SNOWMELT RUNOFF ANALYSIS AND IMPACT ASSESSMENT OF TEMPERATURE CHANGE IN THE UPPER PUNATSANG CHU BASIN, BHUTAN

Jigme Tenzin and Suwit Ongsomwang*

Received: June 04, 2015; Revised date: August 11, 2015; Accepted date: August 11, 2015

Abstract

In the an area like Bhutan, the accessing and monitoring of glacier and snow melt is difficult due to its the unfriendly and rugged terrain,; thus, the Ssnowmelt Rrunoff Mmodel (SRM) with remote sensing data offers the potential for furnishing information to improve water resources management and decision making. The main objective of the study is to estimate runoff during the snowmelt period and the impact of hypothetical temperature change on streamflow. Herewith, the model input data include basin characteristics, variables, and parameters to execute the model. The processes are routinely operated by a calibration and validation process and accuracy assesses assessments with standard measurements. The output includes runoff volume and average runoff with a hydrograph for a the melting season (April- August) of the years 2005-2009. Besides, the impact of temperature change on the streamflow are is investigated using three 3 different hypothetical scenarios: (1). T + 1˚C, (2) T + 2˚C, and (3) T + 3˚C. The simulated average runoff volumes were 446.08, 416.49, 422.51, 480.19, and 440.29 m^3/s, respectively, for the years 2005-2009. The computed discharge is was then correlated with the measured discharge and it was found that the Nash-Sutcliffe efficiency efficiency rangingrange: was 70 – 93%, the absolute percent bias: ranging ranged from 3.45 to 5.18%, and the difference in volume different rangingranged from: -5.18 to 3.45 for all the hydrological years. Based on the hydrograph, it was observed that the SRM model has simulated the daily flows reasonably well showing a generally a good agreement with the daily observed flows except for a few peaks. However, it was found that the SRM model has some limitations to for modelling the a period where when there is an occurrence of extreme weather conditions like a cyclone, storm, and or heavy rainfall. In the case of the impact of temperature change on the streamflow, it was observed that with every 1˚C increase in every 1˚C of the average temperature, an the average runoff increased by 7%. In conclusion, the results achieved by the SRM model for the basin considerable displayed considerably good agreement and the model proved to be an efficient tool to simulate snowmelt runoff and study the impact of temperature change on streamflow. The output can be used as a guideline for water resources management, hydraulic system design, and a mitigation plan to combat the effects of climate change effect.

Keywords : Snowmelt runoff analysis / SRM Model / Impact of temperature change / Punatsang Chu Basin / Bhutan

[1] *School of Remote Sensing, Institute of Science, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand. E-mail: suwit@sut.ac.th*

* *Corresponding author*

Introduction

Snow is an important environment parameter, not only influencing the Earth's radiation balance but also playing a significant role in river discharge. Snowmelt and from snow covered areas (SCA) has been the major source of runoff and groundwater recharge in middle and higher latitudes areas (Jain, *et al*., 2010). The process of converting snow and ice into water, known as snowmelt, needs the input of energy (heat). Hence, snowmelt is linked to the flow and storage of energy into and through the snowpack (United States Army Corps of Engineers USACE, 1998). Therefore, estimation of the snowmelt runoff is very important for regulating the flow from the reservoirs, estimating flood flow for the design of hydraulic structures, and for other water resource development activities in the Himalayan region.

Singh and Jain (2003) affirmed that the snowpack depletes either fully or partially during the forthcoming summer season depending up on the climatic conditions. Attributing Contributing to the climatic condition, there is a change in the areal extent of snow covered areathe (SCA) and snow free areas (SFA) over the time, and the contribution from the rain and snow to the streamflow varies with the season. However, the precipitation like rain dominates the precipitation in the lower altitude part of the basins (< 2000 m amsl.) and, rain and snow in the middle and higher altitude regions of the basins (about > 2000 m amsl.) with change in altitude. With an increase in the altitude of the basin, the rain's contribution to streamflow reduces and the snowmelt's contribution increases; therefore, runoff is dominated by the snowmelt runoff above an altitude of 3000 m (amsl.) altitude (Singh and Jain, 2003). In higher altitude and latitude regions where snowfall is predominatedpre-dominant, runoff depends on the heat supplied to the snowmelt rather than just the timing of the precipitation. Hence, to understand the hydrological behavior and simulate the stream-flow in such areas, it is very important to model the snowmelt runoff (Jain *et. al*., 2012).

In line with research on climate change by Liu and Rasul (2007), it should be clearly mentioned that, according to the Intercontinental Panel on Climate Change (IPCC) report, the climate change is a major concern in the Himalayas because of potential impacts on the economy, ecology, and environment of the Himalayas and the areas downstream. Bhutan, being part of the eastern Himalaya region, is adversely affected by climate change which causing causes the snow and glaciers residing on the mountains to melt faster and to ain larger extent as compared to with other parts of the world. This causes change in the hydrological cycle which may further disturb river runoff, accelerate water-related hazards, and affect agriculture, vegetation, forests, biodiversity, and health. However, the vulnerability of the Himalayas is unclear because of the lack of data and knowledge at the regional level (Chettri *et al*., 2010).

Bhutan has witnessed flash floods and glacier outburst floods which devastated acres of agriculture lands and infrastructure properties, destruction to historical monuments, and caused a threat to people living downstream in the Punatsang Chu basin in the years 1957, 1960, and 1994.

The basin shelters the fertile Punakha-Wangdue fertile valley along two 2 major rivers: the Pho (Mmale) Chu and Mo (female) Chu which are fed by snow and glaciers in the upper region of the basin. After the confluence of these two 2 rivers, the main river is called Punatsang Chu which and it flows to the south entering Indian Territory and joining the Brahmaputra River. The Punatsang Chu basin is the second largest basin amongst the five basins of Bhutan. Taking advantage of its topographical features - rugged, steep terrain and fast flowing rivers - the basin is has been declared as the home to the biggest ongoing hydropower projects: the Punatsang Chu Hydropower Project Phase I (1200 MW) and Phase II (1000 MW),; thus, from the economic perspectives the hydropower plants have been the major contributors to the economy of the country accounting for the increase in the overall gross domestic product.

Therefore, the information on spatio-temporal variations of snow and the snowmelt runoff can be applied practically to build the hydraulics infrastructure for the future hydropower projects after the completion of this research. Furthermore, it can provide sufficient information on water availability during different seasons which will be an advanceadvancing in the field of water resource planning and management.

The specific objectives of the research are: (1) to estimate the runoff from snowmelt to the river during the snow melting period, and (2) to assess the impact of temperature change on stream flowstreamflow by simulating the stream flowstreamflow under different future temperature change scenarios.

Concept of Snowmelt Runoff Model (SRM)

There are several temperature index-based snowmelt models like the SSARR Mmodel, the HEC-1 and HEC-1F Mmodels, the NWSRFS Mmodel, the PRMS Mmodel, the SRM, and the GAWSER Mmodel (Singh and Jain, 2003; and Jain *et al*., 2012). Among many models, the snowmelt runoff model (SRM), which uses the snow cover information as input, has been the most widely used for both simulation and forecasting (Martinec and Rango, 1989; Rango and van Katwijk, 1990; Ferguson, 1999; Martinec *et al*., 2007; DeWalle and Rango, 2008; Butt and Bilal, 2011). The SRM, or variations of it, were have been applied to over 100 basins in 25 countries at latitudes 32–60-N, and 33–54-S with basin sizes varying from <1 to 120000 km^2 and documented in about 80 scientific journals (Seidel and Martinec, 2004). This model has proved to be valuable for use in Himalayan regions where meteorological and gauging field networks are sparse (Immerzeel, *et al*., 2010).

