Simulation of Snowmelt and Runoff Based on Component in Northwest of China

Liu Yang, Yang Yongchun, and Zhang Ke

Abstract—**Integration has become an efficient method in nature resources assessment and management along with the need of achieving the goal of sustainable natural resource management. The physically based cold regions hydrological modeling platform (CRHM) was used to create two cold region hydrological models for Binggou watershed, located in northwestern of China and Zuomaokong watershed, located in the hinterland of the Qinghai-Tibet plateau. To evaluate CRHM, simulations of snow depth with/without sublimation module compared to observations were carried out in Binggou watershed. Another comparison which aimed at finding out what influence the frozen soil has to runoff was implemented in Zuomaokong watershed. The model performance in predicting snow depth and runoff was evaluated against field observations. Root-mean-square error (RMSE) between simulation and observations ranged from 0.067949 to 0.076158 for the simulated snow depth in 2007/2008, with higher RMSE in the simulation that the sublimation module was used. The model was able to capture the timing and magnitude of peak autumn basin discharge, but it underestimated the basin discharge without the frozen soil module included in spring 2008 and 2009, respectively. The results suggest prediction of northwestern of China snow hydrology is possible with no calibration if physically based models are used with physically meaningful model parameters that are derived from high resolution geospatial data.**

Index Terms—**Binggou watershed, CRHM method, simulation.**

I. INTRODUCTION

Tremendous progress has been made in discovering basic principles in different scientific disciplines that created major advances in modeling technology for natural resource systems. However, understanding natural resource management issues, particularly in water resources management and agricultural management, become more and more important and compound (Thomas and Durham, 2003; Biswas, 2004). Along with a growing understanding that single model for particular problem can be insufficient for representing all the details needed for problem understanding, decision making and planning, it is argued that achieving the goal of sustainable natural resource management should involve consideration of whole system effects (Pahl-Wostl, 2007). As a result, integration has become an efficient method in nature resources assessment and management in recent years (Argent, 2004; Gaber *et al.*, 2008; Voinov *et al.*, 2010). This integrated multidisciplinary scheme usually requires accounting for a significant number of various models (e.g., crop growth, hydrology, ecology, and solute transport), data sources, management alternatives, and analysis algorithms.

In the last few years, numerous scientists have oriented their researches to enhance the knowledge on the complex interactions between agricultural systems and the hydrological cycle, contributing to the development of eco-hydrologic model and soil-plant-atmosphere model (Smith *et al.*, 1997; Shaffer *et al.*, 2001; van Ittersum, 2003; Smettem, 2008). Although a myriad of hydrological models are available, they are typically constrained to the specific scales and purposes for which they have been developed and therefore are more robust in some areas than others (depending on the primary goal guiding their development) [1]. Furthermore, most of these monolithic models are not modular; are very difficult to update, add to, or connect with other models; have diminishing technical support; and lack of the flexibility to satisfy the needs for more integrated analysis of changing natural resource issues.

The state-of-the-art challenges in optimal management of the natural resources is to create a flexible and easy-to-use modeling framework that can conveniently integrate existing and/or future models. Such a system will maintain modularity, reusability, and interoperability or compatibility of both science and auxiliary components. The system could be driven by problem objectives, scale of application, data constraints. These functionalities of the system will be obtained by establishing standard libraries of interoperable scientific and auxiliary components or modules that provide the building blocks for a number of similar applications. Module libraries have been successfully used in several domains, such as the hydrological, ecological, and other systems (Breunese *et al.*, 1998; Praehofer, 1996) [2]. The earliest modular model development was done for SHE, the European Hydrologic System Model (Abbot *et al.*, 1986). Leavesley *et al.* (1996) reported the conversion of the Precipitation Runoff Modeling System (PRMS) to a Unix-based Modular Modeling System (MMS) for hydrologic modeling. Leavesley *et al.* (2002) presented some successful applications of this concept. Other examples of model integration framework include the Interactive Component Modeling System (ICMS) (Rahman *et al.*, 2004), Tarsier (Watson and Rahman, 2004), Invisible Modeling Environment (TIME) (Rahmana *et al.*, 2003), Spatial Modeling Environment (SME) (Maxwell and Costanza, 1995, 1997), European Open Modeling Interface (OpenMI) (Gregersen, 2007), Common Component Architecture (CCA) (Bernholdt *et al.*, 2004), Earth System Modeling Framework (ESMF) (Collins, 2005), Catchment Modeling Toolkit (CMT)

Manuscript received July 20, 2013; revised September 22, 2013.

