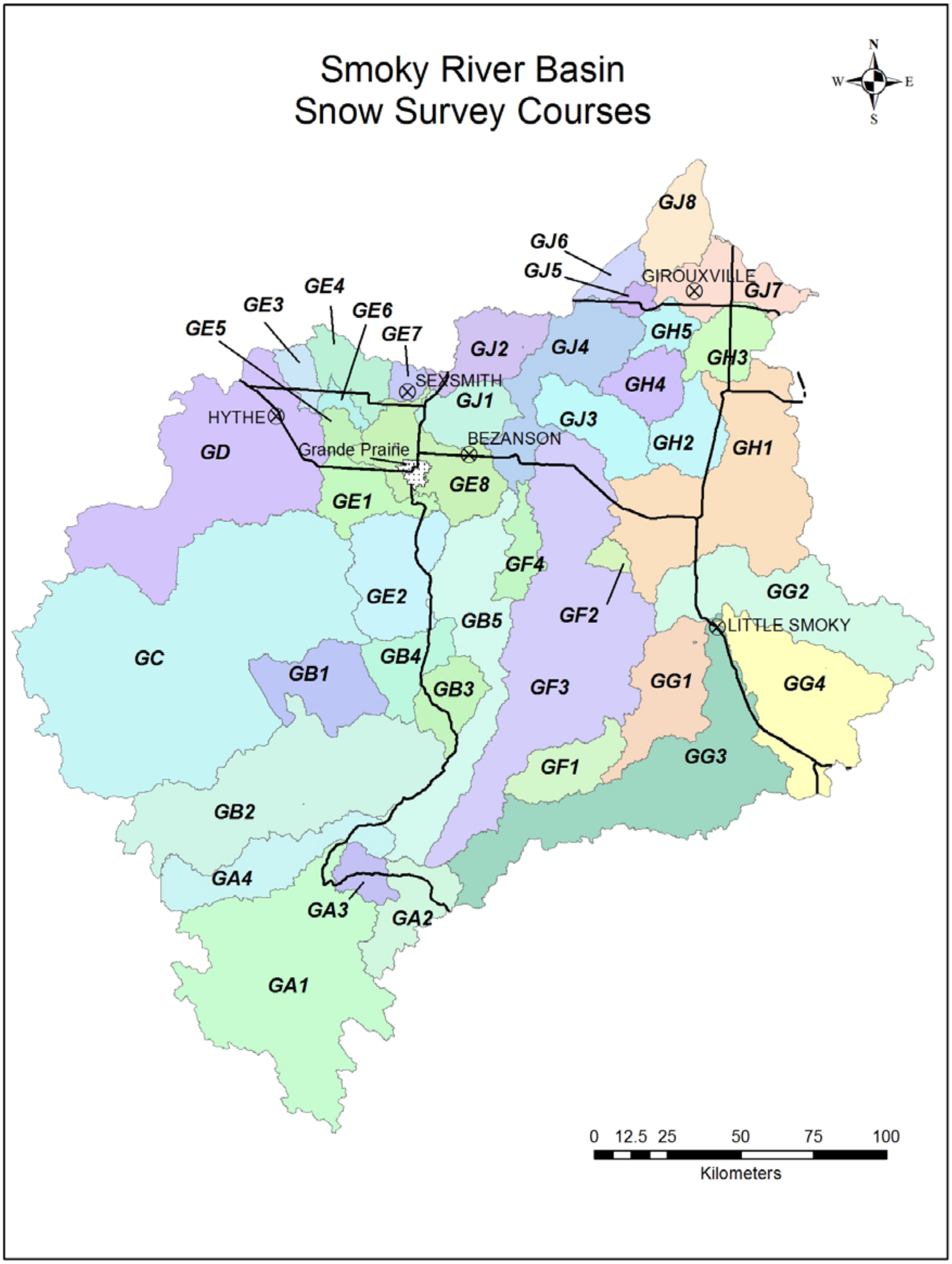


Figure 3. Smoky River Basin AESRD snow survey courses.

2.4 Data Interpolation and Quality

CRHM observation data were assembled from the five meteorological stations (i.e. BEAV, YQU, HEND, PEOR, and VALL) during October 2001 to July 2012 along with three more stations (i.e. EAGL, GLAC, and Jean Cote) during October 2007 to September 2008 and four more stations (i.e. EAGL, GLAC, Jean Cote, and TEEP) during October 2008 to July 2012. The CRHM observation datasets cover the period of 1 October 2001 - 31 July 2012. Two CRHM observation files were created:

"**Smoky_subbasin_hourly_t_rh_u_1Oct01-31Jul12_new.obs**", containing 26 records of hourly air temperature, relative humidity and wind speed

"**Smoky_subbasin_daily_PPT_1Oct01-18Aug12_new.obs**", which consists of 26 records of daily precipitation

Grande Prairie Airport station (YQU) is the only station having complete and continuous data records. The other four meteorological stations had missing hourly records of air temperature, relative humidity and wind speed, and of daily precipitation at various times during the model simulation period from 1 October 2001 to 30 September 2010. Table 3 summarizes the percentage of missing data in the model simulation period. An example of missing precipitation from the stations is shown in Figure 4, which demonstrates a gap in the data by a flag value of -1. Missing data can strongly affect the accuracy of model simulations, which should be taken into account when evaluating model's performance.

Table 3. Station data quality assessed by the percentage of missing data. All numbers in % of record from October 2001 through September 2010, except for stations Eaglesham AGCM, La Glace AGCM and Jean Cote AGCM were assessed from October 2007 to September 2010.

Station	Air Temperature	Relative Humidity	Wind Speed	Precipitation
Beaverlodge RCS	12	13	13	1
Eaglesham AGCM	2	2	29	39
Hendrickson Creek	13	13	100	20
La Glace AGCM	16	16	37	69
Jean Cote AGCM	3	31	31	45
Peoria AGDM	10	10	10	16
Valleyview AGDM	15	16	17	19

Data gaps in the hourly meteorological data were infilled using either spatial or temporal interpolation to create continuous records of hourly air temperature, relative humidity and wind speed. Gaps shorter than 3 hours were infilled by averaging the last and next datapoints and infilling the gap with the average. Data gaps longer than 3 hours were infilled by spatial interpolation using the spatial correlations between the stations with gaps and with Grande Prairie Airport (YQU), as shown in Table 4. Gaps in precipitation measurements in the wet year of 2007 are large, making simulations in the spring of 2007. Wind speed at the Hendrickson Creek station was missing during the entire modelling period and so wind speed from Valleyview AGDM station was used for the Hendrickson Creek station due to their proximity and good fetch characteristics at the Valleyview meteorological station. Special care was taken when infilling gaps in precipitation so as not to introduce a cumulative bias in seasonal precipitation. Table 4 also shows the double mass curve ratiometric equations developed between stations to fill in the missing daily precipitation data so that no bias was introduced.

Hourly and daily station data were spatially interpolated to each of 26 modelled Smoky River sub-basins using the inverse distance weighted (IDW) method. Water vapour pressure was interpolated instead of relative humidity, as it tends to be conserved in the atmosphere when unsaturated. From one to three meteorological stations were used to interpolate to the sub-basins, depending on proximity to the sub-basin. Locations of the sub-basin centroids were derived from ArcGIS and used to calculate the IDW ratio with regard to the adjacent meteorological stations. The IDW ratio for interpolating station data to sub-basin CRHM observation data is shown in Table 5. Since there are differences in elevation in the Smoky River Basin an "observation elevation" for each sub-basin was calculated using the IDW method from the station elevations. Elevation corrections are applied within CRHM to meteorological variables to adjust for differences between observation elevation and hydrological response unit elevation. To account for the higher elevation of the mountain upper basin, only the 1448 m.a.s.l. (metres above sea level) Hendrickson Creek meteorological station was used for the uppermost sub-basins (GA3, GA4).

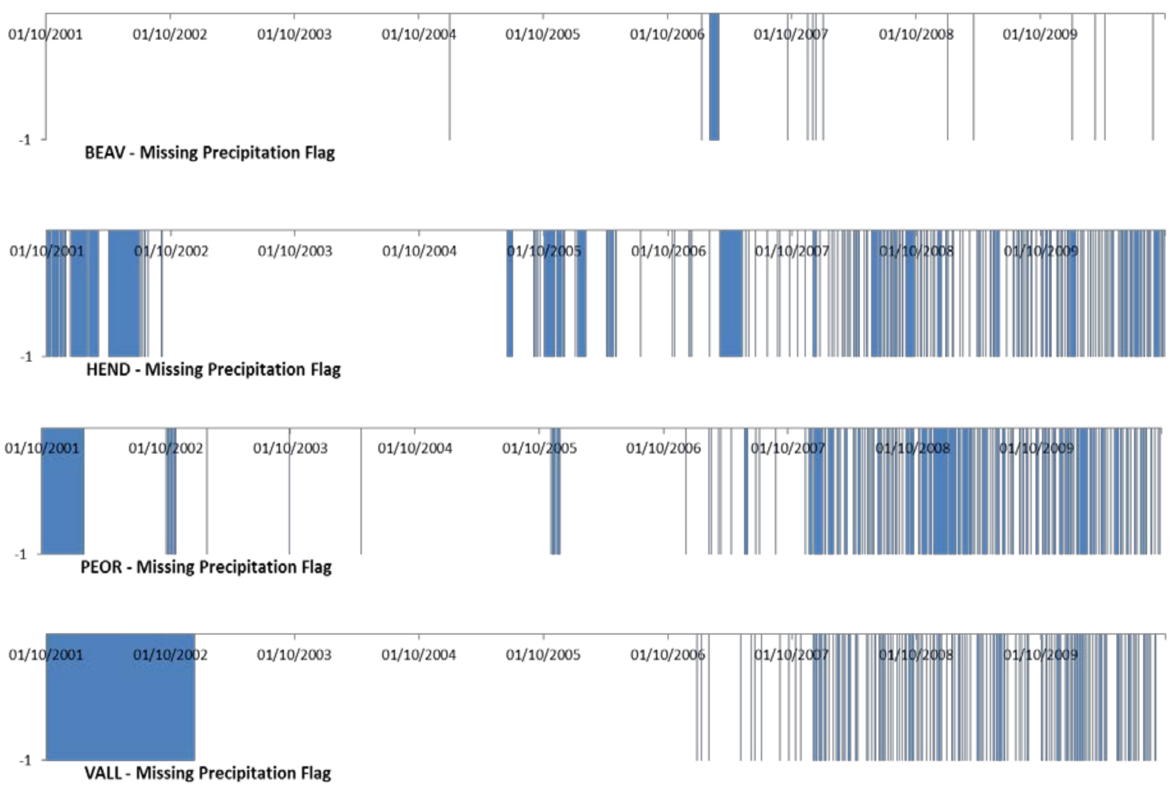


Figure 4. Missing precipitation data at Beaverlodge, Hendrickson Creek, Peoria and Valley View meteorological stations. Missing data is indicated by flag value of -1.

Table 4. Spatial interpolation equations based on correlations (t, rh, u) and double mass curves (precipitation) between stations.

Stations	Equations
Beaverlodge RCS	t_BEAV = 0.9086*t_YQU + 0.5678, (r^2 = 0.9657)
	rh_BEAV = 0.914*rh_YQU + 3.443, (r^2 = 0.7415)
	u_BEAV = 0.667*u_YQU + 3.0765, (r^2 = 0.5452)
	ppt_BEAV = 0.84*ppt_YQU, (r^2 = 0.9984)
Eaglesham AGCM	t_EAGL = 0.9976*t_YQU + 0.1694, (r^2 = 0.9574)
	rh_EAGL = 0.8754*rh_YQU + 8.003, (r^2 = 0.7078)
	u_EAGL = 0.4588*u_YQU + 6.3357, (r^2 = 0.3434)
	ppt_EAGL = 0.7655*ppt_YQU, (r^2 = 0.997)
Hendrickson Creek	t_HEND = 0.784*t_YQU - 1.7462, (r^2 = 0.8393)
	rh_HEND = 0.7457*rh_YQU + 20.15, (r^2 = 0.408)
	u_HEND = u_YQU
	ppt_HEND = 1.1829*ppt_YQU, (r^2 = 0.9859)
La Glace AGCM	t_GLAC = 0.9798*t_YQU - 0.7024, (r^2 = 0.9771)
	rh_GLAC = 0.9314*rh_YQU + 5.93, (r^2 = 0.8344)
	u_GLAC = 0.583*u_YQU + 3.5945, (r^2 = 0.5422)
	ppt_GLAC = 1.1795*ppt_YQU, (r^2 = 0.9702)
Jean Cote AGCM	t_Jean = 0.9534*t_YQU + 0.07, (r^2 = 0.9396)
	rh_Jean = 0.7735*rh_YQU + 14.657, (r^2 = 0.6075)
	u_Jean = 0.3822*u_YQU + 7.9291, (r^2 = 0.2747)
	ppt_Jean = 0.8324*ppt_YQU, (r^2 = 0.9964)
Peoria AGDM	t_PEOR = 0.9718*t_YQU - 0.2339, (r^2 = 0.9643)
	rh_PEOR = 0.9227*rh_YQU + 7.3706, (r^2 = 0.7363)
	u_PEOR = 0.3954*u_YQU + 5.7028, (r^2 = 0.3546)
	ppt_PEOR = 0.8578*ppt_YQU, (r^2 = 0.9997)
Teepee Creek AGCM	t_TEEP = 0.998*t_YQU - 0.2692, (r^2 = 0.9786)
	rh_TEEP = 0.9365*rh_YQU + 6.7279, (r^2 = 0.8078)
	u_TEEP = 0.4456*u_YQU - 3.118, (r^2 = 0.5107)
	ppt_TEEP = 0.797*ppt_YQU, (r^2 = 0.9993)
Valleyview AGDM	t_VALL = 0.9128*t_YQU + 0.764, (r^2 = 0.9563)
	rh_VALL = 0.8632*rh_YQU + 9.7239, (r^2 = 0.6732)
	u_VALL = 0.2971*u_YQU + 10.572, (r^2 = 0.1712)
	ppt_VALL = 0.8563*ppt_YQU, (r^2 = 0.9957)

Table 5. Inverse distance weighted (IDW) ratios for station data interpolation.

For period: 1 October 2001 to 30 September 2007						
OBS Array #	Sub-basin	BEAV	YQU	HEND	PEOR	VALL
1	GA3			1.00		
2	GA4			1.00		
3	GB3		0.36	0.44		0.20
4	GB4		0.51	0.31		0.18
5	GB5		0.44	0.33		0.23
6	GE2		0.83	0.08		0.09
7	GE3	0.88			0.12	
8	GE4	0.77			0.23	
9	GE5	1.00				
10	GE6	0.91			0.09	
11	GE7	0.50			0.50	
12	GE8		1.00			
13	GF4		0.63			0.37
14	GG2					1.00
15	GG3			0.61		0.39
16	GG4			0.22		0.78
17	GH1					1.00
18	GH2				0.12	0.88
19	GH3				0.37	0.63
20	GH4				0.47	0.53
21	GH5				0.59	0.41
22	GJ1		0.55		0.45	
23	GJ2				1.00	
24	GJ3		0.17		0.46	0.37
25	GJ4				0.90	0.10
26	GJ5				0.75	0.25

Table 5. *Continued*.

For period: 1 October 2007 to 30 September 2008									
OBS Array #	Sub-basin	BEAV	EAGL	YQU	HEND	GLAC	Jean Cote	PEOR	VALL
1	GA3				1.00				
2	GA4				1.00				
3	GB3			0.36	0.44				0.20
4	GB4			0.51	0.31				0.18
5	GB5			0.44	0.33				0.23
6	GE2			0.83	0.08				0.09
7	GE3	0.21				0.76		0.03	
8	GE4	0.09				0.89		0.02	
9	GE5	0.47				0.53			
10	GE6	0.03				0.97			
11	GE7	0.21				0.58		0.21	
12	GE8			1.00					
13	GF4			0.63					0.37
14	GG2								1.00
15	GG3				0.61				0.39
16	GG4				0.22				0.78
17	GH1								1.00
18	GH2		0.13				0.10	0.09	0.68
19	GH3		0.26				0.47	0.10	0.17
20	GH4		0.35				0.18	0.22	0.25
21	GH5		0.52				0.26	0.13	0.09
22	GJ1			0.55				0.45	
23	GJ2							1.00	
24	GJ3			0.17				0.46	0.37
25	GJ4		0.21				0.06	0.66	0.07
26	GJ5		0.84				0.08	0.06	0.02

Table 5. *Concluded*.

For period: 1 October 2008 to 30 September 2010										
OBS Array #	Sub-basin	BEAV	EAGL	YQU	HEND	GLAC	Jean Cote	PEOR	TEEP	VALL
1	GA3				1.00					
2	GA4				1.00					
3	GB3			0.36	0.44					0.20
4	GB4			0.51	0.31					0.18
5	GB5			0.44	0.33					0.23
6	GE2			0.83	0.08					0.09
7	GE3	0.21				0.76		0.03		
8	GE4	0.09				0.89		0.02		
9	GE5	0.47				0.53				
10	GE6	0.03				0.97				
11	GE7	0.16				0.43		0.16	0.25	
12	GE8			1.00						
13	GF4			0.35					0.45	0.20
14	GG2									1.00
15	GG3				0.61					0.39
16	GG4				0.22					0.78
17	GH1									1.00
18	GH2		0.11				0.09	0.09	0.09	0.62
19	GH3		0.26				0.47	0.10		0.17
20	GH4		0.30				0.15	0.19	0.15	0.21
21	GH5		0.48				0.25	0.12	0.07	0.08
22	GJ1			0.08				0.07	0.85	
23	GJ2							1.00		
24	GJ3			0.11				0.28	0.39	0.23
25	GJ4		0.15				0.05	0.47	0.28	0.05
26	GJ5		0.84				0.08	0.06		0.02

3. Basin Relationships

3.1 Basin Overview

The Smoky River arises in the northern Canadian Rockies in Adolphus Lake at the north end of Jasper National Park and in headwater basins in the Willmore Wilderness Park. The upper basin is dominated by alpine meadows and montane boreal forest in mountains and foothills. It flows north from the foothills through a boreal forest upland that has been strongly impacted by forest harvesting for wood and access to resource extraction. Draining this upland, which extends into British Columbia, it reaches the Peace River District agricultural region where original prairie grassland and parkland forest has been cleared and cultivated or used for grazing or hay production. A major tributary enters here – the Little Smoky River, which drains an agricultural and boreal forest basin from foothills and uplands to the south and east. The agricultural portion of the Smoky River basin is often referred to as the lower Smoky River basin. From the agricultural district it flows into the Peace River south of Peace River, Alberta. The full drainage area of the Smoky River Basin is 51,839 km^2 and the main stem of the river is approximately 492 km long.

Basin relationships refer to the basin structure at various scales. At the largest scale this means the spatial extent of the main basin and its sub-basins, including the hydrometry and drainage areas. In order to determine basin relationships, data on topography, hydrometry, soils, and land cover must be analysed in a Geographic Information System (GIS) to determine the number, location and type of HRU, the number and location of sub-basins and routing features that must be included.

3.2 CRHMTools

An open source Python Graphical User Interface (GUI) application, CRHM-tools, was developed to allow for the automated and systematic creation of basin relationships for input to CRHM. The open source Python language was chosen for its cross-platform compatibility, its readable novice friendly syntax, and ability to allow for rapid application development. Because of the strengths in the Python architecture, a modular tool system, akin to what exists in ArcGIS, was implemented allowing for a user to easily and seamlessly create their own functions. These functions allow for terrain-based calculations, such as slope, aspect, and fetch, or statistical classification such histogram binning. Manual classification is also possible, allowing for a user to fine-tune the results. Due to the reliance upon the respected open source GDAL (geospatial data abstraction library), any single-band raster is compatible (such as ArcGIS rasters), including masked 'no-data' regions. HRUs are generated by combining various classified 'primary landclass' data into HRUs, and parameterizing the HRUs using 'secondary landclass' data.

Overview of the GUI

Figure 5 shows the main CRHMTools GUI with loaded and processed files from various functions. On the left of the GUI is the Basin treeview. This is where the loaded data and module are presented. Going top-to-bottom in the treeview: *Imported Files* contains all the files that have been imported into the tool, *From functions* lists all data that have been generated via a module, *Primary land classes* lists the data that have been classified and are available for use in creating HRUs. Data from modules may be dragged-and-dropped into this section. The *Secondary land classes* are for any non-classified data that can be used to parameterize each HRU; compatible data is dragged-and-dropped into this section.

Finally, the *Generated HRUs* section is where the final generated HRU is displayed. Treeview items may be interacted with via a right-click context menu. This example data is a 30m DEM from Trail Valley Creek in the NWT. The white region is the no-data region.

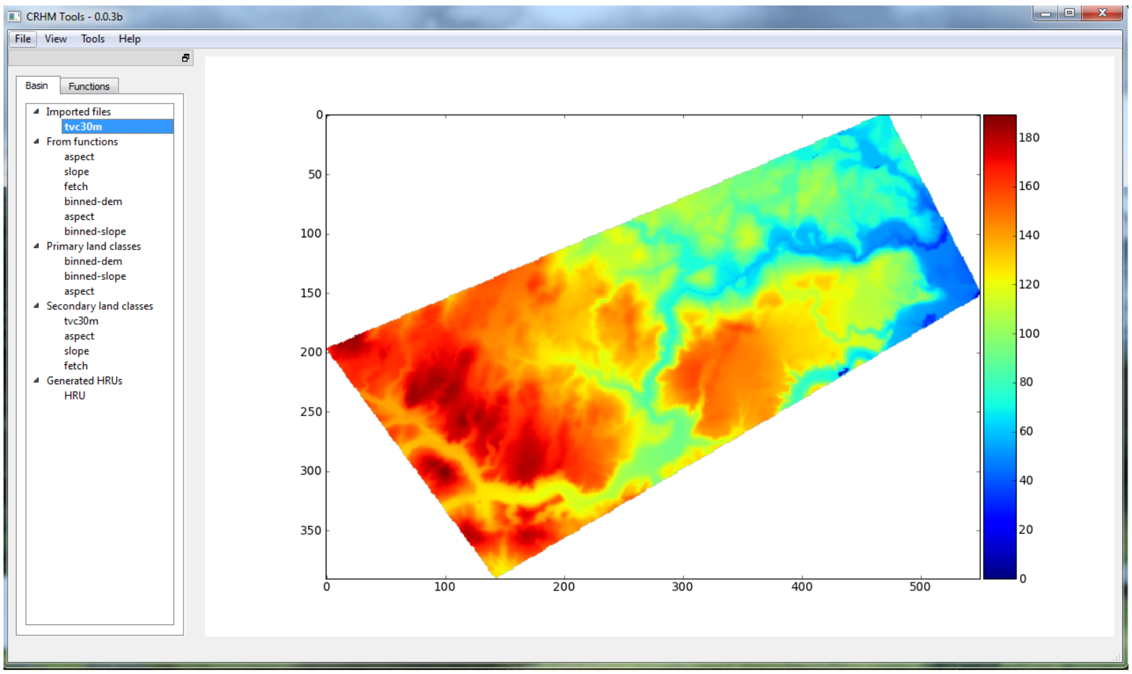


Figure 5. Example of the CRHMTools GUI with a loaded DEM file.

Figure 6 shows the main GUI but with the treeview tab switched to the functions view. This is where the function modules are shown to the user. This is dynamically created at start up, thus any new modules are instantly available for use. Modules are grouped by a category as defined in the module. The output from each module can be used as input to another module, allowing for robust combinations to be used. All modules must conform to a standard interface that has been designed to allow for command-line usage. This, coupled with an Application Programming Interface (API) for the main application, allows for robust scripting thus facilitating batch processing. An example of a module in action is shown in Figure 7. Whenever possible, a module will show an estimated time and current progress. However, because of how some of the algorithms are implemented, progress is not possible to determine. Because the modules are multithreaded, the GUI remains responsive during execution.

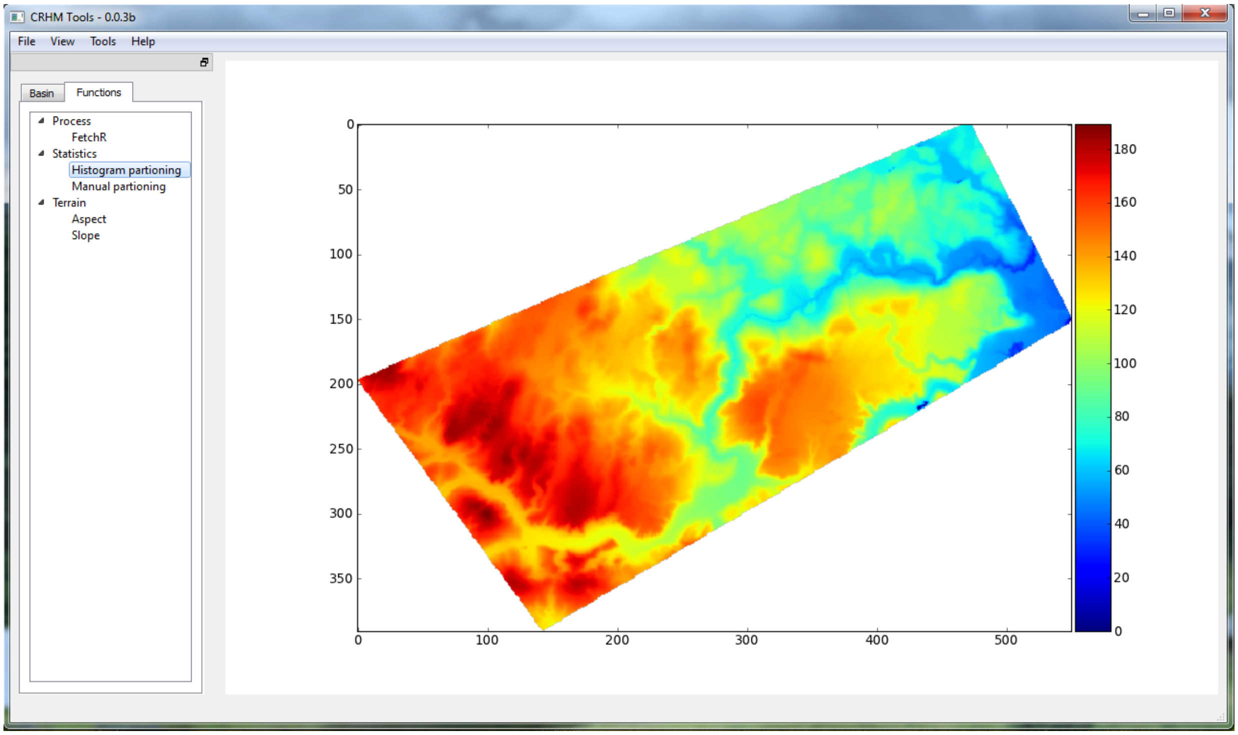


Figure 6. CRHMTools GUI, same as Figure 5, but demonstrating the Functions tab showing the various modules.

