IMPACT OF CLIMATE CHANGE ON SNOWMELT RUNOFF: A CASE STUDY OF TAMAKOSHI BASIN IN NEPAL

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ABSTRACT: The Himalayas and glaciers are huge storage and very important source of fresh water. On the other hand, they are one of the most sensitive indicators of climate change as they grow and shrink in quick response to changing air temperature. Surface temperature of the earth is rising globally, which is the major indicator of global climate change. The global climate change has already greatly affected the world in many folds. The Himalayan ice and glaciers are gradually melting due to global temperature rise resulting to significant shrinkage in snow-covered area, retreating of glaciers at rate of tens of meters per year and formation of glacier lakes. These changes are greatly affecting runoff patterns and increasing the risks of Glacier Lake Outburst Flood (GLOF). Himalayan snow and glaciers are sources of many rivers in the regions and Tamakoshi River is one of them. This research aims to assess impact of the climate change on snowmelt runoff in Tamakoshi basin. It is located at above than 1960m altitude and more than 60% area lies above 4000m. For simplicity, the Positive Degree Day (PDD) (temperature index) is used for snow and glacier melt estimation. Geographical Information System (GIS) is used for automatic delineation of watersheds from Digital Elevation Model (DEM) and ERDAS Imagine software is used to delineate the snow and glacier covered area of rugged and inaccessible terrain from processing of satellite images. Runoff pattern is analyzed using conceptual precipitation and snowmelt runoff modeling (SRM) tools in different climatic conditions (i.e. temperature). The results highlight considerable contribution of snowmelt and glaciers to runoff, and significant impact of climate change on snowmelt runoff.

Key words: Impact, Climate change, Himalayas, Nepal, Geographic Information System (GIS), Digital Elevation Model (DEM), Positive Degree Day (PDD), Snow Melt Runoff (SRM)

1. INTRODUCTION

The Himalayas have the largest concentration of glaciers out side the polar region and thus it is also known as Third Pole of the earth. Glaciers of the Hindu Kush Himalayas (HKH) are natures' renewable storehouse of fresh water from which one sixth of the world population benefit just when it is most needed during the hot season before the start of monsoon. The cryosphere (consisting of snow, ice and frozen ground) on land stores about 75% of the world's freshwater. The Himalayan range alone has a total area of 35,110 sq.km. of glaciers and ice cover with total ice reserves of 3735 cu.km which is equivalent to 3250 cu.km fresh water (Qin, 2002 and IPCC, 2008) and it provides the 86 million cubic meter of water annually (Rao et al., 2007). The Himalayas, the water tower of the world is the source of nine giant river systems of Asia: the Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, and Trim, and are the water lifeline for 500 million inhabitants of the region, or about 10% of the total regional human population (IPCC, 2007). While in Nepal, there are 3,252 glaciers that cover 5,323 sq.km in area with estimated ice reserve of 481 cu.km and the Koshi River Basin alone comprises 779 glaciers with an area of 1,409.84 sq.km and has an estimated ice reserve of 152.06 cu.km (Mool et al., 2001). The contribution of snow and glacial melt to the major rivers in the region ranges from less than 5% to more than 45% of the average flow (Jianchu et al., 2008). It has been estimated that some 225 billion cu.km of surface water flows through Nepalese territory annually, which amounts to about 118,200 m^3/sq.km. This is about four times the world average. The available surface runoff flows through more than 6,000 rivers and rivulets, totaling about 45,000 km in length, having hydropower potential of 83000 MW (Shrestha, 1966) and eventually drains to the Ganges River in India through several river systems. Although about 14% of the catchments area of the Ganges lies in Nepal, the

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contribution of Nepalese rivers to the Ganges is about 41% to the total runoff, and 71% of its lean season flow (Alfred, 1992). However, the runoff pattern has been significantly affected due to the melt of the Himalayan ice and glaciers, the main sources of Nepalese river systems, as a result of climate change i.e. change in global temperature.

The estimated linear trend in global surface temperature from 1906 to 2005 is a warming of 0.74°C with a more rapid warming trend over the past 50 years (IPCC, 2008). The average surface temperature of the earth has increased between 0.3ºC and 0.6ºC over the past hundred years and the increase in global temperature is predicted to continue rising during the 21st century. On the Indian subcontinent, temperatures are predicted to increase between 3.5 and 5.5ºC by 2100 (IPCC, 2001a) and an even greater increase is predicted for the Tibetan Plateau (Lal, 2002) and while in Nepal, the temperature rise is 0.6°C per decade (Shrestha et al., 1999).