The SRM is a conceptual, deterministic, degree-day hydrologic model used to simulate and/or forecast daily runoff resulting from snowmelt and rainfall in mountainous regions. The SRM requires daily temperature, precipitation, and daily snow-covered area values as input parameters.

Based on the input values, the SRM computes the daily stream flowstreamflow for a lag time of 18 h (Martinec *et al*., 2007) as:

$$Q_{n+1} = [C_{Sn}.\alpha_n(T_n + \Delta T_n)S_n + C_{Rn}.P_n].\; A\frac{10000}{86400}(1 - k_{n+1}) + Q_n.k_{n+1}] \quad (1)$$

According to Equation. (1), the daily average discharge (Q) on day n+1 is computed by summation of the snowmelt and precipitation that contributes to runoff with the discharge on the preceding day. Snowmelt from the preceding date is found by multiplication of the degree-day factor, α, (cm °C^{-1} d^{-1}), zonal degree- days (T+ΔT)(°C), and the snow-covered area percentage (S). To determine the percentage that contributes to runoff, the result of the above multiplication is further multiplied with CS, the snowmelt runoff coefficient, and the total area of the zone, A (km^2).

Measured/forecasted precipitation (P) is multiplied by CR, the rainfall runoff coefficient, and the zonal area to calculate the precipitation contributing to runoff. Discharge computed on the preceding date is multiplied by the recession coefficient (k) to calculate the effect on today's runoff. Equation. (1) is applied to each zone of the basin when the model is applied in a semi-distributed manner, the basin is subdivided into zones, and then the discharges are summed up. The SRM adjusts the input data if a lag time other than 18 h is used (Martinec *et al*., 2007).

For accuracy assessment of the model's performance, the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and volume difference in volume (DV) are used with the following equations.:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - Q')^2} \quad (2)$$

where Q_i is the measured daily discharge, Q_i' is the computed daily discharge, Q' is the average measured discharge of the season under study, and n is the number of daily discharge values.;

$$PBIAS = \frac{\sum_{1=1}^{n}(Q_i - Q_i')^2}{\sum_{1=1}^{n}(Q_i)^2} \times 100 \quad (3)$$

where Q_i is the measured daily discharge, and Q_i' is the computed daily discharge;

$$D_V[\%] = \frac{(V_R - V_R')}{V_R} . 100 \quad (4)$$

where V_R is the measured yearly or seasonal runoff volume, and V_R' is the computed yearly or seasonal runoff volume.

The SRM was has been successfully applied for runoff simulation by many researchers in various basins, namely, Ganges, Toutunhe, Gongnisi, Beas-Thalot, Brahmaputra, Parbati, Beas-Manali, and Kabul River under in the Himalayan region. The accuracies obtained from the mentioned studies are vary from 0.66 to 0.94 for the NSE and -7.5-12 for the DvDV, (Martinec *et al*., 2007).

Materials and Methods

Study Area

The study area, is in the upper region of the Punatsang Chu basin covering three 3 districts: Gasa, Punakha, and Wangduephodrang (partially), with a total area of 5636.95 sq. km encompassing the geographical area between 28° 14' N and 27° 27' N and 89° 19' E and 90° 22' E, is dissected by a discharge gauging station located at latitude 27° 27' N and longitude of 27° 27' N and 89° 54' E from the overall basin (Figure 1). The topography of the study area varies from an altitude of 1180 to 7087 m (amsl).

Data and Tools

A Ssummary of the data and tools used in this study is as follows:

(1) Temperature and precipitation. The daily temperature and precipitation of from the weather stations at Wangdue Renewable Natural Resources Research Centre (13640046) were collected from the Ministry of Economic Affairs (MoEA) and examined for to extrapolating extrapolate the average temperature to for each zonal hypsometric elevation.

(2) Discharge. The daily discharge data at station Wangdue station (13490045) was were collected from the MoEA for to assessing the SRM model's accuracy.

(3) Digital elevation model (DEM). The Shuttle Radar Technology ModelSRTM DEM which is more accurate than the Advanced Spaceborne Thermal Emission and Reflection RadiometerASTER DEM (Forkuor and Matthuis, 2012) was chosen and downloaded from the Consultative Group for International Agriculture Research CGIAR Consortium for Spatial

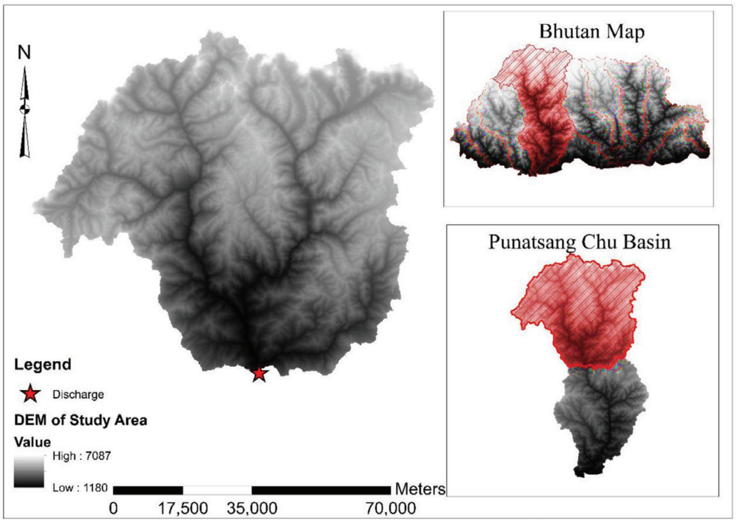


Figure 1. The study area and its location

Information website (http://www.cgiar-csi.org) for this study. This data is are used to generate the basin's characteristics.

(4) MODIS data. The Moderate Resolution Imaging Spectroradiometer (MODIS) snow products, MOD10A2 (Terra) and MYD10A2 (Aqua), with spatial and temporal resolutions of 500 m and 8-day, respectively, were downloaded from the NASA website (http://reverb.echo.nasa.gov/reverb) to calculate the zonal snow cover area based on the developed algorithm of Hall *et al*. (1995; 2001) and Hall *et al*. (2001). In this study, 225 scenes of MOD10A2 and 225 scenes of MYD10A2 were downloaded. This These products demonstrated the capability to detect and discriminate the snow from the clouds (Tekeli *et al*. 2005).

(5) WinSRM model. The WinSRM model is used for studying the snowmelt runoff and the impact of changing temperature on the snow cover area.

(6) ESRI ArcMap. This software is used for processing the DEM for delineating the watershed boundary and generating the hypsometric zones of the study area. In addition, the ArcMap Model Builder module is used to create a semi-automate model to extract the zonal snow cover area from multiple MODIS data.

(7) MODIS Reprojection Tools (MRT). The MRT enables users to read data files in the HDF-EOS format to specify a geographic subset or specific science data sets as the input to for processing, perform geographic transformation to a different coordinate system/cartographic projection, and write the output to file formats other than HDF-EOS.

(8) MODIS Snow Tool. It This was developed by the Mountain Environment and Natural Resources Information System division of MENRIS, ICIMODthe International Centre for Integrated Mountain Development (ICIMOD) in order to facilitate the processing and analysis of daily and 8-day standard MODIS snow products.

(9) MATLAB. It This is a high-level language and interactive environment for numerical computation, visualization, and programming. This software is used to interpolate the snow cover area of missing days between two consecutive 8-day snow products by the Piecewise Cubic Hermite Interpolation technique (Li and Williams, 2008).

Research Methodology

The schematic workflow of the research methodology, which consists of three 3 components: (1) input data preparation, (2) runoff simulation during snowmelt period by the SRM model, and (3) impact of temperature change on stream flowstreamflow, is schematically displayed in Figure 2. The Mmajor tasks of each component is are separately summarized in the following sections.