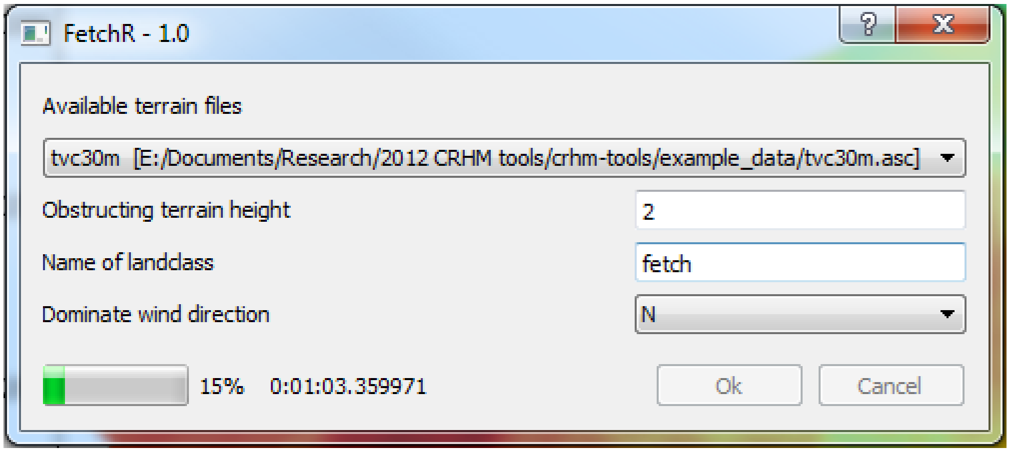


Figure 7. Example of a long running module. Estimated time and progress are shown.

Figure 8 demonstrates a final HRU classification for the Marmot Creek Research Basin (MCRB), Alberta with HRU parameters shown. The aspect, slope, and DEM were binned into two classifications, thus representing 0-180/180-360 aspects, high/low slope, and high/low elevation.

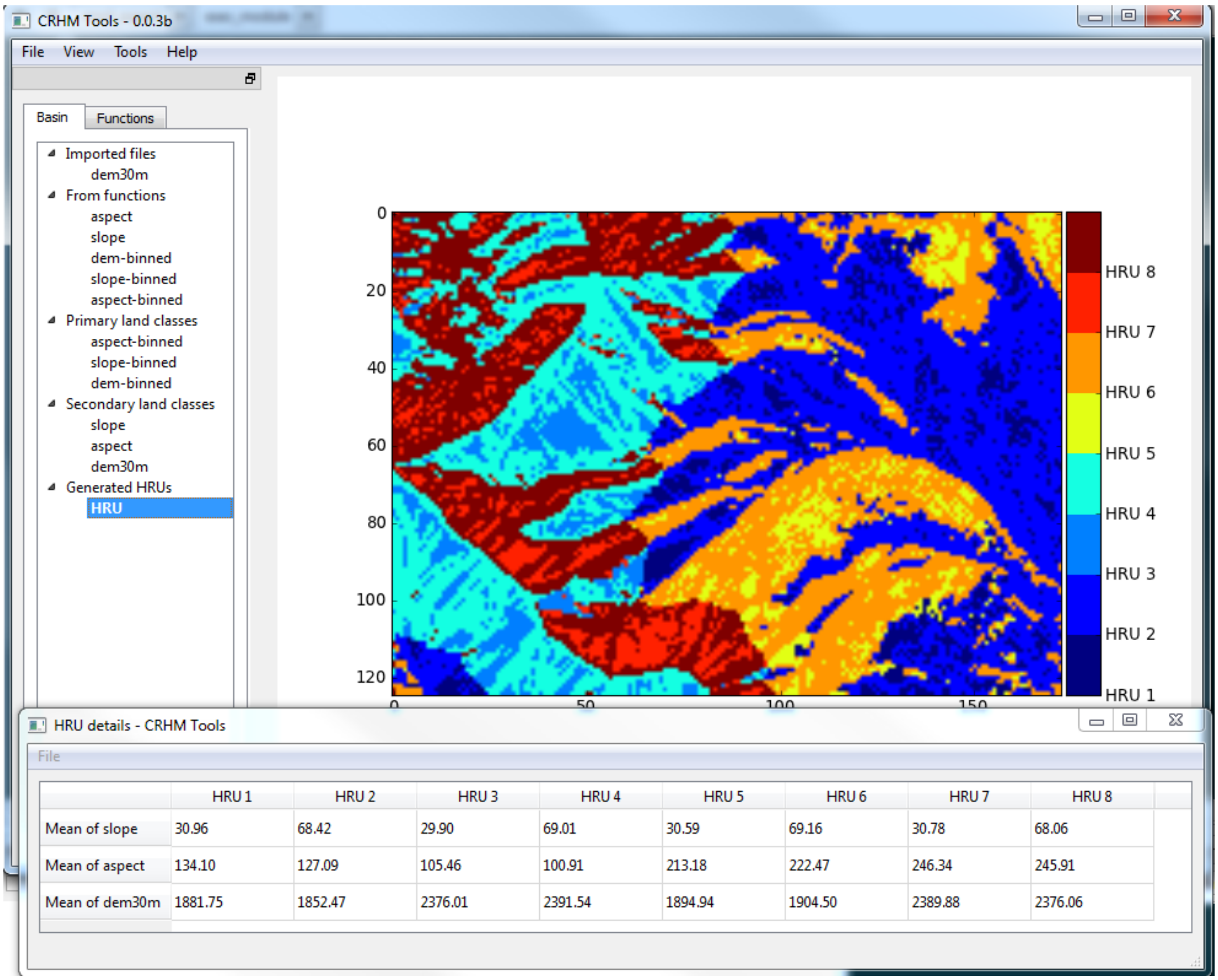


Figure 8. Final HRU classification of the Marmot Creek Research Basin, as well as the HRU parameters.

CRHMTools is still a work in progress, with new modules being actively developed to allow for parameterization for the CRHM wind models and soil models. Site-specific modules, such as those for the mountains and prairies are being added. Currently, the software is able to work with a single input DEM and from this create HRUs with the needed parameters that are required most modelling endeavours. Internal documentation is currently being converted for a more user-friendly experience, both for the modules and the API.

3.3 Basin Data

Characterizing the Smoky River Basin for the Cold Regions Hydrological model (CRHM) required a digital elevation model (DEM), soils maps, hydrometry information and a vegetation cover map. The following lists brief information on the data received and their purpose for setting up basin relationships and parameters for CRHM.

AB_CWCS_MergedWetlandInventory.shp: this is the Alberta Canada wetland classification system.

Hydro_Points.shp: this includes dams, control devices, rapids, waterfalls and icefields, and can be used to identify the location of control structures such as dams.

Land_Use_Agriculture_Food_Canada_Soil.shp: this is Agriculture Canada's agricultural/White Zone Soil Inventory. This provides information on surface soil cover types.

Waterbodies.shp and **Watercourses.shp**: are water bodies such as lakes and water courses including differentiation into different types of channels.

Peace River DEM: this is the Base Features Derived Fully Hydrologically Corrected DEM and is used in GIS terrain analysis to provide elevation, aspect, slope, and to delineate the basin.

Alberta Vegetation Inventory: this provides the land cover information that is important in defining HRUs.

The "25-m Base Features Derived Fully Hydrologically Corrected DEM for the Peace River" (ffhc_dem1) includes the majority of Smoky River Basin, except for the British Columbia side of basin and a small area near Watino (Figure 9). Elevations range from 321 m near the mouth to 3310 m in the headwaters. This DEM was used to conduct the basic GIS analysis to derive basin parameters such as aspect (Figure 10) and slope (Figure 11). The basin tends to have a slightly north-facing aspect, though the majority of the basin area has gentle slopes of less than 3^{o}, with only the mountain headwaters having most slopes greater than 20^{o}.

An automated basin delineation tool "TOPAZ" was used to extract the sub-basin stream network. Due to the limitation of computing memory for such a large basin, the original 25-m DEM was resampled to 75 m for the TOPAZ run. The extracted TOPAZ stream network is shown for all sub-basins (Figure 12). The PFRA "non-contributing area" is also mapped in Figure 12; this area was estimated by PFRA to not contribute to streamflow for flows that occur in one year out of two. The corresponding area, elevation, channel length and gradient for the stream network were computed using SAGA GIS terrain analysis profile tool and ArcGIS "extract by mask" tool.

Alberta Biodiversity Monitoring Institute (ABMI) land cover polygons were acquired from their open access data portal to provide land cover information for the Smoky River Basin (Figure 13). ABMI land cover polygons do not provide coverage for the British Columbia part of basin, but that does not affect the CRHM modelling because this part belongs to the gauged sub-basins. Eleven classes are present in the ABMI land cover polygons and include water, snow/ice, rock/rubble, exposed land, developed, shrubland, grassland, agriculture, coniferous forest, broadleaf forest, and mixed forest.

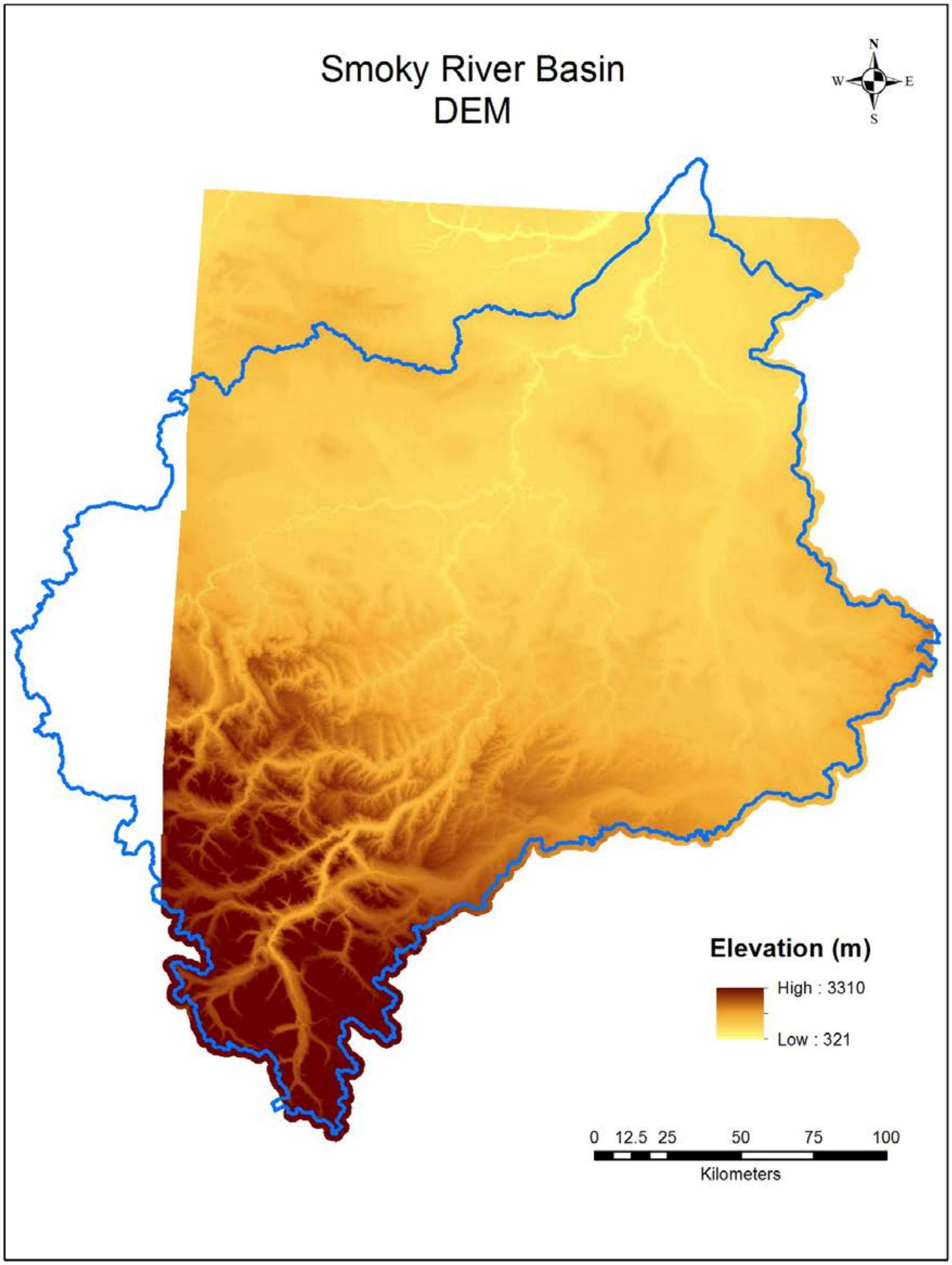


Figure 9. Base Features Derived Fully Hydrologically Corrected DEM for Smoky River Basin (25 m resolution), Alberta portion only.

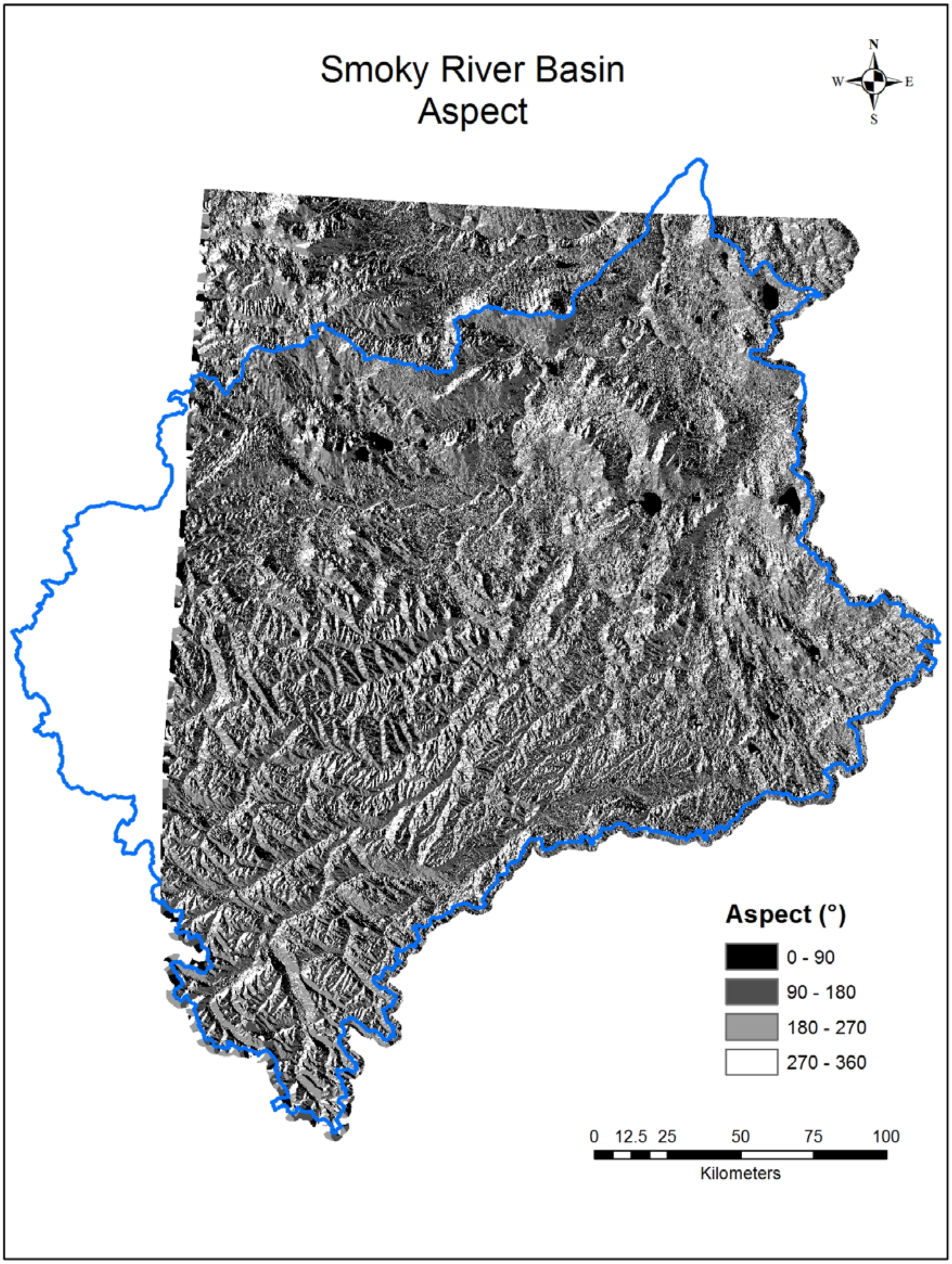


Figure 10. Aspect of slopes in the Smoky River Basin calculated from the DEM.

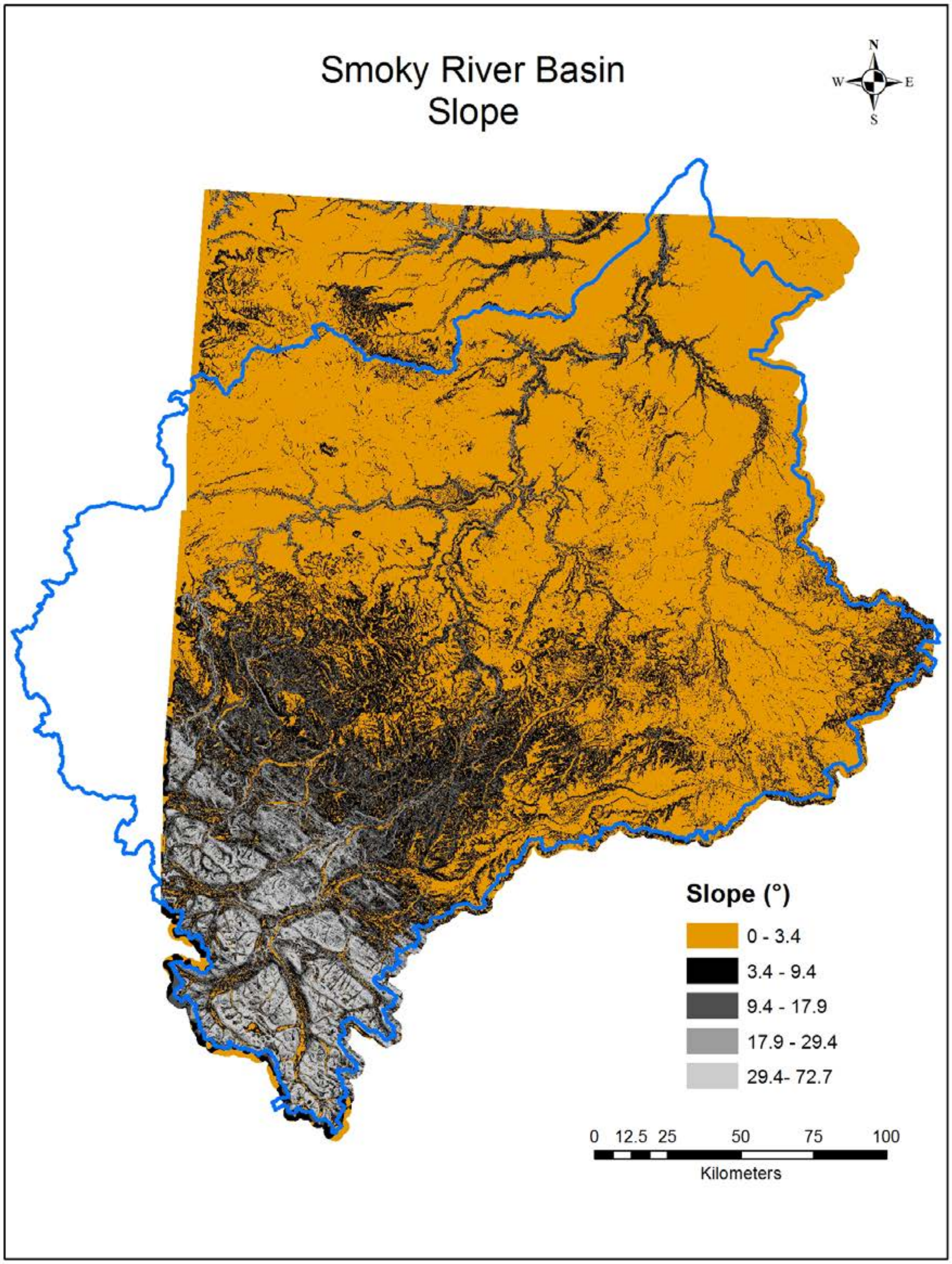


Figure 11. Slope angle in the Smoky River Basin, calculated from the DEM.

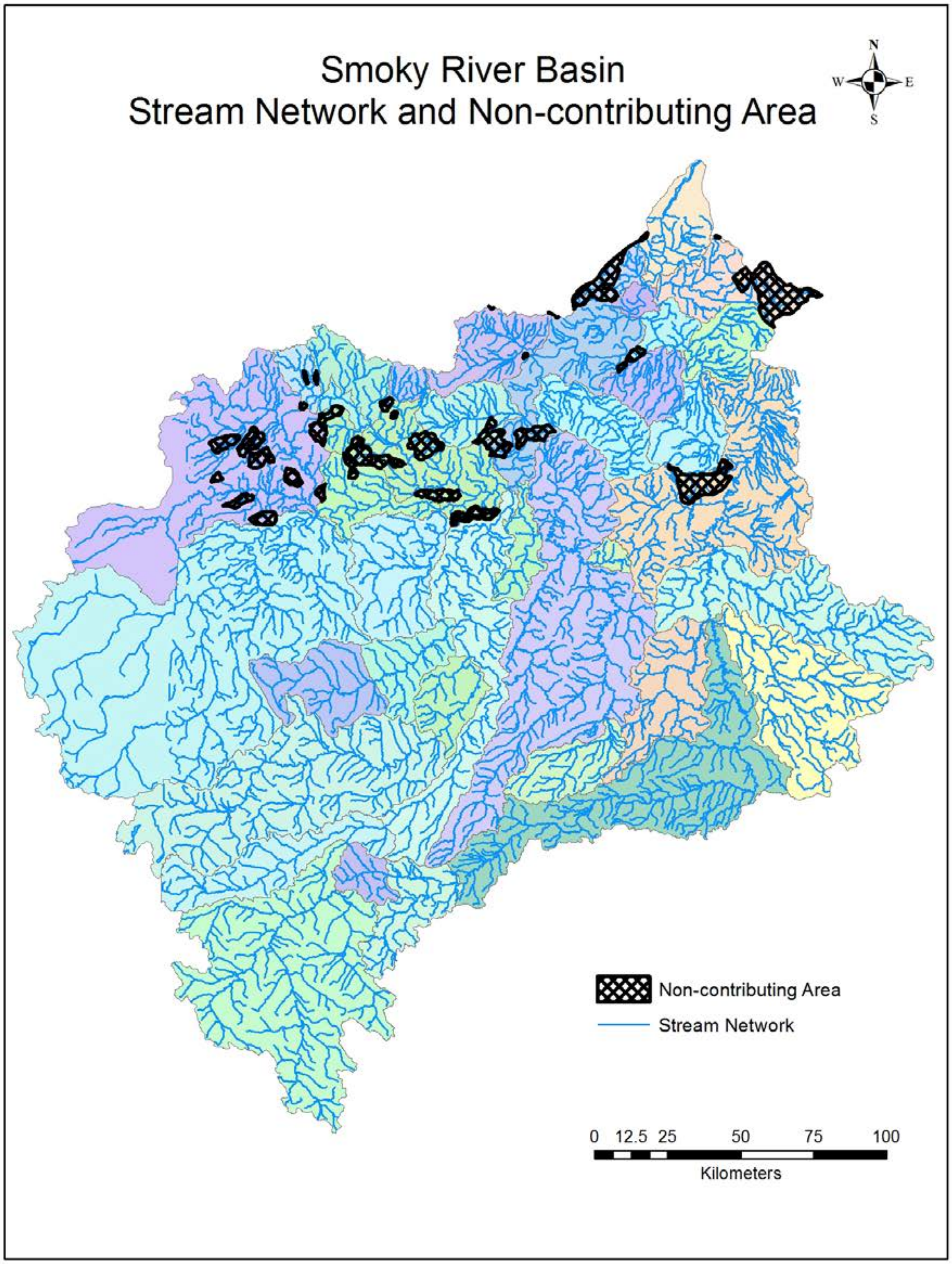


Figure 12. Smoky River sub-basins, TOPAZ-derived stream network and the PFRA non-contributing area for 1:2 year flows. Colours are used to distinguish sub-basins and have no other meaning.