Climate change is a major concern in the Himalayas because of potential impacts on economy, ecology, and environment of the Himalayas and areas downstream. They are the largest bodies of ice outside the polar caps and the glaciers are water source for above mentioned nine major populated river basins. Rapid shrinkage of these glaciers is likely to seriously threaten water availability in the region, particularly during lean flow seasons when melt water contribution is crucial to sustain the river flow which supports human activities and ecosystem services in these areas and downstream. Temperature data available since 1000 AD indicates that 20th century was unusually warm and decade of the 1990 was the hottest on record with six of the warmest years occurring in this last decade (IPCC, 2007 and Jianchu et al., 2007). Recent examples of erratic weather patterns have been experienced by humans on regular basis across the world with the Indian subcontinent hence Nepal being no exception (Rao et al., 2007). Many Himalayan glaciers are retreating faster than the world average (Dyugerve and Meier, 2005) and thinning by 0.3~1 m/year (Jianchu et al., 2007). The Rate of retreat for the Gongotri Glacier is 23 m/year which was more than three times than the during the preceding 200 years (Hasnain et al., 2004). Similarly Imja Tsho Glacier in Nepal are retreating at rate of 42~74 m/year (Bajracharaya et al., 2007). Most glaciers studied in Nepal are undergoing rapid de-glaciations with the reported rate of glacial retreat ranges from several meters to 20 m/year (Kadaota et al., 1997). In the last half century, 82% of the glaciers in western China have retreated (Liu et al., 2000 and 2007). On the Tibetan Plateau, the glacial area has decreased by 4.5% over the last twenty years and by 7% over the last forty years (Jianchu et al., 2007 cited CNCCC, 2007).

Nepal has a precipitation pattern of unevenly distributed over the year. In the low altitudes, precipitation predominantly occurs as rainfall; whereas, in high altitudes mostly as snowfall. Liquid precipitation i.e. rain water either flows directly as surface runoff or infiltrates into ground as subsurface runoff. The solid precipitation i.e. the snow mass is accumulated on the ground or flows down slowly as glaciers. The surface or subsurface runoff at high altitudes occurs as melt-water or glaciers. The more the portion of solid precipitation, the more sustained flow in the rivers during dry season and the less of probability of rainfall induced flood occurrences. The changing climatic parameters are causing the changes in the ratio of solid and liquid precipitation. In the recent decades the ratio of solid and liquid precipitation is decreasing due to global warming (McCarthy et al., 2001). The increased liquid precipitation badly affects on the water storage capacity of mountains in two ways. Firstly, it will create a direct runoff and possible flooding and secondly it will accelerate the process of ice/snow melting (Chaulagai, 2003). Thus changing climatic parameters have doubled the adverse effects on the water resources of the Nepalese Himalayas- firstly, warmer temperature accelerates the glacier retreat and secondly, the liquid precipitation further accelerates the retreating of glacier. However, there is not any definitive trend/pattern of changing in the precipitation (IPCC, 2007), though there is changing scenario like increase in monsoon precipitation as mentioned above.

Many attempts and study has been done on the subject of climate change and its impact. It is found most of them focused on the extreme event like flood, draughts etc. In context of impact of climate change in Nepalese Himalayas, the study focuses on the glacier melting, retreating and Glacial Lake Outburst Flood (GLOF), the climate change trend etc. Though few researches has been done on contribution of snow melt in stream flow, however, the previous works lack to investigate the impact of climate change to the snowmelt runoff both in the winter and summer flow in the context of Nepalese basin. This research is the study of Tamakoshi basin in view of the contribution of snow melt in stream flow and impact of climate change on water resource in view of contribution of snowmelt runoff in winter and summer season.

2. STUDY AREA

The study area is the Tamakoshi basin in Nepal. It is situated at about 90 km North East of Kathmandu, capital of Nepal and the watershed spreads over trance-border between Nepal and China with 80% catchment in Tibet, China (Figure 2.1). It is located in the southern of the central Hindu Kush Himalayan Range. Politically it lies at the Lamabagar VDC of Dolakha District of Nepal. It is the headwater side of the Tamakoshi River. This river has annual runoff of 60.95m^3/s, which is about 3.7% of the runoff of the Koshi River. It is in central northern part of Nepal and is one of the river basins with good hydrology and a suitable topography for planning any type of hydropower schemes. It is one of seven tributary of Koshi river basin. It originates from the Tibetan Himalayas above 7000m elevation and flows south across the Himalaya before finally merging into the Sunkoshi river, yet another tributary of Koshi river system.

