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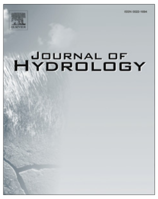

Simulating cold regions hydrological processes using a modular model in the west of China

Jian Zhou[a], John W. Pomeroy[b,*], Wei Zhang[a], Guodong Cheng[a], Genxu Wang[c], Chong Chen[d]

[a] Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China
[b] Centre for Hydrology, University of Saskatchewan, 117 Science Place, Saskatoon, Saskatchewan S7N 5C8, Canada
[c] Key Laboratory of Terrestrial Processes in Mountainous Regions and Ecological Control, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610041, China
[d] School of Information Science and Engineering, Lanzhou University, Lanzhou, Gansu 730000, China

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SUMMARY

The Cold Regions Hydrological Model platform (CRHM), a flexible object-oriented modeling system, was devised to simulate cold regions hydrological processes and predict streamflow by its capability to compile cold regions process modules into purpose-built models. In this study, the cold regions hydrological processes of two basins in western China were evaluated using CRHM models: Binggou basin, a high alpine basin where runoff is mainly caused by snowmelt, and Zuomaokong basin, a steppe basin where the runoff is strongly affected by soil freezing/thawing. The flexibility and modular structure of CRHM permitted model structural intercomparison and process falsification within the same model framework to evaluate the importance of snow energy balance, blowing snow and frozen soil infiltration processes to successful modeling in the cold regions of western China. Snow accumulation and ablation processes were evaluated at Binggou basin by testing and comparing similar models that contained different levels of complexity of snow redistribution and ablation modules. The comparison of simulated snow water equivalent with observations shows that the snow accumulation/ablation processes were simulated much better using an uncalibrated, physically based energy balance snowmelt model rather than with a calibrated temperature index snowmelt model. Simulated seasonal snow sublimation loss was 138 mm water equivalent in the alpine region of Binggou basin, which accounts for 47 % of 291 mm water equivalent of snowfall, and half of this sublimation loss is attributed to 70 mm water equivalent of sublimation from blowing snow particles. Further comparison of simulated results through falsification of different snow processes reveals that estimating blowing snow transport processes and sublimation loss is vital for accurate snowmelt runoff calculations in this region. The model structure with the energy balance snowmelt and blowing snow components performed well in reproducing the measured streamflow using minimal calibration, with R^2 of 0.83 and NSE of 0.76. The influence of frozen soil and its thaw on runoff generation was investigated at Zuomaokong basin by comparing streamflow simulated by similar CRHM models with and without an infiltration to frozen soil algorithm. The comparison of simulated streamflow with observation shows that the model which included an algorithm describing frozen soil infiltration simulated the main runoff events for the spring thawing period better than that which used an unfrozen infiltration routine, with R^2 of 0.87 and NSE of 0.79. Overall, the test results for the two basins show that hydrological models that use appropriate cold regions algorithms and a flexible spatial structure can predict cold regions hydrological processes and streamflow with minimal calibration and can even perform better than more heavily calibrated models in this region. Given that CRHM and most of its algorithms were developed in western Canada, this is encouraging for predicting hydrology in ungauged cold region basins around the world.

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* Corresponding author at: Centre for Hydrology, University of Saskatchewan, 117 Science Place, Saskatoon, Saskatchewan, S7N5C8, Canada. Tel.: +306 966 1426; fax: +306 966 1428.

E-mail addresses: zhoujian@lzb.ac.cn (J. Zhou), john.pomeroy@usask.ca (J.W. Pomeroy), zw@lzu.edu.cn (W. Zhang), gdcheng@lzb.ac.cn (G. Cheng), wanggx@imde.ac.cn (G. Wang), chenchong87@gmail.com (C. Chen).

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1. Introduction

Many of the major rivers in China, such as the Yellow River, the Yangtze River, and the Lancang River originate from the Qinghai-Tibet Plateau (QTP) and other high altitude mountains in western China. Permafrost, seasonally frozen soils and snowcover are widely distributed over this region (Zhang et al., 2003a, 2008). The high altitude and cold winters result in substantial water storage as the seasonal snowpack, seasonally or perennially frozen ground, and glacial geomorphology. Spring snowmelt and thaw of frozen soils along with the rise of air temperature are generally considered the most important hydrological events in western China. Snow ablation and frozen soil thawing processes provide a reliable and substantial spring runoff (Peterson et al., 2002; Woo et al., 2008; Yang et al., 2002; Zhang et al., 2003b), which is important to water supply for irrigation, ecological protection, and flood control (Zhao and Gray, 1999). Concerns are being raised about the maintenance of this water supply under warming climate conditions (Adam et al., 2009; Gao and Shi, 1992). However, the classical hydrological concepts of rainfall–runoff response cannot be used in cold regions to describe hydrological behavior. In order to forecast runoff in these regions, it is necessary to understand snow redistribution, snow ablation, meltwater generation and soil freezing–thawing processes, and their interactions (Pomeroy et al., 2007; Fang et al., 2013).

In the last 20 years, simulation of cold regions hydrology has received much attention in many international organizations and research projects. The Climate and Cryosphere (CliC) Project Science and Coordination Plan (http://ipo.npolar.no/reports/archive/wcrp_114.pdf) declared in 2000 that cold regions hydrological processes and their corresponding impacts are important research items for global warming research. The Predictions in Ungauged Basins (PUB) decade (http://pub.iahs.info/index.php) operated by the International Association of Hydrological Sciences (IAHS) focused on predicting streamflow for ungauged or poorly gauged basins, including the effect of snow ablation and ice-melt to streamflow processes in cold regions throughout the decade of 2003–2012. The Improved Processes and Parameterization for Prediction in Cold Regions (IP3) Network (http://www.usask.ca/ip3/index.php), funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), operated from 2006 to 2011 as a research network with a prime objective of improving understanding of cold regions meteorological and hydrological processes.

Computer models of basin hydrology are important technology to help understand cold regions hydrological processes and their role in basin-scale hydrological response to precipitation and snowmelt. Numerous studies have been conducted to describe water flow and heat transport in thawing and frozen soils (Flerchinger and Saxton, 1989a,b; Hansson et al., 2004; Jansson and Moon, 2001). Since the first successful demonstration of snowmelt simulation using an energy-balance approach by Anderson (1976), numerous such snowmelt models have been developed, e.g. EBSM (Gray and Landine, 1988), SNTHERM (Jordan, 1991), Snobal (Marks et al., 1999), SNOWPACK (Lehning et al., 2002a,b; Bartelt and Lehning, 2002). Due to the differing objectives specific to each energy balance model, there is considerable variation in the detail to which snow energetic processes may be described, as well as forcing data and parameterization requirements. For instance, EBSM has a single layer, operates at a daily time-step and has no parameters to set but is only appropriate for shallow snowpacks, whilst Snobal has two layers, operates at hourly or finer time steps, requires few parameters to set, but is appropriate for a wide range of snow depths and thermal conditions. SNTHERM and SNOWPACK have many layers and many parameters but presumably a wide range of applicability. For infiltration into thawing and frozen soils, several one-dimensional numerical codes currently exist for simulating water and heat transport, including freezing and thawing, such as SHAW (Flerchinger and Saxton, 1989a,b), HAWTS (Zhao and Gray, 1999; Zhao et al., 1997) and Coupmodel (Jansson and Moon, 2001). Models that simulate cold regions hydrological processes at basin scale have also been developed in the last years and include models such as ARHYTHM (Zhang et al., 2000), GEOtop (Rigon et al., 2006) and VIC (Liang et al., 1994). Many models have been used to describe cold regions hydrological processes in the west of China (e.g. Jia et al., 2009; Wang et al., 2010; Zhang et al., 2012). The more sophisticated models generally have parameter and driving meteorological requirements that may prohibit their successful employment in many environments, such as where forcing data and parameter information is typically lacking or poorly approximated. It is recognized that it is inappropriate to run detailed distributed models where meteorological data is sparse or parameter and hydrological uncertainty are so great as to make the operation of these models physically unrealistic. However, models with unidentifiable parameters or overly simplistic treatment of cold regions mass and energy exchange processes are also physically-unrealistic and do not have transferable parameterisations due to uncertainty caused by physical unrealism. Therefore, simulating and forecasting streamflow face great challenges in the cold regions, because of the lack of appropriate information at the basin scale and the lack of hydrological models that are appropriate for cold regions applications.