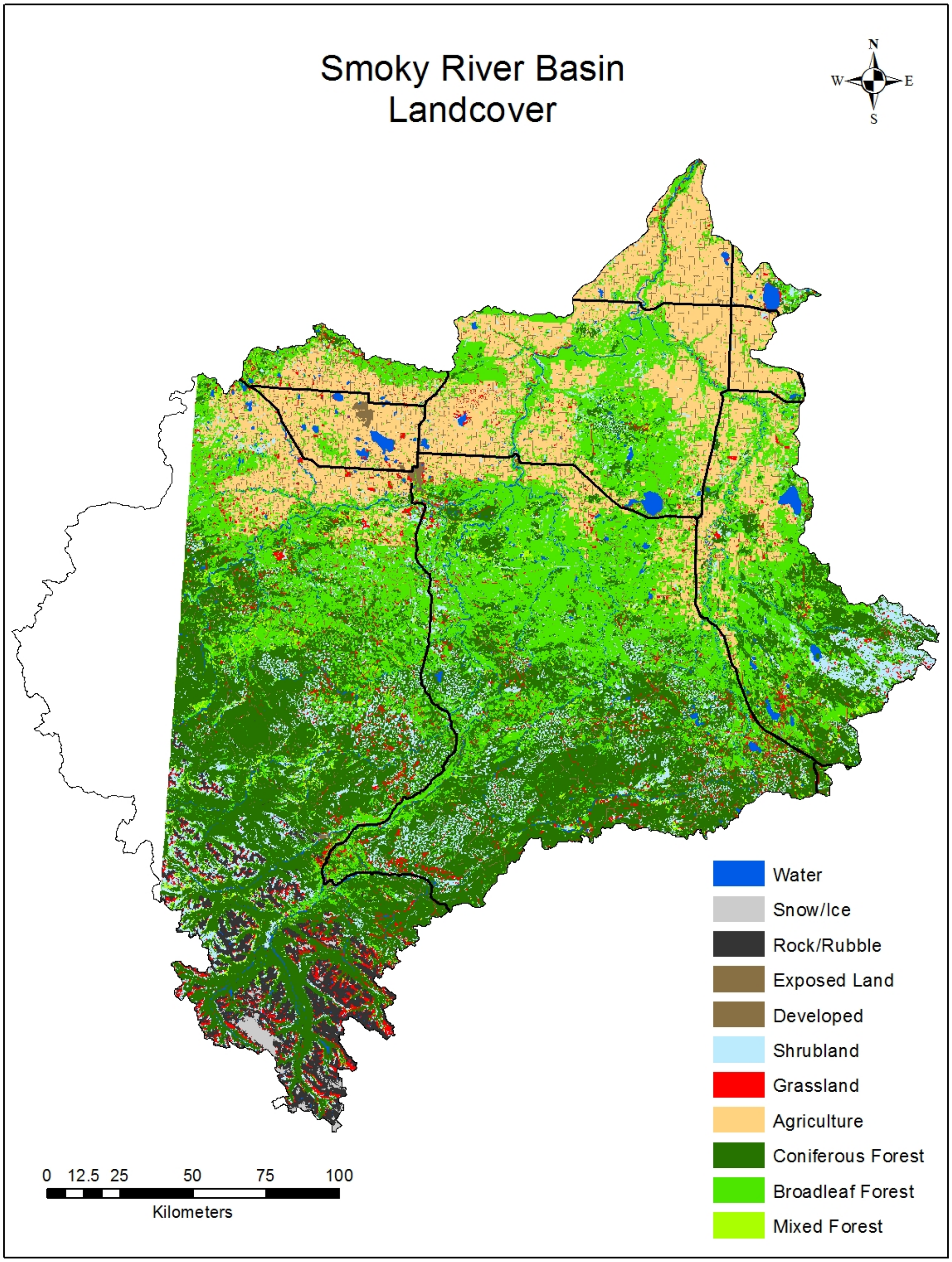


Figure 13. Alberta Biodiversity Monitoring Institute land cover and major road network for the Smoky River Basin.

3.4 Selection of Sub-basins for Modelling

ArcView GIS terrain preprocessing was carried out using the DEM to delineate sub-basins, which assists in the sub-basin setup for the purpose of CRHM modelling. In total, 38 sub-basins were delineated; sub-basin delineation for CRHM was based on the location of stream network and of Water Survey of Canada stream gauge stations. The Smoky River sub-basins delineated in this manner are shown in Figures 1, 2, 3 along with meteorological stations, real-time and other hydrometric stations and snow survey courses. Real-time hydrometric stations report on a daily basis and can be used for streamflow routing, while other stations provide data that can only be accessed well after the measurement time. For the purposes of this project, a gauged sub-basin was defined as the basin upstream of a real-time stream gauging station, such that it does not need to be modelled for streamflow routing. An un-gauged sub-basin is a sub-basin without a real-time stream gauge station and these are the sub-basins that are to be modelled with CRHM. Any gauged data from these non-real time basins can be used for model validation and calibration. From this definition there were 26 sub-basins that are ungauged and need to be modelled. These are GA3, GA4, GB3, GB4, GB5, GE2, GE3, GE4, GE5, GE6, GE7, GE8, GF4, GG2, GG3, GG4, GH1, GH2, GH3, GH4, GH5, GJ1, GJ2, GJ3, GJ4 and GJ5 and are shown in Figure 14. These modelled sub-basins encompass 23,768.80 km^2 in area, approximately 46% of the total Smoky River Basin area, which is 51,839.31 km^2. The area for each of these 26 modelled sub-basins is listed in Table 6.

Table 6. Area of the 26 modelled sub-basins.

Sub-basin	Area (km^2)	Sub-basin	Area (km^2)	Sub-basin	Area (km^2)	Sub-basin	Area (km^2)
GA3	288.77	GE4	507.06	GG3	2998.99	GJ1	568.79
GA4	1069.28	GE5	164.40	GG4	1953.21	GJ2	710.92
GB3	526.06	GE6	119.20	GH1	3014.34	GJ3	791.78
GB4	600.35	GE7	144.18	GH2	596.00	GJ4	1283.95
GB5	1973.68	GE8	1179.19	GH3	576.51	GJ5	126.90
GE2	1181.01	GF4	364.31	GH4	498.93		
GE3	223.44	GG2	2035.10	GH5	271.67		

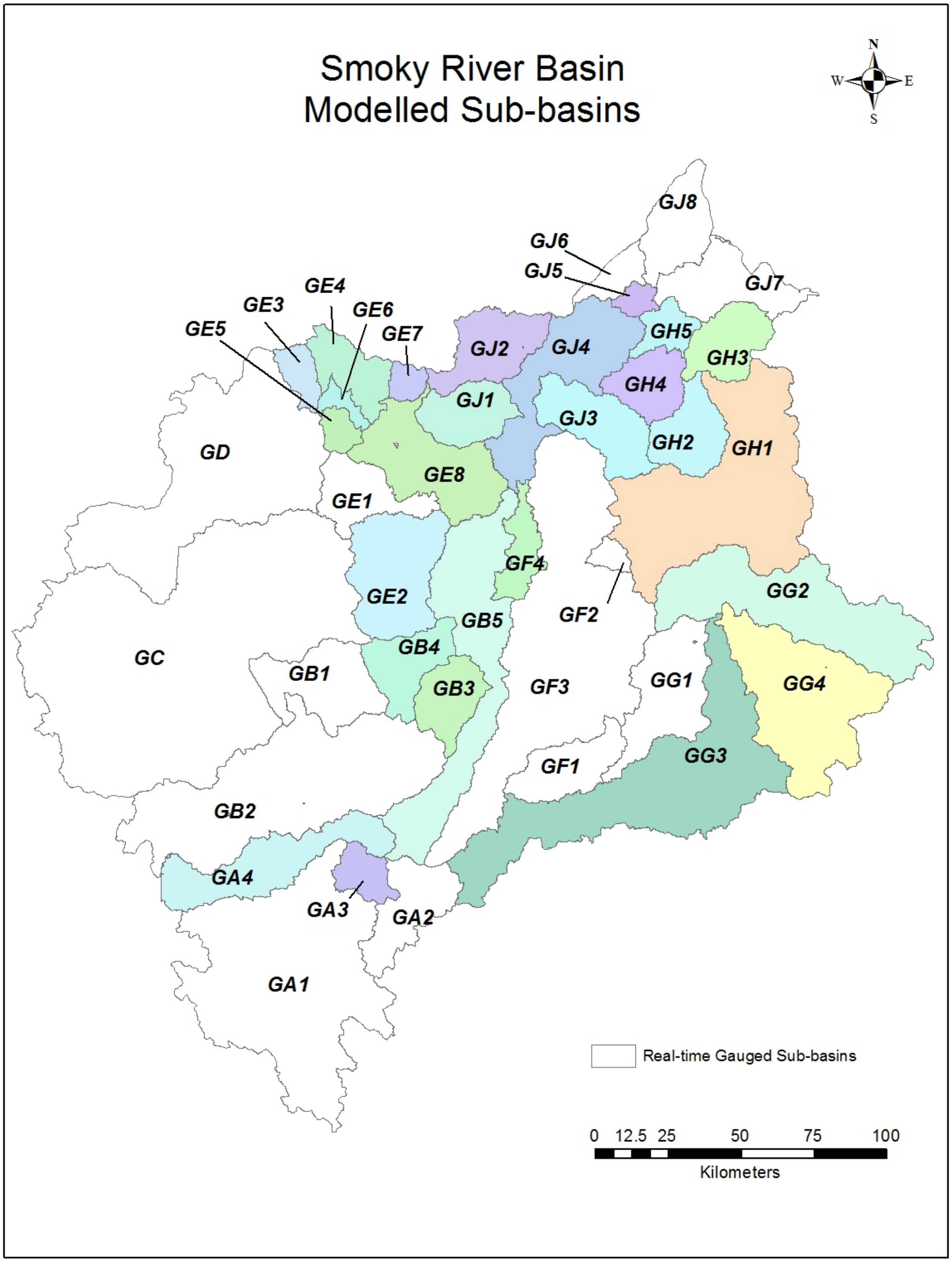


Figure 14. Smoky River modelled sub-basins. Modelled basins are coloured and basins with real-time gauging are white – colours are used to visually distinguish sub-basins have no other meaning.

3.5 Sub-basin Characterization and Typing

Previous applications of CRHM to create hydrological models in western Canada have involved basins that were clearly within a sub-arctic, boreal forest, mountain, or prairie ecoregion setting. The resulting projects used one type of model structure that was repeated for various sub-basins. However the Smoky River Basin is diverse and large, almost 52,000 km^2, and flows south from high alpine headwaters through upland boreal forest, down to the lowland Peace River agricultural district. Some tributary streams originate in the forests of the boreal plain in the eastern edge of the basin. Parts of the boreal forest have been cleared for agriculture and other parts are disturbed from logging and extensive oil and gas exploration. To model this basin, four “ecoregion types” of sub-basins were defined, each corresponding to a major ecoregion in the basin: mountain, boreal forest, agriculture with cropland, and mixed boreal forest/agriculture. The 26 modelled sub-basins were then classified into ecoregion types using land cover information and information from site visits.

Land cover polygons from ABMI were used to provide the land cover for the modelled sub-basins (Figure 15). There are 10 classes presented in the ABMI land cover polygons for the modelled sub-basins: water, rock/rubble, exposed land, developed, shrubland, grassland, agriculture, coniferous forest, broadleaf forest, and mixed forest. These were interpreted based on the ecoregion type and generalized to non-channel HRUs. Agriculture land cover was further divided into several types of cropland HRUs based on Agriculture Canada's agricultural/White Zone Soil Inventory and the dominant soil texture as shown in Figure 16. In Figure 16 soil types used for HRU delineation are clay, clay-loam, loam and silt; soil texture from various ecodistrict types was aggregated into these classes. The TOPAZ stream network and Alberta drainage network were used to distinguish the small channel and main river valley HRUs.

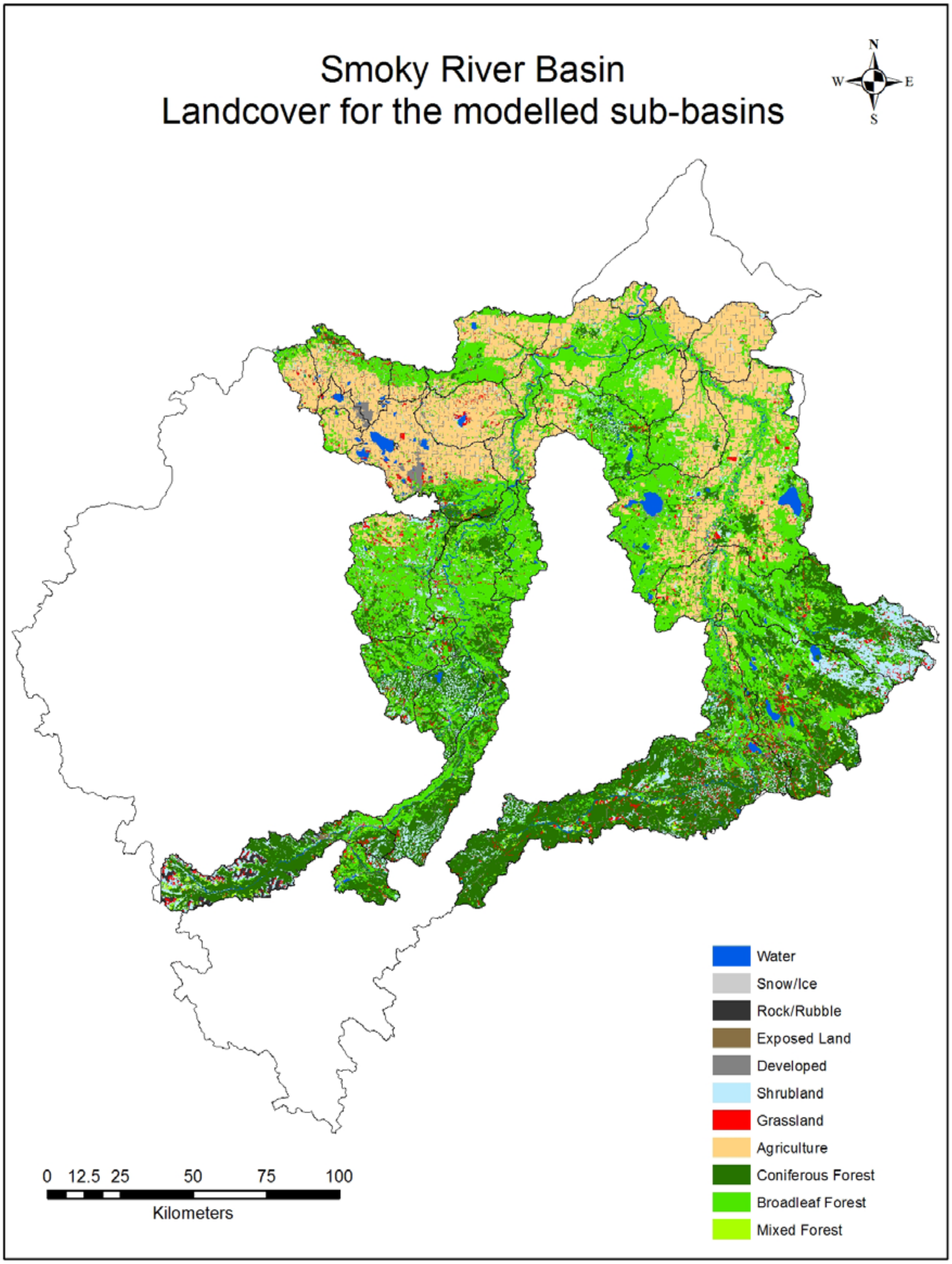


Figure 15. ABMI land cover for the Smoky River modelled sub-basins.

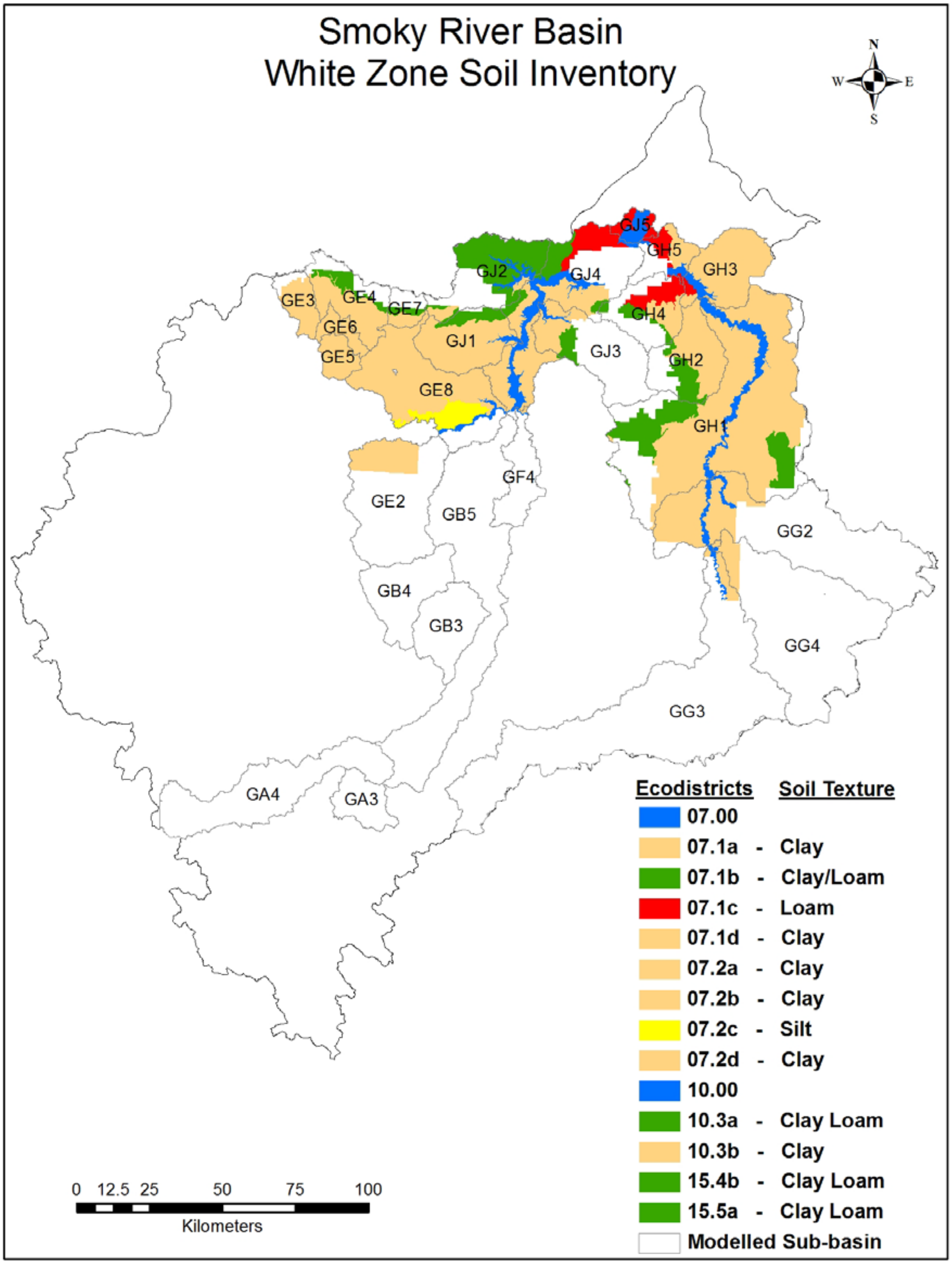


Figure 16. White zone (agricultural zone) soil texture for the Smoky River modelled sub-basins. Ecodistricts refer back to Agriculture Canada's classification system, but are not used in HRU delineation.

4 CRHM Lower Smoky River Model

4.1 Module Structure within Hydrological Response Units

A set of physically based modules was constructed in a sequential manner to simulate the dominant hydrological processes for the Smoky River, based on the experience of the modellers in constructing models in western Canada. Modules were selected that could be run in forecast mode to robustly simulate the hydrological cycle of the region in a physically based manner. Figure 17 shows the schematic setup of these modules, which include:

1). Observation module: reads the meteorological data (temperature, wind speed, relative humidity, vapour pressure, precipitation, and radiation) used to operate CRHM, adjusting temperature with environmental lapse rate and precipitation with elevation and wind-induced undercatch, and providing these inputs to other modules.

2). Radiation module (Garnier and Ohmura, 1970): calculates the theoretical global radiation, direct and diffuse solar radiation, as well as maximum sunshine hours based on latitude, elevation, ground slope, and azimuth, providing radiation inputs to the sunshine hour module, the energy-budget snowmelt module, and the net all-wave radiation module.

3). Sunshine hour module: estimates sunshine hours from incoming short-wave radiation and maximum sunshine hours, generating inputs to the energy-balance snowmelt module and the net all-wave radiation module.

4). Short-wave radiation module (Annandale et al., 2002): estimates incident short-wave incoming solar radiation using a simple temperature method and adjusts the incident short-wave to a slope if the slope presents. The measured incoming short-wave radiation from the observation module and the calculated direct and diffuse solar radiation from the radiation module are used to calculate the ratio for adjusting the short-wave radiation on the slope.

5). Long-wave radiation module (Sicart et al., 2006): estimates incoming long-wave radiation using short-wave radiation. This is inputted to the energy-balance snowmelt module.

6). Albedo module (Gray and Landine, 1987): estimates snow albedo throughout the winter and into the melt period and also indicates the beginning of melt for the energy-balance snowmelt module.

7). Canopy module (Ellis et al., 2010): estimates the snowfall and rainfall intercepted by the forest canopy and updates the under-canopy snowfall and rainfall and calculates short-wave and long-wave sub-canopy radiation. This module has options for open environment (no canopy adjustment of snow mass and energy), small forest clearing environment (adjustment of snow mass and energy based on diameter of clearing and surrounding forest height), and forest environment (adjustment of snow mass and energy from forest canopy).

8). Blowing snow module (Pomeroy and Li, 2000): simulates the inter-HRU wind redistribution of snow transport and blowing snow sublimation losses throughout the winter period.

9). Energy-Budget Snowmelt Model (Gray and Landine, 1988): estimates snowmelt by calculating the energy balance of radiation, sensible heat, latent heat, ground heat, advection from rainfall, and change in internal energy.

10). All-wave radiation module (Granger and Gray, 1990): calculates the net all-wave radiation from short-wave radiation for input to the evaporation module for snow-free conditions.

11). Infiltration module: Gray's snowmelt infiltration algorithm (Gray et al., 1985) estimates snowmelt infiltration into frozen soils; Ayers' infiltration (Ayers, 1959) estimates rainfall infiltration into unfrozen soils based on soil texture and ground cover. Both infiltration algorithms link moisture content to the soil column in the soil module. Surface runoff forms when snowmelt or rainfall exceeds the infiltration rate.

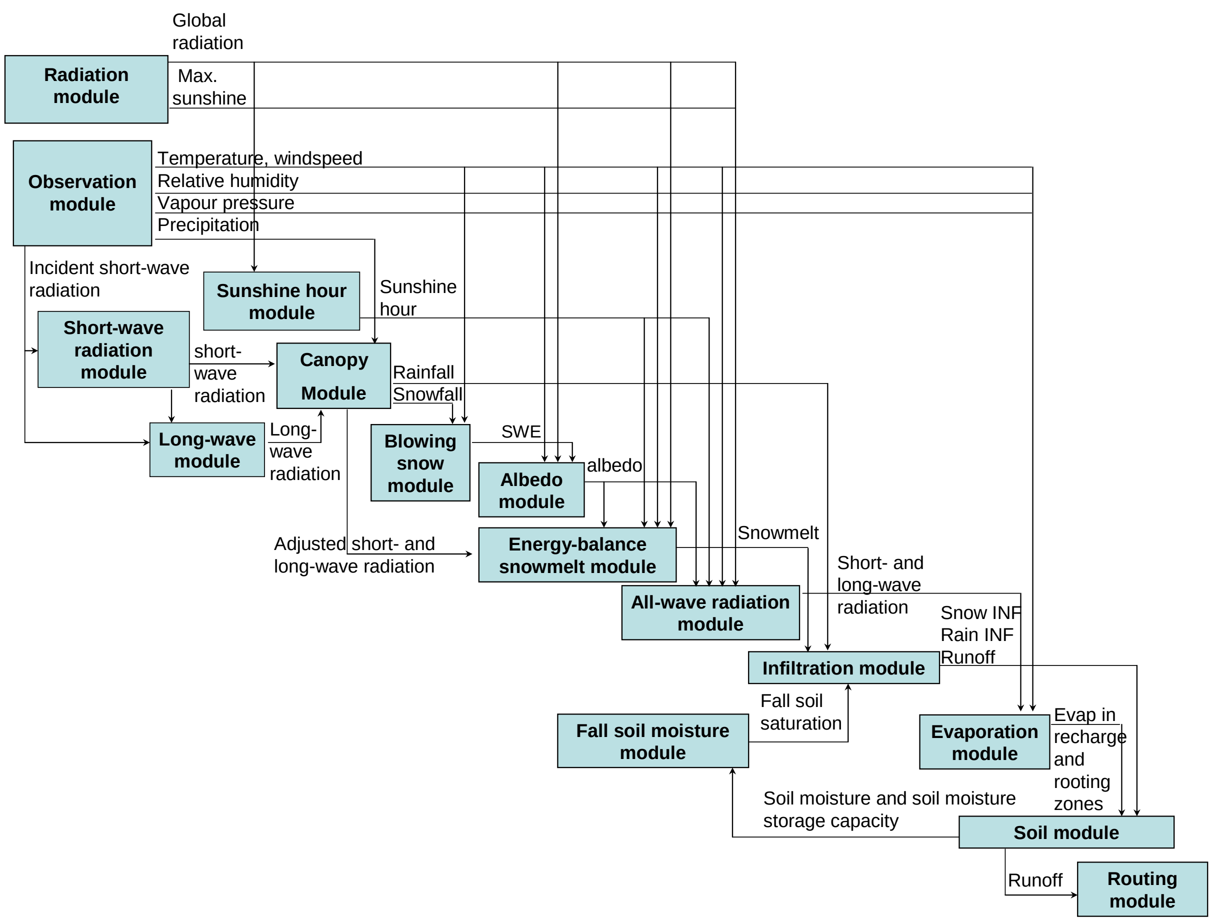


Figure 17. Flowchart of physically based hydrological modules used in the Lower Smoky River Model (LSRM).

12). Fall soil moisture module: this is a module to set the fall soil moisture status for running the multiple-year simulation. The amount of soil moisture and the maximum soil moisture storage in the soil column are used to estimate the fall soil moisture status, which provides the initial fall soil saturation for the infiltration module.

13). Evaporation module: Granger's evaporation expression (Granger and Gray, 1989; Granger and Pomeroy, 1997) estimates actual evapotranspiration from unsaturated surfaces using an energy balance and extension of Penman's equation to unsaturated conditions; Priestley and Taylor evaporation expression (Priestley and Taylor, 1972) estimates evaporation from saturated surfaces such as stream channels. Both evaporation algorithms modify moisture content in the interception store, ponded surface water store and soil column and are restricted by water availability to ensure continuity of mass, and the Priestley and Taylor evaporation also updates moisture content in the stream channel.