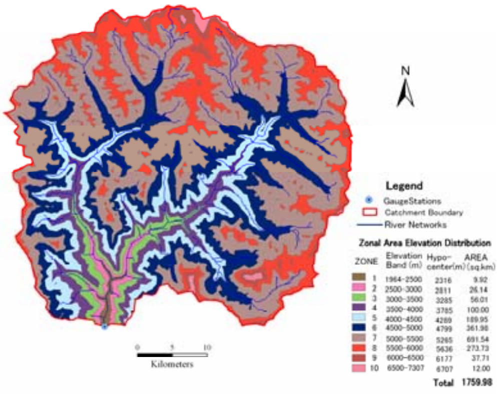
Fig 2.1 Location of Study Area: Upper Tamakoshi Basin

Geographically, the study area extends from lower left corner 86^{O}04’E, 27^{O}54’N to upper right corner 86^{O}34’E, 28^{O}19’N with centroid at 86^{O}18’30”E, 28^{O}06’00”N. The elevation of the study basin varies from about 1964 m at Gauging station, at Lamabagar to 7307 m amsl (average mean sea level) at Himalaya with mean hypo centric elevation 5076m. There are at least 7 high peaks with elevation greater than 6000m in this catchment. Among them, one of the major peaks in the Nepal is the Gauri Shankar Himal with elevation 7146m, which is the Time Meridian of Nepal. The total drainage area of the Upper Tamakoshi River up to Lamabager Gauging Station is about 1759 sq.km with 58% area above 5000m amsl.

The principal tributary of Upper Tamakoshi River, known as Rongchar Chhu and Lapcha, both originate from Tibet and meet at Nepali territory forming this river. The length of the longest tributary, Rongchar Chhu is 56km with gradient of 9.5%. The topographical setting and availability of abundant water provide great potential (1107MW) for hydropower generation in the Nepali part of the Tamakoshi River. Therefore, several hydropower schemes either are under execution (456MW, UTKHEP), or planned (370MW) on this river. In conjunction to this high potentiality of the basin, there is also the risk of Glacier Lake Outburst Flood, GLOF. There are 404 glacier lakes, area of each of them more than 1,600 sq.m, amounting to total lake area of about 7.92sq.km (Nor consult AS, 2005). Most GLOF events risk in the Tamakoshi river basin may be of magnitude more serious and devastating than that of meteorological floods. Owing to large differences in the relief, the basin is characterized by diversified climatic patterns. It gains precipitation about 2450mm annually at Jiri. The precipitation is spatially distributed with increasing trends toward the high altitude (Seko, 1985). As the snowline is at about an elevation of about 4500m amsl, the precipitation occurs mostly as snow fall above that elevation. This basin alone receives the total precipitation of 2000mm in summer (from June to September). This is about 80% of annual precipitation and most of precipitation occurs in the form of snow.

3. DATA USED

Data used in this study are three types: topographic, hydro-meteorological and satellite images. The topographic data used is derived from the Digital Elevation Model DEM, of 90m by 90m spatial resolution. Since the study area is located in the Zone 45, the DEM of that Zone 45 was acquired in 2008 December, from the USGS (Jarvis et al, 2008). By spatial analysis of this DEM, in ArcGIS the basin is divided into the ten elevation bands at rate of 500m interval to derive the area elevation map and the hypo-centric elevation as shown in the Figure 3.1.



Zonal Area Elevation Distribution

ZONE	Elevation Band (m)	Hypo-center(m)	AREA (sq.km)
1	1964-2500	2316	9.92
2	2500-3000	2811	26.14
3	3000-3500	3285	56.01
4	3500-4000	3785	100.00
5	4000-4500	4289	189.95
6	4500-5000	4799	361.98
7	5000-5500	5265	691.54
8	5500-6000	5636	273.73
9	6000-6500	6177	37.71
10	6500-7307	6707	12.00
		Total	1759.98