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DOI: 10.7763/IJSSH.2014.V4.340

(Moore, 2007), Object Modeling System(OMS) (David *et al.*, 2002) and Cold Regions Hydrological Model Platform(CRHM)(Pomeroy *et al.*, 2007) [3].

The objectives of this study are to evaluate and validate CRHM model, demonstrate, using examples, how CRHM has proven to be a potentially useful research tool in diagnosing the hydrological cycle and in predicting elements of this cycle in the Chinese cold regions where calibration against measured streamflow is not possible or warranted.

II. METHODS

A. Cold Regions Hydrological Modeling Platform

Modular programming and object-oriented programming have been widely used in environmental simulation (Leavesley *et al.*, 1996; David, 2002) and other applications. With modular programming, software is composed of separate, interchangeable components, called modules by breaking down program functions into modules, each of which accomplishes one function and contains everything necessary of the function. Conceptually, modules represent a separation of concerns, and improve maintainability by enforcing logical boundaries between components. Modules are typically incorporated into the program through interfaces (Fig. 1). Object-oriented programming (OOP) can be used to associate real-world objects and processes with digital counterparts more directly. An object bundled with both data and methods can reflect real-world object better than conventional no-OOP modular method. Featured with the encapsulation, inheritance and polymorphism, object-oriented development improves manageability, reusability and flexibility of software.

CRHM is a modularized object-oriented modeling framework, following the core idea of MMS, for cold region hydrological simulation and study, developed by a large multidisciplinary research group from various institutions in Canada (Pomeroy *et al.*, 2008; Rykaart and Hockley, 2010) [4]. CRHM incorporates a more complete range of cold regions hydrological processes which involve blowing snow, snow interception in forest canopies, sublimation, snowmelt, infiltration into frozen soils, hillslope water movement over permafrost, actual evaporation, and radiation exchange to complex surfaces [5]. Each process is implemented as a software module with C++ and can be integrated with other modules to construct a more complex model. Furthermore, CRHM is quite user-friendly because of its full-featured Graphic User Interface (GUI) and flexible macro with which different models can be glued together conveniently.

Based on the modular and object-oriented techniques, CHRM offers not only a model library which has contained a wide range of models, but also a robust framework for enabling models integration with the flexible construction. In CRHM, every module describes a physically based algorithm or data transformation. The physically-based algorithms or selected algorithms are integrated into a model in the framework. Not only can the modellers add the existing algorithms into the framework, but also can modify the existing algorithms for their own sake or develop new algorithms to the module library. The selected modules from the module library are coupled to create a model on specific purpose. Note that CRHM module development has focused on specific and often neglected cold region aspects of hydrology.

Furthermore, by balancing complexity and parameter uncertainty, the most appropriate approach and structure for the selected process is suggested to the researchers by the model (Pomeroy *et al.*, 2010) [6].

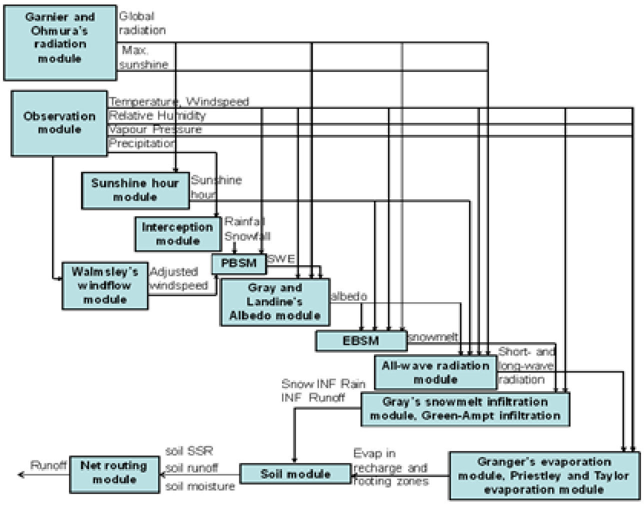

Fig. 1. Flowchart of physically based hydrological modules in CRHM.