14). Soil & Hillslope module: this recently developed module is for calculating sub-surface flow and simulating groundwater-surface water interactions using physically based parameters. This module was revised from an original soil moisture balance routine developed by Leavesley et al. (1983) and modified by Pomeroy et al. (2007), Dornes et al. (2008), Fang et al. (2010) and Fang et al. (2012) and now calculates the soil moisture balance, groundwater storage, subsurface and groundwater discharge, depressional storage, and runoff for control volumes of two soil layers, a groundwater layer and surface depressions. A conceptual representation of this module is shown in Figure 18. In this diagram, the top layer is called the recharge layer, which obtains inputs from infiltration of ponded surface water, snowmelt or sub-canopy rainfall. Evaporation first extracts water from canopy interception and surface storage and then can withdraw moisture via transpiration from only the recharge layer or from both soil column layers depending on rooting characteristics, and is restricted to plant available soil moisture (Armstrong et al., 2010). Evaporation does not withdraw soil moisture until canopy interception and surface water storage are exhausted. Groundwater recharge occurs via percolation from the soil layers or directly from depressional storage via macropores. Subsurface discharge occurs via horizontal drainage from either soil layer; groundwater discharge takes place through horizontal drainage in the groundwater layer. Surface runoff occurs if snowmelt or rainfall inputs exceed subsurface withdrawals from saturated soils or if the rate of snowmelt or rainfall exceeds the infiltration rate. The drainage factors for lateral flow in soil layers and groundwater layer (i.e. subsurface and groundwater discharges) as well as vertical flow of excess soil water to groundwater (i.e. groundwater recharge) are estimated based on Darcy's flux. Brooks and Corey (1964) relationship is used to calculate the unsaturated hydraulic conductivity.

15). Routing module: the Muskingum method is based on a variable discharge-storage relationship (Chow, 1964) and is used to route runoff between HRUs in the sub-basins. The routing storage constant is estimated from the average distance from the HRU to the main channel and average flow velocity; the average flow velocity is calculated by Manning's equation (Chow, 1959) based on the average HRU distance to the main channel, average change in HRU elevation, overland flow depth and HRU roughness.

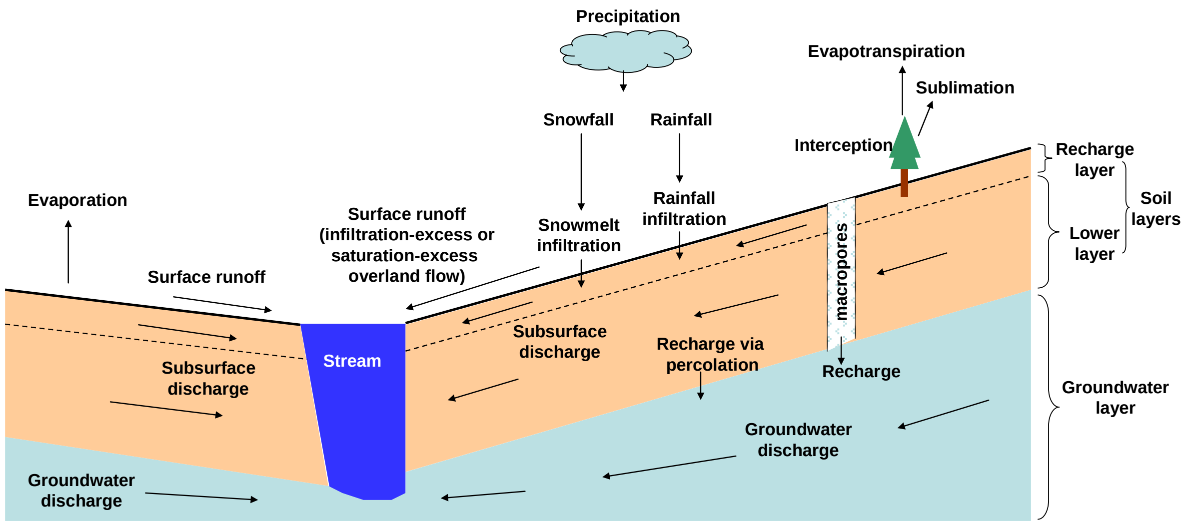


Figure 18. Conceptual representation of soil & hillslope module with control volumes of two soil layers, a groundwater layer and surface depressions or macropores.

4.2 Hydrological Response Unit and Sub-basin Structure and Parameterisation

Hydrological response units (HRU) are based on combination of vegetation, soils, drainage, waterbody and topographic parameter information. The 10 ABMI land cover classes (Fig. 15) were generalized to non-channel HRUs, and the agriculture land cover was further divided into several types of cropland HRUs based on the soil texture shown in Figure 16. TOPAZ stream network and Alberta drainage network were used to set up small channel and main river valley HRUs. The HRU generation process is shown in Figure 19.

As noted earlier, in these 26 modelled sub-basins, two sub-basins GA3 and GA4 are located in the mountain and foothill forest ecoregion of the Smoky River Basin, and three sub-basins GB3, GB4 and GB5 are located in the Boreal Plain forest ecoregion of the basin, while sub-basins GE2, GF4, GG2, GG3 and GG4 are in the transition ecoregion between the Boreal Plain forest and agricultural land. The rest of the sub-basins are location in the agricultural ecoregion. It should be noted that the ABMI land cover was designed for the general purpose of classifying the entire Province of Alberta; the same ABMI land cover classes have different meanings in different ecoregion types and thus have different characteristics in each ecoregion type for hydrological modelling. Therefore, some of ABMI land cover classes need to be redefined based on the ecoregion type. In Figure 19, for the mountain sub-basins, ABMI 'rock/rubble' land cover was further separated to 'rock south-facing', 'rock north-facing', and 'rock east-west-facing' HRUs; ABMI 'grassland' land cover was defined as 'alpine tundra' and was further separated based on aspect. For the mountain and boreal forest sub-basins, ABMI 'shrubland' land cover was defined as 'regenerated forest clear-cut' HRU'. 'Shrubland' was further divided to 'regenerated forest clear-cut' and 'fen' HRUs for the boreal forest/agriculture transition sub-basins, whereas it was defined as wetland HRU for the agriculture sub-basins. For the boreal forest/agriculture transition and agriculture sub-basins, ABMI 'agriculture' land cover was defined as 'cropland' HRU and was divided into several cropland HRUs: 'cropland (clay)', 'cropland (clay loam)', 'cropland (loam)' and 'cropland (silt)' based on the white zone soil texture shown in Figure 16. Figure 20 shows the HRUs mapped on to the modelled sub-basins in the Smoky River Basin. Note that HRU areas falling into PFRA non-contributing areas are not used as these are internally drained sub-basins that do not normally contribute to streamflow. The corresponding area, elevation, aspect, and slope for the HRUs were computed using SAGA GIS terrain analysis profile tool and ArcGIS extract by mask tool. Tables 7 to 10 present the HRU area for these different types of sub-basins. Tables 11 to 14 present the HRU elevation, aspect and slope for these different types of sub-basins.

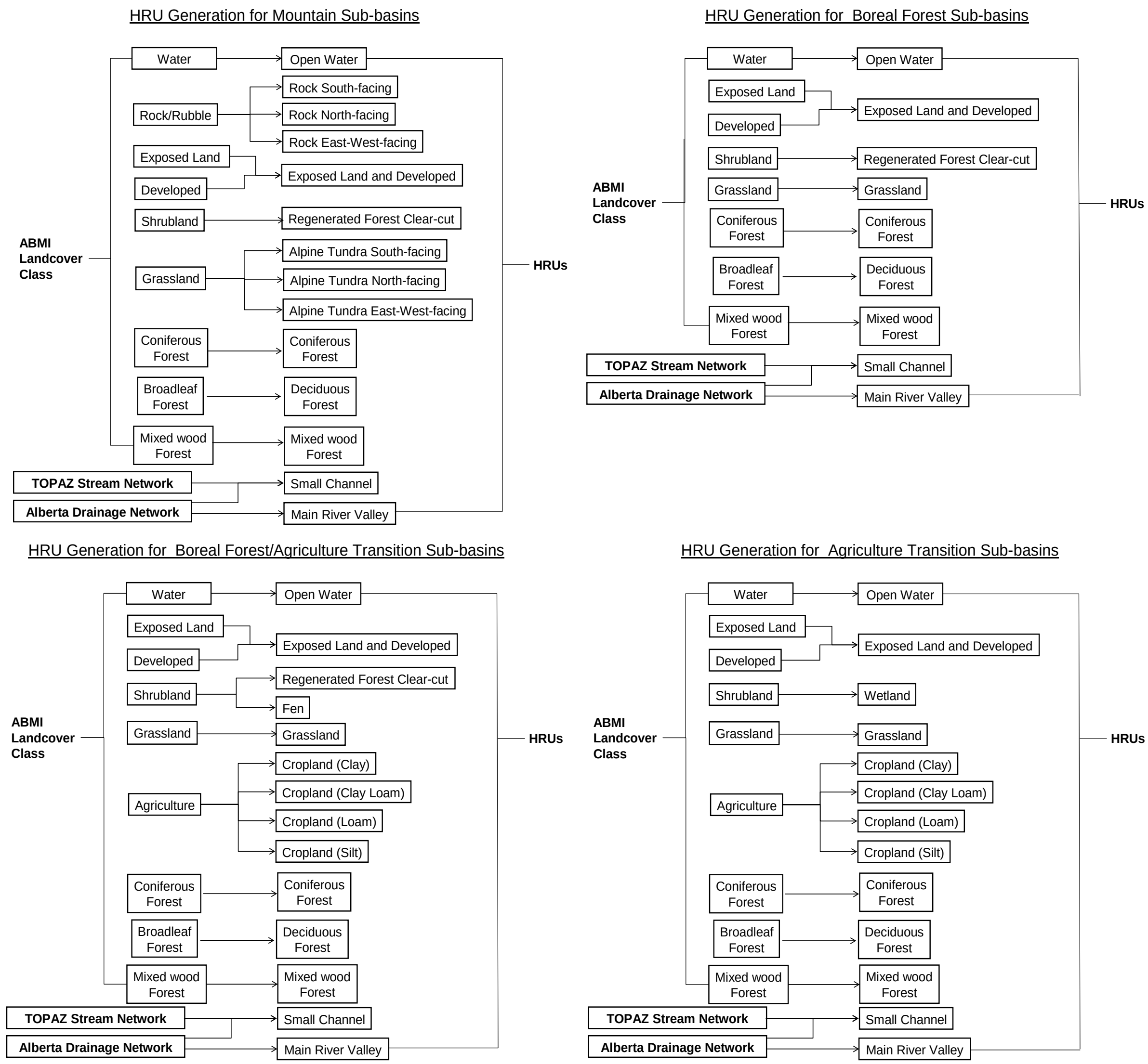


Figure 19. HRU generation for the Smoky River modelled sub-basins.

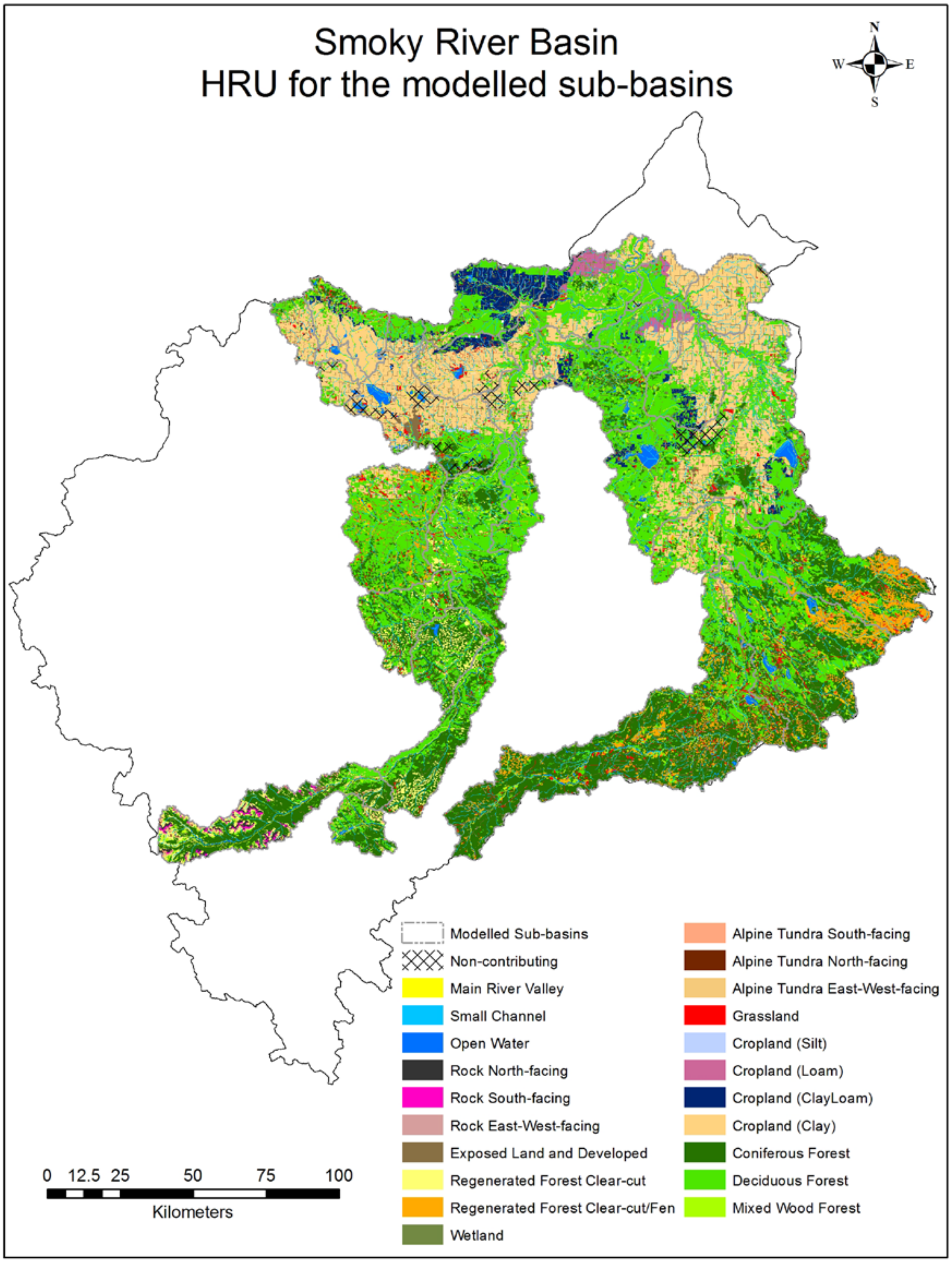


Figure 20. HRU for the modelled sub-basins in the Smoky River Basin.

Table 7. HRU areas for the mountain sub-basins.

	Area (km^2)		(%)	
HRU	GA3	GA4	GA3	GA4
Exposed Land and Developed	8.02	17.66	2.78	1.65
Rock (NF)	0.95	62.16	0.33	5.81
Rock (SF)	0.78	44.05	0.27	4.12
Rock (E-W)	0.01	0.49	0.00	0.05
Alpine Tundra (NF)	2.61	9.45	0.90	0.88
Alpine Tundra (SF)	3.58	36.95	1.24	3.46
Alpine Tundra (E-W)	7.58	0.19	2.62	0.02
Coniferous Forest	150.34	579.84	52.06	54.23
Deciduous Forest	74.17	83.95	25.69	7.85
Mixed Forest	9.02	41.46	3.12	3.88
Regenerated Forest Clearcut	24.32	174.12	8.42	16.28
Open Water	7.16	18.14	2.48	1.70
Small Channel	0.15	0.56	0.05	0.05
Main River Valley	0.09	0.25	0.03	0.02
Sum	288.77	1069.28		

Table 8. HRU areas for the Boreal Plain forest sub-basins.

	Area (km^2)			(%)		
HRU	GB3	GB4	GB5	GB3	GB4	GB5
Exposed Land and Developed	25.62	25.39	68.22	4.87	4.23	3.47
Grassland	4.96	23.51	30.23	0.94	3.92	1.54
Coniferous Forest	240.44	196.30	720.89	45.71	32.70	36.69
Deciduous Forest	150.93	261.38	890.84	28.69	43.54	45.34
Mixed Forest	3.86	14.98	60.40	0.73	2.50	3.07
Regenerated Forest Clearcut	83.88	70.32	142.90	15.95	11.71	7.27
Open Water	15.97	8.00	49.73	3.04	1.33	2.53
Small Channel	0.26	0.35	1.03	0.05	0.06	0.05
Main River Valley	0.13	0.12	0.70	0.02	0.02	0.04
Sum	526.06	600.35	1964.93			

Table 9. HRU area for the Boreal Plain forest/agriculture transition sub-basins.

	Area (km^2)					(%)				
HRU	GE2	GF4	GG2	GG3	GG4	GE2	GF4	GG2	GG3	GG4
Exposed Land and Developed	67.49	4.43	45.99	111.45	74.56	5.71	1.22	2.26	3.72	3.82
Cropland (Clay)	72.85	1.24	199.24	22.11	24.02	6.17	0.34	9.79	0.74	1.23
Grassland	50.97	2.70	51.82	118.37	74.85	4.32	0.74	2.55	3.95	3.83
Coniferous Forest	154.08	42.50	630.23	1908.36	844.14	13.05	11.67	30.97	63.63	43.22
Deciduous Forest	681.28	270.94	680.46	422.62	579.33	57.69	74.37	33.44	14.09	29.66
Mixed Forest	38.03	21.15	63.27	71.65	84.42	3.22	5.81	3.11	2.39	4.32
Regenerated Forest Clearcut	90.75	13.84	280.64	261.61	207.45	7.68	3.80	13.79	8.72	10.62
Fen	12.87	0.16	51.28	15.29	13.60	1.09	0.04	2.52	0.51	0.70
Open Water	11.79	7.05	30.10	64.45	48.92	1.00	1.93	1.48	2.15	2.50
Small Channel	0.66	0.17	1.49	2.12	1.19	0.06	0.05	0.07	0.07	0.06
Main River Valley	0.25	0.14	0.59	0.96	0.73	0.02	0.04	0.03	0.03	0.04
Sum	1181.01	364.31	2035.10	2998.99	1953.21					

Table 10. HRU area for the agriculture sub-basins.

	Area (km^2)			(%)		
HRU	GE3	GE5	GE6	GE3	GE5	GE6
Exposed Land and Developed	19.44	11.22	0.00	9.08	8.52	0.00
Cropland (Clay)	127.48	87.77	99.79	59.59	66.62	85.47
Grassland	7.62	2.37	2.35	3.56	1.80	2.01
Coniferous Forest	5.40	0.34	0.17	2.52	0.26	0.15
Deciduous Forest	43.23	29.25	5.59	20.21	22.20	4.79
Mixed Forest	4.14	0.32	0.37	1.94	0.24	0.31
Wetland	5.80	0.02	0.00	2.71	0.01	0.00
Open Water	0.62	0.30	8.38	0.29	0.23	7.18
Small Channel	0.16	0.11	0.02	0.07	0.08	0.02
Main River Valley	0.05	0.05	0.09	0.03	0.04	0.07
Sum	213.94	131.74	116.76			

Table 10. *Continued*.

	Area (km^2)	(%)
HRU	GJ5	GJ5
Exposed Land and Developed	7.54	5.94
Cropland (Loam)	66.89	52.71
Grassland	0.84	0.66
Coniferous Forest	0.10	0.08
Deciduous Forest	38.38	30.25
Mixed Forest	0.67	0.53
Wetland	4.28	3.37
Open Water	8.07	6.36
Small Channel	0.03	0.03
Main River Valley	0.10	0.08
Sum	126.90	

Table 10. *Continued*.

	Area (km^2)							(%)						
HRU	GE4	GE7	GH1	GH2	GJ1	GJ2	GJ3	GE4	GE7	GH1	GH2	GJ1	GJ2	GJ3
Exposed Land and Developed	0.00	9.90	129.33	24.30	36.84	35.40	12.40	0.00	6.86	4.50	4.11	6.87	4.99	1.57
Cropland (Clay)	274.80	36.37	850.12	217.31	343.91	26.95	95.25	54.65	25.23	29.57	36.78	64.17	3.80	12.03
Cropland (Clay Loam)	25.61	8.52	71.37	51.73	52.75	283.28	28.02	5.09	5.91	2.48	8.75	9.84	39.94	3.54
Grassland	21.51	4.80	68.86	2.98	20.64	11.54	16.21	4.28	3.33	2.40	0.50	3.85	1.63	2.05
Coniferous Forest	25.85	4.13	182.37	19.98	0.15	19.15	125.35	5.14	2.86	6.34	3.38	0.03	2.70	15.83
Deciduous Forest	121.85	76.40	1292.61	236.77	55.38	299.57	389.35	24.23	52.99	44.97	40.08	10.33	42.24	49.17
Mixed Forest	13.10	0.88	49.57	11.48	0.58	7.89	35.39	2.61	0.61	1.72	1.94	0.11	1.11	4.47
Wetland	14.20	2.35	85.75	24.92	14.77	17.58	73.13	2.82	1.63	2.98	4.22	2.76	2.48	9.24
Open Water	5.41	0.59	141.07	0.70	10.35	7.15	15.75	1.08	0.41	4.91	0.12	1.93	1.01	1.99
Small Channel	0.30	0.22	2.70	0.42	0.51	0.60	0.75	0.06	0.16	0.09	0.07	0.09	0.08	0.09
Main River Valley	0.23	0.02	0.89	0.21	0.09	0.16	0.18	0.05	0.01	0.03	0.04	0.02	0.02	0.02
Sum	502.87	144.18	2874.63	590.81	535.97	709.28	791.78							

Table 10. *Continued*.

	Area (km^2)		(%)	
HRU	GH3	GH5	GH3	GH5
Exposed Land and Developed	37.55	8.93	6.61	3.46
Cropland (Clay)	439.16	87.46	77.27	33.92
Cropland (Loam)	11.88	25.35	2.09	9.83
Grassland	5.82	2.37	1.02	0.92
Coniferous Forest	0.81	0.51	0.14	0.20
Deciduous Forest	57.14	120.65	10.05	46.79
Mixed Forest	2.20	1.22	0.39	0.47
Wetland	9.32	4.08	1.64	1.58
Open Water	3.77	7.04	0.66	2.73
Small Channel	0.58	0.17	0.10	0.07
Main River Valley	0.11	0.07	0.02	0.03
Sum	568.35	257.86		

Table 10. *Continued*.

	Area (km^2)	(%)
HRU	GE8	GE8
Exposed Land and Developed	102.07	10.69
Cropland (Clay)	497.42	52.10
Cropland (Silt)	12.33	1.29
Grassland	30.80	3.23
Coniferous Forest	46.89	4.91
Deciduous Forest	187.35	19.62
Mixed Forest	9.58	1.00
Wetland	10.66	1.12
Open Water	56.57	5.92
Small Channel	0.62	0.07
Main River Valley	0.54	0.06
Sum	954.83	

Table 10. *Concluded*.

HRU	Area (km^2) GH4	GJ4	(%) GH4	GJ4
Exposed Land and Developed	13.09	44.44	2.65	3.76
Cropland (Clay)	88.67	276.78	17.92	23.40
Cropland (Clay Loam)	9.21	84.45	1.86	7.14
Cropland (Loam)	47.14	98.27	9.53	8.31
Grassland	0.85	15.95	0.17	1.35
Coniferous Forest	11.50	31.79	2.32	2.69
Deciduous Forest	284.65	525.12	57.52	44.39
Mixed Forest	14.89	21.73	3.01	1.84
Wetland	22.31	37.92	4.51	3.21
Open Water	1.87	45.04	0.38	3.81
Small Channel	0.60	0.70	0.12	0.06
Main River Valley	0.06	0.65	0.01	0.05
Sum	494.83	1182.85		

Table 11. HRU elevation, aspect and slope for the mountain sub-basins.

HRU	Elevation (m) GA3	GA4	Aspect (°) GA3	GA4	Slope (°) GA3	GA4
Exposed Land and Developed	1200	1256	147	163	8.1	13.2
Rock (NF)	1861	2071	30	352	13.2	28.8
Rock (SF)	1834	2046	192	183	14.1	27.5
Rock (E-W)	1843	2073	90	90	0.0	0.0
Alpine Tundra (NF)	1491	1794	40	23	15.1	12.7
Alpine Tundra (SF)	1452	1829	177	160	17.3	18.4
Alpine Tundra (E-W)	1406	1821	90	90	0.0	0.0
Coniferous Forest	1430	1533	162	175	12.8	14.2
Deciduous Forest	1331	1294	164	167	13.5	14.9
Mixed Forest	1423	1621	163	176	14.1	13.6
Regenerated Forest Clearcut	1360	1717	174	163	9.7	15.6
Open Water	1081	1210	110	168	6.3	6.5
Small Channel	1209	1399	90	90	8.2	7.0
Main River Valley	1114	1263	90	90	9.9	11.6

Table 12. HRU elevation, aspect and slope for the Boreal Plain forest sub-basins.

	Elevation (m)			Aspect (°)			Slope (°)		
HRU	GB3	GB4	GB5	GB3	GB4	GB5	GB3	GB4	GB5
Exposed Land and Developed	958	940	939	170	156	169	3.7	3.5	4.8
Grassland	980	919	927	134	160	175	4.3	3.8	4.2
Coniferous Forest	915	893	963	173	166	191	4.2	4.2	5.9
Deciduous Forest	939	894	796	165	163	175	5.3	4.8	5.3
Mixed Forest	913	910	764	167	148	181	4.1	4.9	3.5
Regenerated Forest Clearcut	918	925	1044	168	164	162	3.8	3.9	5.4
Open Water	808	722	638	117	176	174	3.7	5.2	4.0
Small Channel	855	818	772	90	90	90	2.9	3.9	3.1
Main River Valley	793	759	670	90	90	90	8.0	7.3	7.0

Table 13. HRU elevation, aspect and slope for the Boreal Plain forest/agriculture transition sub-basins.