Input Data Preparation

• Hydro-meteorological data. The daily temperature, precipitation, and discharge which are recorded manually and supplied in raw format were converted to a time series format using MS Excel for executing the model. The Ddaily average temperature is derived using the observed maximum and minimum temperature readings. The Ddaily average temperature and precipitation during the snowmelt period for the years 2005-2009 is are displayed in Figure 3.

• Basin characteristics. The watershed basin boundary is subdivided into different elevation zones using the Reclassify tool and the area of each zone is calculated (Table 1). Herein, a curve is plotted between the cumulative zone area and the elevation range, and the zonal mean hypsometric elevation is calculated from the curve by balancing the areas above and below the mean elevation (Figure 4). The individual zone area and its mean hypsometric elevation are the basic basin characteristics used for setting up the model with the zone-wise approach

• Snow cover area (SCA) extraction. The MODIS products obtained for the study area in a HDF format are firstly re-projected to the Universal Transverse Mercator, Zone 45 N projection with reference datum WGS1984 and converted from HDF to the*.tiff format using the MRT tool software. Then both the MOD10A2 and MYD10A2 snow products are combined and apply cloud removal and spatial filtering are applied using the MODIS Snow Tool. The output obtained after applying the cloud removal

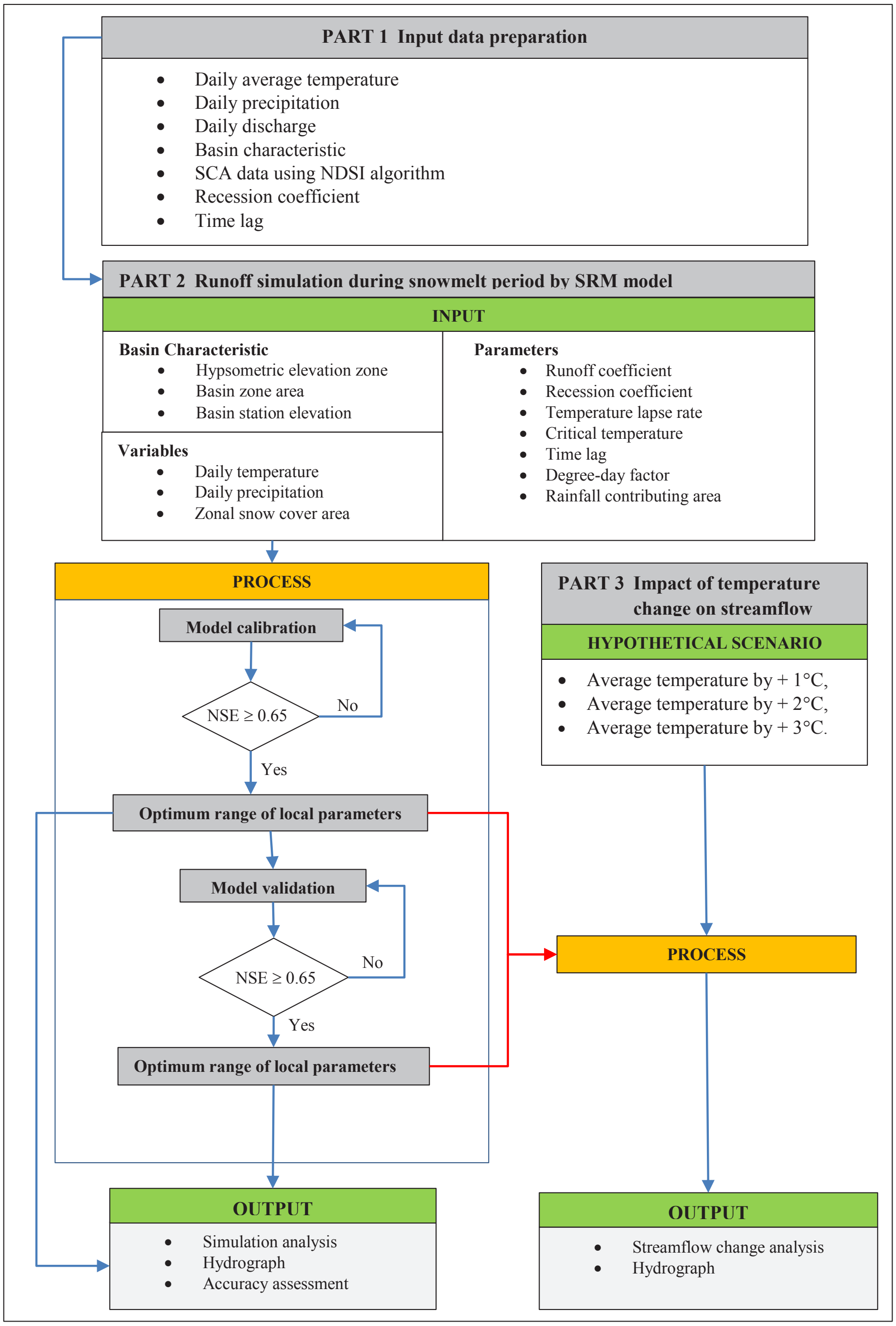


Figure 2. Workflow diagram of research methodology

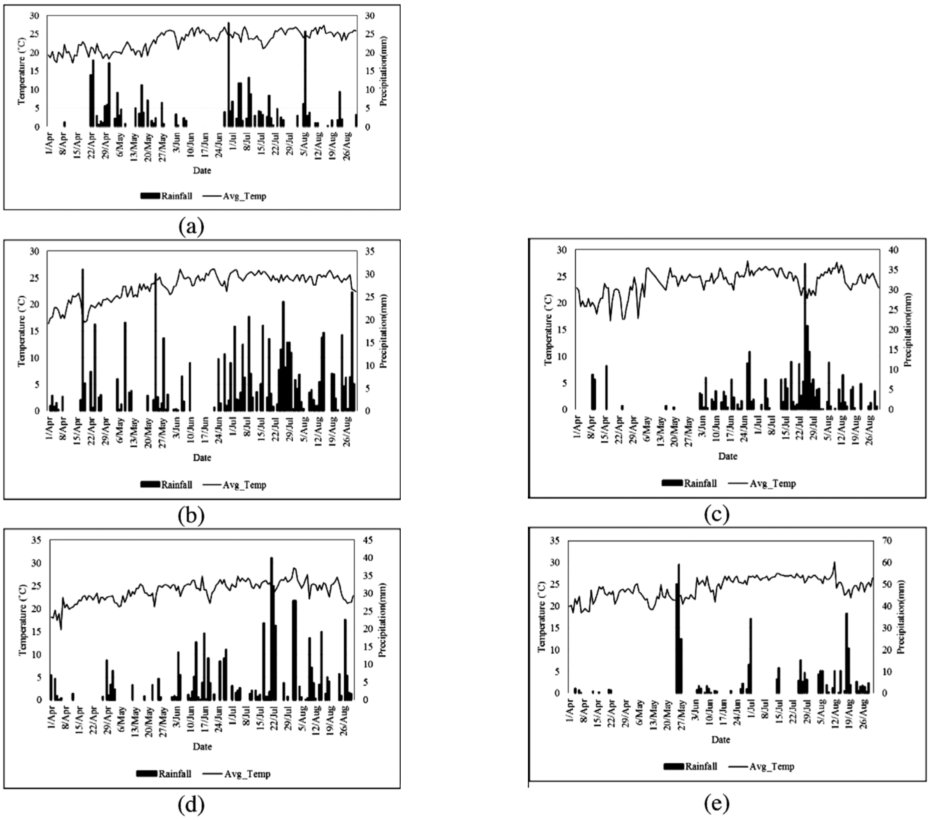


Figure 3. Daily average temperature and precipitation during snowmelt period for years (a) 2005, (b) 2006, (c) 2007, (d) 2008, and (e) 2009