An urgent need in hydrology is to apply models to predict in ungauged basins where traditional calibration of models is not possible (Sivapalan et al., 2003). This need is not at odds with the need for models that have a physical complexity matching available parameter and meteorological information, but adds further constraints as the algorithms in physically based models must be able to operate with minimal or no calibration. Solutions to this problem have been sought using the Cold Regions Hydrological Model (CRHM) platform, which was developed as a modular object-oriented modeling framework to simulate the cold regions hydrological cycle over small to medium sized basins by a multidisciplinary research group from various institutions in Canada (Pomeroy et al., 2007). Many of the algorithms were derived from field investigations of cold regions processes in western and northern Canada, and most algorithms have a strong physical basis and extensive field testing. CRHM is fundamentally different from most hydrological models, because it is a modeling platform from which models can be created, based on a good physical understanding of the principles and characteristics of hydrology in a basin, with an appropriate structure and appropriate spatial resolution and parameter selection given information that is available. Logical selection and design of model strategy, structure, and their inherent assumptions are governed by local problems and local hydrology. This is not just parameter selection but involves selection of an appropriate model structure. By offering a range of spatial complexity from lumped to distributed, of physical realism from the conceptual to physically based approaches and by offering a wide selection of process modules, CRHM permits the user to tailor the model to the appropriate complexity that is warranted by the modeling objective, scale, and available information on the basin (Pomeroy et al., 2007, 2012). Models created using CRHM have been used to study blowing snow redistribution in sub-arctic and mid-continental mountains and sub-humid prairies (Fang and Pomeroy, 2008, 2009; MacDonald et al., 2009, 2010; Kort et al., 2011), mountain snow ablation (Pomeroy et al., 2012; DeBeer and Pomeroy, 2010; Dornes et al., 2008; Ellis et al., 2010; Lopez-Moreno et al., 2012; Fang et al., 2013), runoff generation over permafrost soils (Dornes et al., 2008), runoff over seasonally frozen soils (Pomeroy et al., 2012; Fang and Pomeroy, 2007; Fang et al., 2010; Guo et al., 2012) and evapotranspiration and soil moisture dynamics in boreal forest and semi-arid steppe environments

(Armstrong et al., 2010; Pomeroy et al., 2007). Simulations have all been done without calibration or with minimal calibration of parameters within clearly identified ranges.

In this study, two basins monitored by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (CAREERI, CAS) were chosen to evaluate CRHM for basin scale modeling of cold regions hydrological processes in western China. Binggou basin is a high alpine basin, where snow redistribution, accumulation and melt processes are expected to have an important influence on runoff and Zuomaokong basin is a permafrost steppe basin, where the effects of the soil freeze–thaw cycle on spring runoff are expected to be large. The CRHM platform was used to create hydrological models for comparing and testing of different algorithms, evaluation and falsification of different model structures, diagnosing various elements of the hydrological cycle and estimating runoff. CRHM has not been tested in Asia and there was interest in whether its applicability extended outside of its region of derivation. The objectives of this paper are: (a) to test the ability of the models created with the CRHM platform to simulate elements of the cold regions hydrological cycle with minimal calibration, such as snow accumulation and snow melt, infiltration into frozen soil and runoff; (b) to evaluate the impacts of different module complexities and model architectures on diagnosing variables of the hydrological cycle in the conditions of the uplands of western China.

2. Materials and methods

2.1. The study regions

2.1.1. Snowmelt–runoff basin

Binggou basin (100°11′–100°18′E and 38°05′–38°50′N) is located in the Qilian Mountain in the northeast of the QTP, and was chosen to study snow accumulation and melt, and the influence of snowmelt on runoff processes. The Binggou basin ranges from 3440 to 4400 meters above sea level (m.a.s.l.) and its area is about 30.3 km^2. The Binggou basin is characteristic of a seasonally snow-covered high mountain region in the QTB. The mean depth of the seasonal snowpack is about 50 cm, up to a maximum of 80 cm. Snow redistribution is remarkable because of the interaction between blowing snow and complex terrain. Snowfall normally occurs from October to April, with more snowfall in spring and early winter than in mid-winter, followed by a rainy season from May to August. The mean air temperature at an altitude of 3450 m was about −2.5 °C during the 2008 snow season; the annual extreme minimum temperature was −29.6 °C, and the maximum was 19.9 °C.

Meteorological data (including air temperature, wind speed and humidity observations at 2 m and 10 m height; incoming and outgoing short and long wave radiation fluxes at 1.5 m height) were collected using two Automatic Weather Stations (AWS); Dadongshu Mountain Pass Snow Observation Station (DY) (4146.8 m, E100°14′, N38°01′) and Binggou Cold Region Meteorological Station (BG) (3449.4 m, E100°13′, N38°04′) (Fig. 1) from November 1, 2007 to July 17, 2009. Precipitation was recorded with an Alter-shielded weighing gauge (T-200B, Geonor, Norway) at 1 h intervals. The air temperature threshold for distinguishing between rainfall and snowfall was determined as 2.7 °C according to field staff observations. Snowfall was corrected with wind speed for wind undercatch according to standard accepted procedures (Goodison et al., 1998; Smith, 2006). Rainfall was corrected with wind speed using the undercatch relationship of Yang et al. (1998). Soil moisture and soil temperature sensors were installed at depths of 0.1, 0.2, 0.4, 0.8 and 1.2 m. A stream gauge was installed at the outlet of the basin to measure daily stream discharge. Soil samples were collected from the top of the ground to a depth of 1.5 m at 30 cm intervals below two meteorological stations. Soil samples were analyzed in the laboratory to determine soil bulk density, water retention properties (soil water contents at 0–1000 kPa matric potentials) and percentages of sand, silt, and clay. The soils were classified as sandy according to the USDA classification system. The majority of land is coved by alpine meadow with sparse short grasses. Snow characteristics were observed through a series of field measurements in the snow season of 2008. These observations included basic snow properties such as snow depth, density, grain size, temperature, and emissivity. Table 1 provides details of the main instruments used at two stations.