B. Model Description

In CRHM, in accordance with the different stages and physical processes, eight types of physically-based models are abstracted and implemented. For the detail, they reflect snow transport, interception, radiation, evaporation, snowmelt, infiltration, soil moisture balance, and flow respectively (Pomeroy *et al.*, 2007). To represent either the different algorithms of the same process or the same process resulting from different initial or boundary conditions, there are different implementations for the same type of models. For instance, one of the infiltration modules FrozenAyers handles unfrozen soil infiltration using Ayers and frozen soil using Zhao and Gray while Ayers handles only unfrozen soil infiltration (CRHM doc), "NO_pbsm" model handles snowfall with no snow transport while "pbsm" model is a fully functioning blowing snow model and "pbsm_M" model is a more advanced version of "pbsm" with more comprehensive snow transport distribution features [7]. Such mechanism ensures the diversity of models to satisfy different environments. Obviously, this increases the difficulty to select the appropriate models for the practices of simulation; however, it is worth it.

In our study, the version of CRHM for this analysis and several modules which have been applied to the generic framework described by Pomeroy *et al.* (2007). The relevant modules and the forcing data used in this model are showed in Fig. 2. There are two main subdivisions: (1) physically-based modules, include algorithms developed using the physical principles governing processes, such as energy balance snowmelt, evaporation and infiltration into frozen soils; and (2) conceptual modules, which represent processes that are less well understood, such as the soil moisture balance and flow routing.

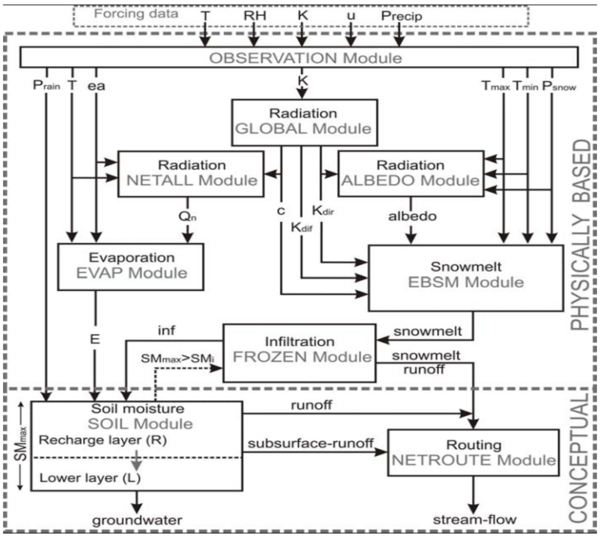

Fig. 2. Outline of the modular structure of the CRHM model used.

C. Component Architecture

Model development is based on CBT (David *et al.*, 2002, 2010) within OMS3. The main idea of CBT is to develop software systems by selecting appropriate off-the-shelf components and then to assemble them with a well defined software architecture (Arvinder and Kulvinder, 2010). Components are context-independent, both in the conceptual and technical domain. They represent self-contained software units that are separated from the surrounding framework environment. The components not only respect the module, but also could implement a specific simulation concept.

III. RESULT AND ANALYSIS

To demonstrate, how a modular-based, object-oriented model—CRHM has proven to be a potentially useful research tool in diagnosing the hydrological cycle and in predicting elements of this cycle in the cold regions where calibration against measurements is not possible or warranted. The examples was carried out in Binggou watershed, located in northwestern of China and Zuomaokong watershed, located in the hinterland of the Qinghai-Tibet plateau. Two comparisons were implemented in the two watersheds.

