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Relating Air Temperatures to the Depletion of Snow Covered Area in a Himalayan Basin

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A procedure for evaluating depletion of snow covered area (SCA) using mean air temperature has been outlined and tested. Because depletion of snow is a cumulative effect of climatic conditions in and around snow cover area, the cumulative mean temperature (CTM) at a nearby station should represent depletion of SCA. The study was carried out for Satluj basin (22,305 km^2) located in the western Himalayan region. Melting starts around beginning of March, therefore, reference date for computing CTM was considered March 1. Data of three ablation seasons (1987-1989) were used to establish relationship between SCA and CTM. It was found that depletion of SCA is exponentially correlated with CTM ($R^2 > 0.98$). An exponential reduction of SCA can be explained on the basis of snow distribution in the mountainous basins. This method has a potential for estimating missing data and extending time series on daily, weekly or monthly basis. Once the depletion trend is established in the basin in the first part of melt season, SCA can be simulated with good accuracy using CTM data for the rest period of melt season. Such applications can reduce the number of satellite images required for obtaining SCA information. A forecast of SCA can also be made using forecasted air temperatures. Impact of climate change on depletion of SCA over the melt period indicated that for the considered range of temperature increase (1-3°C), melting area of snow increased linearly with increase in temperature. An increase in temperature by 2°C enhanced the melting area of snow over the melt season by 5.1%.

Introduction

Snow is a very important component of the hydrological cycle and plays a vital role in the water resources in many parts of the world. In a region or basin, snow cover is developed from a series of winter storms and is depleted during spring and summer period due to warmer climate. Depending upon the location of the basin and climatic conditions there, snow cover developed during preceding winter can deplete totally or partially. Snow cover is a major component of water storage on seasonal timescale and changes in its extent, depth, and its water equivalent has a major impact on regional and continental water resources. The amount and rate of runoff induced by melt processes in a basin can be related to variation in snow covered area (SCA). There are various hydrological applications of SCA on the basin scale. Modelling of snow melt runoff carried out using SCA data is very important for various practical applications in the field of runoff predictions, reservoir management, electric power production, irrigation practices, flood control *etc.* There are some hydrological models, for example, snow melt runoff model (SRM), which use SCA as an input variable on the daily basis for snow melt computation (Martinec *et al.* 1983). At the same time, variation in SCA plays a crucial role in modelling and simulating alterations of global change effects on water resources, the ecological conditions, the albedo, and ultimately on the radiation budget.

Application of SCA for snow melt modelling studies becomes inevitable for the large and inaccessible Himalayan basins, which experience high snowfall, but do not have sufficient meteorological network to quantify it. Early use of remote sensing focused on empirical relationships between SCA and monthly or accumulated runoff (Rango *et al.* 1977; Ramamoorthi 1987). These simple relationships worked well for some applications and particularly in data sparse regions of the world. Estimation of daily snow melt runoff in the Himalayan river basins using satellite-derived SCA is being increasingly recognized as an immensely useful procedure in water resources research and management (Rango *et al.* 1977; Ramamoorthi and Subba Rao 1981; Gupta *et al.* 1982; Dey *et al.* 1983, 1989; Dey and Goswami 1984; Jain 2001). The prediction of snow melt induced runoff in the Himalayan rivers has a great potential for application in irrigation, hydropower generation, and domestic and industrial water supply.

The SCA has also been used as an indicator of snow reserve or water equivalent in a basin (Meier 1973; Ødegaard and Østrem 1977; Rango *et al.* 1977). Schjødt-Osmo and Engeset (1997) reported that the Norwegian Water Resources and Energy Administration (NVE) uses information on the changing distribution of snow during the periods of accumulation and, in particular, ablation (Østrem 1974; Andersen 1983). The areal extent of snow is one of the principal variables, and is directly related to the summer runoff potential. The snow water equivalent of a snowpack can not be derived from the current remote sensing data. However, the derivable snow cover fraction is still a very important parameter to monitor for operational flood forecasting (Schjødt-Osmo and Engeset 1997). Singh *et al.* (1997) and Singh and Jain (2002) used SCA in estimating snow and glacier contributions in the annual flows of Himalayan rivers using the water balance approach. Singh and Singh (2001) have discussed various applications of regional snow cover on the climate system.