2.1.2. Permafrost basin

The QTP permafrost region is characterized by its cold semiarid climate (precipitation <450 mm) and relatively low annual snowfall. To clearly delineate the influence of freeze–thaw cycles of the ‘active’ soil layer on runoff processes in the permafrost basins of the QTP, a typical permafrost steppe basin, the Zuomaokong basin (92°50′–93°30′E and 34°40′–34°48′N) was selected as the study area (Fig. 2). Here, the influences of glacier and snowmelt water are much less important than elsewhere in the QTP. The basin area is 127.6 km^2, and its altitude ranges from 4610 to 5323 m.a.s.l. The vegetation of the study region is dominated by alpine grasses, i.e. *Kobresia pygmaea* C.B. Clarke and *Kobresia humilis Serg* (Wang et al., 2007; Zhou, 2001). Annual mean air temperature is −5.2 °C, and the monthly mean air temperature is above 0 °C from May to September so that the freezing season is from October to the following May. Annual precipitation was between 269 and 311 mm over the period 2005–2008, with precipitation between July and September accounting for 83% of the annual depth. This seasonality is reflected in the relative humidity, which ranges from 17% to 96%, with higher values in summer and lower values in winter.

Two meteorological stations were established in the basin to measure precipitation, air temperature, wind speed, humidity and solar radiation. Soil moisture and soil temperature sensors were installed at depths of 0.20, 0.30, 0.40, 0.55, 0.65, 0.85 and 1.20 m. Soil samples were collected from the ground to a depth of 1.5 m with 30 cm interval below two meteorological stations. The main instruments at two stations are the same as the instruments used at the stations in the Binggou basin. The samples were analyzed in the laboratory to determine soil bulk density, water retention properties (soil water contents at 0–1000 k matric potentials) (Equi-pf, New Zealand) and percentages of sand, silt, and clay. The predominant soil type of the study region is clay from the surface to a depth of 40 cm and sandy loam from 40-cm to 150-cm depth. The organic matter content in the topsoil (0–20 cm depth) in this area ranges from 4.5 to 13.6 g kg^{-1}. The depth of frozen soil ranges from 50 to 120 cm, the depth of the seasonally thawing ‘active layer’ ranges from 80 to 150 cm, and the permafrost temperature ranges from −1.5 °C to −3.7 °C (Zhou et al., 2000). A hill-slope runoff plot (Fig. 2) was established on a 15° hillside to observe surface and subsurface runoff. Discharge at the basin outlet (Fig. 2) was measured every 2 h from May to September, and twice per day (09:00–10:00 h and 15:00–16:00 h) from October to April throughout the study period (from the year of 2005 to the year of 2008).

2.2. Model description

CRHM (Pomeroy et al., 2007) was inspired by the capabilities of modular modeling object-oriented structures pioneered in hydrology by Leavesley et al. (1996). It is a flexible modeling framework to develop and evaluate physically-based algorithms of cold region hydrological processes and effectively integrate selected algorithms by compiling them into a model. Because it was developed for year-round operation in Canada, it has an extensive range of

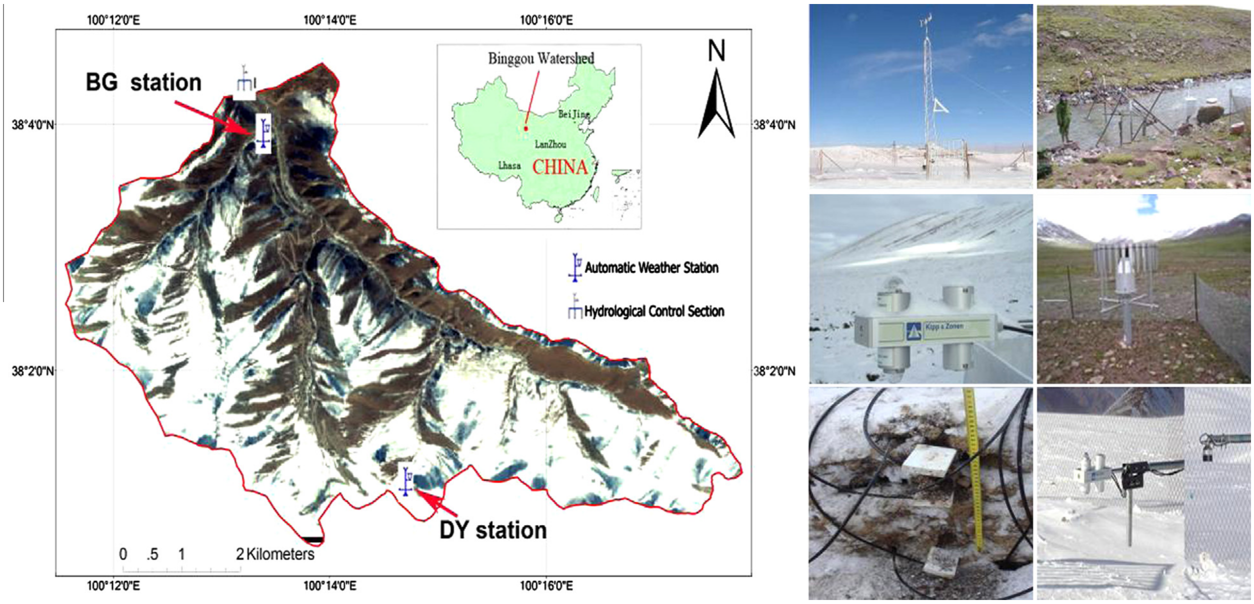

Fig. 1. The location and photographs of meteorological and hydrological stations at Binggou basin.

Table 1
Main instruments used at meteorological stations of Binggou basin.

Item	Unit	Instrument	Precision
Air temperature	°C	Humidity and temperature probe (HMD45D, Vaisala Oyj, Finland)	±0.2 °C
Relative humidity	%	Humidity and temperature probe (HMD45D, Vaisala Oyj, Finland)	±2%
Air pressure	hPa	Analog barometer (CS100, Campell, USA)	±0.5 mb
Wind speed	$m\ s^{-1}$	Anemometer (010C-1, MetOne, USA)	±0.11 m/s
Precipitation	mm	Weighing gauge (T-200B, Geonor, Norway)	±0.1 mm
Shortwave radiation	$W\ m^{-2}$	Radiometer (CM3, Campell, USA)	±10%
Longwave radiation	$W\ m^{-2}$	Infrared radiometer (CG3, Campell, USA)	±10%
Soil temperature	°C	Pt-thermometer (109, Campell, USA)	±0.2 °C
Soil moisture	$m^3\ m^{-3}$	Time-domain reflectometry (CS616, Campell, USA)	±2%
Snow depth	mm	Ultrasonic level-meter (SR50, CSI, USA)	±10 mm
Blowing snow		Sensor for counting (Flowcapt, ISAW, Switzerland)	±2%

cold regions hydrology process algorithms in addition to a wide range of temperate hydrology process descriptions. Existing algorithms can be conveniently modified using a macro facility, and new algorithms can be developed and added as modules to the module library. Each module represents a physically-based algorithm or data transformation. Modules from the library are coupled to create a purpose-built model, suited for the specific application.