Fig 3.1 Zonal Area Elevation

The hydrological data is daily runoff at the outlet of the basin, Lamabager gauging station at elevation 1965m amsl and it is operated by the Upper Tamakoshi Hydroelectric Project, UTKHEP, Nepal Electricity Authority, NEA. The discharge is measured three times a day, and then averaged for the daily discharge. The meteorological data are the daily precipitation at Jiri Station at elevation 2003m amsl and the daily maximum and minimum temperature data at Tsho Rolpa station at elevation 4580m. These both stations are operated by the Department of Hydrology and Meteorology, DHM, Nepal. The average temperature is calculated as simple arithmetic mean of the maximum and the minimum temperature. Based on the average monthly temperature at TshoRolpa and at Jiri, the average monthly temperature lapse rates are calculated and the average annual temperature lapse rate is found as 0.508 ^{O}C/100m in the basin. The temperature at the base station, Tsho Rolpa, is distributed to the hypocentric elevation on the basis of this lapse rate using the following equation 3.1:

$$T_{j,n} = T_{n,base} - r\left(h_{j,n} - h_{n,base}\right) \quad \ldots\ldots\ (3.1)$$

where $T_{j,n}$ is the daily mean temperature (°C) on the nth day in zone j, $T_{n,\text{base}}$ is the daily mean temperature (°C) on the nth day at the base station, h_j is the zonal hypocentric mean elevation (m), h_{base} is the elevation of the base station (m) and r is the temperature lapse rate (°C/100m). Since the precipitation increased as elevation in the Himalayas, the precipitation data at the base station, Jiri are spatially distributed to the hypo centric elevation of each zone according to the equation 3.2 (Seko, 1987):

$$P_{j,n} = P_{BH,n} \qquad \text{For } h_j < 4000\text{m}$$

$$P_{j,n} = P_{BH,n}\left[1 + 0.0003\left(h_j - 4000\right)\right]$$

$$P_{j,n} = 1.3 \cdot P_{BH,n} \qquad \text{For } h_j > 5000\text{m}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.2)$$

Where, $P_{j,n}$ is precipitation at hypocentric elevation h_j of the j^{th} zone, P_{BH} is the precipitation at base station in the n^{th} day. A preselected threshold temperature, T_{CRIT}, determines whether this precipitation is rainfall and immediate. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hither to snow free area until melting conditions occur.

The next data used for the snow cover delineation is the Satellite Image. Three types of images are used: i) Landsat 7 images with the spatial resolution of 30m by 30m, dated 14th Apr, 2003 and 8th Oct 2003, acquired in December 2008 from USGS website (**http://glcf.umiacs.umd.edu**); ii) MODIS Terra Snow with spatial resolution of 500m by 500m dated 1st Jan, 1st Mar, 18th Apr, and 1st Dec in 2002 and 1st Jan, 1st Mar, 2nd Apr, 8th Oct, 1st Nov and 3rd Dec in 2003, acquired in December 2008 from USGS website (**http://nsidc.org)** via ftp access and iii) Scanned digital map of Glacier cover of Tamakoshi basin i.e. prepared by Reynolds using Spot 5 satellite image, dated 2nd Jan 2002 (Nor consult AS, 2005). The snow and glacier covered area are delineated from these satellite image using the ERDAS Imagine software (Figure 3.2). The zonal snow covered maps are generated using these snow cover area map in conjunction with the zonal area DEM map in ArcGIS. These zonal snow cover area are interpolated and extrapolated to each day of the year. For the accumulation period, simple algebraic interpolation is done. For the depletion period, the exponential interpolation is done (A. Emre et al., 2005). The derive snow depletion curve is shown in the Figure 3.3

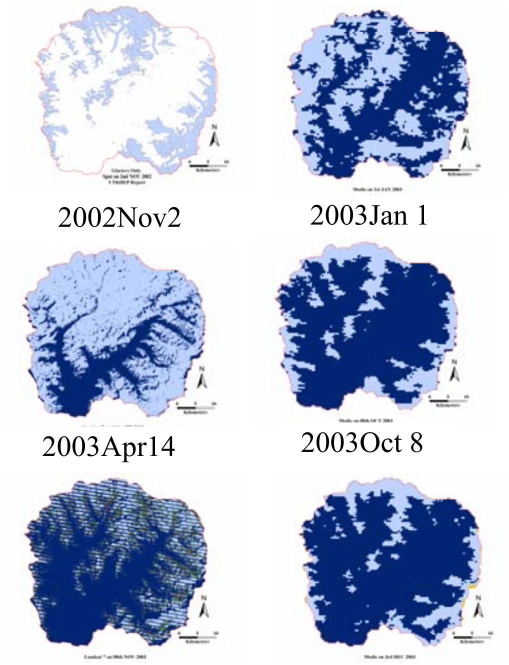

2002Nov2
2003Jan 1
2003Apr14
2003Oct 8
2003Nov 8
2003Dec 3

Fig 3.2 Classified Satellite Images of 2003
The Light color indicates Snow and Glacier