Simulated and measured values were compared using the model efficiency (*ME*) and root mean square error (*RMSE*) [8]. Model efficiency ($ME \leq 1$) is defined as the fraction of variation in observed values explained by the model (Nash and Sutcliffe, 1970), it is an indication of model performance compared to the mean of the observations. The *RMSE* is a weighted measure of the difference between observation and simulation and has the same units as the observed and simulated values, is a quantification of the absolute unit error between simulations and observations. The model efficiency (*ME*) and root-mean-square error (*RMSE*) were calculated as:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(Y_M - Y_O) \qquad (1)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(Y_M - Y_O)^2\right]^{1/2} \qquad (2)$$

where

Y_M and Y_O are the respective simulated and observed values at a given time step for *N* number of paired simulated and observed values [9].

A. Simulations in Binggou Watershed

The first example was implemented in Binggou watershed. The model was initialized without sublimation process and then in comparison, the sublimation module was added to the model.

The Binggou watershed is located in the upstream of the Heihe river basin in northwestern of china. The minimum altitude of Binggou watershed is 3440m while the maximum is 4400m. The area of Binggou watershed is 30.27 km^2 [3]. It is a seasonally sonw-covered region. The maximum depth of seasonal snowpack is 0.8-1.0 m and the average value is 0.5 m. The snow redistribution is remarkable because of the interaction between blowing snow and complex terrain. During the redistribution process, the sublimation is significance. The snowfall always takes place from November to April which is spring and autumn. Then a rainy season occurs form May to August. The minimum air temperature is-29.6 ℃ and the maximum is 19.9 ℃. The mean air temperature is-2.5℃ which is observed during 2008 snow season.

Two automatic weather stations (AWSs), Dadongshu Mountain Pass Snow Observation Station (DY) (4146.8 m, 100°14′E, 38°01′N) and Binggou Cold Region Meteorological Station (BG) (3449.4m, 100°13′E, 38°04′N) (Fig. 3) are used to collect meteorological data. The daily discharge is measured by a hydrological gauge which is installed at the outlet of the watershed. The basic snow properties such as snow depth, density, temperature, emissivity and so on are collected through a series of field measurements in 2008. The topographic information is obtained from the DEM of the Binggou watershed, with a 50m resolution.

Simulated and observed snow depth (with/without sublimation process) at Binggou watershed is shown in Fig. 4 (without sublimation model) and Fig. 5 (with sublimation model) with model performance index values given in Table I.

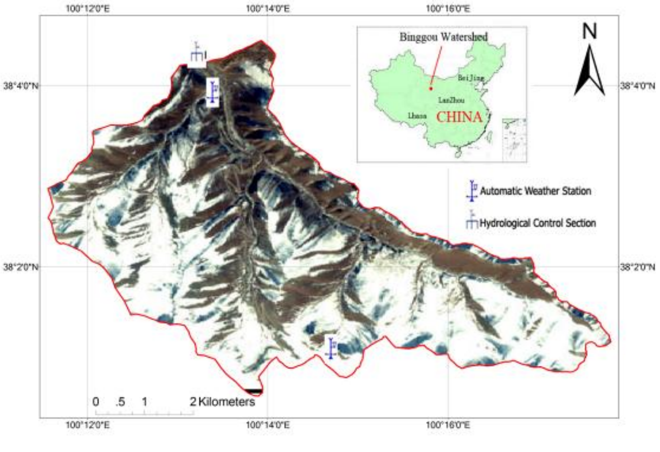

Fig. 3. Map of the Binggou watershed.

In Table I, simulations reveal a systematic under-prediction of mean SWE for all sites (*MB*=0.97). In comparison, a greater under-prediction of maximum SWE at all sites was realised (*MB*=0.94). Yet, the high ME value indicates CRHM well represented the variability in mean and maximum SWE accumulations between sites. Similar to *MB* results, the ME shows superior prediction of mean SWE to that of maximum SWE, as well as better prediction for clearing sites relative to forest sites. However, due to less snow at the forest sites, the lower *MB* and ME indexes at the forest sites translate into similar magnitudes of absolute error to that at the clearings (*RMSE*=-16 kg/m2), and even lower absolute errors for the prediction of maximum SWE.