The modular library of CRHM has a complete set of modules describing hydrological processes which involve blowing snow, precipitation interception in forest canopies, snow sublimation, snow ablation, snowmelt, infiltration into frozen soils or unfrozen soils, hillslope water movement over permafrost or unfrozen soils, depressional storage, actual evapotranspiration for unsaturated conditions, radiation exchange to complex surfaces and streamflow routing. The details are described by Pomeroy et al. (2007, 2012), Ellis et al. (2010), MacDonald et al. (2010) and Fang et al. (2013). For many hydrological processes, there is a choice of modules ranging from basic to strongly physically-based, so as to permit the most appropriate algorithms to be used for the available data, information reliability, basin characteristics, scale, and intended prediction. There is an attempt to maximize the physical basis whilst minimizing the parameter requirements for each module. This flexible integrated application is encouraging for predicting in ungauged basins where information is often scarce and calibration from local streamflow impossible.

Spatial application of CRHM is over hydrological response units (HRU) which are biophysical/drainage units that are assumed to be capable of being represented by one set of parameters and set of modules. HRU are the control volumes for coupled mass and energy balance calculations and have state variables that are tracked and flow variables that interact with other HRU or flow out of the basin. Flow between HRU can be episodic and sequential permitting description of the often poorly drained glacial geomorphology that characterizes many cold regions (Fang et al., 2010). A unique feature of CRHM is that blowing snow can be routed between HRU and in and out of the basin according to aerodynamic considerations, whilst surface and subsurface runoff is routed according to gravity and drainage characteristics. As blowing snow is one of the major horizontal flows of water in many cold regions basins, this is an important feature in modeling cold environments (Pomeroy et al., 1993; MacDonald et al., 2010).

2.3. Model establishment

A set of physically based modules was assembled in a sequential fashion to simulate the hydrological processes relevant to Binggou basin (Fig. 3). Key modules include the radiation model of Garnier and Ohmura (1970), Prairie Blowing Snow Model (PBSM) (Pomeroy and Li, 2000), albedo model of Gray and Landine (1987), the Snobal energy-balance snowmelt model (Marks et al., 1999), a temperature-index snowmelt algorithm (Male and Gray, 1981), Gray's

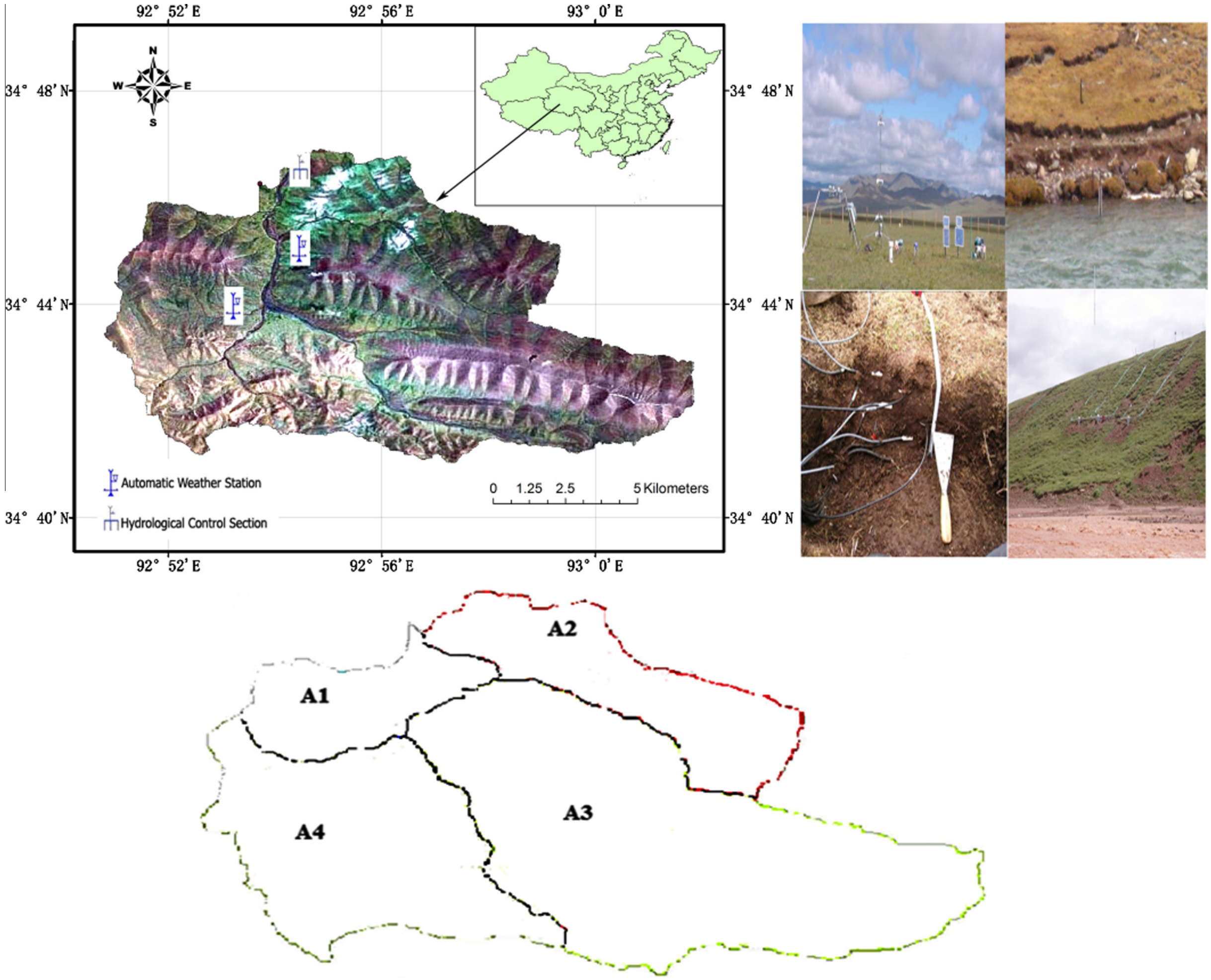

Fig. 2. The location and photographs of meteorological and hydrological stations, and HRU delineation at Zuomaokong basin.

expression for frozen soil infiltration during the spring snowmelt period (Granger et al., 1984; Gray et al., 1985), Green-Ampt infiltration model for unfrozen soil infiltration (Ogden and Saghafian, 1997), Granger and Gray's (1989) evaporation expression for unsaturated surface actual evaporation, a soil moisture balance routine developed by Dornes et al. (2008) from that proposed by Leavesley et al. (1983), and the routing of surface runoff, subsurface runoff and HRU routing using the lag and route method of Clark (1945). The soil moisture balance model divides the soil column into two layers; the top layer is called the recharge zone. Inputs to the soil column layers are derived from infiltration of both snowmelt and rainfall. Evaporation only occurs from the recharge zone, and water for transpiration is taken out of the entire soil column. Surface infiltration satisfies the available storage of the recharge layer first before moving to the lower soil layer. Excess water from both soil layers satisfies the ground water flow (GW) before being discharged to the sub-surface flow (SSR). A flowchart of the cold region hydrological model for Binggou basin is shown in Fig. 3.

Binggou basin is small and mostly north-facing, and was therefore generalized as one hydrological response unit (HRU). Vegetation cover and soil classification are also homogeneous over the basin; grass accounts for 76% of the gross basin area. Whilst greater spatial discretization would be desirable to address elevational control of wind speed, precipitation, temperature, and humidity and whilewhilst it is recognized that slope and aspect play an important role on snow redistribution and melt rates, the lack of continuous observations for model forcing or verification from the DY station, lack of distributed snow surveys and knowledge of snow redistribution, scarcity of south facing slopes and relatively uniform soil and vegetation meant that there was little basis on which to further spatially distribute the model.