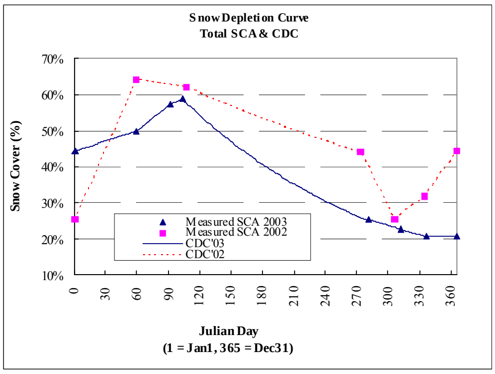


Fig 3.3 Snow Depletion Curve

4. METHODOLOGY

4.1. Models

Prediction of melting of snow and ice in a glacierized basin is very important to estimate basin discharge. In the Himalayan region, the main source of water is glacier melt water which is closely related to summer mass balance and snowmelt runoff form galcierized basins. For simulating snowmelt runoff, there exist numerous methodologies. These vary from the simple system model i.e. index methods to more physical based detailed energy balance approaches. Rana et al. (1996); Nakawa and Takahashi (1982); Kayastha et al. (1999); Oerlemns and Hoogendoorn (1989); Kuhn (1989); Braithwaite and Olesen (1990); Oerlemans (1993); Munro (1991) and Arnolds et al. (1996) used the mass and energy balance model for estimation of snowmelt from the Himalayan glaciers. The main draw back of this type of the detailed study is the complexities nature with numbers of data required which usually not easily available. For the remedy of this problem, Laumann and Reeh (1993); Hohnnesson et al. (1995); Braithwaite and Zhang (2000); Braithwaite and Olesen (1989); Hock (1999); Kayastha et al. (2000) and Kayastha et al. (2005) used the simple index method i.e. positive degree day approach to estimate the snowmelt. Similarly for the study of contribution of the snowmelt in stream flow and the impact of climate on it, various scholar use different method like temperature index method, mass balance method etc. Singh et al. (1997b); A. Emre at el. (2005); Singh et al. (2003); Singh and Jain (2003) used the simple PDD method and William et al. (1994) used restricted PDD method incorporating the radiation component. Angele et al. (2005) used the energy balance method to develop simple restricted PDD with incorporation of the effect of the wind on snow melting process. While Kumar et al. (2007); Singh et al. (1997) and Bryan et al. (2006) used the water balance method. In the context of study of impact of climate change, Sing et al. (2004) and Jordan (2005) used PDD method. Sing et al. (1997a) used UBC model for this purpose. Rango and Martinec (1997) and Rango and Martinec (1994) used the SRM model for assessment of the impact of climate change.

Among above mentioned different models, the temperature index model is simple and useful for this study basin. It is probably the best single index that stores most of climatic information and climate change pattern and it represents areal snow cover change along with its readily availability nature. The popularity of temperature index models also arises from the fact that they give melt estimates that are comparable to those determined from a detailed evaluation of various terms in the energy equation (Male and Gray, 1981).

4.2. Model Structure (SRM)

The model used in this research is positive degree-day index and used the SRM model (Martinec et al., 2008) for snowmelt estimation and runoff simulation. In this model, the study basin is divided into number of elevation zones at rate of 500m interval. The zonal area A, hypocentric elevation and snow covered area A_{SCA} are calculated for each zone. Based on the elevation of base station/s (where temperature and precipitation are measured), hypocentric elevation of each zone and regional temperature lapse rate, the temperature and precipitation are distributed at each elevation zone. The form of precipitation is determined by considering the Critical Temperature T_{CR} for snowfall and the air temperature at each hypocentric elevation for each zone. The snowmelt (M_S in cm) is computed in each zone with the input of snow cover area, temperature and degree-day factor in each zone by temperature index method (equation 4.1).

$$M_S = a \cdot \left(T - T_b\right) \quad \text{………} \ (4.1)$$

Where, a is the degree-day factor (cm °/C/day), T is the daily average and T_b the base temperature (°C) above which melting occurs. For cases in which $T < T_b$, no melt is produced. Usually base temperature T_b is 0^{O}C. The snowmelt and the rain will be now runoff of the zone and runoff from each zone are summed up and simulated which gives the simulated river flow discharge. The model SRM, used in this study, estimate the snowmelt and each day, the water produced from snowmelt and rainfall is computed, superimposed on the calculated recession flow and transformed into daily discharge from the basin (Martinec et al.., 2008). After fine simulation with optimum parameter and best coefficient of determination (R^2>0.7) with least volume difference, this is taken as present climate runoff simulation. Now the climate change scenario i.e. in rising temperature (ΔT 1 to 3 ^{O}C) is given as input. The SRM is then, run for the climate change simulation with changed snow depletion calculated by itself.