Usually, information on the extent of SCA is derived from satellite data because snow can readily be identified and mapped within the visible bands of satellite imagery due to its high reflectance in comparison to non-snow areas. Therefore, remote sensing is a valuable tool for obtaining snow data for predicting snowmelt runoff as well as climate studies. Use of satellite data for snow mapping has become operational in several regions of the world. Currently, NOAA develops snow cover maps for about 3000 river basins in North America of which approximately 300 are mapped according to elevation for use in streamflow forecasting (Carroll 1990). NOAA also produces regional and global maps of mean monthly snow cover (Dewey and Heim 1981). Rango (1993) presented a review of the status of remote sensing in snow hydrology. Snow cover mapping with satellite data in the Swiss Alps is reviewed by Seidel *et al.* (1989, 1995). Haefner *et al.* (1997) suggested for setting up snow cover information systems for individual basins or other hydrological units, planning regions or even entire mountain ranges on a long-term perspective. On the practical side, these applications are related to the monitoring of seasonal and yearly alterations of the snow cover under presently existing climatic conditions to simulate and forecast runoff, to map the regional distribution of the water equivalent, and to document the recession processes of the snow cover during the melting period.

In order to get information on SCA, systematic and continuous mapping of snow cover become essential for snow hydrological applications. However, in general, there are discontinuities in the SCA data required for the studies. It is difficult to develop SCA database on the daily time scale because of the cost involved in acquiring satellite data, time consumed in the analysis of data, and inaccurate data due to the presence of cloud cover. In the melt season, the cloud cover represents a major obstacle when deriving information from optical imagery (Schjødt-Osmo and Engeset 1997). Haefner *et al.* (1997) reported that even the acquisition of 5-10 (or more) satellite scenes for a single melting season is rather costly. Even if one can afford the resources, a lot of time is consumed in the analysis. Such problems become more important for the Himalayan basins, which are larger in size and have longer ablation period with higher probability of cloud cover during pre-monsoon and monsoon period. A higher number of imageries are needed for such basins for snow melt modelling studies, which need lot of investment and also require much time for analysis. Usually, satellite data are obtained for a few dates in the melt season and linearly interpolated for the period of unavailability of data. There is no method available which can be used to interpolate, extrapolate or fill the missing SCA data during the ablation season. In the present paper, an attempt has been made to develop a methodology to interpolate/extrapolate SCA data using temperature data of stations located in the basin. Following this approach, one can reduce the number of imageries for the melt period to obtaining SCA. Air temperature can then be used to generate SCA data for the basin.

Methodology

The SCA at a particular time after first melt can be considered a function of the initial value of SCA before start of the melting and patterns of the temperature during the melt period. The use of degree-day or temperature index approach is a well-established method for snow melt estimation. At present there are a number of snow melt models which use this approach for computing snow melt runoff from the basin (Singh and Singh 2001). Melt starts first in the warmer lower parts of a basin, where usually, the snow cover is thinnest. Consequently, the snow disappears first from the lower part of the basin. As summer season progresses, the melt continues in the upper part of the basin. The SCA reduces with time and at each point of time melt can be related to air temperatures. Therefore, cumulative temperature over the melt period should represent the depletion of SCA. A given extent of seasonal snow cover will disappear at a faster rate during warmer climatic conditions, while it will follow slow depletion under a colder temperature regime. Dependency of the SCA reduction is also influenced substantially by the availability of initial snow water equivalent in the basin. As discussed by Rango and Martinec (1994), an initially thin snowpack would disappear more quickly than a thick one. They correlated SCA and cumulative depth of melt to infer the changes in SCA under warmer climatic scenarios, which indirectly supports the dependency of SCA on temperature because cumulative melt is mainly governed by the temperature. In the present paper, to keep the methodology simple and directly applicable, temperature data of the stations located in or near the snow covered area are used. For the Himalayan basins melt season sets in about March, therefore March 1 has been considered as reference date for CTM computation and accordingly SCA data is used.