Model parameters were primarily estimated using field survey data, the ASTER global digital elevation model (30 m resolution DEM), and ETM+ remote sensing images. The average elevation, latitude, aspect and slope of the HRU were calculated by a GIS procedure using the 30 m resolution DEM. The average canopy height of 20 cm was determined from field surveys. The maximum water holding capacity in the soil recharge zone (or whole soil profile) was determined from multiplying rooting zone depth (or soil profile depth) by the difference between the soil field capacity and wilting point, which were derived from the water retention properties analyzed in the laboratory. The initial values of available water in the soil recharge zone and in the whole soil profile were determined by the product of the corresponding maximum water holding capacity and volumetric fall soil moisture content, which were derived from soil moisture observations. The albedo for new snowfall and bare soil were set to default values of 0.85 and 0.17, respectively, which correspond to measured values from high elevations in Canada. Subsurface drainage factor controls the rate of flow in the subsurface domains. It was estimated from the saturated hydraulic conductivity and slope using the method outlined by Fang et al. (2013). Routing lag and storage values were estimated based on the HRU size, shape, and landform type. The drainage factors, routing lag and storage values were further adjusted

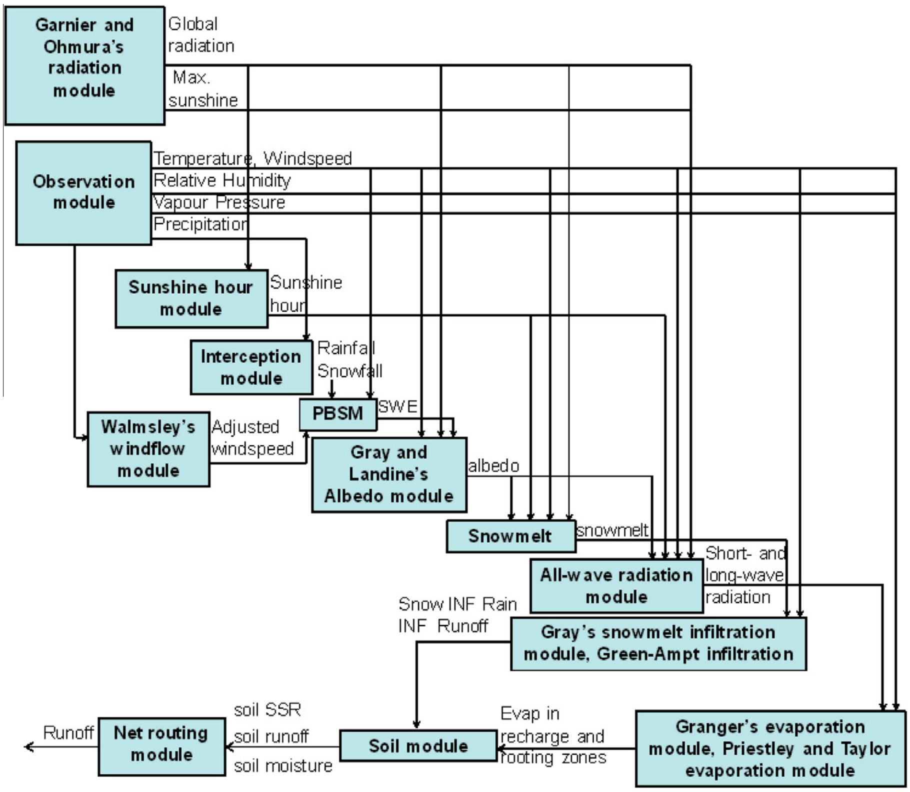

Fig. 3. Flowchart of modular snowmelt–runoff model for Binggou basin.

Table 2
The values of key CRHM model parameters for Binggou basin and Zuomaokong basin.

		Binggou basin	Zuomaokong basin			
	HRU name	–	A1	A2	A3	A4
Parameters were calculated using the 30 m resolution DEM	Elevation (m)	3800	4775	4800	4900	4950
	Latitude	38.07°N	34.75°N	34.78°N	34.50°N	34.20°N
	Area (km^2)	30.27	10.89	17.76	54.54	29.31
	Ground average slope (°)	13	8	12	9	14
Parameter was estimated from main canopy type	Canopy height (m)	0.20	0.25	0.20	0.20	0.15
	Temperature lapse rate	0.75	0.75	0.75	0.75	0.75
Default values	New snowfall albedo	0.85	0.85	0.85	0.85	0.85
	Bare albedo	0.17	0.17	0.17	0.17	0.17
Parameters were estimated from the water retention properties analyzed in the laboratory	Soil recharge maximum (mm)	30	40	40	40	40
	Maximum available water (mm)	60	80	80	80	80
Manual adjusted parameters	Fetch distance (m)	3000	2000	2000	2500	2500
	Routing order	–	4	3	2	1
	Subsurface drainage factor (mm/d)	1	4	4	4	4
	Subsurface runoff storage constant (d)	10	10	10	10	10
	Runoff storage constant (d)	5	2	2	2	2
	Storage constant (d)	0.5	1	1	1	1

through comparing simulated streamflow with observation, which constitutes a minimal calibration of hydrograph shaping components of the model.

CRHM was used to investigate the influence of blowing snow and sublimation on the snow mass balance, and the prediction of snowmelt–runoff at Binggou basin. In order to further evaluate the performance in simulating snow accumulation and ablation with differing levels of realism in snowmelt representation, a model using a temperature index snowmelt routine was compared to a model using a physically based snowmelt module. The models had identical model structure except for the differing snowmelt modules.

1. Scheme 1 implemented an empirical temperature index snowmelt model, linked to the physically based blowing snow module, PBSM. Surface sublimation was not estimated by the temperature index melt module. PBSM calculates the snow mass balance by coupling to the temperature index model for melt, then using measured precipitation, wind speed, air temperature and humidity to calculate blowing snow transport

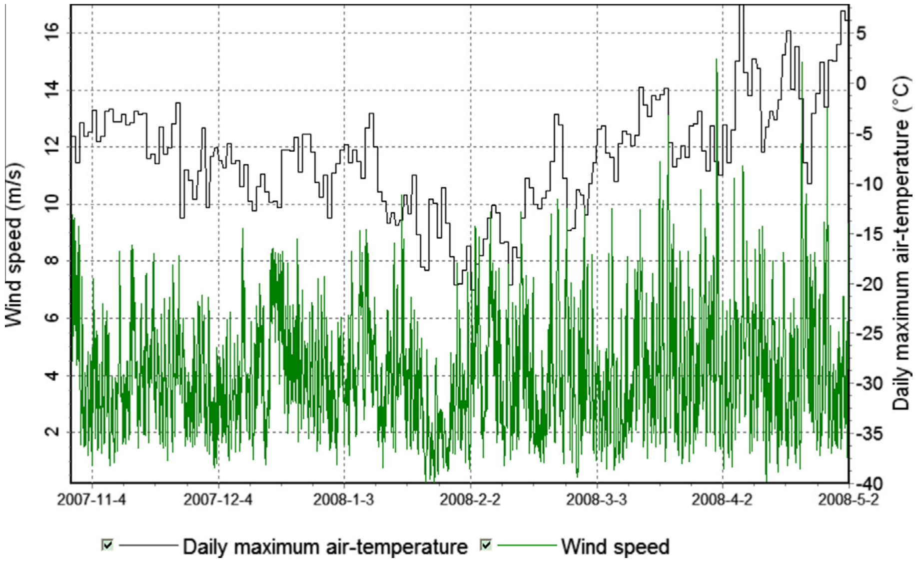

Fig. 4. Observed daily maximum air-temperature and wind speed during spring season at BG meteorological station (Binggou basin).