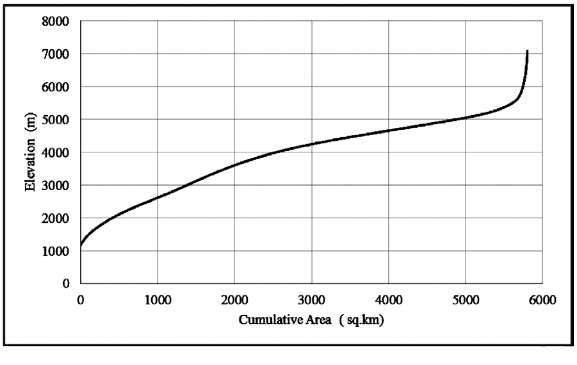


Figure 4. Hypsometric curve of Upper Punatsang Chu Basin

algorithm is then used as input to the ArcMap Model Builder module to extract the snow cover area SCA (Figure 5). The derived SCA for the years 2005-2009 is are displayed as a zonal snow depletion curve in Figure 6, and Table 2 summarized summarizes the ratio area of the SCA of the melting season, which is the significant variable, to execute the model.

Table 1. Summary of the hypsometric zones of the Upper Punatsang Chu Basin

Zone	Elevation Band (m)	Area (sq.km)	%Zone Area	Mean Hypsometric Elevation (m)
A	1180-2500	841.088	14.921	2021
B	2501-4000	1610.938	28.579	3281
C	4001-7087	3184.810	56.500	4681

Table 2. Ratio of the SCA of the melt season (April- August) for different years and their changes with comparison to the base year 2005

Zone	Ratio of the SCA of year				
	2005	2006	2007	2008	2009
A	7.428	1.947	7.094	9.444	7.628
B	20.448	7.610	18.882	22.208	19.324
C	59.426	52.809	53.698	56.205	59.791

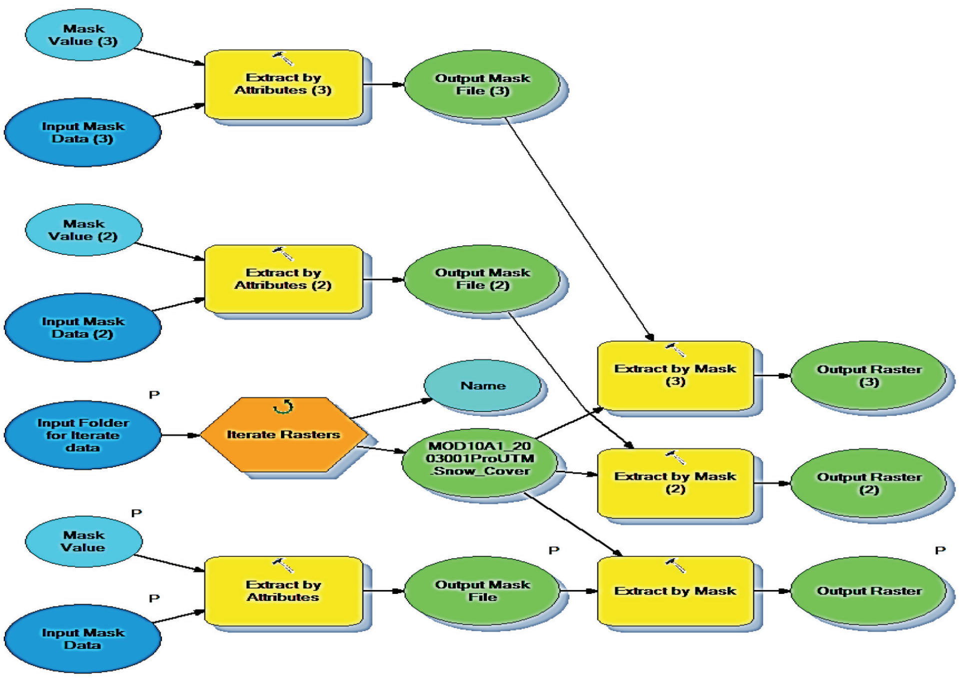


Figure 5. Schematic diagram of input, process, and output of the ArcMap Model bBuilder module for zonal SCA extraction

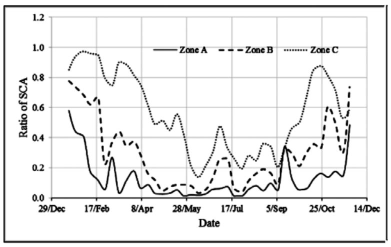
• Initial input parameters. The Iinitial input parameters, besides the basin characteristics and variables which are required to execute the SRM model, are synthesized from the literature reviews and calculated based on the hydro-meteorological data of the study area (Table 3).

Runoff Simulation During Snowmelt Period by the SRM Model

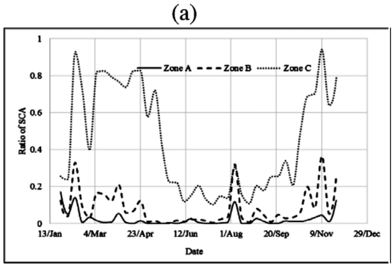
• Model Calibration. For model calibration, the initial parameters sets available in the SRM literature, include including γ, α, TCRIT ,CS, CR, and RCA, are tested with multiple variables and parameters configurations by trial and error to understand the relationship between the inputs and their simulated hydrographs. In this study the zone-wise approach was used with parameters adjustments at a daily or period time step. The permissible range of values for parameters adjustments during the calibration mode should be strictly monitored. The model is iteratively calibrated by accessing the NSE value until it achieves equal to or more than 65%, as suggested by Kult *et al*. (2014) for obtaining the optimum range of local parameters.

• Model validation. The derived optimum range of parameters value of the calibration year is further used to validate the model by estimating runoff during the snowmelt period for the years 2007, 2008, and 2009 by accessing the accuracy using the NSE. During the validation process, there is a constant need of to changing change the parameters values due to changes in the average temperature and snow covered areas SCA of the validation years.

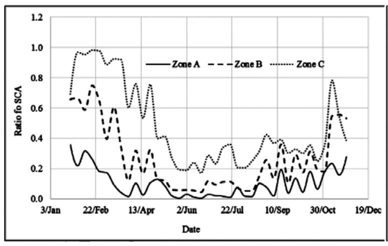
• Data output. The Mmain derived output products from data processing under the SRM model are the estimated runoff from snowmelt during the snow melting period from the calibration and validated periods with its the optimum range of parameters and accuracy assessment.



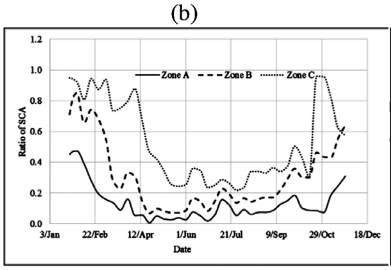
(a)



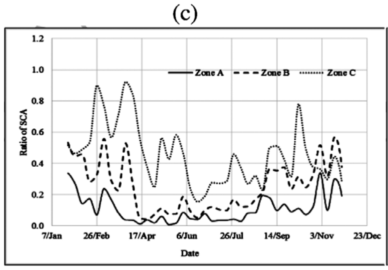
(b)



(c)



(d)



(e)

Figure 6. Zonal snow cover depletion curve for years (a) 2005, (b) 2006, (c) 2007, (d) 2008, and (e) 2009

Impact of Temperature Change on Streamflow

Other than simulating the snowmelt contribution to river discharge from all the hydrological years, the impact of temperature change on the streamflow are is investigated using three 3 different hypothetical scenarios: (1) average temperature + 1˚C, (2) average temperature + 2 ˚C, and (3) average temperature +3 ˚C for the calibration and validation periods. This impact was investigated by maintaining all the derived parameters and variables constants, except the average temperature. The output achieved from the investigation are is the effect of the hypothetical scenarios on the average streamflow.