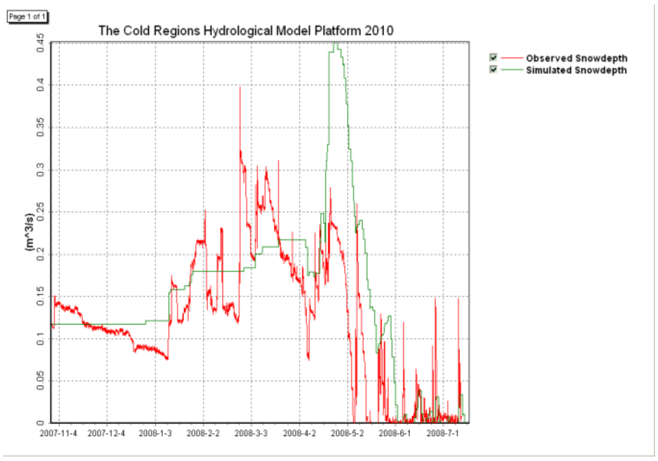

Fig. 4. The observed and simulated snow depth of the Binggou watershed from date to date without sublimation process included.

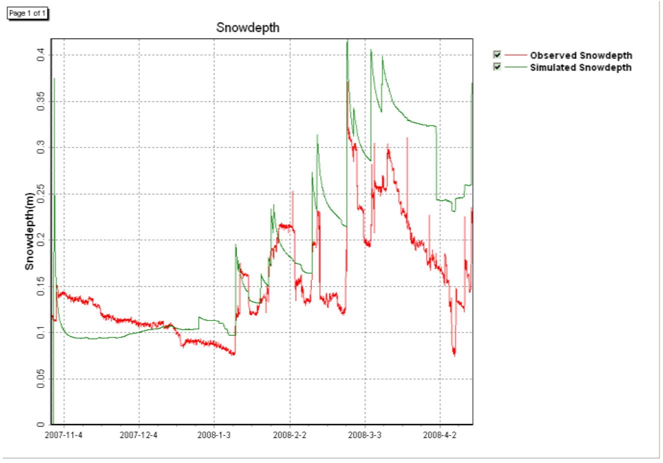

Fig. 5. The observed and simulated snow depth of the Binggou watershed from date to date with sublimation process included.

B. *Simulations in Fenghuoshan Watershed*

Another comparison is carried out using the observations in Fenghuoshan watershed which is characterized by frozen soil.

Located in the upper watershed of the Zuomao Kong River, a tributary of the Yangtze River, the Fenghuoshan permafrost region of the Qinghai-Tibet plateau (92°50′–93°3′E and 34°40′–34°48′N) served as the study area. It embraces a total area of 127.63 km2 at elevations ranging from 4510 m to 4723 m (Fig. 6). The annual mean (1973–2005) air temperature (Ta), relative humidity and precipitation were -5.2 ℃, 57%, and 310.7 mm, respectively. The vegetation is dominated by Kobresia pygmaea C.B. Clarke and Kobresia humilis Serg [10]. According to the degree of degradation, vegetation cover of the region’s grasslands was divided into three categories: non-degraded, moderately degraded and severely degraded, corresponding to 93%, 65% and 30% coverage. In severely degraded grassland Kobresia sp. was replaced by Festuca sp. and Poa spp. (Wang *et al.*, 2011; Zhou, 2001) [11]. Soil in the region is dominated by mattic gelic cambisols. The main physical properties and nutrient contents of the region’s alpine frost meadow soils under different levels of cover are presented in Table I. In severely degraded alpine frost meadow, the coarse sand and gravel contents of the topsoil were significantly increased. The greater the vegetation cover, the larger the soil organic matter content and the lesser the soil bulk density (Table I). In the study area the permafrost was well developed, averaging between 50 and 120 m in depth, with an active layer of 0.8–1.5 m (Zhou *et al.*, 2000). There are two meteorological stations, and the meteorological indexes, such as air temperature, land surface temperature, precipitation, wind, humidity, total radiation, net radiation were observed.