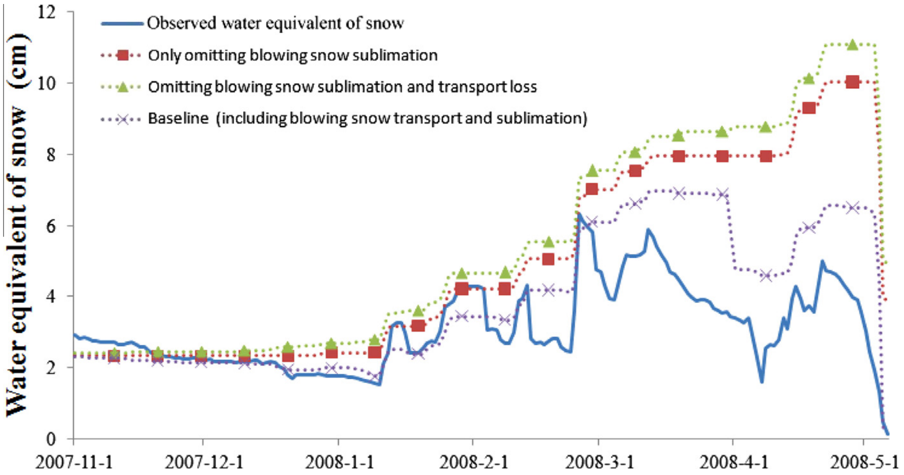

Fig. 5. Comparison between simulated snow water equivalent with temperature index melt in scheme 1 and observations at Binggou basin.

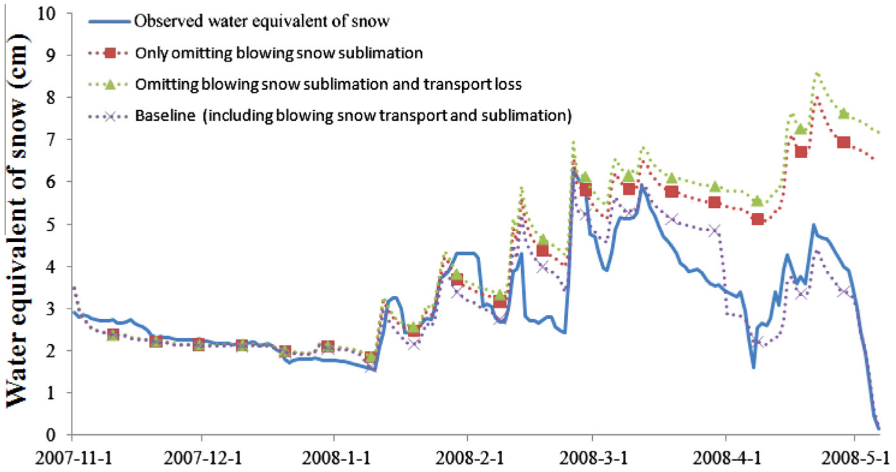

Fig. 6. Comparison between simulated snow water equivalent with energy balance melt in scheme 2 and observations at Binggou basin.

Table 3
Statistics comparing simulated and observed snow water equivalent (BG station).

Scheme	Baseline (including blowing snow transport and sublimation loss)			Omitting blowing snow sublimation and transport loss			Only omitting blowing snow sublimation		
	ME (mm)	RMSE (mm)	R^2	ME (mm)	RMSE (mm)	R^2	ME (mm)	RMSE (mm)	R^2
1	7.7	21.3	0.64	23.7	39.2	0.40	19.1	34.2	0.43
2	0.3	12.4	0.78	11.2	24.0	0.44	9.1	21.1	0.47

and sublimation, snow density, depth and water equivalent. Options in PBSM permitted tests to suspend the calculation of blowing snow transport or sublimation. In this application, the degree day melt factor was set to 7 mm/day/°C by calibration to snow depth observations.

2. Scheme 2 implemented a physically based snowmelt model: the hourly snowpack energy and mass balance module, SNOBAL, linked to a compatible version of PBSM. SNOBAL calculates the coupled energy and mass balance including snow density, depth and water equivalent based on detailed snow physics, radiation and turbulent flux calculations and linked to a subset of PBSM which included blowing snow transport and calculation fluxes in the mass balance. Options in this version of PBSM permit tests to suspend the calculation of blowing snow transport or sublimation.

For the SNOBAL module, fresh snow density was set to 80 kg/m^3 derived from snow properties observations. The maximum active layer thickness was fixed at 0.1 m (default value) which was found to work best for simulating snowpack dynamics in the Rocky Mountains of North America (Marks et al., 2008). For the PBSM module in both schemes, blowing snow fetch distance is the upwind distance without disruption to the flow of snow and determined from the DEM and vegetation distribution. Because of uncertainty in the estimation of these parameters and the lumped nature of modelling for this basin, the snow surface roughness length and blowing snow fetch distance were further adjusted through comparing simulated snow depths with observations. The values of key parameters used to running CRHM model are presented in Table 2.

The model structure and key modules of Zuomaokong basin are similar to the energy balance snowmelt model of Binggou basin except for replacing the soil infiltration modules. The ArcGIS Hydrology procedure was used to extract sub-basins using 30 m resolution DEM (ASTER global digital elevation model). The spatial discretization of the sub-basins is as drainage HRUs with a conceptual landscape sequence or water flow cascade. The delineation of the four HRUs is shown in Fig 2. The parameterization for HRUs was similar to that for the Binggou basin. The values of key CRHM model parameters are presented in Table 2. An investigation into the influence of soil freezing and thawing on runoff was conducted by comparing modeled streamflow under two scenarios using a module structure that handles unfrozen soil and frozen soil infiltration compared to results using a model structure that only considered unfrozen soil infiltration.

3. Model performance evaluations

The CRHM models performance was evaluated on the basis of the coefficient of determination for a linear regression between simulated and observed values (R^2), the mean error (ME), the root mean square error (RMSE), and the Nash–Sutcliffe coefficient (NSE). The latter are calculated as:

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(X_{sim,t} - X_{obs,t})$$

$$\mathrm{RMSE} = \frac{1}{N}\sqrt{\sum_{t=1}^{N}(X_{sim,t} - X_{obs,t})^2}$$

$$\mathrm{NSE} = 1 - \left(\sum_{t=1}^{N}(X_{sim,t} - X_{obs,t})^2 \bigg/ \sum_{t=1}^{N}(X_{obs,t} - \overline{X})^2\right)$$

where N is the number of observations and. $X_{obs,t}$, and $X_{sim,t}$ are the observed and simulated values, respectively.