Results and Discussion

The SRM Runoff Simulation Under Calibration Process

The SRM model with all its required input data is calibrated iteratively varying the value of the parameters on a trial and error method and the

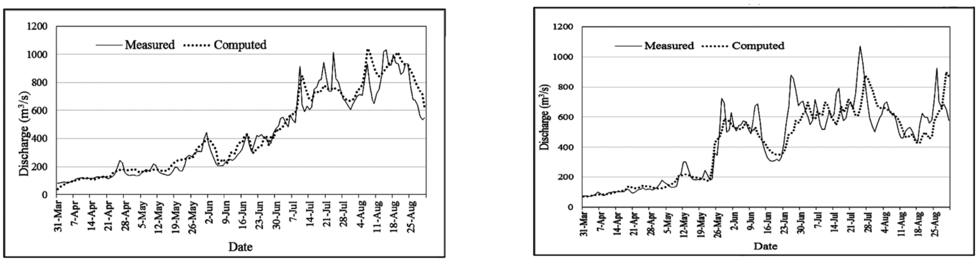


Figure 7. Comparison of measured and computed hydrograph for years: (a) 2005, and (b) 2006

Table 3. Summary of initial input parameters

Parameter	Value of range	Reference
Temperature Lapse (γ)	0.65 ˚C/100 m	Duran-Ballen *et al*., (2012)
Critical Temperature (T_{CRIT})	1.2˚C	1.2˚C from Dai (2008) +1.5˚C to 0˚C from United States Army Corps of Engineers USACE (1956)
Runoff coefficient for rain (C_R)	0.1-0.9	National Resources Conservation Service USDA NRCS (2004)
Runoff coefficient for snow (C_S)	0.1-0.9	National Resources Conservation Service USDA NRCS (2004)
RCA (rainfall contributing area)	1	Martinec *et al*. (2007)
Degree- day factor (α)	2-6 cm ˚$C^{-1}d^{-1}$	Hock (2003); Zhang *et al*. (2006); Tahir *et al*. (2011); Butt and Bilal (2011); Zhang *et al*. (2014)
Time lag	Zone A = 11 h, Zone B = 12 h, and Zone C = 13 h	Modified from Martinec and Rango (1986)
Recession coefficient (k)	x=0.899; y = 0.010 for 2005 x=1.051; y = 0.033 for 2006 x=1.048; y = 0.032 for 2007 x=1.048; y = 0.032 for 2007 x=0.884; y = 0.008 for 2008 x=1.007; y = 0.047 for 2009	Derived from generic equation ($K_{n+1} = xQ_n^{-y}$ with historical discharge data as suggested by Martinec *et al*. (1983) and Martinec and Rango (1986)

NSE values obtained were 92.97 and 81.36%, and the absolute PBIAS values were 4.5460 and 3.4509% for the hydrological years 2005 and 2006, respectively. The results of the calibration year, include including the simulation hydrograph and statistics data of the runoff with the accuracy assessment, are displayed and summarized in Figure 7 and Table 4. The optimum range of the parameter values derived from the calibration periods is summarized in Table 5.

As a results, it revealed that the simulated runoff for the years 2005 and 2006 from the SRM model shows a very good performance rating of the NSE. The simulated average runoff volume for year 2005 is slightly overestimates overestimated with a DV of -4.546 % but the simulated runoff volume for year 2006 is slightly underestimates underestimated with a DV of 3.4509%.

The SRM Runoff Simulation Under the Validation Process

Using the derived basin characteristics, with the local recession coefficient value and initial parameter range from the calibration process, the model was set up for the validation period (2007, 2008, and 2009) and their NSE values vary between 70.16 and 92.15%. The validation hydrographs are shown in Figure 8 and the

Table 4. Statistics data of the SRM simulated runoff and its the accuracy for years 2005 and 2006

Statistics	2005	2006
Measured Runoff Volume (10^6 m^3)	5677.29	5739.73
Average Measured Runoff (m^3/s)	426.68	431.38
Computed Runoff Volume (10^6 m^3)	5935.38	5541.66
Average Computed Runoff (m^3/s)	446.08	416.49
NSE (%)	92.97	81.36
Absolute |PBIAS| (%)	4.5460	3.4509
Volume DifferenceDV (%)	-4.546	3.4509

Table 5. Range of optimum local parameters of calibration period

Year	Calibrated parameters				
	α (cm ˚C^{-1} d^{-1})	C_S	C_R	RCA	Lapse Rate (˚C/100m)
2005	0.2 - 0.6	0.20-0.90	0.20-0.85	1	0.65
2006	0.2 - 0.6	0.20-0.90	0.20-0.85	1	0.65

Table 6. Statistics data of the SRM simulated runoff and its the accuracy for years 2007, 2008, and 2009

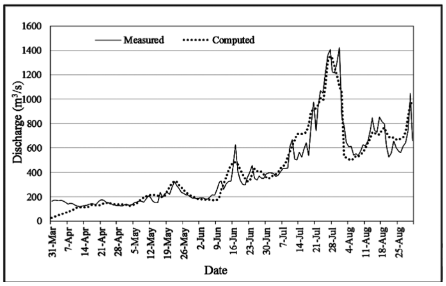
Statistics	2007	2008	2009
Measured Runoff Volume (10^6 m^3)	5578.34	6593.33	5569.92
Average Measured Runoff (m^3/s)	419.25	495.53	418.61
Computed Runoff Volume (10^6 m^3)	5621.74	6389.23	5858.35
Average Computed Runoff (m^3/s)	422.51	480.19	440.29
NSE (%)	92.15	90.81	70.16
Absolute PBIAS (%)	0.7779	3.0956	5.1784
Volume DifferenceDV (%)	-0.7779	3.0956	-5.1784

statistical results in Table 6. The optimum range of the local parameters during the validation period is displayed in Table 7.

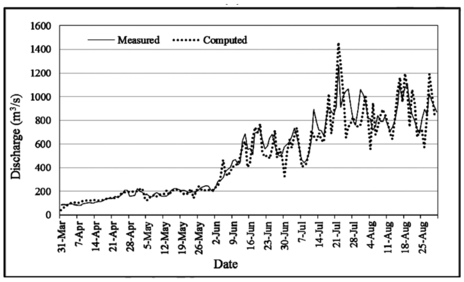
The results revealed that the validated runoff for years 2007 and 2008 show the NSE higher than the defined range of the performance rating. However, the validated runoff for year 2009 shows an comparatively show less NSE value of 70.16%, comparatively less than the other hydrological years. The low NSE value for hydrological year 2009 was mainly triggered by Cyclone Aila which hit the Bay of Bengal on 25-26 May, 2009, and had a disastrous effect causing flash floods and river flooding events overin Bhutan (Figure 9). Thus, the river water levels in Wangdue and Punakha districts exceeded the water level recorded in the 1994 Gglacier lake outburst flood (Tenzing Lamsang, 2009). Tahir *et al.* (2011) stated that it is difficult to model the a period where there is an occurrence of extreme weather conditions like a cyclone, storm, and or heavy rainfall. Herewith the simulated average runoff volume for year 2009 is slightly overestimated with a DV of -5.1784%.