The simulations of runoff during the February–April of 2008 and 2009 were evaluated against observations. For the simulation period, two comparisons: the observed and simulated runoff without frozen soil module included, and the observed and simulated runoff with the frozen soil module in use were conducted. Fig. 7 and Fig. 8 show the comparisons of the observed runoff and simulated runoff with/without frozen infiltration module included in Fenghuoshan watershed. For the May 2006 to July 2006 and May 2007 to July 2007 simulation periods, the model tended to underpredict the runoff compared to the observations because of the lack of frozen infiltration module (Shown in Fig. 7). However, when frozen infiltration was added into the model, as Fig. 8 demonstrated, a nice result was obtained in which the predicted runoff was generally in good agreement with the observations.

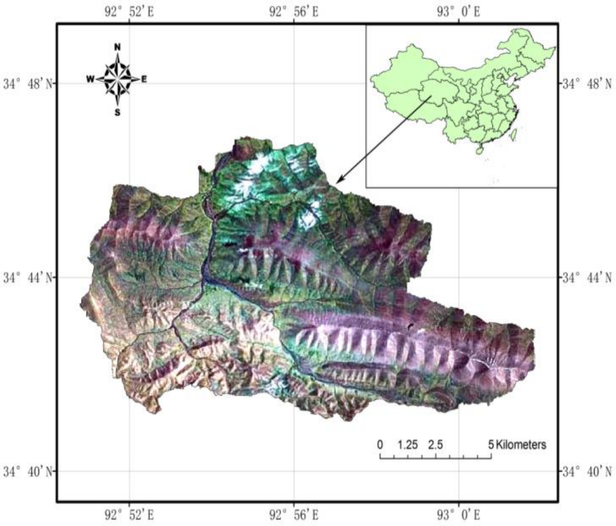

Fig. 6. Map of the Binggou watershed.

Dissimilar model performances were observed for the considered models [12]. Differences between simulated and observed results were small in the summer and autumn due to the reduction in the spatial variability of the initial SWE compared to 2002 (Fig. 8). For the summer and autumn season, simulated runoff values of both the with-frozen-soil-module and the without-frozen-soil-module models showed a close agreement with the observations; however, model results diverged in the spring season. The with-frozen-soil-module model adequately described the runoff with a ME value of 0.117886217 (Table II), whereas the without-frozen-soil-module model was unable to simulate the beginning of the springtime, showing a much lower runoff than the observed with a ME value of-0.066718093 (decreasing to a value of 0.68). This difference in performance resulted in an increase of the RMSE from 9 to 24.5 mm of runoff. Conversely, for the summer and autumn periods, simulated runoff values of both the with-frozen-soil-module and the without-frozen-soil-module models exhibited a very similar description of the evolution of the observed runoff. Analysis of the model performances showed ME values for the with-frozen-soil-module and without-frozen-soil-module model of 0.70 and 0.72 for 2003 and 0.74 and 0.80 for 2004, respectively. Similar performances in terms of the RMSE were also observed.

TABLE I: MODEL EFFICIENCY INDEX (*ME*), AND ROOT MEAN SQUARE ERROR (*RMSE*) OF SIMULATED SNOW DEPTH AT BINGGOU WATERSHED

items	with sublimation process	without sublimation process
ME	0.0356	0.029
RMSE	0.067949	0.076158

TABLE II: MODEL EFFICIENCY INDEX (*ME*), AND ROOT MEAN SQUARE ERROR (*RMSE*) OF SIMULATED RUNOFF AT FENGHUOSHAN WATERSHED

items	with-frozen-soil-module	with-frozen-soil-module
ME	0.375524	0.06672
RMSE	0.845618	0.384314