	Elevation (m)					Aspect (°)					Slope (°)				
HRU	GE2	GF4	GG2	GG3	GG4	GE2	GF4	GG2	GG3	GG4	GE2	GF4	GG2	GG3	GG4
Exposed Land and Developed	754	679	791	1010	837	150	151	176	168	169	2.1	2.4	2.1	2.5	1.9
Cropland (Clay)	691	616	702	742	748	143	155	158	226	140	1.2	1.6	1.1	1.6	1.4
Grassland	725	696	854	1008	833	154	174	186	163	167	1.6	1.0	2.4	2.0	1.8
Coniferous Forest	799	671	857	1107	844	165	176	190	163	178	3.2	1.6	2.4	2.7	1.9
Deciduous Forest	759	684	778	874	812	152	167	182	169	186	2.8	2.0	2.3	2.7	2.1
Mixed Forest	714	670	789	1008	831	155	166	181	157	176	1.8	0.9	1.5	1.6	1.6
Regenerated Forest Clearcut	733	675	939	1045	868	154	173	190	152	187	2.0	1.1	3.4	2.1	2.2
Fen	733	675	939	1045	868	154	173	190	152	187	2.0	1.1	3.4	2.1	2.2
Open Water	633	635	701	923	770	160	80	162	125	38	4.2	1.3	3.3	1.8	0.7
Small Channel	702	653	789	1029	804	90	90	90	90	90	2.7	2.1	2.7	1.9	2.0
Main River Valley	698	628	757	961	791	90	90	90	90	90	4.6	5.0	3.0	2.9	2.0

Table 14. HRU elevation, aspect and slope for the agriculture sub-basins.

	Elevation (m)			Aspect (°)			Slope (°)		
HRU	GE3	GE5	GE6	GE3	GE5	GE6	GE3	GE5	GE6
Exposed Land and Developed	782	756	709	153	139	164	1.2	1.4	1.4
Cropland (Clay)	763	749	732	150	136	152	0.9	1.2	1.0
Grassland	767	794	732	153	112	161	0.9	1.2	0.6
Coniferous Forest	817	785	678	152	126	174	1.8	3.4	3.2
Deciduous Forest	818	804	743	150	119	173	1.7	1.8	1.2
Mixed Forest	824	748	765	148	136	141	1.4	0.4	0.9
Wetland	798	742	765	148	127	141	1.1	1.0	0.0
Open Water	774	727	721	116	17	15	0.6	0.2	0.1
Small Channel	763	741	714	90	90	90	0.7	1.5	0.9
Main River Valley	744	735	710	90	90	90	1.0	1.2	1.0

Table 14. *Continued*.

HRU	Elevation (m) GJ5	Aspect (°) GJ5	Slope (°) GJ5
Exposed Land and Developed	487	167	2.7
Cropland (Loam)	505	156	1.7
Grassland	553	194	1.3
Coniferous Forest	430	297	11.1
Deciduous Forest	485	169	5.2
Mixed Forest	417	195	8.9
Wetland	492	151	4.3
Open Water	392	163	2.6
Small Channel	445	90	2.0
Main River Valley	393	90	3.5

Table 14. *Continued*.

	Elevation (m)		Aspect (°)		Slope (°)	
HRU	GH3	GH5	GH3	GH5	GH3	GH5
Exposed Land and Developed	593	550	193	174	0.9	1.3
Cropland (Clay)	593	557	192	171	0.7	0.7
Cropland (Loam)	593	557	192	171	0.7	0.7
Grassland	568	549	194	167	3.2	1.8
Coniferous Forest	594	521	159	160	5.2	6.2
Deciduous Forest	564	528	193	165	4.3	3.8
Mixed Forest	616	487	195	189	1.0	7.1
Wetland	597	512	174	161	1.9	3.5
Open Water	452	464	177	141	2.8	2.5
Small Channel	574	502	90	90	1.5	2.1
Main River Valley	535	480	90	90	3.2	7.6

Table 14. *Continued*.

	Elevation (m)						
HRU	GE4	GE7	GH1	GH2	GJ1	GJ2	GJ3
Exposed Land and Developed	780	827	682	658	711	703	670
Cropland (Clay)	773	770	668	641	700	664	644
Cropland (Clay Loam)	773	770	668	641	700	664	644
Grassland	858	847	691	708	687	675	693
Coniferous Forest	866	897	704	713	660	714	723
Deciduous Forest	863	887	704	714	700	726	712
Mixed Forest	875	904	687	702	693	728	729
Wetland	834	818	678	685	687	692	699
Open Water	769	861	675	651	667	632	700
Small Channel	789	816	663	639	680	650	681
Main River Valley	768	748	651	645	649	641	666
	Aspect (°)						
HRU	GE4	GE7	GH1	GH2	GJ1	GJ2	GJ3
Exposed Land and Developed	178	189	180	145	161	160	191
Cropland (Clay)	183	182	175	156	154	161	214
Cropland (Clay Loam)	183	182	175	156	154	161	214
Grassland	185	188	181	116	151	163	201
Coniferous Forest	198	191	171	142	192	159	178
Deciduous Forest	189	184	180	153	154	165	189
Mixed Forest	189	189	163	145	149	172	195
Wetland	180	189	179	153	160	168	184
Open Water	50	152	47	110	128	71	52
Small Channel	90	90	90	90	90	90	90
Main River Valley	90	90	90	90	90	90	90
	Slope (°)						
HRU	GE4	GE7	GH1	GH2	GJ1	GJ2	GJ3
Exposed Land and Developed	1.6	1.9	1.5	1.0	1.3	1.6	1.0
Cropland (Clay)	1.4	1.3	1.1	0.9	1.2	1.3	0.6
Cropland (Clay Loam)	1.4	1.3	1.1	0.9	1.2	1.3	0.6
Grassland	1.9	2.2	1.4	1.3	1.4	5.4	1.8
Coniferous Forest	1.4	2.4	0.9	1.3	7.2	3.5	1.3
Deciduous Forest	2.3	2.7	1.9	2.4	2.9	3.0	1.7
Mixed Forest	1.5	2.1	0.8	1.7	3.4	2.6	1.3
Wetland	1.3	2.0	1.3	1.7	1.5	2.9	1.6
Open Water	0.3	1.2	1.1	0.5	0.4	1.8	0.3
Small Channel	1.5	2.1	1.9	2.3	1.5	2.9	1.9
Main River Valley	1.6	0.9	2.6	3.3	2.6	3.9	3.0

Table 14. *Continued*.

HRU	Elevation (m) GE8	Aspect (°) GE8	Slope (°) GE8
Exposed Land and Developed	675	159	1.2
Cropland (Clay)	687	159	1.1
Cropland (Silt)	687	159	1.1
Grassland	658	152	1.4
Coniferous Forest	631	175	2.9
Deciduous Forest	625	165	3.7
Mixed Forest	623	174	3.6
Wetland	662	172	2.6
Open Water	651	41	0.7
Small Channel	648	90	1.5
Main River Valley	632	90	2.7

Table 14. *Concluded*.

	Elevation (m)		Aspect (°)		Slope (°)	
HRU	GH4	GJ4	GH4	GJ4	GH4	GJ4
Exposed Land and Developed	602	614	146	150	1.1	1.3
Cropland (Clay)	589	617	148	154	0.7	1.1
Cropland (Clay Loam)	589	617	148	154	0.7	1.1
Cropland (Loam)	589	617	148	154	0.7	1.1
Grassland	729	568	210	177	2.8	7.1
Coniferous Forest	735	569	178	152	2.2	3.5
Deciduous Forest	644	575	149	170	2.2	4.0
Mixed Forest	717	559	160	175	2.6	4.4
Wetland	619	583	141	165	0.9	3.4
Open Water	592	462	96	171	0.6	3.9
Small Channel	601	551	90	90	2.4	2.1
Main River Valley	582	488	90	90	2.4	7.7

Blowing snow parameters

Table 15 shows the values of blowing snow module parameters for the HRUs. Blowing snow fetch distance is the upwind distance without disruption to the flow of blowing snow. Fetch distances were set to 1000 m for 'Cropland' and 'Grassland' HRUs. A 300 m fetch length was assigned for other HRUs such as 'exposed land and developed', 'rock', 'alpine tundra', 'forest', 'fen', 'wetland' and 'open water'. These values are comparable to the estimated values for the prairie fields by Fang et al. (2010) using the computer program "FetchR" (Lapen and Martz, 1993) and for alpine zones set by MacDonald et al., 2010 in the Canadian Rockies. Values of vegetation height, stalk density and stalk diameter were set for these

HRUs to represent them in the prairie and mountain forest environments during fall and winter; these parameters values are comparable to those reported for the prairie by Fang et al. (2010) and for the alpine region in the Canadian Rockies and the Yukon (MacDonald et al., 2010; Pomeroy et al., 1997). The distribution factor parameterizes the allocation of blowing snow transport from aerodynamically smoother (or windier) HRU to aerodynamically rougher (or calmer) ones and was decided upon according to the landscape aerodynamic sequencing suitable for Prairie parkland regions (Fang and Pomeroy, 2009).

Table 15. Blowing snow module parameters in the Lower Smoky River Model (LSRM). Note (-) means parameter is dimensionless.

HRU Name	Fetch Distance (m)	Vegetation Height (m)	Stalk Diameter (m)	Stalk Density (#/m^2)	Distribution Factor (-)
Exposed Land and Developed	300	0.001	0.003	1	1
Rock	300	0.001	0.003	1	1
Alpine Tundra	300	1.5	0.01	5	2
Cropland	1000	0.15	0.003	150	1
Grassland	1000	0.7	0.003	150	2
Coniferous Forest	300	15	0.6	1.5	5
Deciduous Forest	300	10	0.4	1.5	5
Mixed Forest	300	15	0.6	1.5	5
Regenerated Forest Clearcut	300	7	0.2	1.5	5
Fen	300	1.5	0.05	75	5
Wetland	300	1.5	0.05	50	5
Open Water	300	0.001	0.003	1	5
Small Channel	300	0.001	0.003	1	1
Main River Valley	300	0.001	0.003	1	1

Albedo and canopy parameters

Table 16 presents the values of albedo and canopy parameters for HRUs. For the albedo of bare ground, measured values in the prairie by Armstrong (2011) were used to set values for 'tundra', 'grassland', 'cropland', 'wetland' and 'fen' HRUs, whilst measured values in the boreal forest environment by Granger and Pomeroy (1997) were used for the forest HRUs. The albedo of fresh snow was set to 0.85 based on recommended values by Male and Gray (1981) and measurements in the Canadian Rockies and northern prairies. For the leaf area index (LAI), a value of 0.45 was set for the 'alpine tundra' HRU and is comparable to the value for the northern tundra (Pomeroy et al., 2006); a value of 0.4 was assigned for the deciduous forest HRU and this is similar to the value used for aspen forest in the prairie during winter (Pomeroy et al. 1999). Measured values in the boreal forests (Hedstrom and Pomeroy, 1998; Pomeroy et al., 2002) were used for coniferous, mixed and regenerated forest HRUs. Non-wooded HRUs were given a small LAI value of 0.1. The canopy snow interception capacity was set to 6.3 kg m^{-2} for coniferous, mixed, and regenerated forest HRUs as this value was found experimentally for similar forest types (Schmidt and Gluns, 1991; Pomeroy et al., 2002). Deciduous forest HRUs received a smaller value of 0.5 kg m^{-2} which is similar to the value found for aspen trees during winter in northern prairies (Fang et al., 2010).

Soil parameters

Table 17 lists the values of soil parameters for HRUs. Both saturated hydraulic conductivity and pore size distribution parameters are used in the Brooks and Corey (1964) relationship to calculate the drainage factors for lateral flow in soil layers and the groundwater layer as well as the vertical flow of excess soil water to groundwater. Saturated hydraulic conductivities and pore size distributions for various layers were determined based on well-established experimental relationships to soil texture (Brooks and Corey, 1964; Clapp and Hornberger, 1978; Zhang et al., 2010).

The water storage capacities of recharge and soil layers were determined by multiplying soil layer depth by soil porosity. For the soil depth and porosity, averaged values for 'cropland', 'grassland', fen, and forests HRUs were estimated from the reported values in the regional soil surveys (Odynsky et al., 1956; Knapik and Lindsay, 1983). For the 'rock' and 'alpine tundra' HRUs, the water storage capacity in the recharge and soil layers were set based on the values in the central Canadian Rockies (Fang et al. 2012). 'Wetland', 'open water', 'small channel' and 'main river valley' HRUs were treated without soil layers, and thus water storage capacity is not applied to these HRUs. The groundwater storage capacity is relatively unknown in the region; a value of 500 mm was set as an estimate of typical values in the prairies, foothills and mountains of western Canada. Surface depressional storage capacities found in the prairie environment by Fang et al. (2010) were used for agricultural ecoregion HRUs.

Routing parameters

Figures 21 and 22 demonstrate the routing sequence between HRUs within the sub-basin and routing sequence between sub-basins, respectively. The routing sequence within the sub-basin from upland HRUs to the wetland HRUs and then to the channel HRUs is adopted from the sequence used in the CRHM-PHM modeling study (Pomeroy et al., 2010); the routing distribution parameter is used to partition amount of runoff between HRUs; the values of the routing distribution parameters were estimated by applying the Hack's law length-area relationship (Fang et al., 2010). The routing sequence between sub-basins follows the channel flow order from the upstream part to the downstream part of the basin.

Table 16. Albedo and canopy parameters in the Lower Smoky River Model (LSRM). Note LAI is leaf area index and (-) means parameter is dimensionless.

	Albedo Parameter		Canopy Parameter	
HRU Name	Albedo_bare ground (-)	Albedo_snow (-)	LAI (-)	Canopy Snow Interception Capacity (kg/m^2)
Exposed Land and Developed	0.152	0.85	0.1	0
Rock	0.152	0.85	0.1	0
Alpine Tundra	0.17	0.85	0.45	0
Cropland	0.18	0.85	0.1	0
Grassland	0.17	0.85	0.1	0
Coniferous Forest	0.091	0.85	3.1	6.3
Deciduous Forest	0.145	0.85	0.4	0.5
Mixed Forest	0.145	0.85	0.54	6.3
Regenerated Forest Clearcut	0.129	0.85	1.7	6.3
Fen	0.11	0.85	0.1	0
Wetland	0.11	0.85	0.1	0
Open Water	0	0.85	0.1	0
Small Channel	0	0.85	0.1	0
Main River Valley	0	0.85	0.1	0

Table 17. Soil parameters in the Lower Smoky River Model (LSRM). K_{s_gw}, K_{s_upper} and K_{s_lower} are the saturated hydraulic conductivity in the groundwater, upper and lower of soil layers, respectively. λ is the pore size distribution index. $soil_{rechr\_max}$, $soil_{moist\_max}$ and gw_{max} are the water storage capacity for the recharge, soil of both recharge and lower and groundwater layers, respectively. sd_{rechr_max} is the depressional storage capacity. Note (-) means parameter is dimensionless.

HRU Name	K_{s_gw} (m s^{-1})	K_{s_upper} (m s^{-1})	K_{s_lower} (m s^{-1})	λ (-)	$soil_{rechr\_max}$ (mm)	$soil_{moist\_max}$ (mm)	gw_{max} (mm)	sd_{max} (mm)
Exposed Land and Developed	1.28×10^{-6}	1.28×10^{-6}	1.28×10^{-6}	0.088	10	20	500	0
Rock	3.4×10^{-6}	7×10^{-3}	3.4×10^{-6}	2.55	10	20	0	0
Alpine Tundra	3.4×10^{-6}	7×10^{-3}	3.4×10^{-6}	2.55	50	100	500	0
Cropland	1.28×10^{-6} to 6.95×10^{-6}	1.28×10^{-6} to 6.95×10^{-6}	1.28×10^{-6} to 6.95×10^{-6}	0.088 to 0.186	98 to 135	380 to 578	500	67
Grassland	1.28×10^{-6}	1.28×10^{-6}	1.28×10^{-6}	0.088	117 to 135	397 to 578	500	97
Coniferous Forest	3.4×10^{-6}	2.5×10^{-4}	3.4×10^{-6}	0.096	72 to 93	311 to 487	500	86
Deciduous Forest	3.4×10^{-6}	2.5×10^{-4}	3.4×10^{-6}	0.096	87 to 91	389 to 410	500	86
Mixed Forest	3.4×10^{-6}	2.5×10^{-4}	3.4×10^{-6}	0.096	90 to 97	397 to 695	500	86
Regenerated Forest Clearcut	3.4×10^{-6}	2.5×10^{-4}	3.4×10^{-6}	0.096	91 to 97	398 to 695	500	86
Fen	1.28×10^{-6}	4.2×10^{-3}	1.28×10^{-6}	0.088	128	438	500	500
Wetland	1.28×10^{-6}	1.28×10^{-6}	1.28×10^{-6}	0.088	N/A	N/A	500	500
Open Water	1.28×10^{-6}	1.28×10^{-6}	1.28×10^{-6}	0.088	N/A	N/A	500	500
Small Channel	1.28×10^{-6}	1.28×10^{-6}	1.28×10^{-6}	0.088	N/A	N/A	500	0
Main River Valley	1.28×10^{-6}	1.28×10^{-6}	1.28×10^{-6}	0.088	N/A	N/A	500	0

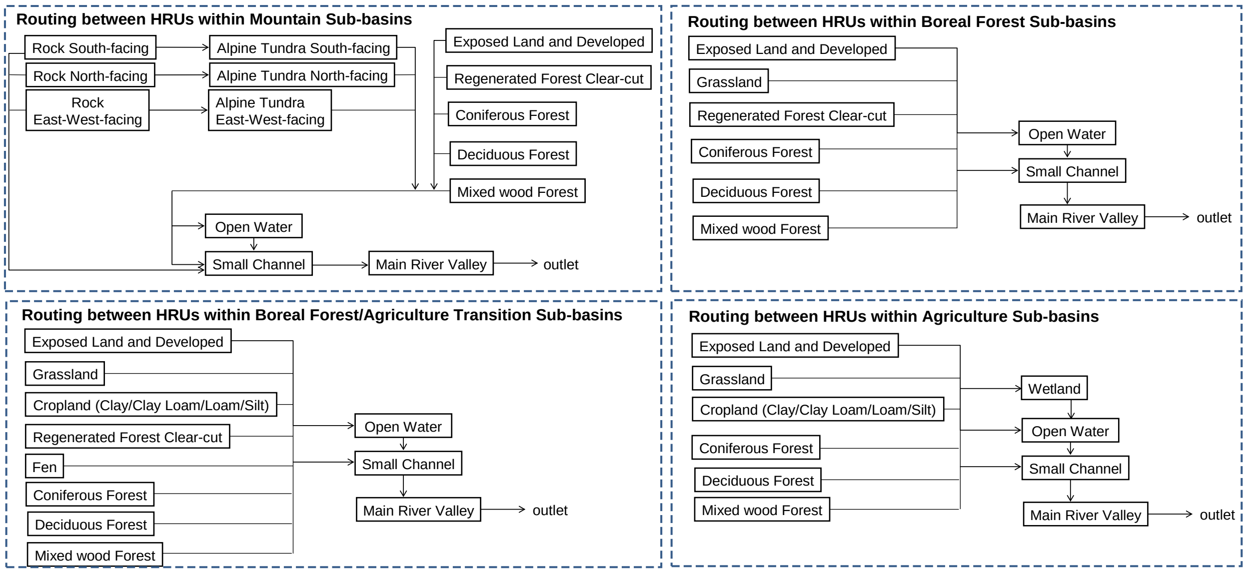


Figure 21. Routing sequence between HRUs within the modelled sub-basins in the Smoky River Basin.

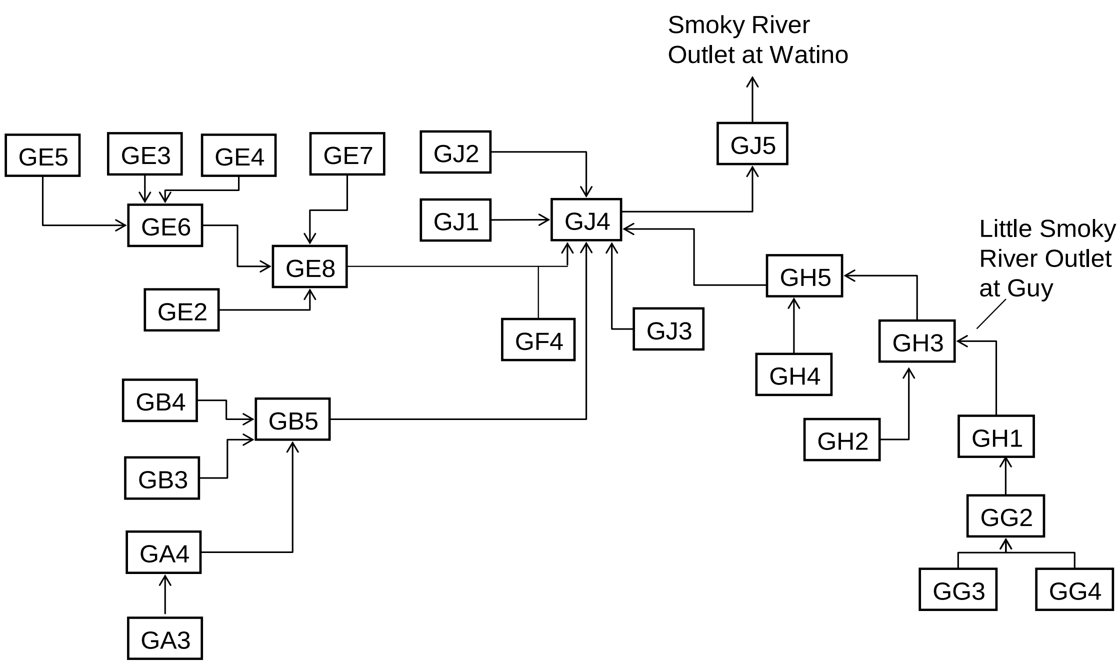


Figure 22. Routing sequence between the modelled sub-basins in the Smoky River Basin.

The Muskingum routing method was used and flow travel times were calculated from the routing length and average flow velocity. For routing between HRUs within sub-basins, the routing lengths for the non-channel HRUs: ‘exposed land and developed’, ‘rock’, ‘alpine tundra’, ‘cropland’, ‘grassland’, ‘forest’, ‘fen’, ‘wetland’ and ‘open water’ were calculated using a modified Hack’s law length-area relationship (Fang et al., 2010). The length-area relationship was derived from the CRHM-Prairie Hydrological Model modeling study conducted in the Smith Creek Research Basin (Pomeroy et al., 2010) and it is believed that it can be widely applied in the northern Prairies due to its fractal nature and common agricultural patterns in the parkland region. Routing lengths for the ‘main river valley’ HRU were determined from the channel length in Alberta drainage network GIS dataset; routing lengths for the ‘small channel’ HRU were calculated based on the difference between the channel length of TOPAZ stream network and Alberta drainage network datasets. Routing lengths between the sub-basins was determined from the channel length in Alberta drainage network GIS dataset.

Manning’s equation (Chow, 1959) was used to estimate the average streamflow velocity, which requires longitudinal channel slope, Manning’s roughness coefficient, and hydraulic radius as parameters. The longitudinal channel slope of a HRU or a sub-basin was estimated from the average slope of the HRU or sub-basin. Average slope was derived from the terrain pre-processing GIS using the 25-m Smoky River DEM (i.e. ffhc_dem1). Manning’s roughness coefficient was assigned based on surface cover and channel condition using a Manning’s roughness lookup table (Mays, 2001) and information gleaned from a site visit in October 2012 to many channel cross-sections. The hydraulic radius was determined from the lookup table using channel shape and channel depth as criteria. Shape was also determined from site visits and was set as rectangular for the ‘main river valley’ HRU and parabolic for the rest of HRUs. For routing between sub-basins, channel shape was set as rectangular. The dimensionless weighting factor controls the level of attenuation, ranging from 0 (maximum attenuation) to 0.5 (no attenuation); a medium value of 0.25 was assigned.

4.3 Model Tests for Sub-basins

Daily discharge data were obtained for four “non-real-time” gauges: 07GE003, 07GE007, 07GG002, 07GG003 from AESRD. The discharge data from these “non-real-time” gauges were used to evaluate the LSRM discharge prediction for their corresponding sub-basins: Grande Prairie Creek near Sexsmith (GE7), Bear River near Valhalla Centre (GE3), Little Smoky River at Little Smoky (GG3) and Iosegun River near Little Smoky (GG4) respectively (Table 18). GE3 and GE7 are agricultural sub-basins and GG3 and GG4 are boreal-agricultural transition basins by ecoregion type. This model evaluation at a smaller basin scale provides diagnostic information that can be useful for model parameter identification at the larger basin scale.

Both the Beaverlodge and the Hendrickson Creek weather stations that provide forcing meteorological data for the model had substantial missing precipitation data in the late winter and spring of 2007. As a result model simulations of streamflow discharge are greatly exceeded by gauged flows and there is no correction possible to account for the missing precipitation. As a result the hydrological year (1 Oct to 30 Sept) 2006-2007 was excluded from the sub-basin analysis as the missing precipitation makes it impossible to run any hydrological model for that year with sufficient confidence. Simulations were conducted using the Lower Smoky River Model (LSRM) for the period from 1 October 2001 to 30

September 2010. Daily streamflow discharge was estimated for four Smoky River sub-basins and compared to the daily observed discharges from the corresponding Water Survey of Canada gauge stations shown in Table 18.

Table 18. Lower Smoky River Model (LSRM) evaluation at Smoky River sub-basins compared to the Water Survey of Canada gauge stations.

Station Name	Station ID	Sub-basin
Grande Prairie Creek near Sexsmith	07GE003	GE7
Bear River near Valhalla Centre	07GE007	GE3
Little Smoky River at Little Smoky	07GG002	GG3
Iosegun River near Little Smoky	07GG003	GG4

The initial model simulation of daily discharges was compared to observed daily discharges in Figure 23. These initial simulations are without any model calibration, and the simulated hydrographs are quite flashy. Figure 23 shows that the simulated hydrographs for agriculture sub-basins GE3 and GE7 have large spikes after the peak spring snowmelt runoff, and the simulated hydrographs have large spikes prior to the peak spring snowmelt runoff for the boreal/agriculture transition sub-basins GG3 and GG4. The simulated peak spring discharges for all sub-basins are higher than the observed ones. To address these problems, the following revisions to model parameters were made, in some cases they are parameter revisions made with new information to improve the realism of the model, in other cases they are simple calibrations to improve simulation of streamflow:

1) The fall soil saturation “fallstat” parameter in the infiltration module, was changed from an initial value of 37% to 5% for the cropland and grassland HRUs; this change is to address the formation of large surface cracks in the area since cultivation of heavy clay soils (Pawluk and Dudas, 1978; Darwent and Bailey, 1981), which results in a greater proportion of soils in the unlimited infiltrability status and hence an increase in infiltration (Pomeroy et al., 1990). This change was made to improve model realism.