Study Basin

The present study has been carried out for the Satluj river basin up to Bhakra dam (Indian part) located in the western Himalaya. The Satluj river is a highly snowfed river having about 60% contribution of snow and ice melt runoff in its annual flows (Singh and Jain 2001). The Satluj river rises in the lakes of Mansarover and Rakastal in the Tibetan plateau at an elevation of about 4,600 m and forms one of the main tributaries of the Indus river. The catchment area of the study basin is about 22,305 km^2 and its elevation varies from about 500 m to 7,000 m, although only a very small area exists above 6,000 m. Mean elevation of the basin is about 3,600 m. The shape and location of this basin is such that the major part of the basin area lies in the greater Himalayas where heavy snowfall is experienced during winters. A major part of the basin is covered by snow during winter. Owing to large differences in seasonal temperatures and great range of elevation in the catchment, the snowline is highly variable, descending to an elevation of about 2,000 m during winter and retreats to above 4,000 m after summer season. The topographical setting and availability of abundant water provides a huge hydropower generation potential in this river and hence several hydropower schemes are existing, planned or coming up on this river.

Study Period and Data Used

The study has been carried out for the melt season (March-August) using 5 years SCA and temperature data. In general, SCA was available once a month, while daily mean temperatures were available for the whole study period. The daily mean temperatures of two high altitude stations, namely, Kalpa (2,436 m) and Kaza (3,639m) were used in this study. March 1 was considered as reference starting point to compute the cumulative mean temperature. The procedure and analysis made to obtain SCA for the study basin is described in detail by Jain (2001). Landsat (MSS) (80 m resolution) data have been used for 1987, whereas IRS (LISS-I) (72.5 m resolution) data were used for 1988-1991.

Results and Discussions

The depletion of SCA in Satluj basin with time during summer period and trends of CTM at Kalpa for three ablation seasons (1987, 1988, and 1989) are shown in Fig. 1. Fig. 2 shows the relationship between SCA with CTM for Kalpa for different years. It can be noticed from Fig. 2 that SCA reduces exponentially with CTM for the summer season. Similar trends for all the years confirm such relationship. This relationship can be expressed as

$$SCA = a * \exp(-b * CTM) \tag{1}$$

The derived values of coefficients a and b, coefficient of determination (R^2) for different years are given in the Table 1.

The high value of R^2 for all years shows that the SCA and CTM are highly correlated. Exponential relationship implies that initial increment in temperature lead to higher changes in the snow cover area than later increments in temperature of the same magnitude. Such trends can be explained on the basis of distribution of snow in the basin. The depth of snow in a mountainous basin increases with altitude (Singh and Kumar 1997). Consequently, snowpack developed in the basin during

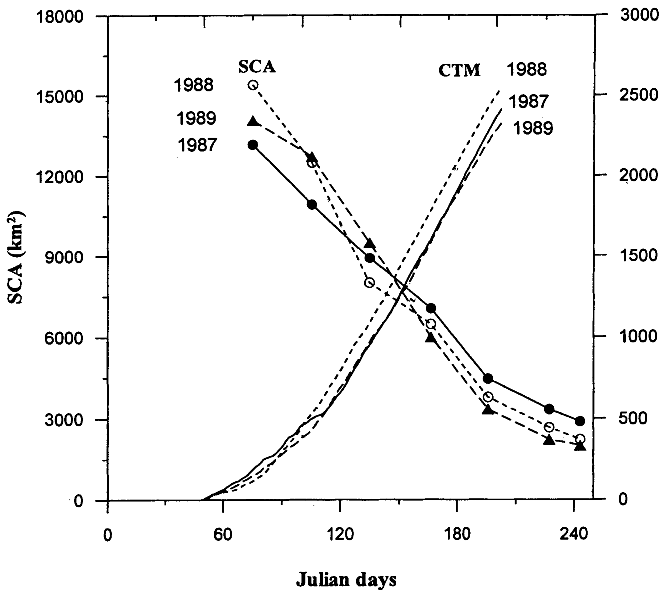

Fig.1. Depletion of snow covered areas (SCA) with time in the Satluj basin along with trend of daily cumulative mean temperature (CTM) observed at Kalpa (2,436 m) for different years. CTM was computed March 1 onward.