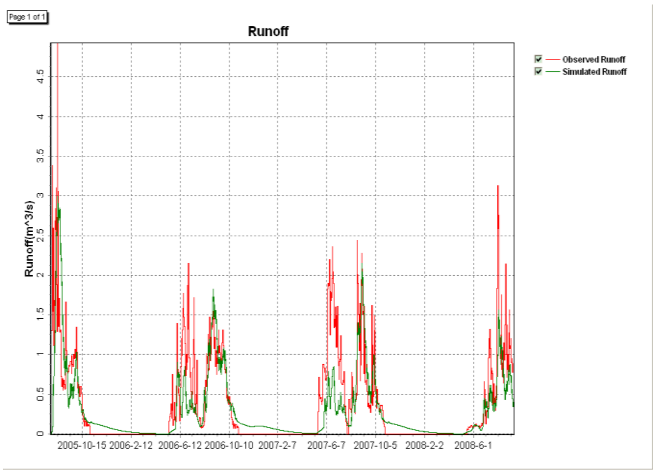

Fig. 7. The observed and simulated runoff of the Fenghuoshan watershed from date to date without frozen soil module included.

C. *High Quality of Module Implementation*

Based on a modular, object-oriented structure in which component modules represent basin descriptions, observations, or algorithms for calculating hydrological processes, CRHM, as an integrated modeling system, allow the scientists and researchers to apply the most suitable science for specific problems (increase the probability of using the best science available in various combinations for the given conditions and problem), to enhance their productivity and quality of science module implementation. The component-oriented and modular approach of the integrated framework and the modules/models implemented in it will provide the basis for more efficient and collaborative model development in the future. This type of integrative and open-source approach is desperately needed in order to solve global challenges impacting natural resource systems such as sustainable management of natural resource systems and the impact of global climate change on natural resource systems.

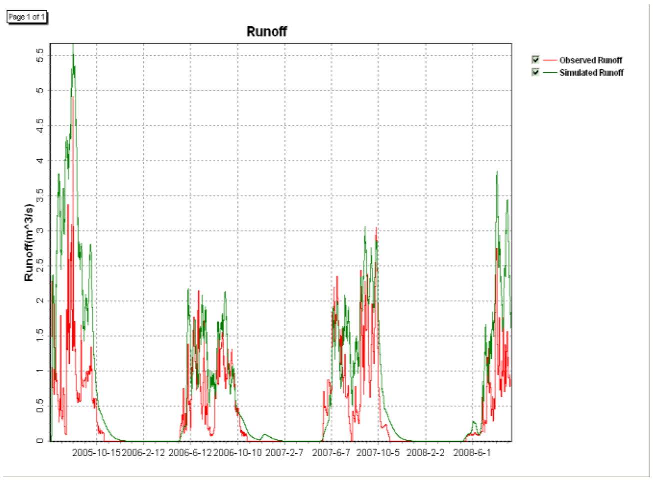

Fig. 8. The observed and simulated runoff of the Fenghuoshan watershed from date to date with frozen soil module included.

IV. CONCLUSIONS

By sites, a simple application has been demonstrated that examines the influence of different modules on specific catchment by balancing complexity and parameter uncertainty with necessary process representation and spatial resolution of the model. Two separate hydrological models which represent two study areas were assembled using a suite of physically-based model algorithms provided with the CRHM platform. Under conditions when snow sublimation is considered, the snow depth is closer to the observed snow depth and of Binggou watershed. Better results were obtained in terms of containing the frozen infiltration process in the simulation of runoff in Fenghuoshan watershed.

Overall, results show that CRHM is able to well represent the quantity and timing of snow depth and runoff in northwestern of China and the Qinghai-Tibet plateau which is relatively ungauged basins.

Future efforts need to concentrate on several aspects. One issue is to develop some new modules to enrich the module library of CRHM, so that CRHM can be more appropriate for China cold regions' simulations. The transformation of CRHM modules to OMS modules is another concern. Future environment scientists could develop the most suitable models for their specific problems very rapidly with fewer efforts.

ACKNOWLEDGMENT

This work is supported by the Fundamental Research Funds for the Central Universities (grant number: NCET-07-0398) & Plan for person with ability of Chinese Ministry of Education in the 21st century (grant number:NCET-07-0398) and the NSFC (National Science Foundation of China) project (grant number: 41171143 & 40771064). Gratitude is expressed to these funds for supporting our work.

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