2) The saturated hydraulic conductivity in the upper soil layer “K_{s_upper}” parameter was changed from initial values of 2.5×10^{-4} and 4.2×10^{-3} m s^{-1} for forest and fen HRUs to 3.4×10^{-6} and 1.28×10^{-6} m s^{-1}, which are same as the values for saturated hydraulic conductivity in the lower soil layer “K_{s_lower}” as there was no evidence of higher conductivities in the upper layers. This change was made to improve model performance.

3) The subsurface travel time “ssrKstorage” parameter in the routing module was set to 12 days for the cropland, grassland, and forest HRUs in the agriculture sub-basins reflecting the low velocity of interflow in mineral soils. This change was made to improve model performance.

4) The canopy snow interception capacity “Sbar” parameter in the canopy module was changed from initial values of 6.3, 0.5, 6.3, and 6.3 kg m^{-2} to 5.8, 0.1, 2.1, and 1.1 kg m^{-2} for the coniferous, deciduous, mixed, and regenerated forest HRUs, respectively. The initial values were measured in the northern boreal forest in Saskatchewan, a relatively calm environment. For the windy environment in the Smoky

River Basin, forest interception efficiency is lower, thus the initial values were reduced. This change was made to improve model realism.

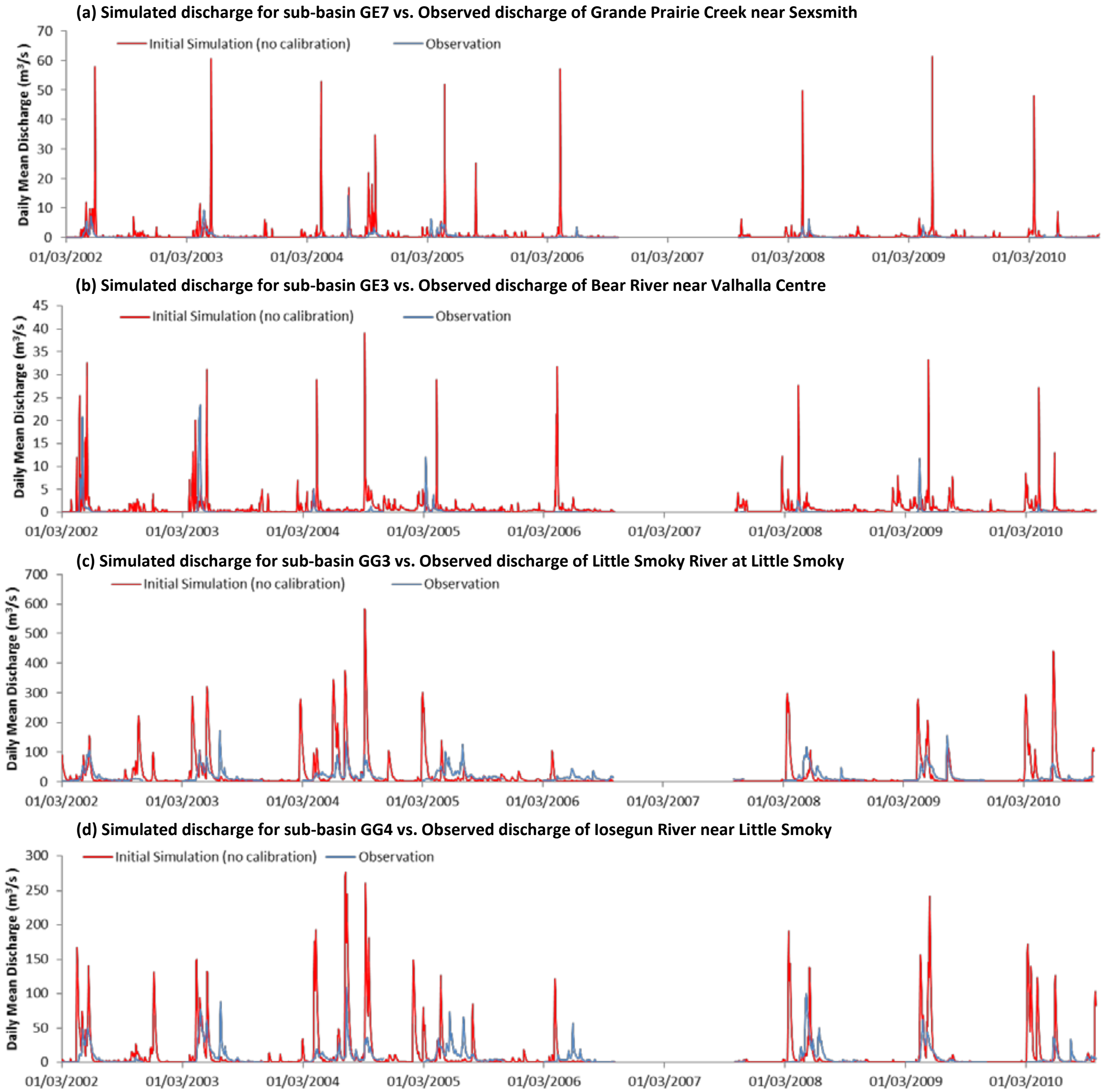


Figure 23. Initial simulations and observations of daily streamflow discharge from 1 March 2002 to 30 September 2010 for sub-basins: (a) GE7, (b) GE3, (c) GG3, and (d) GG4.

Model simulations with the revised parameters were conducted and compared to the observations (Figure 24). As a result of reduced saturated hydraulic conductivity in the upper soil layer for the forest HRUs, large spikes after the peak spring snowmelt runoff for agriculture sub-basins GE3 and GE7 shown in the initial simulation (Fig. 23) are substantially reduced or eliminated in Fig. 24. Similarly, for boreal/agriculture sub-basins GG3 and GG4, the revised simulations reduced large spikes prior to the peak spring snowmelt runoff. In addition, the magnitude and timing of peak discharge from the revised simulations are much closer to that of the observations as a result of reduced saturated hydraulic conductivity, snow interception capacity, and lagged subsurface flow.

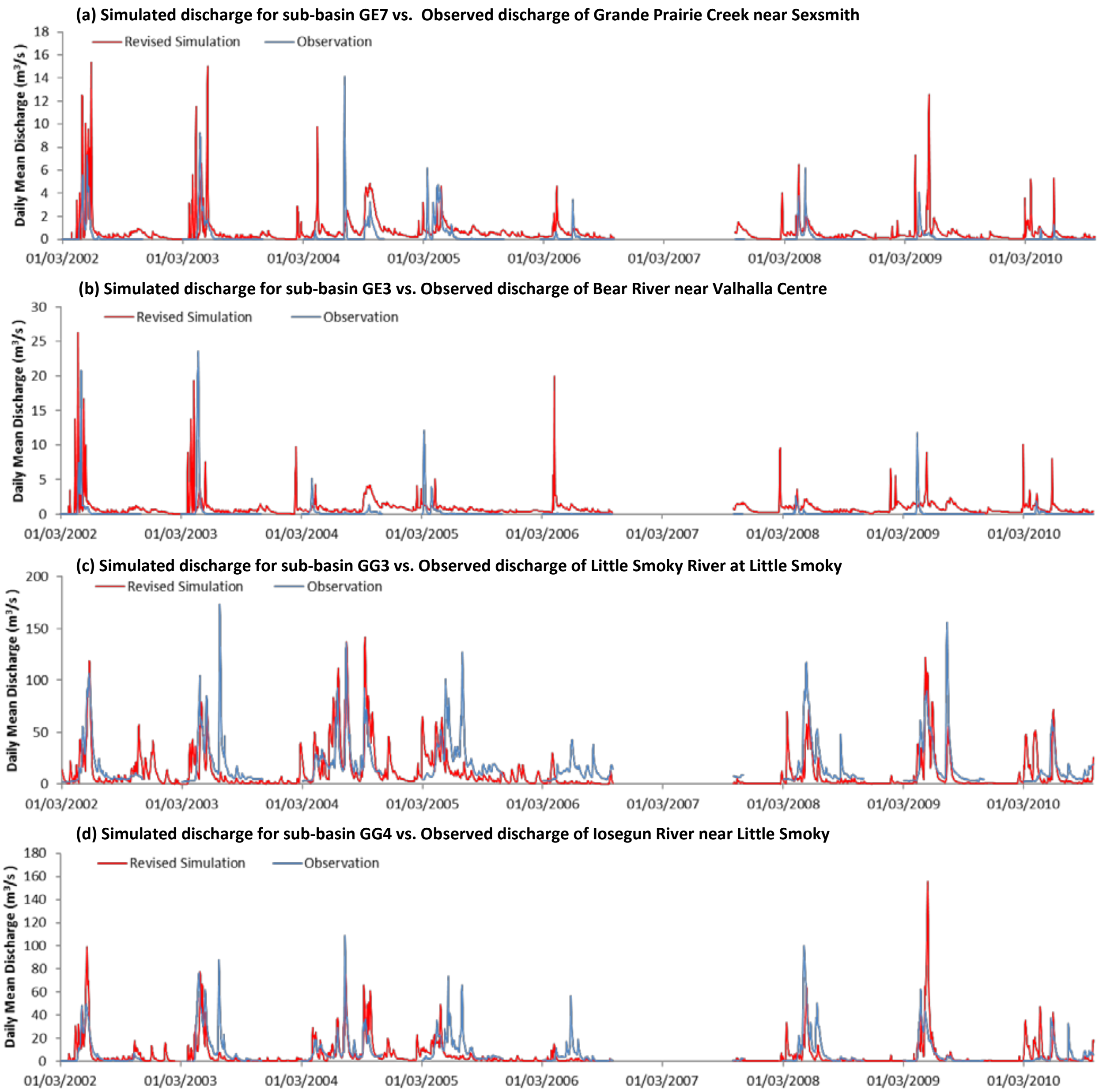


Figure 24. Revised simulations and observations of daily streamflow discharge from 1 March 2002 to 30 September 2010 for sub-basins: (a) GE7, (b) GE3, (c) GG3, and (d) GG4.

4.4 Model Tests at the Basin Scale

CRHM was used to estimate streamflow for the 26 sub-basins in the Smoky River Basin that do not have real-time hydrometric stations. For this evaluation all years of available data were used, including 2006-2007. In order to evaluate the modelled discharge against gauged discharge at the scale of the Smoky River and Little Smoky River basins, two comparisons were used for both the Smoky River and Little Smoky River, i) comparison of modelled ungauged local inflow contributions to discharge to estimates derived from gauged flow subtraction, and ii) comparison of modelled discharge to gauged discharge.

Comparison of ungauged flows

In the first comparison, the real-time gauged discharge of the upstream sub-basins was subtracted from gauged discharge at the Smoky River at Watino and Little Smoky River at Guy. For the Smoky River Basin, discharge from 7 upper basin "real-time" gauges: 07GA001, 07GA002, 07GB001, 07GB003, 07GE001, 07GF001 and 07GG001 were first shifted-forward based on their SSARR-routed travel time to Watino then subtracted from the gauged discharge of the Smoky River at Watino (07GJ001). This provides an estimate of the "local inflow" discharge which can be used to evaluate the LSRM discharge prediction for the Smoky River modelled sub-basins at Watino. The estimated "local inflow" discharge of Smoky River at Watino was calculated as follows:

$$Q_{SmokyRiver\_local} = Q_{07GJ001} - Q_{07GA001\_shifted} - Q_{07GA002\_shifted} - Q_{07GB001\_shifted} - Q_{07GB003\_shifted} - Q_{07GE001\_shifted} - Q_{07GF001\_shifted} - Q_{07GG001\_shifted}$$

where: $Q_{SmokyRiver\_local}$ is the estimated "local" discharge of Smoky River at Watino, $Q_{07GJ001}$ is the observed discharge of Smoky River at Watino at gauge 07GJ001, $Q_{07GA001\_shifted}$ is the shifted gauged discharge at gauge 07GA001, $Q_{07GA002\_shifted}$ is the shifted gauged discharge at gauge 07GA002, $Q_{07GB001\_shifted}$ is the shifted gauged discharge at gauge 07GB001, $Q_{07GB003\_shifted}$ is the shifted gauged discharge at gauge 07GB003, $Q_{07GE001\_shifted}$ is the shifted gauged discharge at gauge 07GE001, $Q_{07GF001\_shifted}$ is the shifted gauged discharge at gauge 07GF001, $Q_{07GG001\_shifted}$ is the shifted gauged discharge at gauge 07GG001.

Similarly, for the Little Smoky River system, gauged discharge from upstream "real-time" gauge 07GG001 was first shifted forward based on its SSARR-routed travel time to Guy, then subtracted from the gauged discharge of Little Smoky River near Guy (07GH002). This provides the estimated "local" discharge used to evaluate the LSRM modelled local inflow discharge from the modelled Little Smoky River sub-basins upstream of Guy. The estimated "local inflow" discharge of Little Smoky River near Guy was calculated as follows:

$$Q_{LittleSmokyRiver\_local} = Q_{07GH002} - Q_{07GG001\_shifted}$$

where: $Q_{LittleSmokyRiver\_local}$ is the estimated "local inflow" discharge of Little Smoky River near Guy, $Q_{07GG001\_shifted}$ is the shifted gauged discharge at gauge 07GG001.

The revised LSRM was used to simulate the spring snowmelt for the Smoky River at Watino and Little Smoky River near Guy for the period from 1 October 2001 to 30 September 2010. Comparisons of the simulated daily local inflow discharge and estimated daily local inflow discharge of Smoky River at Watino and Little Smoky River near Guy during 4 March 2002 - 30 September 2010 are shown in Figure 25. The modelled local inflow streamflow for Little Smoky River and Smoky River generally match the pattern of the estimated local streamflow in the period, with a Nash-Sutcliffe coefficient of 0.22 and 0.04 for the Little Smoky and Smoky River ungauged flows respectively showing moderate predictive capability. However, there are large differences between the simulated and estimated ungauged streamflow in 2007 for both rivers and 2009 for the Smoky River. The underestimation of spring local inflow discharge in 2007 is due to missing precipitation observations, while the underestimation of local inflow discharge for the Smoky River in 2009 occurred in July, which was result of rainfall runoff from a storm in the upper basin that was not measured in any precipitation gauge due to the sparse precipitation measurements in the upper basin.

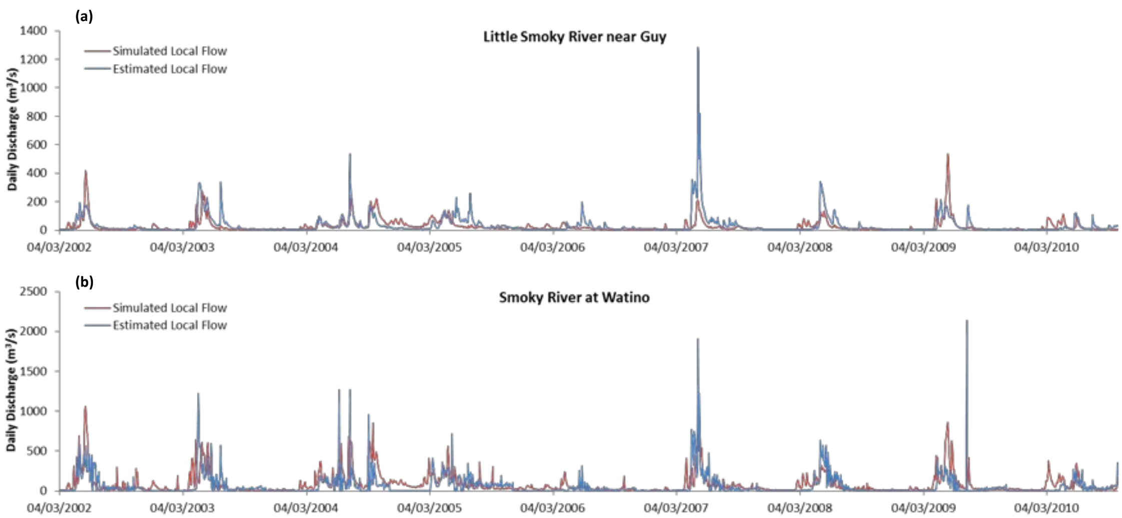


Figure 25. Simulations (CRHM LSRM) and estimates from routed gauged flows of daily contributions of local ungauged inflows to streamflow discharge from 4 March 2002 to 30 September 2010 for: (a) Little Smoky River near Guy and (b) Smoky River at Watino.

Comparison of gauged discharge

While comparisons of modelled local inflows and estimated ungauged flows are instructive, the real operation of the LSRM by AESRD will be to supplement routed gauged flows with modelled ungauged flows. To evaluate LSRM for this purpose, in the second comparison, local inflows simulated by LSRM were added to the shifted (based on SSARR routing) gauged upstream flows and compared to the gauged flows on the Little Smoky River at Guy and the Smoky River at Watino in Fig. 26. Inclusion of the upstream gauged flows greatly reduces the underprediction of largely unmeasured precipitation events in spring 2007 and summer 2009. The Nash-Sutcliffe coefficient was calculated for these simulations and is 0.41 and 0.87 for Little Smoky River and Smoky River, respectively, which suggests strong predictive capability.

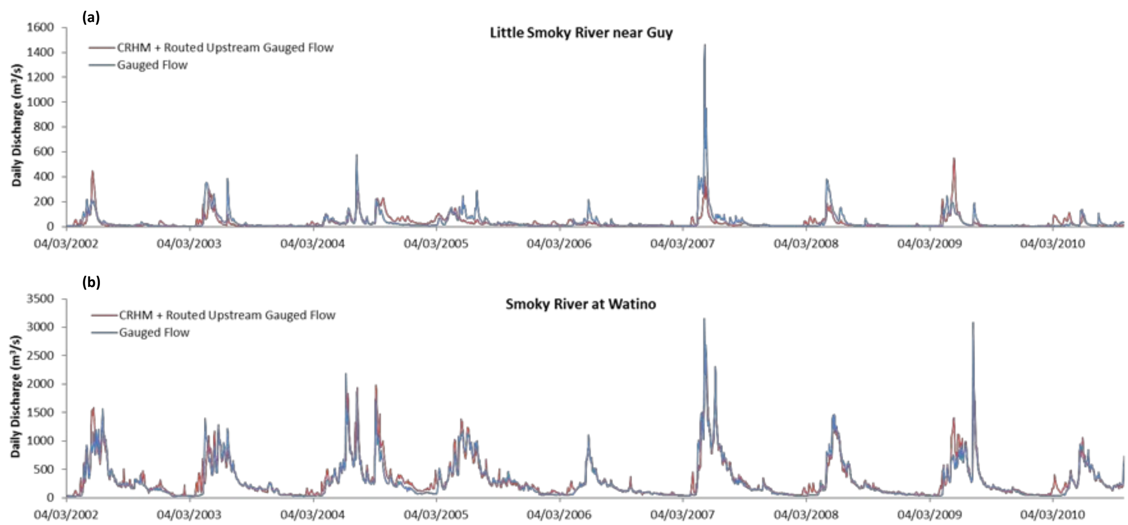


Figure 26. Comparisons of CRHM (LSRM) simulated plus routed real-time upstream gauged streamflows and gauged daily streamflows from 4 March 2002 to 30 September 2010 for: (a) Little Smoky River near Guy and (b) Smoky River at Watino.

To examine the model simulations of spring snowmelt runoff in more detail, comparisons between the model simulations plus routed upstream gauged flows to Watino and Guy gauged flows focused on the period from 15 March to 31 May of each year. Figures 27 and 28 compare the model simulations plus routed upstream gauged flows to the gauged flows at the Little Smoky River near Guy and the Smoky River at Watino, respectively.

In spring 2002, as shown in Figures 27(a) and 28(a), snowmelt runoff discharge was underestimated for the Little Smoky River before 6 May and overestimated after 17 May; it well simulated for the Smoky River before 17 May and then overestimated after this date. The large unmeasured discharge peak predicted for both the Little Smoky River and Smoky River in late May was caused by rainfall rather than local snowmelt runoff.

In spring 2003, as shown in Figures 27(b) and 28(b), the simulations missed the observed peak discharge in late middle April for the Little Smoky River and Smoky River, but snowmelt runoff discharge was fairly well predicted from late April onwards.

In spring 2004, as shown in Figures 27(c) and 28(c), simulations matched gauged flows very well for the Little Smoky River. For the Smoky River the mid-April predicted discharge was higher than observed. The predictions improved substantially after 20 April.

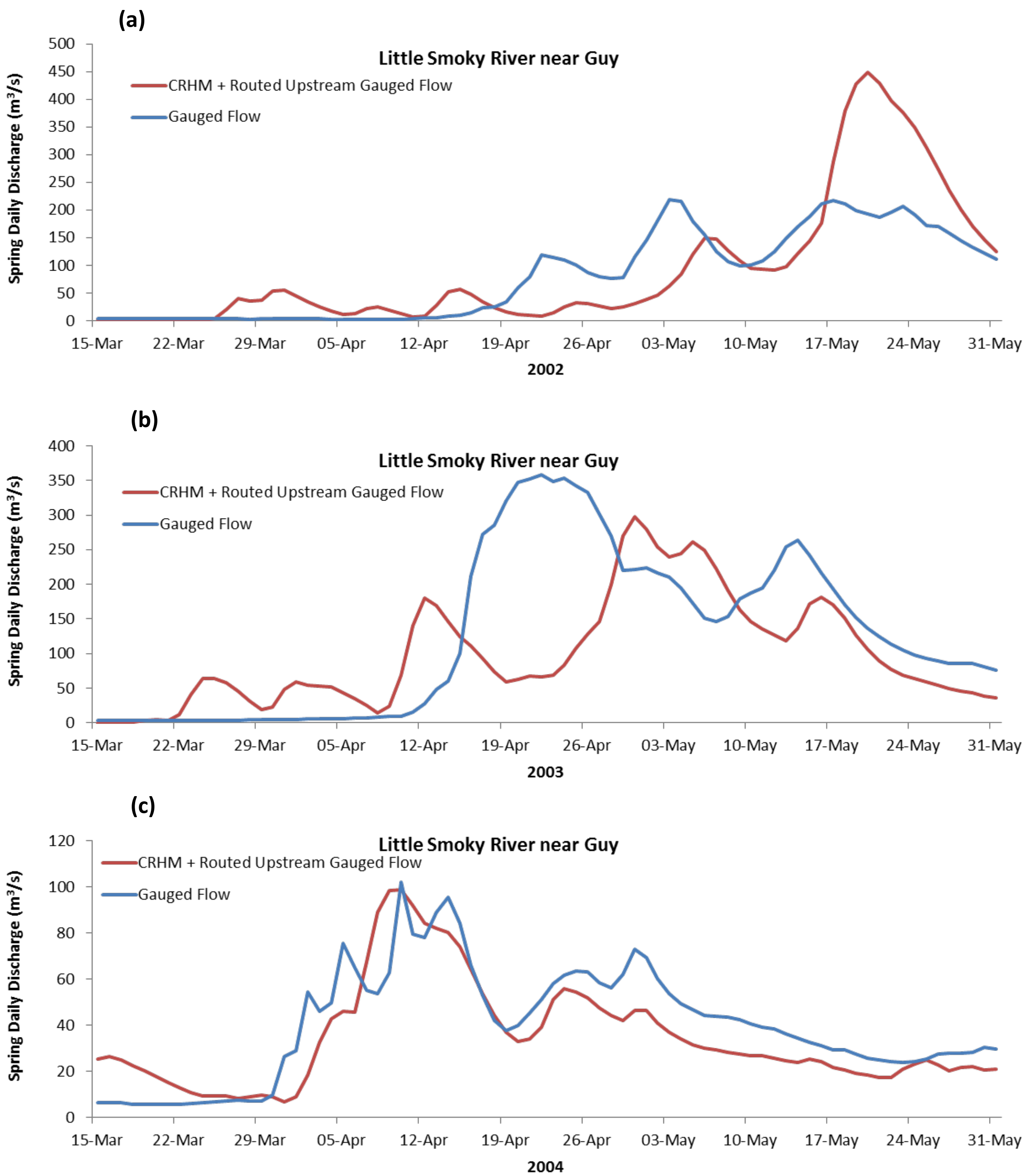


Figure 27. CRHM simulated plus real-time upstream gauged streamflow and gauged daily spring snowmelt runoff discharge of Little Smoky River near Guy from 15 March to 31 May: (a) 2002, (b) 2003, (c) 2004, (d) 2005, (e) 2006, (f) 2007, (g) 2008, (h) 2009, and (i) 2010.