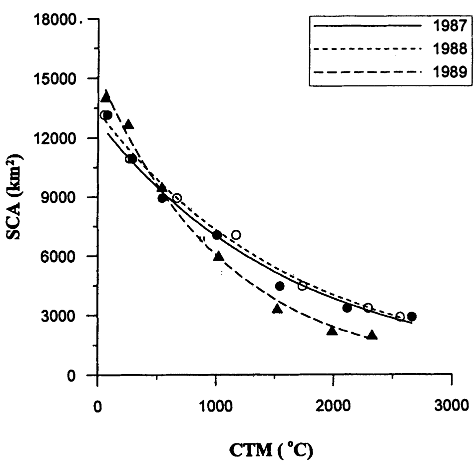

Fig.2. Relationship between snow cover depletion and cumulative mean temperatures (CTM) at Kalpa (2,436) m station.

Table 1 – Values of coefficients *a* and *b* used in Eq.(1) and R^2 for different ablation seasons

Melt season	*a*	*b*	R^2
1987	12821.6	0.00060	0.98
1988	13337.9	0.00060	0.99
1989	15263.9	0.00092	0.99

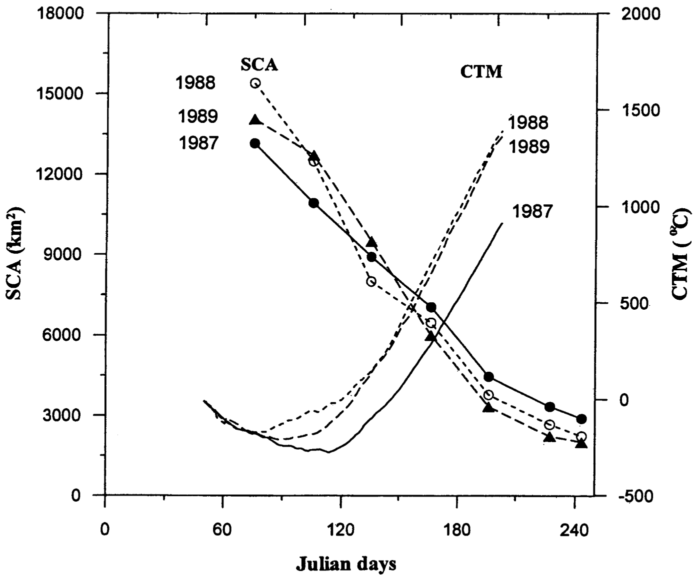

Fig.3. Depletion of snow covered areas (SCA) with time in the Satluj Basin along with a trend of daily cumulative mean temperatures (CTM) observed at Kaza (3,639 m) for different years. CTM was computed March 1 onward.

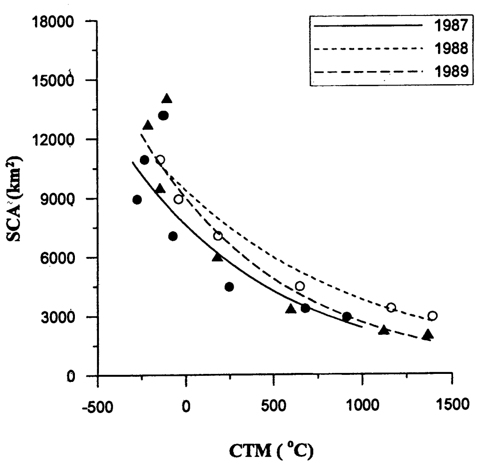

Fig.4. Relationship between snow cover depletion and cumulative mean temperatures (CTM) at Kaza (3,639) m station.

winter season is thin at lower altitudes and thick at higher altitudes. During summer, the snow line retreats from the lower altitude to higher altitude and consequently SCA in the basin is reduced. The retreat rate is reduced in the later part of the melt season due to higher depth of snow at high altitudes. Kattelman (1997) reported rapid melting of snow at low elevations in Sierra Nevada, California, USA. Therefore, distribution of snow in the mountainous basins attributes to exponential depletion of SCA with CTM. Using SCA and computed snow melt runoff for four years data, Gupta *et al.* (1982) reported a logarithmic relationship between SCA in the end of melt season and the volume of seasonal snow melt runoff for four Himalayan basins. Assuming that snow melt is linearly related with temperature, one can conclude that SCA and CTM should have exponential relationship, which corroborates the relationship for mountainous basins obtained in the present study.