Efficiency of the SRM for runoff simulation and recommended local parameter

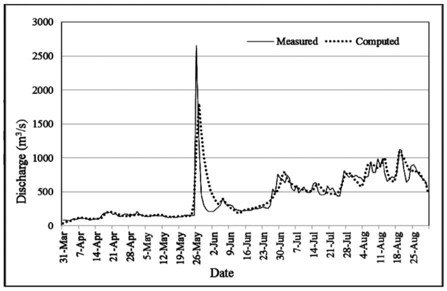
The SRM model has been applied for simulating the daily flows for the snow melting season of the Upper Punatshang Chu Basin for five 5 years. The flow data for the years 2005 and 2006 have been considered for calibrating the model, whereas the years 2007, 2008, and 2009 have been considered for validating the model



(a)



(b)



(c)

Figure 8. Comparison of measured and computed hydrograph for years: (a) 2007, (b) 2008, and (c) 2009

Table 7. Range of optimum local parameters for validation period

Year	Validated parameters				
	α (cm ˚C^{-1} d^{-1})	C_S	C_R	RCA	Lapse Rate (˚C/100m)
2007	0.25-0.6	0.20-0.90	0.20-0.85	1	0.65
2008	0.20-0.52	0.20-0.70	0.20-0.50	1	0.65
2009	0.20-0.50	0.20-0.60	0.20-0.65	1	0.65

and the obtained results of the efficiency of the model are summarized in Table 8.

The efficiency of the model has been computed based on the daily simulated and observed flow values for five 5 years. The values of the model efficiency, the NSE, are 92.97, 81.36, 92.15, 90.81, and 70.16% and the absolute PBIAS are 4.546, 3.4509, 0.7779, 3.0956, and 5.1784 %, respectively, for years 2005, 2006, 2007, 2008, and 2009. Similarly, the DV are -4.546, 3.4509, -0.779, 3.0956 and -5.1784 %. It is observed that hydrologic year 2005 provides the maximum NSE value of 92.97% and the minimum value of 70.16 % is in hydrologic year 2009, caused mainly due to the extreme event of 'Cyclone Aila'. The overall average NSE value is 85.49% for the whole study period. It is also observed that the maximum DV value of 3.0956% for hydrologic year 2006 underestimated the average runoff compared to with the average measured runoff. On the contrary, the hydrologic year 2009 with a minimum DV value of -5.1784% overestimated the average computed runoff compared to with the average measured runoff. For Tthe overall average difference in the observed and simulated runoff, the DV is -0.7914% for the entire study period. The daily simulated and observed flow hydrograph comparison for

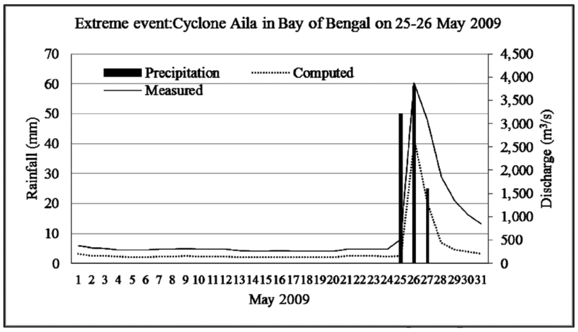


Figure 9. Superimposed data of measured and calculated runoff and rainfall of May 2009

Table 8. Summary of the efficiency of the model of the study

Performance access	Year				
	2005	2006	2007	2008	2009
NSE (%)	0.9297	0.8136	0.9215	0.9081	0.7016
Absolute PBIAS (%)	4.5460	3.4509	0.7779	3.0956	5.1784
DV (%)	-4.5460	3.4509	-0.7779	3.0956	-5.1784

Table 9. Contribution of snowmelt to river discharge

Year	Contribution of snowmelt depth in hypsometric elevation zone (cm)			
	Zone A	Zone B	Zone C	Total
2005	45.96	122.13	235.86	403.95
2006	14.26	44.21	185.18	243.65
2007	48.98	120.21	245.56	414.75
2008	62.47	133.66	231.49	427.62
2009	60.5	132.1	287.73	480.33

the study period, as shown in Figures 7 and 8, shows that the model has simulated the daily flow reasonably well showing a good agreement with the daily observed flow except for a few peaks.

At the global level it was found that the least lowest NSE of 70.16% for year 2009 obtained in this study proved to be more accurate than 42 SRM case studies out of 112 that have been applied over 112 river basins, located in 29 different countries which was compiled by Martinec *et al*., 2007.

Likewise, at the regional level, many researchers have applied the SRM in the

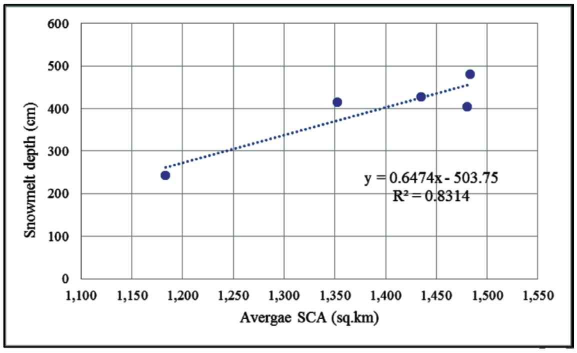
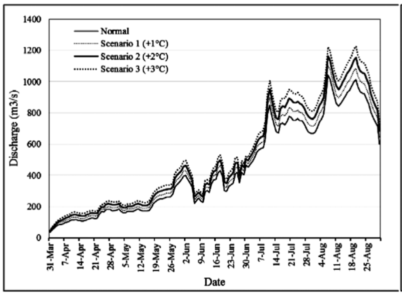
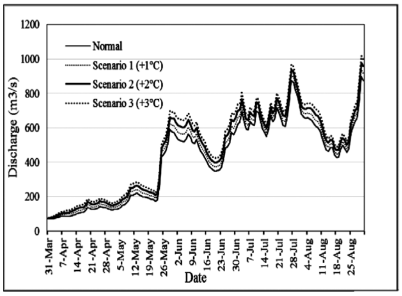


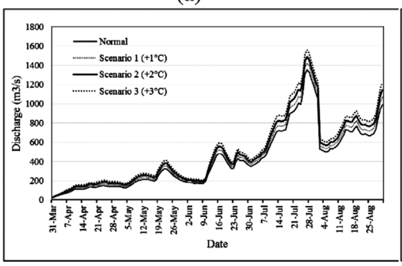
Figure 10. Relationship between snowmelt depth and average snow covered area



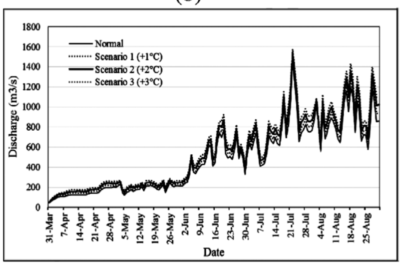
(a)



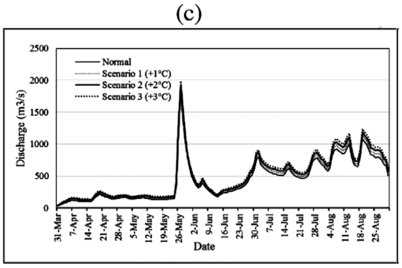
(b)



(c)



(d)



(e)

Figure 11. Comparison of simulated streamflow in each scenario based on simulation data for years: (a) 2005, (b) 2006, (c) 2007, (d) 2008, and (e) 2009

Himalayan region, and the efficiency rating of year 2009 proved to be more accurate than 7 out of 13 SRM applications and the average NSE value of 85.49% for years 2005-2009 is higher than 12 out of 13 applications in the Himalayan region, as compiled by Martinec *et al*. (2007).