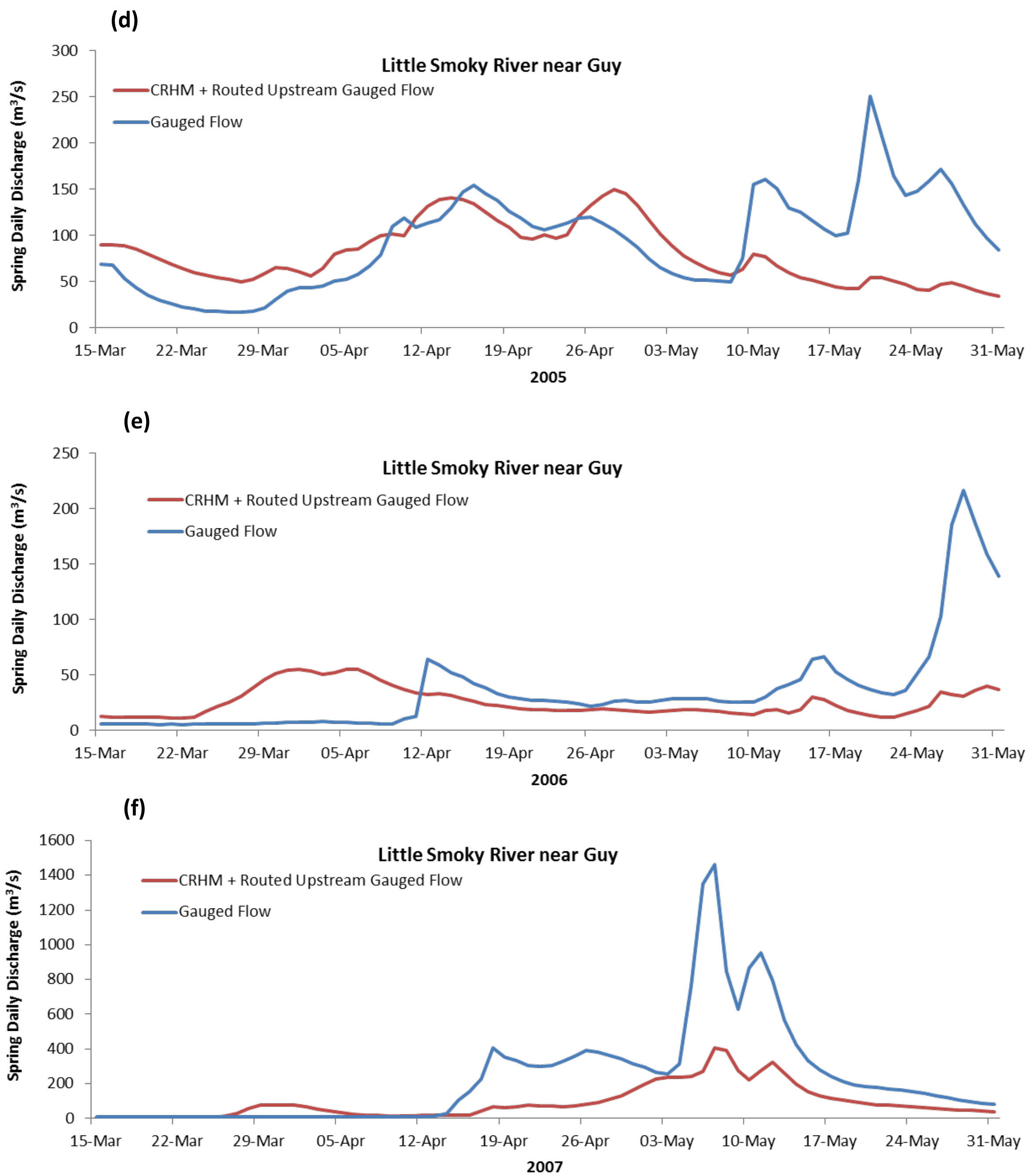
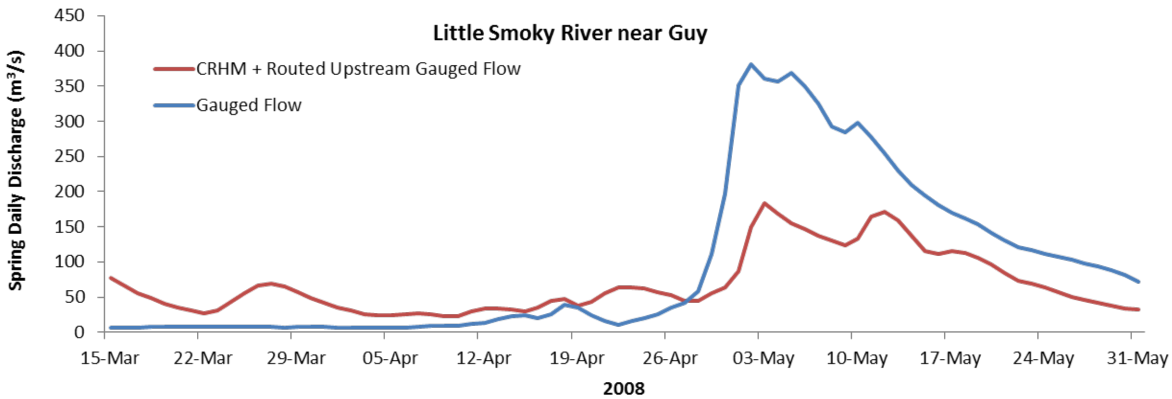
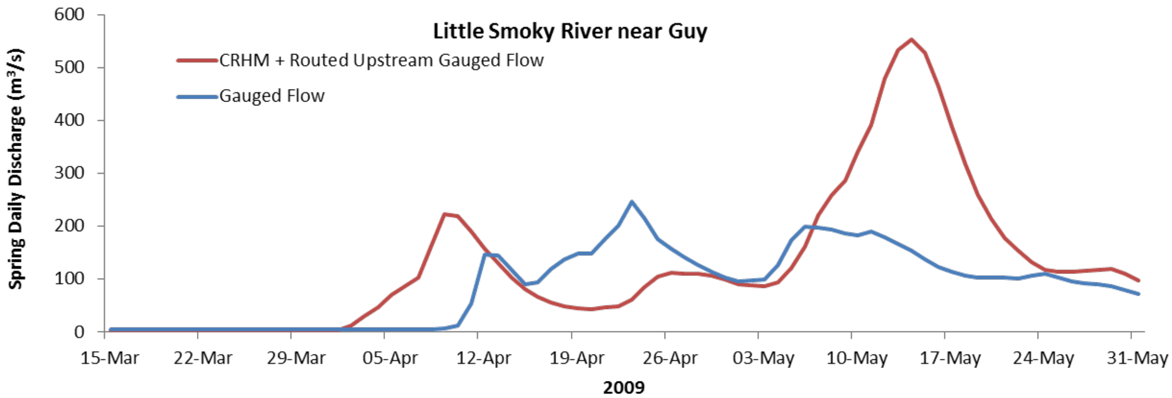


Figure 27. *Continued*.

(g)



(h)



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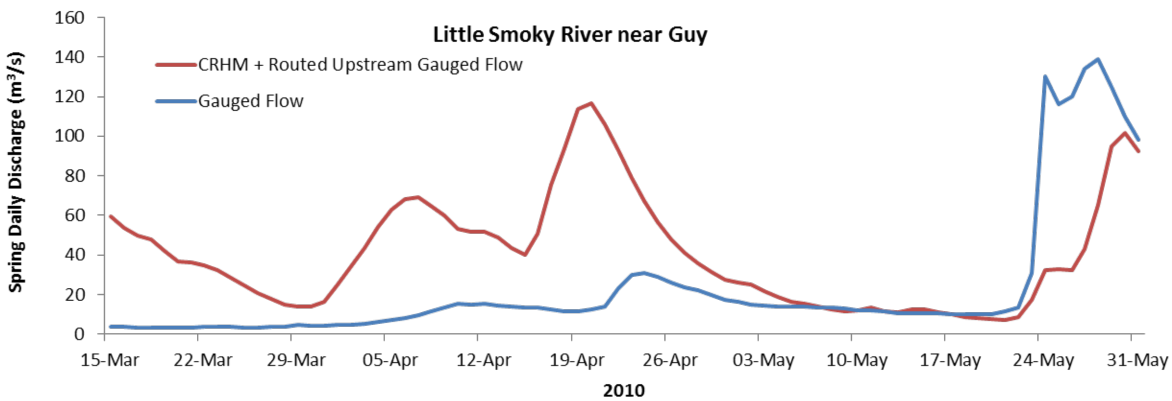

Figure 27. *Concluded*.

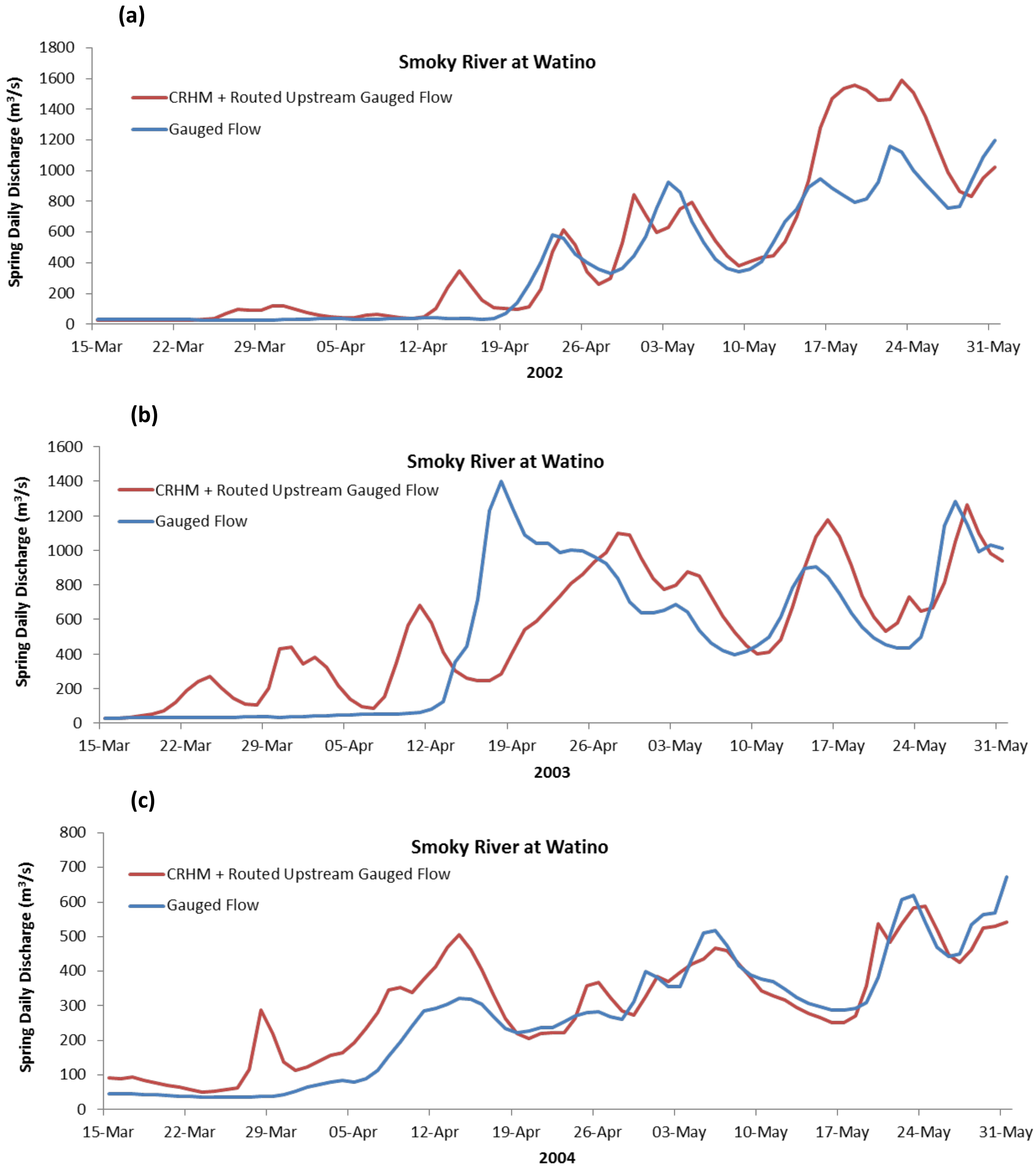

Figure 28. CRHM simulated plus real-time upstream gauged streamflow and gauged daily spring snowmelt runoff discharge of Smoky River at Watino from 15 March to 31 May: (a) 2002, (b) 2003, (c) 2004, (d) 2005, (e) 2006, (f) 2007, (g) 2008, (h) 2009, and (i) 2010.

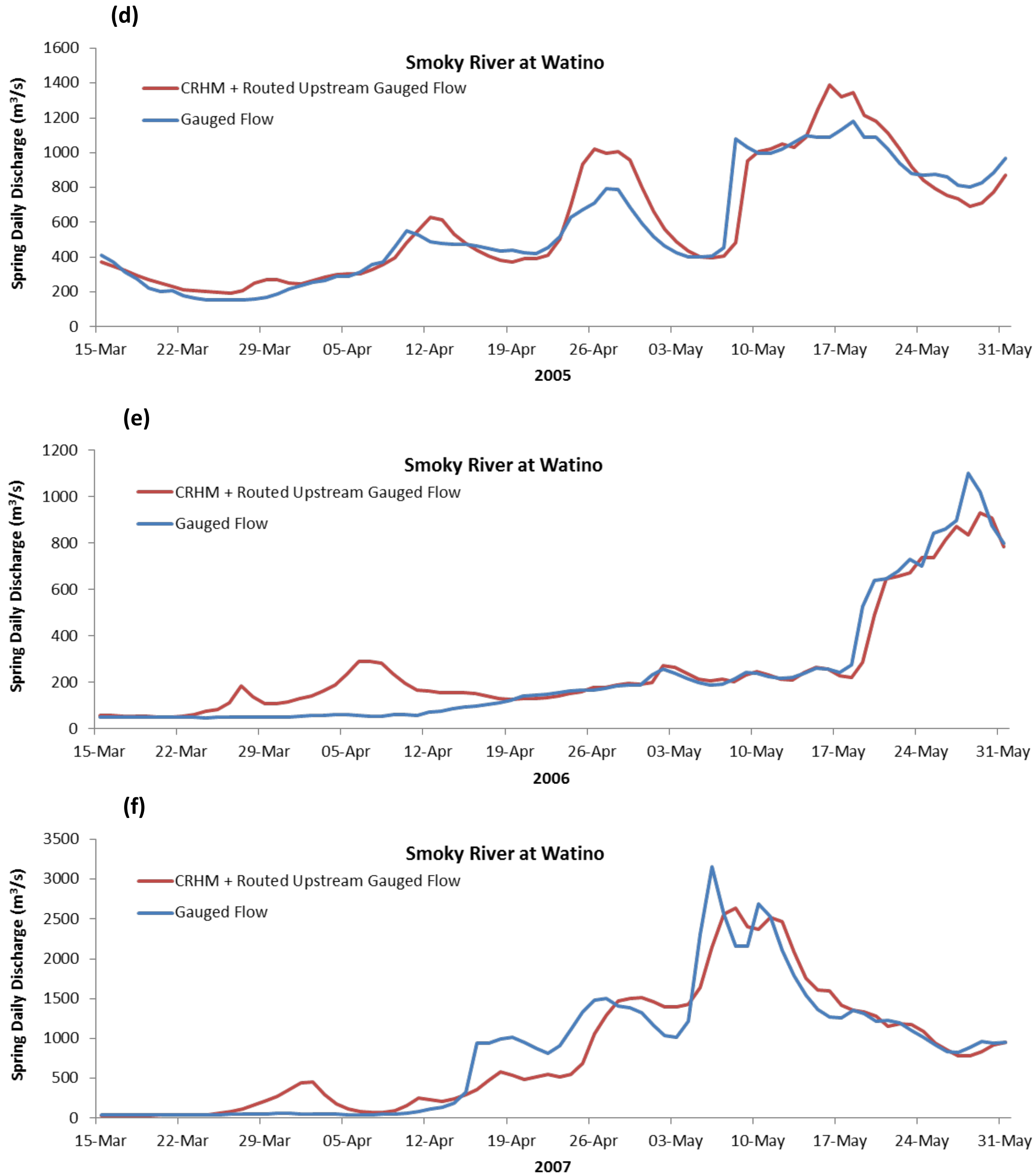

Figure 28. *Continued*.

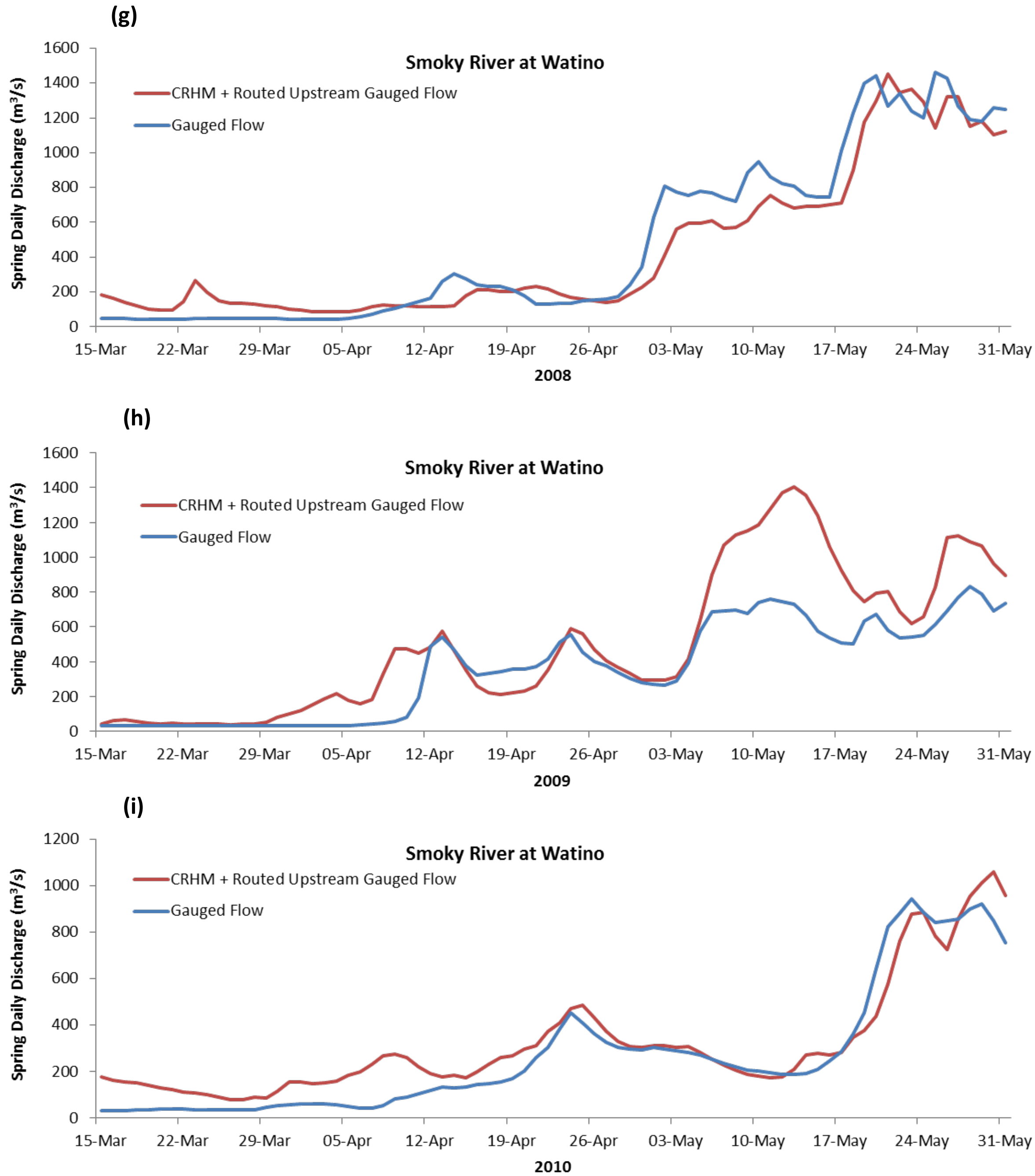

Figure 28. *Concluded*.

In spring 2005, as shown in Figures 27(d) and 28(d), simulations for the Little Smoky River were generally good before 10 May, with substantial underestimation of flows after that, possibly due to unmeasured rainfall. For the Smoky River, the first peak flow around 27 April was underestimated and then flows were well simulated after that.

In spring 2006, as shown in Figures 27(e) and 28(e), simulations match gauge flows reasonably well until a peak in late May which was severely underestimated for the Little Smoky River but well estimated for the Smoky River. The underestimated peak flow on the Little Smoky River was likely due to unmeasured rainfall.

In spring 2007, as shown in Figures 27(f) and 28(f), the simulation of the peak flow event on 5 May on the Little Smoky River was severely underestimated – this may have been influenced by missing precipitation data for that spring at several stations. The hydrograph of the Smoky River was very well estimated. 2007 is the high flow year of record in the period of simulation and evaluation. The good performance of the LSRM in a flood year suggests that the model might also do well in future flood years, even when input data quality is less than satisfactory.

In spring 2008, as shown in Figures 27(g) and 28(g), the general discharge pattern was well simulated, but with an underpredicted peak flow magnitude for the Little Smoky River. Predictions of discharge pattern and peak flow were very good for the Smoky River.

In spring 2009, as shown in Figures 27(h) and 28(h), simulations for both Little Smoky River and Smoky River were fair to good before early May. For both rivers the prediction of a large peak discharge in mid-May did not occur and the reasons for this are not understood at this time.

In spring 2010, as shown in Figures 27(i) and 28(i), the discharge of the Little Smoky River was overestimated before 10 May and underestimated after 24 May, whereas the discharge of the Smoky River was well simulated for both rivers. This was a very low flow year, so absolute differences between modelled and gauged discharge are small.

The predicted seasonal spring discharge (LSRM plus routed upstream gauged flows) from 15 March to 31 May was compared to the gauged flows for both rivers for nine springs (2002-2010) and is shown in Figure 29. Table 19 lists the model bias (MB) to evaluate the estimated cumulative spring discharge. For the Little Smoky River, the MB ranged from -0.60 in 2007 to 0.76 in 2010, indicating the cumulative spring discharge ranged from 60% underestimation to 76% overestimation with an average seasonal underestimation of 3%. Cumulative spring flows were underestimated by 18.5% over the nine springs. For the Smoky River, the MB ranged from -0.07 in 2008 to 0.41 in 2009, indicating the cumulative spring discharge ranged from a 7% underestimation to a 41% overestimation with an average seasonal overestimation of 12%. Cumulative spring flows were overestimated by 9.7% over the nine springs. These statistics, when evaluated along with the Nash-Sutcliffe coefficient for the Little Smoky River and Smoky River of 0.41 and 0.87, suggest good model performance in hydrograph prediction and in estimating the water balance, with model performance improving with increasing basin size and distance downstream. This is partly due to the contribution of the routed gauged flows to the modelled flows and partly due to the effect of increasing basin size on masking unmeasured and missing precipitation data.

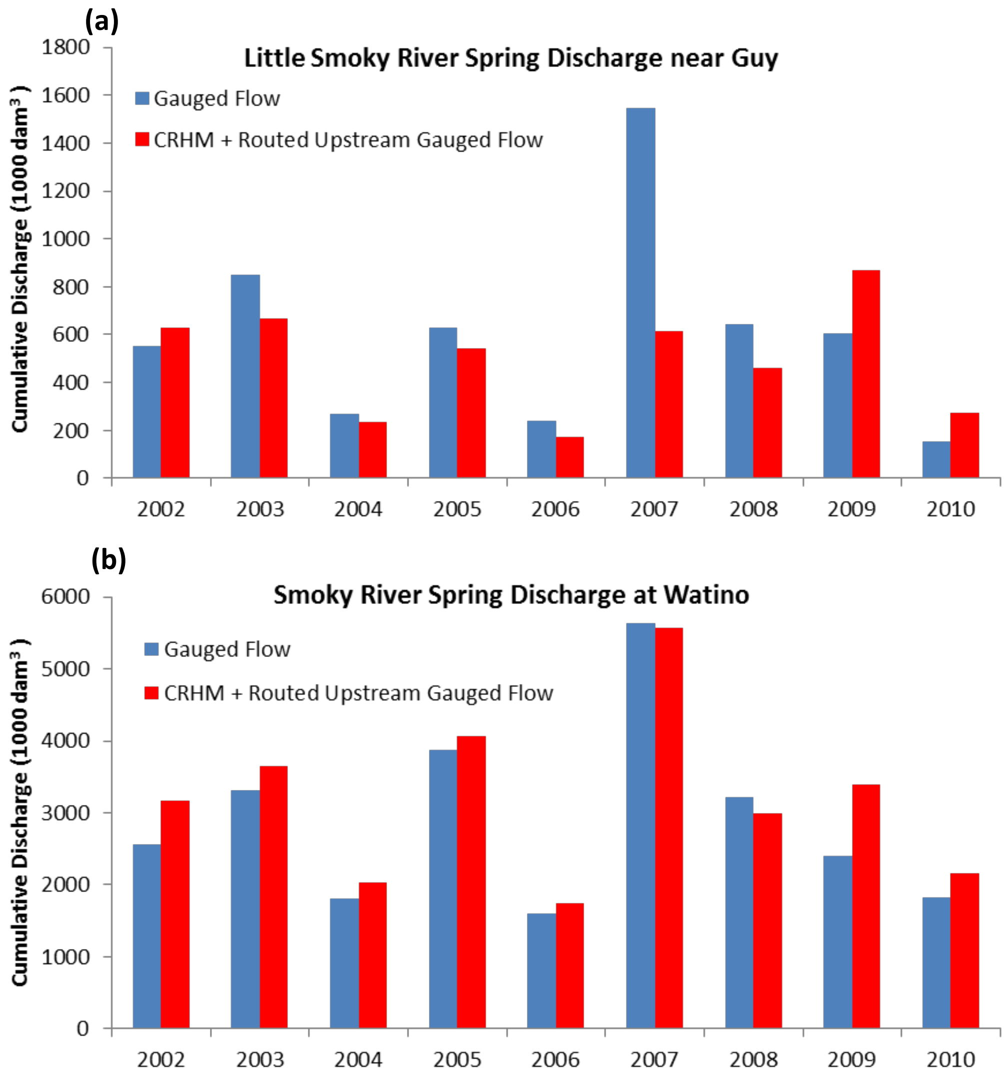

Figure 29. Comparisons of CRHM simulated plus real-time upstream gauged streamflow and observed gauged cumulative spring discharge from during 15 March-31 May in nine springs from 2002 to 2010 for: (a) Little Smoky River near Guy and (b) Smoky River at Watino.

Table 19. Evaluation of simulated cumulative spring snowmelt runoff discharge (1000 dam3) for Little Smoky River and Smoky River with model bias (MB).

	Cumulative Discharge (1000 dam^3)					
Year	Little Smoky River		Smoky River		Model Bias	
	Gauged Flow	CRHM + Routed Upstream Gauged Flow	Gauged Flow	CRHM + Routed Upstream Gauged Flow	Little Smoky River	Smoky River
2002	549.89	628.34	2552.24	3175.25	0.14	0.24
2003	849.67	669.16	3313.32	3654.80	-0.21	0.10
2004	267.48	233.60	1801.75	2025.97	-0.13	0.12
2005	627.14	540.13	3870.12	4064.48	-0.14	0.05
2006	240.17	172.96	1601.16	1746.08	-0.28	0.09
2007	1544.89	613.59	5632.63	5567.63	-0.60	-0.01
2008	642.48	462.36	3209.51	2984.52	-0.28	-0.07
2009	603.32	870.91	2399.75	3385.58	0.44	0.41
2010	155.03	272.93	1827.10	2157.14	0.76	0.18
Mean	608.90	496.00	2911.95	3195.72	-0.03	0.12

The daily peak spring snowmelt runoff discharge from 15 March to 31 May was modelled using LSRM and routed gauged flows and compared to gauged flows for both the Little Smoky River and Smoky River for nine springs (2002-2010) (Figure 30). Apart from a substantial underprediction of peak daily discharge in 2007 and overprediction in 2010 on the Little Smoky River, the results are encouraging. Table 20 shows the model bias (MB) to assess the predicted peak daily spring discharge. For the Little Smoky River, MB ranged from -0.72 in 2007 to 2.73 in 2010, indicating peak discharge ranged from an underestimation of 72% to an overestimation of 273% with a mean seasonal overestimation of 8%. For the Smoky River, the MB ranged from -0.22 in 2003 to 0.13 in 2006, indicating the peak spring discharge ranged from a 22% underestimation to a 13% overestimation with a mean seasonal underestimation of 6%. Table 20 also provides the predictability of the timing of peak spring discharge for both Little Smoky River and Smoky River. The timing of peak discharge for the Little Smoky River ranged from 14 days before the observed peak in 2009 to 12 days after the observed peak in 2005; while on average over the nine simulation years (2002-2010), the timing of peak discharge was identical between model and observation; 23 April. For the Smoky River, the timing of peak discharge ranged from 26 days before the observed peak in 2006 to 10 days after the observed peak in 2003; on average over the eight simulation years the timing of peak discharge was predicted 3 days before the observation. Although there was large difference in magnitude and timing of peak discharge between the simulation and observation in 2006 for Smoky River, the spring 2006 was not a high flow year in terms of cumulative and peak spring snowmelt runoff. Of note is that the model predicted the timing of peak discharge to the day for the Little Smoky River and only two days late for the Smoky River in 2007, which is the high flow of record for the period of evaluation.