3.1. Binggou basin

The simulation time period was from October 30, 2007 to July 20, 2009, with an hourly computational time step. Local meteorological stations were used to provide input variables (wind speed, air temperature, humidity, precipitation, and incoming solar radiation) for the simulations.

Simulations of snow water equivalent using the temperature index and the energy balance snowmelt-based models were evaluated against snow survey observations from October 30, 2007 to May 6, 2008 at the BG meteorological station. The daily maximum air temperature and wind speed data, which are important for snowmelt, are shown to provide context for the simulations in Fig. 4. Three simulations were performed for each scheme: (i) a baseline simulation including calculations of blowing snow transport and sublimation, snowpack sublimation and snowmelt. (ii) a simulation only omitting blowing snow sublimation. (iii) a simulation omitting both blowing snow sublimation and transport loss.

Fig. 5 shows the comparison between simulated water equivalent of snow with the temperature index snowmelt model (scheme 1) and observation, and Fig. 6 shows the comparison between simulated water equivalent of snow with the physically based snowmelt model (scheme 2) and observation. Table 3 summarizes model evaluation statistics for simulating water equivalent of snow. The temperature-index based model simulations exhibit a systematic over-estimation of snow water equivalent, with a ME of 7.7 mm water equivalent in the baseline simulation, due to not taking into consideration the effect of the radiation on snowmelt (Fig. 5). However, the energy balance-based model simulations performed very well in reproducing the water equivalent of snow in both accumulation and ablation periods (Table 3), with RMSE and ME values being relatively small at 12.4 mm and 0.30 mm, respectively. Omitting blowing snow sublimation resulted in an overestimation of the water equivalent of snow, with ME of 19.1 mm for the temperature index-base model, and ME of

Table 4
Snow mass budget expressed as snow water equivalent.

	Snowfall (mm)	Snowmelt (mm)	Snow in situ sublimation (mm)	Sublimation by blowing snow (mm)	Transport loss by blowing snow (mm)
Scheme 1	291	232.8	0	47.4	10.8
Scheme 2	291	146.4	68.0	69.8	6.8

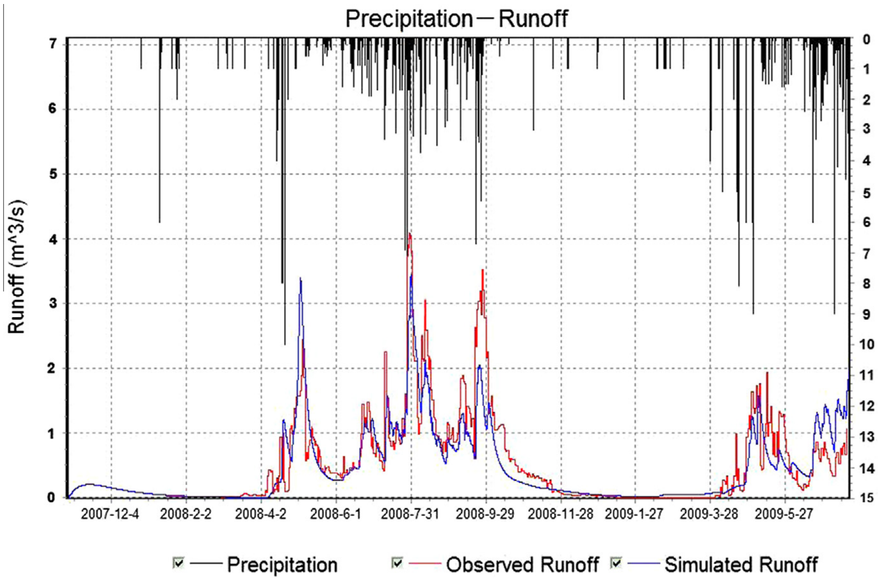

Fig. 7. Comparison between simulated and observed streamflows at outlet of Binggou basin: simulated uses CRHM with the energy budget snowmelt routine and full blowing snow simulation.

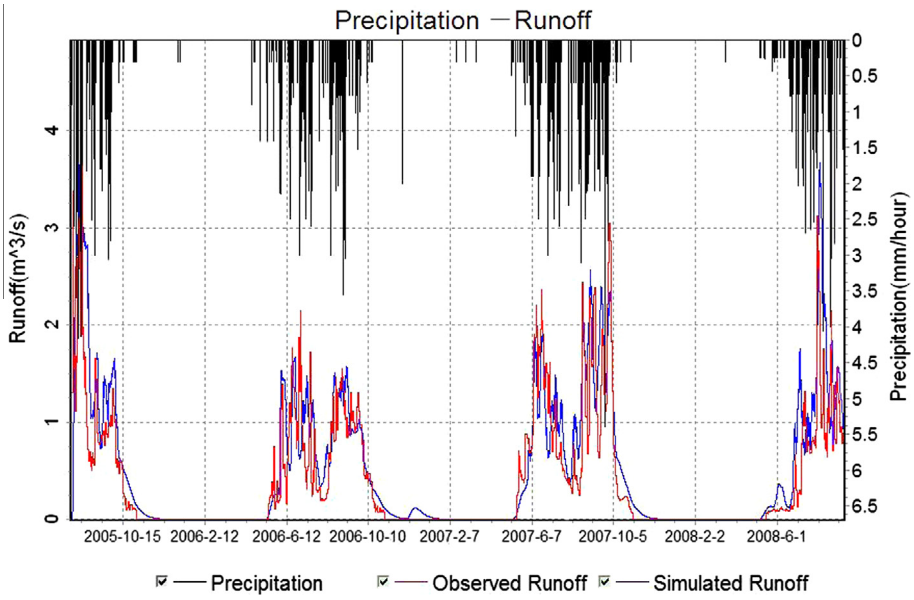

Fig. 8. Comparison between simulated streamflow with CRHM-including frozen soil infiltration module and observation at Zuomaokong basin.

9.10 mm for the energy balance-based model, respectively. Table 4 shows the mass balance terms from the temperature index and energy balance based model simulations. The energy balance simulation attributes about one half of snow ablation to the snowmelt (137.8 mm) and most of the rest to sublimation from blowing and in situ snow. The simulated snow mass loss due to snowpack in situ sublimation (68.0 mm) was nearly as great as that due to blowing snow sublimation (69.8 mm). Transport by blowing snow accounts for only 2% loss, due to an approximate balance between transport in and transport out of Binggou basin. The temperature index model attributes much more ablation to snowmelt than does the energy balance-based model and also fails to capture the winter snow regime correctly. The results indicate that accurate simulation of snow accumulation and ablation in this mountain environment requires consideration of blowing snow transport and sublimation, snowpack sublimation and the energy balance control of snowmelt, including turbulent transfer and radiation effects.

Fig. 7 shows streamflow from Binggou basin estimated with the energy balance snowmelt based CRHM model (scheme 2) and the observed basin discharge rate. With minimal calibration, the coefficient of determination for the linear regressions R^2 and NSE values between simulated and observed streamflows were 0.83 and 0.76, respectively. The comparison of the hydrographs in Fig. 7 shows that the model captured the main streamflow generation events. Especially in spring 2008 and 2009, the model has the capacity to capture the timing and magnitude of peak spring basin discharge after spring snowmelt. The results suggest predicting the snowmelt–runoff process at Binggou basin is possible with calibration restricted to hydrograph shape aspects of the model.