5. RESULTS AND DISCUSSIONS

5.1. Simulation

The Study basin has the total area of 1759 sq.km with altitude variation from 1964 to 7307 and gradient of 9.5%. The area of zones above the 4500m elevation is 78% of total area with the average annual temperature less than 0^{O}C and above 5000m is 58% and -2.50^{O}C respectively (see Table 5.1). Similarly the average annual snow coverage are 40.1% in 2003 and 41.8% in 2002 with peak coverage of 58.9% & 64.3% and least coverage of 22.6% & 25.5% respectively (Table 5.2 & Figure 3.5).

Table 5.1 Zonal Characteristics Tamakoshi Basin

Zone	Hypo-centric Elevation (m)	Area		Average Tempe-rature (^{O}C) in 2003	Precipitation (cm) in 2003			Average Annual Snow Cover Area SCA (2003)	
		sq.km	%		Snow	Rain	Total	sq.km	%
A	2316	9.9	0.6%	12.5	2.1	281.8	283.9	0.01	0.1%
B	2811	26.1	1.5%	10.0	2.2	281.7	283.9	0.16	0.6%
C	3285	56.0	3.2%	7.5	10.6	273.3	283.9	0.22	0.4%
D	3785	100.0	5.7%	5.0	16.7	267.2	283.9	1.70	1.7%
E	4289	190.0	10.8%	2.5	35.5	273.1	308.6	20.33	10.7%
F	4799	362.0	20.6%	-0.1	100.8	251.2	352.0	87.24	24.1%
G	5265	691.5	39.3%	-2.5	197.2	171.9	369.1	321.57	46.5%
H	5636	273.7	15.6%	-4.4	267.3	101.8	369.1	197.36	72.1%
I	6177	37.7	2.1%	-7.1	368.1	1.0	369.1	31.19	82.7%
J	6707	12.0	0.7%	-9.8	368.9	0.2	369.1	10.34	86.2%
Total or Average		**1759.0**	**100%**	**1.3**	**1,369.4**	**1,903.2**	**3,272.6**	**670.1***	**38.1%***

Table 5.2 Snow Coverage in the study basin

Snow Coverage Area in 2003				Snow Coverage Area in 2002			
Image	**Date**	**Area (sq.km)**	**%**	**Image**	**Date**	**Area (sq.km)**	**%**
Modis	1-Jan-03	782.135	44.4%	Modis	1-Jan-02	***448.0***	***25.5%***
Modis	1-Mar-03	879.754	50.0%	Modis	1-Mar-02	1,131.6	64.3%
Modis	2-Apr-03	1009.564	57.4%	Modis	18-Apr-02	1,092.0	62.0%
Landsat7	14-Apr-03	1037.479	58.9%	Spot5	28-Nov-02	448.0	25.5%
Modis	8-Oct-03	447.314	25.4%	Modis	1-Dec-02	557.4	31.7%
Modis	1-Nov-03	725.121	41.2%		**Average (of 5 images)**		**41.8%#**
Landsat7	8-Nov-03	397.532	22.6%				
Modis	3-Dec-03	362.781	20.6%				
	Average (of 8 images)		**40.1%#**				

***Average of 365 days after interpolation**

 # Average of no. of images only

The year 2003 is treated as the Calibration and the simulation year while the year 2002 as the validation year. The year 2003 is also the base year for the assessment of the impact of climate change i.e. warmer climate. The simulated hydrograph is shown in the Figures 5.1 & 5.2. The measured discharge is well simulated in the year 2003 with coefficient of determination R^2 82% (Nash efficiency) and volume difference less than 0.1%. Few Stream flow peaks could not be generated in simulated runoff, which was possibly due to sudden release of stored water at some location in the glacier body, and such events are clearly identified because they are not supported by climatic condition (Singh et al., 2008). In the validation year 2002, there is good coefficient of determination (R^2) 84% and volume difference ΔV 14.8%. The peak discrepancy is due to reason as explained earlier. But considerable volume difference is due to the following reasons:

i) The precipitation is distributed in the basis of precipitation at Jiri which is located out-side the catchment at 2003 m amsl elevation.

ii) The measured discharge in the year 2002 (average annual discharge 78.10 m^3/s) is 18% more than in the year 2003 (average annual discharge 64.19 m^3/s) while the precipitation observed at Jiri is in reverse order. There is

13% less precipitation in the year 2002 (average annual precipitation 7.22 mm) than in year 2003 (average annual precipitation 8.29 mm). It indicates that there should either be more precipitation or some release of water from the glacier which could not be simulated by the SRM model. The measured hydrograph also indicates there should be some precipitation in the months Nov and Dec; however there is no any precipitation at all at the Jiri station in these months.