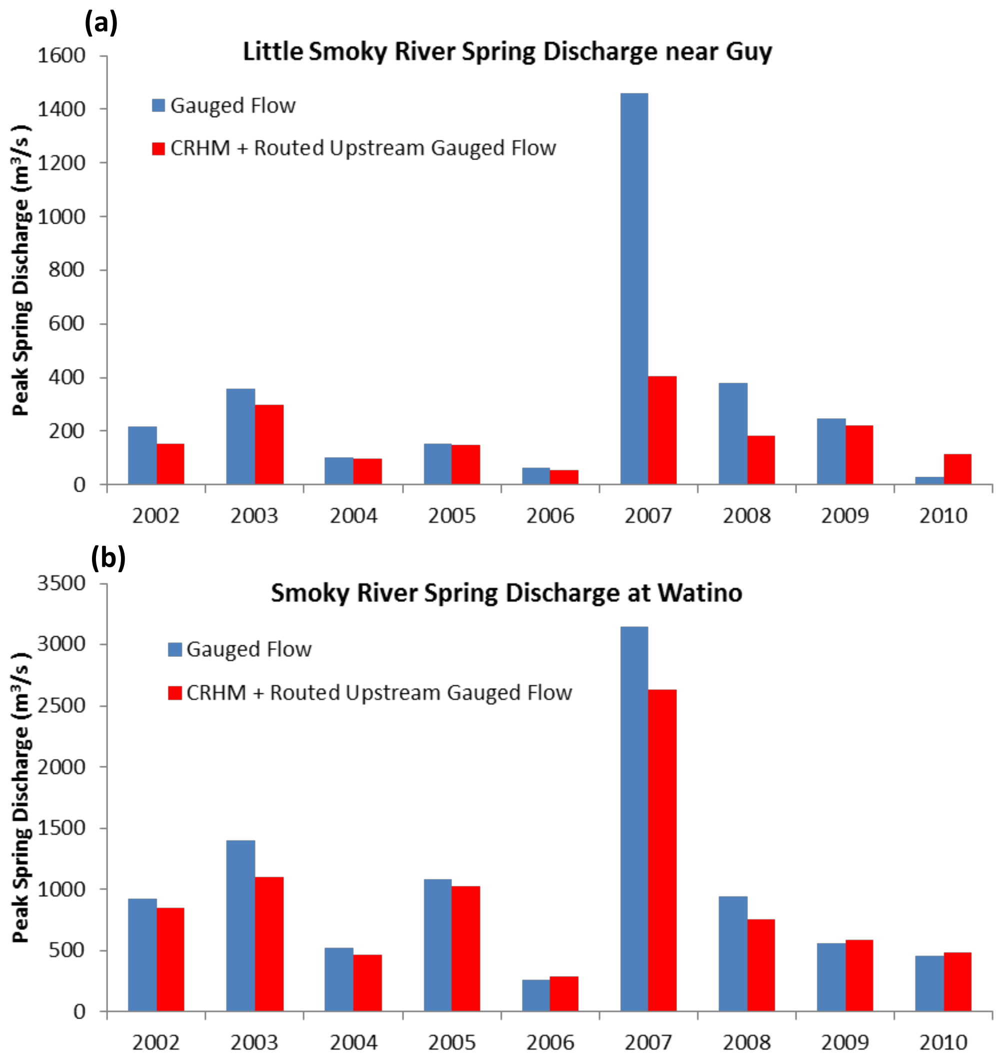

Figure 30. Comparisons of CRHM (LSRM) simulated plus routed real-time upstream gauged streamflow and gauged peak spring discharge from 15 March to 31 May over nine springs from 2002 to 2010 for: (a) Little Smoky River near Guy and (b) Smoky River at Watino.

Table 20. Evaluation of simulated peak spring snowmelt runoff discharge (m3/s) for Little Smoky River and Smoky River with model bias (MB) and date of peak discharge.

Year	Peak Discharge (m^3/s)						Date of Peak Discharge			
	Little Smoky River		Smoky River		Model Bias		Little Smoky River		Smoky River	
	Gauged Flow	CRHM + Routed Upstream Gauged Flow	Gauged Flow	CRHM + Routed Upstream Gauged Flow	Little Smoky River	Smoky River	Gauged Flow	CRHM + Routed Upstream Gauged Flow	Gauged Flow	CRHM + Routed Upstream Gauged Flow
2002	219	155	925	845	-0.29	-0.09	03-May	06-May	03-May	30-Apr
2003	358	298	1400	1099	-0.17	-0.22	22-Apr	30-Apr	18-Apr	28-Apr
2004	102	99	518	467	-0.03	-0.10	10-Apr	10-Apr	06-May	06-May
2005	154	150	1080	1023	-0.03	-0.05	16-Apr	28-Apr	08-May	26-Apr
2006	64.4	55.4	257	290	-0.14	0.13	12-Apr	05-Apr	02-May	06-Apr
2007	1460	404	3150	2637	-0.72	-0.16	07-May	07-May	06-May	08-May
2008	381	184.0	946	754.0	-0.52	-0.20	02-May	03-May	10-May	11-May
2009	247	223.0	558	591.0	-0.10	0.06	23-Apr	09-Apr	24-Apr	24-Apr
2010	31.1	116.0	454	485.0	2.73	0.07	24-Apr	20-Apr	24-Apr	25-Apr
Mean	335.17	187.16	1032.00	910.11	0.08	-0.06	23-Apr	23-Apr	01-May	28-Apr

5 Programs for Modelling in Real Time

5.1 OpenMI Connection for CRHM

OpenMI is a standard which allows models and/or data bases to exchange data at run time. Its use would allow CRHM to obtain data directly from WISKI, and to write the model's results back to WISKI, without using data files and translation programs.

Although WISKI supports OpenMI, CRHM was written before OpenMI was developed and so does not support this standard. Determining if the CRHM model could easily be linked to WISKI using the OpenMI interface was an early goal of this research. We have determined that it would not be possible to add OpenMI connectivity to CRHM in the time available for this project. The difficulties imposed by the limited time available are increased by several CRHM modules which are based on the depletion of accumulated quantities. These modules require CRHM to look ahead in time, which cannot be easily implemented by OpenMI. Until OpenMI supports the CRHM look-ahead capability, it cannot be supported by CRHM.

Although WISKI and CRHM cannot be linked directly by OpenMI, we have devised methods which will allow the two programs to exchange data, ensuring that the CRHM model is driven by up-to-date data, and that the results of CRHM can be plotted and analyzed using WISKI. An advantage of this method is that it omits the processing overhead associated with OpenMI, which is anticipated to significantly slow the model's execution. The proposed method allows the data transfer and conversion to performed by machines other than those used by the model, thereby speeding the execution of CRHM.

5.2 Programs

The Lower Smoky River Model Data Management System (LSRM-DMS) is distributed under the GNU Public Licence (GPL). The LSRM-DMS is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.

The LSRM-DMS performs several tasks. The tasks are:

1. Download three-hourly forecasts from the North America Ensemble Forecast System (NAEFS) of Environment Canada for all driving meteorological variables. This can be done by any workstation or server on the network, as shown in Figure 31. Other weather forecasts are also available from Environment Canada, using the Regional Deterministic Prediction System (RDPS) and Global Deterministic Prediction System (GDPS). Although the RDPS and GDPS have frequent, high-resolution forecasts, there are several problems with their data. The RDPS and GDPS forecast runs are relatively short (2-6 days) which provide very limited look ahead. Although the data might be combined with the NAEFS data, the differing output variables of the models (in particular the humidity variables) makes this difficult. More seriously, the RDPS and GDPS only provide 30 m air temperatures, rather than the 2 m temperatures required by CRHM, and as the humidity variables are either at the surface or 2 m, they

cannot be combined with the air temperatures to estimate the 2 m vapour pressure. Therefore, only the NAEFS simulations are currently usable with CRHM.

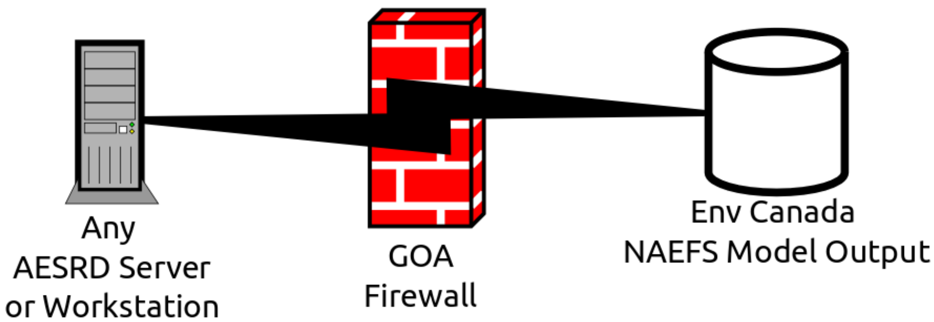

Figure 31. Schematic diagram of forecast downloading.

2. Creation of .obs files used by CRHM by WISKI models to input driving meteorology variables. The WISKI models combine measured and forecast variables, and interpolate the available data to CRHM's hourly time step. Because there are differing methods of dealing with forecast variable, three WISKI models have been developed, each of which creates separate .obs files for CRHM. A schematic of a WISKI model is shown in Figure 32. Each of the links is colour coded according to which meteorological station it references. The numbering of the stations (1 through 9) is used in the code in the CRHM_output node.

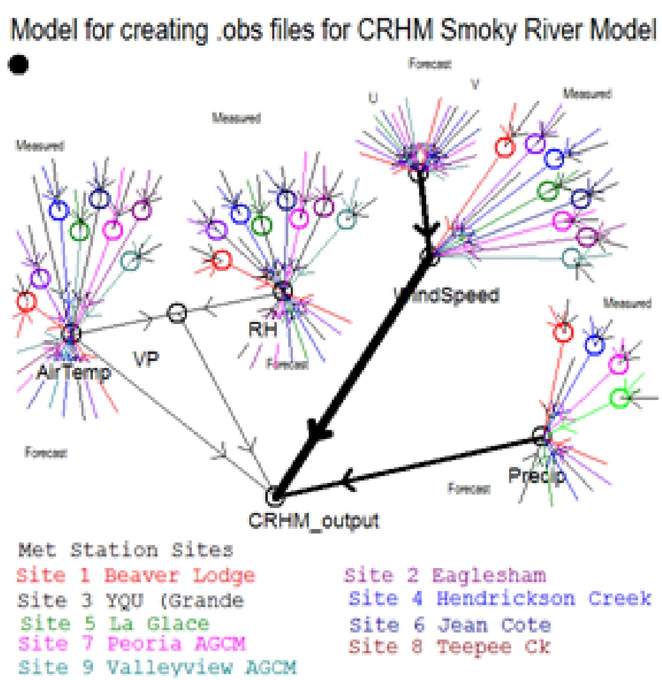

Figure 32. Schematic diagram of WISKI model for creating CRHM .obs files for the LSRM.

Each WISKI model does the following:

i. Brings in the measured data from WISKI and the downloaded forecast data from the 45 .tsm files,

ii. Converts all data to hourly values,

iii. Converts RH and Air Temperatures to vapour pressures,

iv. Combines forecasts of wind vectors (U and V) to wind speeds,

v. Converts measured wind speeds from km/h to m/s,

vi. Selects measured data (when available) or forecast data. When measured and forecast data are not available at a station, values are computed by regressions applied to the Beaverlodge data, and

vii. Calculates the weighted value of each variable for each of the 26 sub-basins in the model.

3. Run CRHM for each scenario and post process the model outputs. Although the CRHM Lower Smoky River model can be run interactively, the large number of scenarios makes it easier to run the models from a .cmd file. After the CRHM run, a bash script is called to convert the hourly flows to a single summary file for each of the Lower Smoky and the Lower Little Smoky. The file contains a tab-delimited table of simulated daily. The output can be viewed with any program (Excel, text editor), or can be imported into WISKI.

The LSRM-DMS is a collection of programs and scripts used to acquire and process forecasts of meteorological variables for the CRHM Lower Smoky River Model. Several programs must be installed to effectively use the LSRM-DMS. These programs are NOT distributed with the LSRM-DMS. All of these programs are available free of cost. The licences of the programs are discussed on their respective websites. All downloading, installation, and compliance with the licencing requirements of these programs are entirely the responsibility of the user of the LSRM-DMS.

Cygwin

All of the programs used by LSRM-DMS, other than CRHM, require Cygwin, which is a port of Unix/Linux utilities to Windows. It is available at http://www.cygwin.com/ and contains the programs bash, gawk, and wget. It also contains some other utility programs (paste) used by the bash scripts. It can

bash

Bash (Bourne Again SHell) is a command-line interpreter similar to, but much more powerful than, the Windows CMD language. The bash shell is a standard component of most unix and Linux implementations, and has been in widespread use since 1989. It is free open source software (F.O.S.S.)

and has been ported to MS Windows. The program and its documentation are available at http://www.gnu.org/software/bash/.

gawk

Gawk (Gnu AWK) is an improved version of the standard unix text processing language awk, which is named for its originators (Aho, Weinberger and Kernighan), and which has been a standard part of all unix/Linux implementations since the 1970s. Gawk is F.O.S.S. and has been ported to MS Windows. The program and its documentation are available at http://www.gnu.org/software/gawk/.

wget

Wget is used to download data files using the http, https and ftp protocols. It is F.O.S.S. and is documented at http://www.gnu.org/software/wget/.

wgrib2

Wgrib2 is used to extract data from grib2 files, which is the format used by Environment Canada. The program is F.O.S.S. and is documented at http://www.cpc.ncep.noaa.gov/products/wesley/wgrib2/. A Windows version of the program, which requires Cygwin, may be obtained at http://opengrads.org/wiki/index.php?title=Installing_GrADS_v2.0_on_Microsoft_Windows. This program is NOT included with Cygwin, and must be installed separately. The executable file wgrib2.exe needs to be in the folder H:\cygwin\bin.

5.3 Sequence of Operation

For simplicity, the programs are operated by thee Windows command (.cmd) files. The .cmd files can be executed by double-clicking on their icons on the desktop. All Windows .cmd files are distributed under the GNU Public Licence (GPL).

1. GetForecastData.cmd

The Windows .cmd file calls five bash scripts (one for each variable) which download and process the data. When the bash scripts have finished running, the .cmd file moves the WISKI model .tsf files to the required directory. The process is shown in the schematic diagram in Figure 33.

This script needs to be run once per day during the forecast season. It downloads the forecast scenarios from Environment Canada for each of the 9 met station sites, for each of 5 variables, producing 45 files. As the process will take over an hour, depending on the network speed, it is recommended that this program be run automatically using the Windows scheduler.

Because of a bug in WISKI, each of the following scripts requires that its WISKI model be executed manually. The rest of the script file is unaffected by the bug.

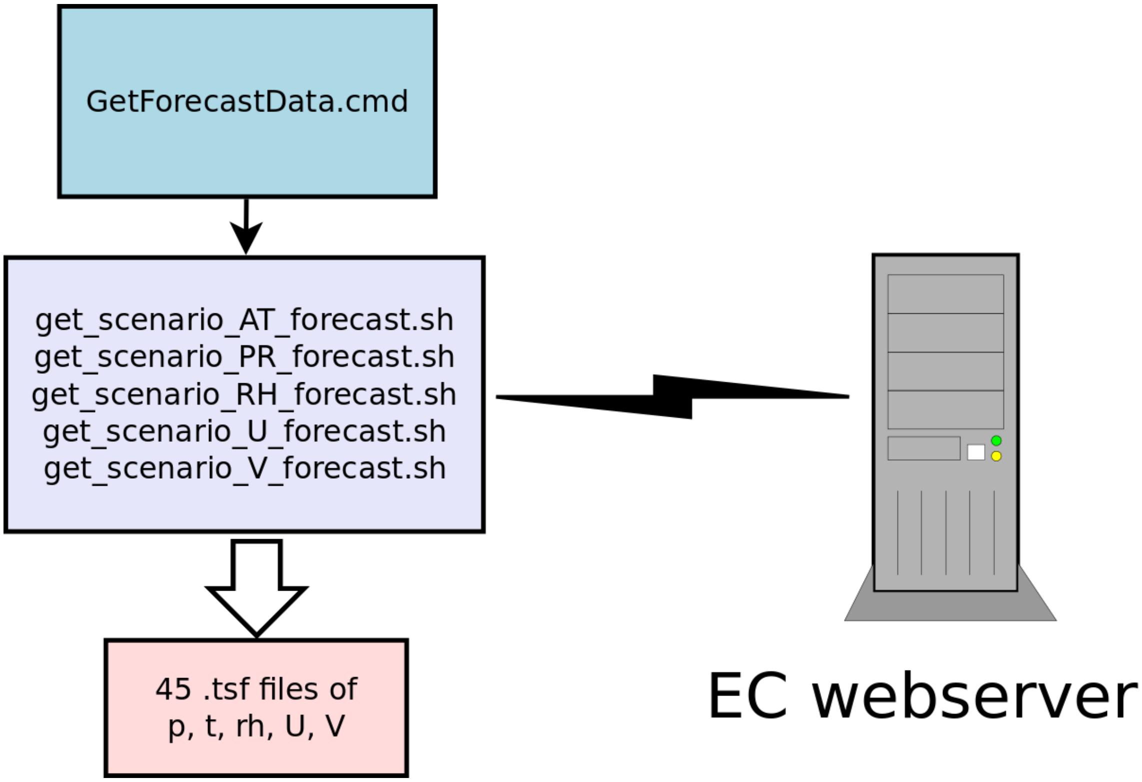

Figure 33. Schematic of GetForecastData.cmd.

2. RunWeatherForecastCRHM.cmd

This script creates the CRHM .obs files using the downloaded weather forecast variables for the future values.

3. RunAdjustedForecastCRHM.cmd

This script is basically the same as RunWeatherForecastCRHM.cmd. The only difference is that the air temperatures at the forecast points are all adjusted by a fixed offset. By default, the offset is +2 °C. The offset is set in the WISKI model, which is Smoky_Obs_File_with_Forecasts_Adjusted.tso.

4. RunTempScenarioCRHM.cmd

This model script executes a WISKI model called Smoky_Obs_File_with_Scenario.tso, which is stored in H:\LSRM-DMS\WISKIModels. This model does NOT use the downloaded forecasts. Instead, it requires values for the temperature scenario for Grande Prairie, which are stored in a standard WISKI model time series file called H:\LSRM-DMS\WISKIModels\GrandePrairieAirTempScenario.tsf.

5.4 Forecast Data Management

All weather forecasts used by the system are derived from the North America Ensemble Forecast System (NAEFS) which is described at http://www.weatheroffice.gc.ca/grib/grib2_ens_naefs_e.html. The files are stored at http://dd.weatheroffice.gc.ca/ensemble/naefs/grib2/raw/. Note that there is NO guarantee that the EC forecasts will continue to be stored at this location and in this form in the future. If they are not being stored at this location and form, then the system will not function properly. Although the scripts use wildcards in the file names to allow for small changes, significant changes may also cause the scripts to stop working. The downloaded forecasts are stored in GRIB2 files. Each file contains the data for a single variable for a three-hour period. Currently, forecasts are available for up to 384 hours into the future. No management is required for the GRIB2 files as they are deleted as soon as they have been processed. Each weather scenario is processed to produce two sets of .obs files for CRHM, one holding daily precipitation, the other containing hourly air temperature, relative humidity and wind. Each time the system is run, the previous day's forecasts will be overwritten

5.5 Model Maintenance

The CRHM models are run from an Initial State File, which has the extension .int. The initial states include all storages (soil moisture and snow water equivalent). The initial state is set on February 28 of the current year. Each year, the initial state will need to be updated, by manually running CRHM from the previous year's State File, and outputting a new file. A WISKI model is provided to generate the .obs files required by the maintenance CRHM run.

5.6 Installation of Software

Obtaining and installing the auxiliary programs is simplified by installing Cygwin, which is a port of Unix/Linux utilities to MS Windows. It is available at http://www.cygwin.com/ and contains bash, gawk, and wget. It also contains other utility programs used by the bash scripts. Wgrib2 is not part of Cygwin, but must be copied to the Cygwin /bin directory. A windows version of the program may be obtained at http://opengrads.org/wiki/index.php?title=Installing_GrADS_v2.0_on_Microsoft_Windows.

6 Summary and Conclusions

The Smoky River tributary of the Peace River has an ungauged (in real-time) basin area of 23,769 km^2, corresponding to 46% of its basin area of 51,839 km^2. The ungauged part of the basin is largely in the lower (northern) part that is dominated by agriculture and from which rapid spring snowmelt can contribute to local annual peak flows and subsequent flooding on the Peace River. The purpose of this study was to develop a model to simulate the daily spring ungauged flows of the Smoky River and its main tributary, the Little Smoky River for recent periods using measured meteorological data and forecast periods using the outputs of a numerical weather forecast model.

A physically-based model of the ungauged local flows contributing to the Smoky River at Watino and the Little Smoky River at Guy, the Lower Smoky River Model (LSRM), was developed using the CRHM platform. The model included calculations of the short and longwave radiation to surfaces, rainfall-snowfall transition, blowing snow redistribution and sublimation, intercepted snow sublimation and rain evaporation, energy balance snowmelt, infiltration to frozen and unfrozen soils, actual evapotranspiration, hillslope hydrology sub-surface flow calculations, soil moisture and groundwater mass balance, and river routing. The model was deployed to 26 ungauged sub-basins, from which discharges were routed and accumulated to produce the ungauged discharges at Guy and Watino. Using hydrological process and basin-scale behaviour information gleaned from decades of hydrological investigations using research basins in the Canadian Rockies, western boreal forest, Prairies and the Yukon, the 26 modelled sub-basins were regionalised into characteristic ecoregion types, mountain, boreal forest, boreal-agriculture transition and agricultural, for purposes of delineating sub-basin HRU structure, interpretation of land cover classifications and parameterisation. A total of 21 HRU, ranging from alpine to forest to field, were derived over the ungauged portion of the Smoky River basin, and applied to sub-basins by ecoregion with 14 for the mountain ecoregion, 9 for the boreal forest ecoregion, 11 for the boreal-agricultural transition ecoregion and 10 for the agricultural ecoregion. Parameters that could not be measured locally from GIS databases of vegetation type, topography and soil texture were interpolated from similar research basins and adjusted to local conditions from the conclusions of a review of published studies in the region, or site visit information, or to better fit the hydrographs of four gauged sub-basins that were modelled for evaluation purposes in the agricultural and boreal-agriculture transition ecoregions.

A significant challenge in operating the model is missing meteorological data and the low density of meteorological stations over much of the basin. The LSRM uses hourly air temperature, humidity and wind speed and hourly or daily precipitation. A flexible system for interpolating from existing observations to infill missing data was developed to compensate for this, but it was found that when substantial precipitation was not measured, the model was incapable of estimating discharge correctly. This was most evident in the Little Smoky River in 2007. For the forecast mode operation of the model, a selection of 21 ensemble forecasts from the Environment Canada GEM model are interpolated to the meteorological stations and then to the LSRM. Operation of the model is automated to assess the uncertainty associated with forecast data. During operational forecasting periods the model is run each day with updated observed and meteorological forecast data.

The LSRM modelled discharge was evaluated over eight years using gauged flows from four small non-real time gauged sub-basins in the agricultural and boreal-agriculture transition ecoregions with encouraging results after parameter adjustment based on the conclusions of a review of published studies in the region, site visit information, and an attempt to better fit the hydrographs by fitting lag and route parameters from the sub-HRU routing. The parameter adjusted LSRM was then applied to estimate the discharge of the Smoky River and Little Smoky River in two modes, i) comparison of modelled ungauged local inflow contributions to discharge to estimates derived from gauged flow subtraction, and ii) comparison of modelled discharge to gauged discharge. The first comparison of ungauged discharge showed moderately good LSRM hydrograph predictive capability, with some differences between modelled and estimated ungauged discharges that are thought to be due to unmeasured or missing precipitation data and cumulative errors in both ungauged discharge estimation and model performance. The second comparison of gauged discharge evaluates the performance of the model in an operational setting with measured meteorological observations. Results from this comparison were very good with a high degree of hydrograph predictability, small bias in flow estimation, and very good prediction of peak daily discharge and excellent prediction of the timing of peak daily discharge. The results were somewhat better for the Smoky River than for the Little Smoky River, showing the effect of increasing basin size in compensating for inadequate precipitation observation density and/or errors in model structure or parameterisation.

For operation in real time, the CRHM LSRM was interfaced with WISKI by creating the LSRM Data Management System (LSRM-DSM). The LSRM-DSM system brings in updated observational data from nine stations and forecast data for 384 hours in the future on a daily basis to run LSRM and then output the LSRM modelled discharges for use by AESRD in forecasting. Missing observational data are infilled by interpolation from other weather stations in the same manner as was used in the evaluation runs. It should be noted that if no observational or forecast weather data is available for a substantial period of time (>3 hours), then the model cannot be run reliably and so automated QA/QC of weather station data and forecasts before input to LSRM by AESRD staff during forecasting periods is highly recommended. The model has not yet been tested in an operational setting during a spring snowmelt event and its full capabilities and usefulness cannot be assessed until it has been tested in such a setting.

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