Depletion of SCA for the study basin was also correlated with CTM of another station (Kaza, 3,639 m), which is located higher up in the basin (Figs. 3 and 4). The relationship between SCA and CTM was exponential for this station also, but it was disturbed due to negative temperatures in the month of March at this station. As shown in Fig. 4, in the beginning of melt season cumulative temperatures were negative at this station for all the three years. Cumulative negative temperature disturbed the exponential relationship for this initial period of melt season (Fig. 4). Therefore, the stations which experience negative temperature during the melt season, can not be used for such application. However, they can be used for a period after which they experience positive temperature and cumulative temperature is positive. Therefore, for further application of this study only Kalpa station was used.

Applications

There are three major applications of this approach, which are described below:

(a) Interpolation of SCA

Once the relationship between SCA and CTM is established using daily values of CTM and few values of SCA, then this equation can be used to interpolate data during the melt period. Using CTM data in the derived equation, one can get daily values of SCA in the basin. The missing data can be generated using known relationship between SCA and CTM.

(b) Simulation of SCA

Because SCA and CTM are exponentially correlated, once the trend of depletion of SCA snow is established in the basin, it can be extended for the later part of the melt season using only CTM data. Such a procedure has been illustrated in Figs. 5 and 6. The two unknowns (a and b) can easily be determined by plotting SCA on log scale and CTM on linear scale. This approach was applied for two years, 1990 and 1991 for simulating daily SCA in the study basin. Simulated SCA was compared with observed SCA in the later part of the melt season. As shown in Figs. 5(b) and 6(b), for both years daily SCA was well simulated using this approach. Thus, following this approach, one can reduce the number of imageries for the later part of the season. However, it is to be pointed out here that for such applications, a setting of depletion trend with CTM is essential.

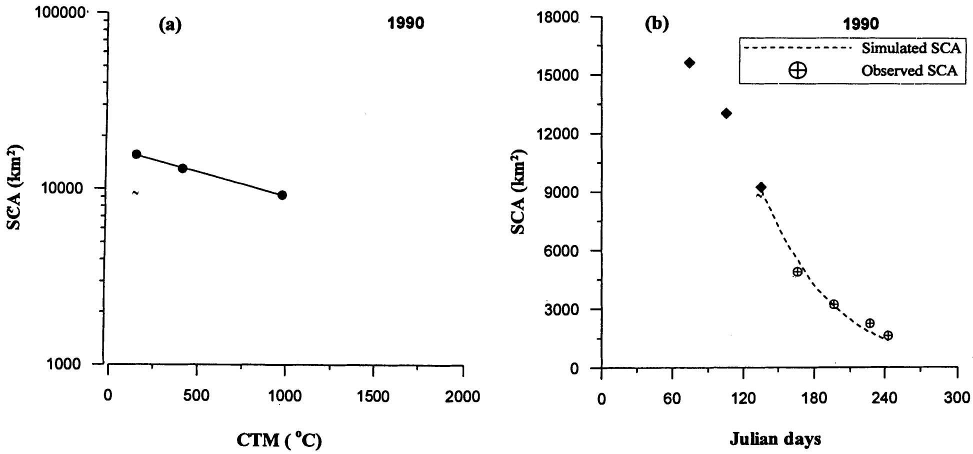

Fig.5. (a) Establishment of snow cover depletion trend for 1990 using cumulative mean temperature (CTM) of Kalpa for the initial part of the summer. (b) Simulation of depletion of snow covered area for the rest part of summer using CTM data, and its comparison with observed snow covered area.