Since there is has been no hydrological study carried out using the SRM model in Bhutan, therefore, the study is compared with three 3 test sites nearby to Bhutan. Firstly, the a results comparison was made against the research work of Silwal (2014) carried out in the Dudhkoshi River, Nepal, whose where the average NSE and DV are 84 and 4.5727%, respectively, with and the difference observed in the value of the NSE is 1.49% and in the DV is 1.4771%

Secondly, the results of the simulation with an average NSE of 85.49 % proved better than the research done by Arya *et al*. (2014) in the Dhualigang River, India whose where the average NSE value for the calibration and validation periods resulted in 80.5%. Lastly, Aggarwal *et al*. (2014) applied the SRM model in two 2 basins in the upper Ganga catchment area in India and the average NSE achieved were 85% and 80% for the Alakkhnanda and Bhagirathi river basins, respectively.

Thus, the simulation results achieved for this research work is are reasonably good when compared to with the above stated results. Herewith, the recommended range of optimum local parameters of the SRM for Bhutan are as follows:

- the degree- day factor varies between 0.2 and 0.6,
- the runoff coefficient value for snow varies from 0.20 to 0.90,
- the runoff coefficient value for rain varies from 0.20 to 0.85, and
- the temperature lapse rate is 0.65˚C / 100m.

Snowmelt Simulation and Its Contribution to River Discharge

Based on the above simulation with the defined range of parameters, the amount of contribution of snowmelt depth to river discharge is summarized in Table 9. It is observed that the total snowmelt depth of year 2006 is relatively low when compared with the remaining four 4 hydrological years. This phenomena phenomenon agrees with the SCA depletion curve, as shown in Figure 6. This agreement can be confirmed by the relationship between the snowmelt depth and the average snow cover area SCA between 2005 and 2009 by a simple linear equation with the coefficient of determination (R^2) of 83.14%, as shown in Figure 10.

Table 10. Comparison of average streamflow, percent increase and average percent increase of streamflow under the hypothetical scenarios of year 2005-2009

Year	Hydrological data	Normal	Scenario 1 (+1°C)	Scenario 2 (+2°C)	Scenario 3 (+3°C)
2005	Average discharge	446.081	479.473	512.874	546.285
	% Increase		7.486	14.973	22.463
2006	Average Rrunoff	416.491	441.029	465.565	490.102
	% Increase		5.892	11.783	17.674
2007	Average Rrunoff	422.509	453.226	483.971	514.743
	% Increase		7.27	14.547	21.83
2008	Average Rrunoff	480.191	513.171	546.153	579.138
	% Increase		6.868	13.737	20.606
2009	Average Rrunoff	440.292	468.355	496.411	524.462
	% Increase		6.374	12.746	19.117
Average		**6.778**	**13.5572**	**20.338**	

Impact of Temperature Change on Streamflow

The result of the impact of temperature change on streamflow under three 3 simulated scenarios based on hydrological years 2005-2009 is displayed as a hydrograph in Figure 11 and summarized the percent increase of the average discharge is summarized in Table 10.

As from the results representing represented in Table 10, there is an evident increase in snowmelt runoff of approximately 7, 14, and 20% under a the hypothetical scenarios by of increasing the temperature by 1, 2, and 3°C, respectively. Hereby, it is observed that with an increase of the average temperature by of 1°C, the streamflow is expected to rise by 7% from the normal runoff.

In 1990, Rango and van Katwijk (1990) applied the SRM model to study the climate change effect in the Wwestern North America Mmountain basins by increasing the mean temperature by 1, 3, and 5˚C. Evidently there was an increase runoff during the snowmelt season in the Rio Grande basin by 2.7, 8.3, and 14.3%, respectively. Similarly, there was increase in the snowmelt season runoff in the Illecillewaet basin by 4.5, 11.1, and 16.3%, respectively.

Likewise, Tahir *et al*. (2011) studied about the temperature change impact on snow runoff in the Hunza river basin, northern Pakistan and concluded with a finding that there is an increase of 33% of in the summer discharge as a resulted from of an increase of 1˚C and an increase of 64% from a 2˚C increase.

Silwal (2014) studied about the climate change in the Dudhkoshi River basin, Nepal and concluded that a rise in of 1˚C in the mean temperature resulted in a 0.37% increase in the annual runoff volume. Regmi (2011) studied on the impact of climate change by varying the temperature from the mean measured temperature and observed there is rise in runoff approximately at a rate of 2% in winter, 5% in summer, and 4% annually under the projected temperature rise of 1˚C.

UnlikeConversely, Singh and Kumar (1997) carried out an analytical studies using the University of British Columbia watershed model representing a temperature increase of 1-3˚C in the western Himalayan region which suggested an increase in glacial melt runoff by 16-50%. Archer (2003), who applied a linear regression analysis for climate variables and streamflow, indicated that a 1˚C rise in the mean summer temperature resulted in a 16% increase runoff into the Hunza and Shyok Rivers due to accelerated glacier melt.

For the Upper Punatshang Chu basin, an increase in temperature by of 1˚C resulted in approximately a 7% increase of snowmelt runoff approximately. Thus, the results of the impact of temperature change on snowmelt associated with the basin contradicted with the above studies. The discrepancy between the results obtained by the different studies may be possible possibly due to the methods, hypothesis, and limitations. Moreover, these results may be specific to a particular region because the catchment response to the climate warming may not be the same as in other catchments, as explained by Tahir *et al*. (2011).

Conclusions

The SRM model is one kind of model which takes the SCA as input instead of the snow depth and is applicable to a mountainous area with scarce hydro-meteorological data to simulate and forecast runoff and study the effect of climate change on runoff. With these abilities of the model, it the model is commonly applied in Himalayan regions for applications such as, flood mitigation, climate change effect, and water management program.

The SRM model applied in the Upper Puntshang Chu basin resulted in a good agreement between the measured and simulated runoff with the NSE ranging: from 70-93%, the absolute PBIAS ranging: from 3.4509-5.1784%, and the DV ranging: from -5.1784-3.4509% for the hydrological years 2005-2009. Hereby, the optimum range of local parameters for the melt season: are $\gamma = 0.65˚C/100m$, $\alpha = 0.2\text{-}06\ cm˚C^{-1}\ d^{-1}$, $C_R = 0.2\text{-}0.9$, $C_S = 0.2\text{-}0.9$, $R_{CA} = 1$, and $T_{CRIT} = 1.2$.

It was also observed that there is an increase in streamflow by 7% with a rise of in temperature by of 1˚C. With this information, the future hydropower project dam can be built with a storage capacity to hold all the melt and, thus, increase the power generation. And more over-Moreover the flood mitigation program should consider the a rise of 7% when preparing to meet future floods.

In conclusion, the model proved to be a good tool to simulate snowmelt runoff and to study about the impact of temperature change on stream flowstreamflow with requirement of very less and very much available input data .

References

Aggarwal, S.P., Thakur, P.K., Nikam, B.R., and Garg, V. (2014). Integrated approach for snowmelt runoff estimation using temperature index model, remote sensing and GIS. Curr. Sci. India, 106(3):397-407.

Archer, D. R. (2003). Contrasting hydrological regimes in the upper Indus Basin. J. Hydrol., 274:198–210.

Arya, D.S., Gautam, A.K., and Murukar, A.R. (2014). Snowmelt modelling of Dhauligang River using snowmelt runoff model. Proceedings of the 11th International Conference on Hydroinformatics, HIC 2014,; August 17-21, 4; New York City, NY, USA, p. 2695-2702.

Butt, M. J., and Bilal, M. (2011). Application of snowmelt runoff model for water resource management. Hydrol. Processes., 25:3735-3747.

Chettri, N, Sharma, E., Shakya, B., Thapa, R., Bajracharya, B., Uddin, K., Oli, K.P., and Choudhury, D. (2010). Biodiversity in the Eastern Himalayas; Status, Trends and Vulnerability to Climate Change: Climate Change Impact and Vulnerability in the Eastern Himalayas. Technical Report 2. The International Centre for Integrated MOD Mountain Development,Technical Report 2. Kathmandu, Nepal.