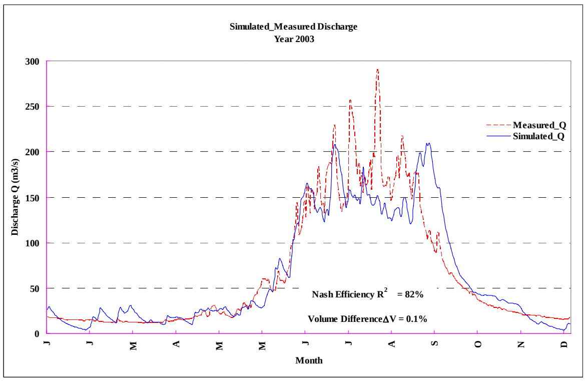


Fig 5.1 Simulated and Measured Discharge in Year 2003

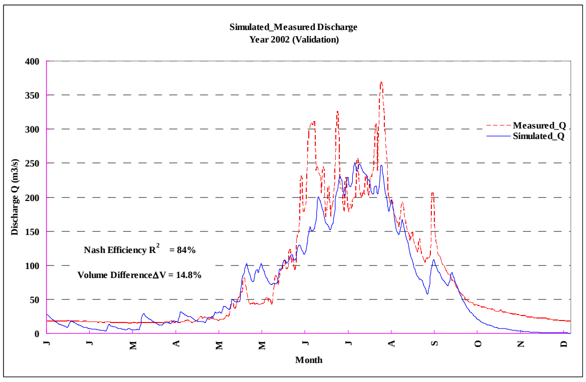


Fig 5.2 Validation for Year 2002 (Simulated and Measured Discharge)

iii) The temperature distribution is carried out on the basis of the data at Jiri station for the period 24th Sep 2002 to 8th Jan 2003 because of missing of data at Tsho Rolpa station during that period. It is noted that the monthly average temperature in 2002 (14.14 ^{O}C) is less than that of 2003 (14.31 ^{O}C) at Jiri while at Tsho Rolpa, it is higher in 2002 (1.43 ^{O}C) than that of 2003 (1.05 ^{O}C), which off course affects melting pattern reversely. That's why there is negligible discharge in the November to December period.

iv) Satellite images in the year 2002 are rough resolution only i.e. 500m by 500m MODIS Terra Snow Images. This may hinder the accuracy level of delineating the snow cover area.

5.2. Contribution of Snowmelt in Stream Flow

The contribution of snowmelt in the stream flow is still considerable though there is high precipitation (6156 M m^3) than the runoff (2036 M m^3). There is 19% contribution by snowmelt in winter season and 7% in summer season altogether 8.2% in the annual stream flow runoff (Figures 5.3 & 5.4) in the year 2003. The low snowmelt in the July and August is because of the low temperature recorded during that period, which shows average monthly temperature is 0.67 and 3.56 ^{O}C respectively in these periods.

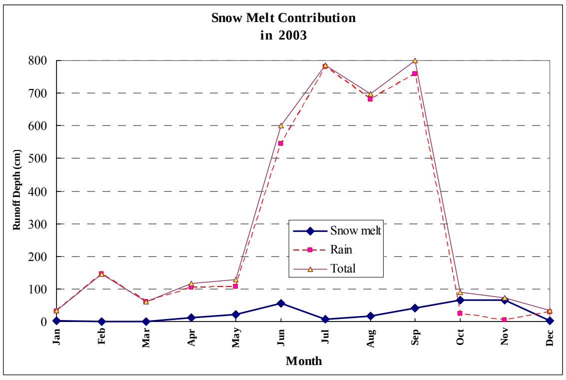


Fig 3.8 Contribution of Snow melt in Stream flow in Year 2003

Similarly, in year 2002 the contribution of snowmelt in stream flow is 18% in the annual flow with 16% contribution in winter season and 19% contribution in summer season.