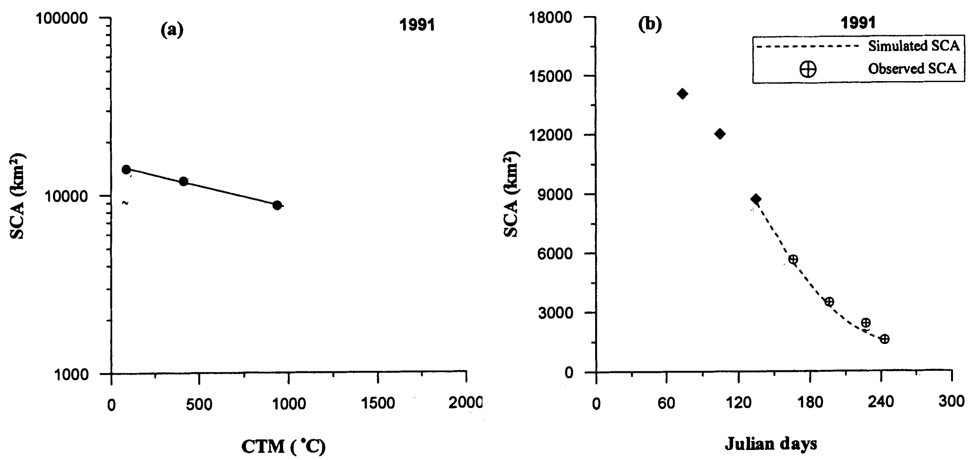

Fig.6. (a) Establishment of snow cover depletion trend for 1991 using cumulative mean temperature (CTM) of Kalpa for the initial part of the summer. (b) Simulation of depletion of snow covered area for the rest part of summer using CTM data, and its comparison with observed snow covered area.

(c) Impact of Climate Change on SCA

Important impact of climate change is expected on the hydrological cycle and water management systems (Askew 1991). A temperature increase is expected in the next decades (Schneider 1989). Climate change effects on the hydrological behaviour of

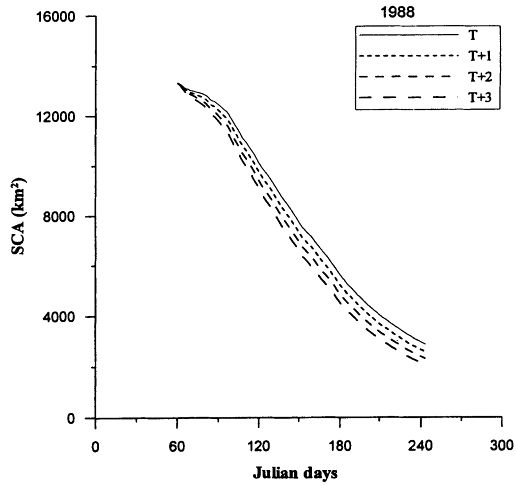

Fig.7. Depletion of snow covered area (SCA) in Satluj basin under different climatic scenarios for 1988.

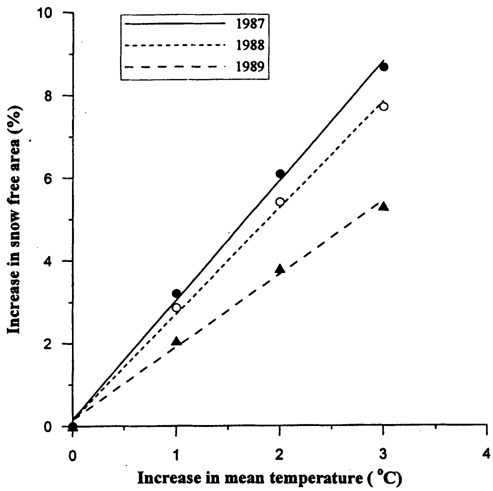

Fig.8. Increase in snow free area at the end of melt season with increase in mean temperature over the melt period in the Satluj basin for different years.

snowfed rivers has been studied by various researchers (Rango 1992; Singh 1996; Singh and Kumar 1997). Singh and Kumar (1997) carried out detailed study on effect of different climatic scenarios on different component of runoff for a highly snowfed river in the western Himalayas. Limited studies have been carried out to study the depletion of snow cover under the warmer climatic conditions. Rango and Martinec (1994) examined the influence of changes in temperature and precipitation on snow cover using snow melt runoff model.