Dai, A. (2008). Temperature and pressure dependence of the rain-snow phase transition over land and ocean. Geophys. Res. Lett., 35(12):L12802:1-6, doi:10.1029/2008GL033295.

DeWalle, D.R., and Rango, A. (2008). Principal of Snow Hydrology. Cambridge University Press, Cambridge, UK,. 428p.

Duran-Ballen, S.A., Shrestha, M., Wang, L., Yoshimura, K., and Koike, T. (2012). Snow cover modelling at the Puna Tsang river basin in Bhutan with corrected JRA-25 temperature. J. Japan Society Civil Eng..

Ferguson, R.I. (1999). Snowmelt runoff models. Prog. Phys. Geog., 23(2): 205-227.

Forkuor, G., and Maathuis, B. (2012). Comparison of SRTM and ASTER derived Ddigital Eelevation Mmodels over two regions in Ghana–Iimplication for Hhydrological and Eenvironmental Mmodeling,. In: Studies on Environmental and Applied Geomorphology,. Dr. Tommaso Placentin, T. and Miccadei, E., (Eeds.),. ISBN: 978-935-51-0361-5, In Tech, Rijeka, Croatia, p. 219-240. [Online] Available: http://www.intechopen.com/books/studies-on-environmental-and appliedgeomorphology/comparison-of-srtm-and-aster-derived-digital-elevation-models-over-two-regions-in-ghana .

Hall, D.K., Riggs G.A., and Salomonson, V.V. (1995). Development of methods of mapping global snow cover using moderate resolution imaging spectroradiometer data. Remote Sens. Environ., 54:127-140.

Hall, D.K., Riggs, G.A., and Salomonson, V.V. (2001). Algorithm Ttheoretical Bbasis Ddocument (ATBD) for the MODIS snow and sea ice–mapping algorithms. [Online] Available: http://modis.gsfc.nasa.gov/data/atbd/atbd_mod10.pdf.

Hock, R. (2003). Temperature index melt modelling in mountain areas. J. Hydrol., 282:104-115.

Immerzeel, W.W, Droogers, P., de Jong, S.M, and Bierkens, M.F.P. (2010). Satellite derived snow and runoff dynamics in the Upper Indus River basin. Grazer Schriften der Geographie und Raumforschung. 45: 303-312.

Jain, S.K., Goswami, A., and Saraf, A.K. (2010). Snowmelt runoff modelling in a Himalayan basin with the aid of satellite data. Int. J. Remote Sens., 31(24): 6603-6618.

Jain, S.K., Lohani, A.K., and Singh, R.D. (2012). Snowmelt runoff modeling in a basin located in Bhutan Himalaya. India Water Week 2012 Conference-Water, Energy and Food Security: Call for Solutions:; April 10-14, 2012; New Delhi, India, p. 1-13pp.

Kult, J., Choi, W., and Choi, J. (2014). Sensitivity of the snowmelt runoff model to snow covered area and temperature inputs. Appl. Geogr., 55: 30-38.

Lamsang, T. (2009). Flood kills 4. Thimphu, Bhutan: Kuensel. Available from: http://www.bhutan-switzerland.org/pdf/Kuensel_27-05-09.pdf. Accessed date: May 5, 2015.

Li, X., and Williams, M.W. (2008). Snowmelt runoff modelling in an arid mountain watershed., Tarim Basin, China. Hydrol. Processes., doi10.1002/hyp22(19):3931-3940.

Liu, J., and Rasul, G. (2007). Climate Cchange, the Himalayan Mmountians, and ICIMOD. Sustainable Mountain Development., 53:11-14.

Martinec, J., and Rango, A. (1986). Parameter values for snowmelt runoff modelling. J. Hydrol., 84: 197-219.

Martinec, J., and Rango, A. (1989). Merits of Sstatistical criteria for the performance of hydrological models. Water Resour.ces Bulletin., 25(2): 421-432.

Martinec, J., Rango, A., and Major, E. (1983). The Snowmelt-Runoff Model (SRM) User's Manual. National Aeronautics and Space Administration, Scientific and Technical Information Branch, Springfield, VA, USA, 110p. Reference Publication 1100.

Martinec, J., Rango, A., and Roberts, R. (2007). Snowmelt Runoff Model (SRM) User's Manual. Updated Edition for Windows, WinSRM Version 1.11. New Mexico State University, Las Cruces, NM, USA, 172p.

National Resources Conservation Service. (2004). National Engineering Handbook. Washinton, DC, USA: United States Department of Agriculture. Available from: http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/home/?cid=stelprdb1043063. Accessed date: Nov 21, 2014.

Rango, A., and van Katwijk, V.V. (1990). Development and testing of a snowmelt runoff forecasting technique. Water Resour.ces Bulletin., 26(1): 135-144.

Regmi, D. (2011). Impact of climate change on water resources in view of contribution of snowmelt in stream flowstreamflow: A case study from Langtang Basin Nepal. [Ph.D. Ddissertation], Tribhuvan University, Kirtipur, Kathmandu, Nepal.

Seidel, K., and Martinec, J. (2004). Remote sSensing in snow Hydrology: Runoff Modelling, Effect of Climate Change. Springer, Berlin, Germany,. 150p.

Silwal, G. (2014). Modelling snow and icemelt runoff in the context of climate change: a case study of Dudhkoshi river basin, Nepal. [Master MSc. Thesis]. Department of Environmental Science, Tribhuvan University, Kirtipur, Kathmandu, Nepal.

Singh, P., and Jain, S.K. (2003). Modelling of streamflow and its components for large Himalayan basin with predominant snowmelts yields. Hydrolg. Sci. J., 48(2):257-276.

Singh, P., and Kumar, N. (1997). Impact assessment of climate change on hydrological response of a snow and glacier melt runoff dominated Himalayan river. J. Hydrol., 193: 316-350.

Tahir, A.A., Chevallier, P., Arnaud, Y., Neppel, L., and Ahmand, B. (2011). Modeling snowmelt runoff under climate scenarios in the Hunza River basin, Karakoram Ranger, Morthern Northern Pakistan. J. Hydrol., 409:104-117.

Tekeli, A.E., Akyurek, Z. Sorman, A.A., Sensoy, A., and Sorman, A. (2005). Using MODIS snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey. Remote Sens. Environ., 97:216-230.

Tenzing Lamsang (2009, 27 May). Flood kills 4. Kuensel. [Online] Available: http://www.bhutan-switzerland.org/pdf/Kuensel_27-05-09.pdf Accessed date: May5, 2015.

United States Army Corps of Engineers. (1956). Snow Hydrology: Summary report of the snow investigations,. Washington D.C.: U.S. Department of Commerce Office of Technical Services PB 151660 North Pacific Division, Corps of Engineers, US Army, Portland, OR, USA, 437p.

United States Army Corps of Engineers. (1998). Engineering and Design: Runoff from snowmelt. Manual No. 1110-2-1406. [Online] aAvailable from: http://www.usace.army.mil/publications/eng-manuals/em1110-2-1406/toc.htm Accessed date May 5, 2014.

USDA NRCS. (2004). National Engineering Handbook. [Online] available: http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/home/?cid=stelprdb1043063. Accessed date November 21, 2014.

Zhang , G., Xie, H., Yao, T., Li, H., and Duan, S. (2014). Quantitative water resources assessment of Qinghai Lake basin using snowmelt runoff model (SRM). J. Hydrol.. 519: 976-987.

Zhang, Y., Liu, S., and Ding, Y. (2006). Observed degree-day factors and their spatial variation on glaciers in western China. Ann.als of Glacialogy Glaciol., 43:301-306.