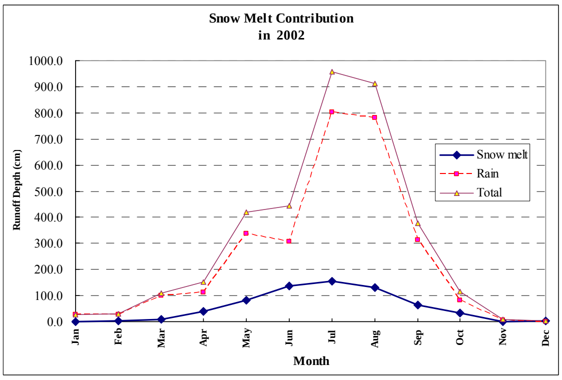


Fig 3.9 Contribution of Snow melt in Stream flow in 2002

This is shown in Figure 3.9. The increase contribution of snowmelt is due to the high temperature at that year and more snow overage. This is also justified by the more runoff in this year than that of the year 2003 (Figures 5.1 & 5.2).

5.3. Impact of Climate Change

After the simulation has been done in the year 2003, this year is taken as the base year to investigate the impact of climate change (rising temperature) in the snow melt runoff. In climate change simulation in SRM, only the temperature is changed from the ΔT 1, 2 and 3 ^{O}C, because there is no definite trend of change in precipitation as described else where. The impact of climate change (i.e. temperature) is increasing trend in stream flow with increased snow melt contribution approximately at rate of 3% in annual and 8% in winter flow per one degree centigrade temperature rise. This pattern is shown in the Table 5.3 and Figure 5.5. The main factor of such increase in snowmelt contribution is melting of snow and glacier in the basins. As shown in the Table 5.1 and explained in the simulation section, there is 58% area of the total watershed above 5000m amsl elevation where annual average temperature is less than equal to -2.5^{O}C and the snow coverage is more than 46% average in year. As a result, though the temperature is raised up to 3 ^{O}C, there will be enhanced melting in the melting period while balanced snow deposition in the accumulation period in the winter. That's why the result of impact of climate change is as anticipative.

Table 5.3 Impact of Climate Change in contribution of Snowmelt in Stream Flow

Season / Period	Present	T+1 ^{O}C	T+2 ^{O}C	T+3 ^{O}C
Winter Season	37%	45%	53%	61%
Summer Season	7%	9%	12%	15%
Annual	9%	12%	16%	19%

From April to Dec, base year 2003

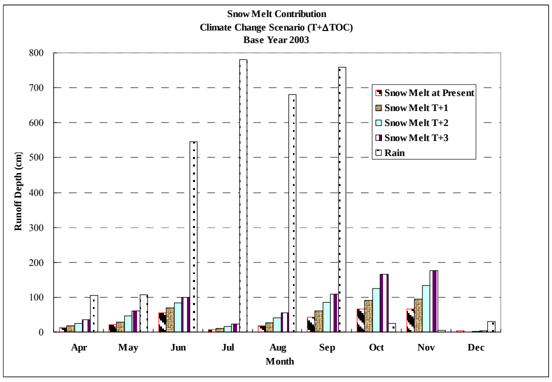


Fig 5.5 Variation of Snow melt in different climate change scenario (base year 2003)

6. Conclusion

The result shows that The Positive Degree Day or Temperature Index method coupled in Snowmelt Runoff Model, SRM can be well applied in rugged and remote Himalayan catchment like Upper Tamakoshi basin with limited data. Required data are only the daily discharge, daily precipitation, daily temperature and daily snow coverage (obtained from remote sensing i.e. satellite image, aerial photos etc). The study area is glacierized basin with more than 40% annual snow coverage. The contribution of snowmelt in stream flow is found as 17.5% in winter, 13% in summer and 13% in annual flow in the average from 2002 to 2003. The study demonstrates that the impact of climate change (i.e. temperature) to stream flow is significant, which is in increasing trend resulting from snow melt contribution. Due to the snow melt contribution, stream flow increases approximately at rate of 8% in winter, 3% in summer and 3% in annual flow per one degree centigrade temperature rise.

The outputs of this study are important guidance for water resources managers to make and implement appropriate strategy for water resources management and hydropower development. It is also useful tool for adoptive planning i.e. more and efficient use of winter flow and mitigative and preventive measure for high flood and GLOF. However the results presented here are not the predictions, but rather the model simulations on the snowmelt. For further study and refinement of the research, it is worthfull to establish the meteorological station within the catchment itself, use the more precise and more numbers of satellite images (at least one per each month in depletion period) and apply the energy budget models.

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