In the present study, depletion of SCA has been correlated with temperature, which enables to study the impact of warmer climatic scenarios on SCA. Effect of increase in temperature from 1 to 3°C has been studied on the depletion trend of SCA for the study basin. Depletion of SCA under different climatic scenarios for 1988 ablation period is shown in Fig. 7. As expected, under warmer climate snow disappears from basin at faster rate resulting in reduction in extent of SCA after melt season. In other words, extent of melting area during summer is increased under warmer climatic conditions. Similar trend were observed for all the years. Fig. 8 shows that for all the years, increase of area that lost its snow cover under warmer conditions was linearly correlated with increase in temperature. Because the initial SCA in the basin and distribution of temperature over the melt period vary from year to year, the impact of climate change would be different for different years. For the study basin, on average, an increase of temperature by 1, 2, and 3°C increased the melting area by 2.7, 5.1 and 7.2%, respectively. Thus, following the present methodology, one can generate SCA in the basin under new climatic scenarios, which can be used as input to the modelling studies and other applications related to snow covered areas.

Conclusions

Satellite-derived SCA is used for various hydrological and climatological studies. Such information is of practical significance in operational water resources practices and is used by water resources managers for various hydrological applications. Primarily the application of SCA is made for the assessment of snow reserve, modelling of snow melt runoff, flood forecasting, effect of climate change on hydrology and water balance studies of snowfed rivers. The emphasis of the present study is on snow melt runoff computation from a basin using SCA data on daily time scale. For large and inaccessible basins, like the Himalayan basins, SCA is very important information for snow melt modelling studies. At the same time, procurement satellite imageries on daily basis becomes very expensive. Higher resolution data for large basins further increases number of imageries to be used to cover the basin and data cost also increases proportionally. Analysis of large number of imageries also takes much time. Under some unavoidable atmospheric conditions like presence of cloud cover, reliable information on SCA is not available. Thus, due to various reasons, satellite data are obtained for a few dates during the melt period and discontinuity in database persists. In the present study, a methodology which can be used to interpolate, extrapolate and/or fill the missing data of SCA, is evolved.

The CTM represents the climatic condition over the melt period for every year and, therefore, depletion of SCA for a particular melt season should be affected by the distribution and magnitude of CTM in that season. In this paper, relationship between SCA and CTM has been studied for the Satluj basin (22,305 km^2) located in the Western Himalayan region. It is found that during the ablation season (March-

August) SCA depletes exponentially with CTM observed at a stations near the snow covered area. Three years data were used for studying the relationship between SCA and CTM and similar relationship was observed for all the seasons, confirming the depletion of SCA is strongly related to CTM. The value of R^2 was obtained above 0.98 for the years. Exponential decrease of SCA with CTM is a consequence of the increase in depth of snow with altitude in the mountainous basins.

Depending upon the initial snow cover in the basin and temperature distribution over the ablation season, a different equation will be obtained for every season. The established equations can be used to interpolate/extrapolate SCA data or extending time series of SCA using CTM data. This study also demonstrates a good application of the established relationship in simulating the SCA for the basin using limited information of SCA in the beginning and middle part of the season. It is observed that once the depletion trend is established in the basin in the first part of melt season, SCA can be simulated with good accuracy using CTM data for the rest period of the melt season. Such applications can reduce the number of required satellite images for obtaining SCA. The variation in extent of SCA with time can also be forecasted using forecasted air temperatures.

Based on 3 years analysis, an increase in temperature by 1, 2 and 3°C enhanced the melting area of snow over the melt season by 2.7, 5.1 and 7.2%, respectively. For the considered range of temperature increase (1-3°C), it was found that in melting area of snow in the basin increased linearly with increase in temperature.

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