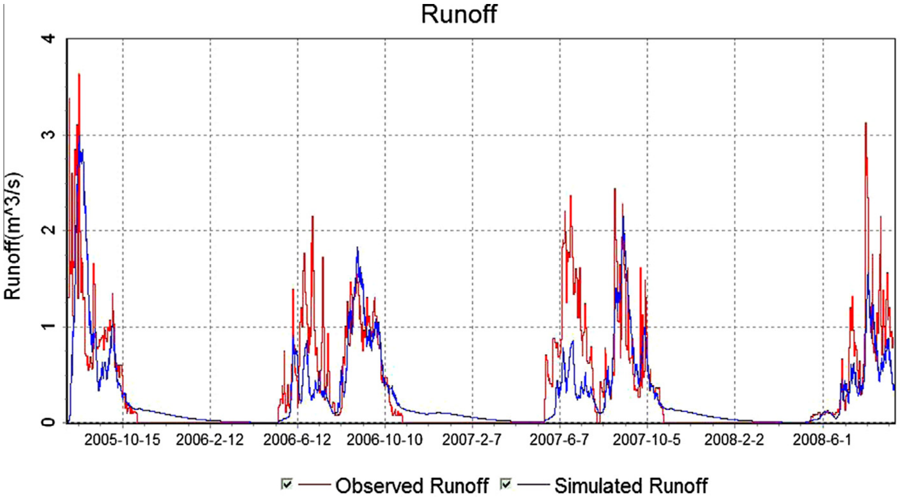

Fig. 9. Comparison between simulated streamflow with CRHM-omitting frozen soil infiltration module and observation at Zuomaokong basin.

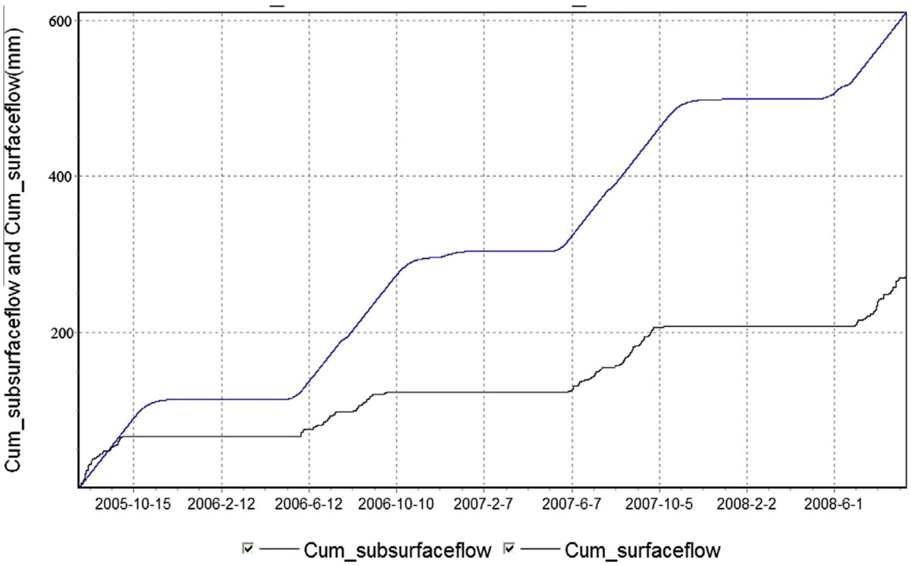

Fig. 10. The modeled cumulative subsurface flow and surface flow with CRHM including module for handling frozen soil infiltration at Zuomaokong basin.

3.2. Zuomaokong basin

The simulation time period for the Zuomaokong basin was from August 1, 2005 to September 7, 2008, with an hourly time step. Local meteorological stations were used to provide input variables (wind speed, air temperature, humidity, precipitation, and incoming solar radiation) for the simulations.

Fig. 8 shows the simulated and observed basin streamflow discharges from the model that included a module for handling both unfrozen and frozen soil infiltration. In both observed and simulated hydrographs, there were two periods of high flow each year: the spring high flow period from May to June with a recession process in July, then the summer high flow period in August with a fall recession from September to October. The coefficient of determination for the linear regressions R^2 and NSE values between simulated and observed streamflows are 0.87 and 0.79, respectively when both frozen and unfrozen soil infiltration was considered. Fig. 9 shows the simulated and observed basin streamflow discharges when the model only included a module for handling unfrozen soil infiltration neglecting frozen soil infiltration. The coefficient of determination for the linear regression R^2 and NSE values between simulated and observed streamflows are 0.58 and 0.55, respectively. Comparison of the modeled results with observations shows that the model which includes a module for handling both frozen and unfrozen soil infiltration can best capture streamflow generation, especially in the spring frozen-soil thawing period.

Using the CRHM model with the module for frozen and unfrozen soil infiltration, the type of runoff can be estimated. The modeled cumulative subsurface runoff (interflow) and surface runoff (Hortonian flow) are shown in Fig. 10. The results reveal that subsurface runoff generated during thawing of frozen soils starts in the first ten-days of May and slightly earlier than surface flow. The modeled cumulative subsurface flow (607 mm) is approximately 2.3 times the surface flow (264 mm) during August 2005 to September 2008. The result agrees with field observations of hillslope runoff (Wang et al., 2009), where the ratio of sub-surface to surface runoff was 2.43 in 2008.

Based on the above analysis, the spring thawing of the active layer generated a higher subsurface flow than the surface runoff, causing a higher runoff yield. The variation of the soil active layer due to freezing and thawing affected seasonal soil water dynamics, water budget and seasonal runoff characteristics, and is considered a major factor in control of the hydrological processes at the Zuomaokong basin.

4. Conclusions

To better predict the hydrological processes of ungauged basins in western China, the CRHM platform, a flexible object-oriented modeling system based on modular modeling concepts, was used to link suitable cold regions hydrological process modules into purpose-built models, appropriate for the cold regions environment, scale of application, data availability, and for the objectives of the simulation. By balancing model complexity and parameter uncertainty with physically-based process representation and rigorous testing of each module, CRHM can help the researcher select the most appropriate approach and structure for simulations with minimal need for model calibration. In this study, CRHM was successfully applied to a seasonally snow-covered alpine basin (Binggou basin) and a semi-arid permafrost steppe basin (Zuomaokong basin) in the high elevations of western China. Simulations that included blowing snow transport and sublimation, energy balance snowmelt and infiltration into frozen soils performed best and demonstrated the necessity of including these processes for hydrological prediction in the region. The physical identifiability of process based module parameters and the ability to develop models that have appropriate process representation meant that parameter uncertainty was much smaller than is typical for conceptual hydrological models and parameters estimated from field studies in the region were able to provide strong model performance. The superiority of physically based approaches was demonstrated by comparing a calibrated temperature index melt estimation to an uncalibrated energy balance melt calculation. The physically-based, uncalibrated energy balance approach provided much better simulations than the calibrated temperature index approach for snowmelt for both snow regime and streamflow. This demonstration of cold regions modelling with minimal calibration far from the source region of the model is encouraging. The modular approach of CRHM and the modules implemented in CRHM will provide the basis for more efficient and collaborative cold regions hydrological model development in the future. This type of integrative and open-source approach is desperately needed in order to solve challenges to complicated natural systems, such as the impact of global climate change on cold regions hydrological processes.

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