Evaluation of spatial and temporal variability of snow cover in a large mountainous basin in Iran

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Abstract Determination of snow characteristics in mountainous basins is difficult due to the complex spatial and temporal variability of snow cover. Accurate representation of snow cover variations in space and time is an important factor in snowmelt modeling, hydrological forecasts, water resources planning, and drought management. This study demonstrates how remotely sensed data can complement the measurements of ground hydro-meteorological data to simulate the spatial and temporal variations of snow cover characteristics in a mountainous basin. In this paper, we studied Karun basin, located in the south west of Iran, because of its importance in accumulating large snow reserves, and subsequently contributing snowmelt to the total runoff. Snow cover variability was simulated by extraction of maps of snow cover indices using remotely sensed data. Contribution of snowmelt to the runoff was determined using a seasonal water balance model as well as estimations based on indirect approaches by modeling variables such as critical temperature, which is an important variable in snow studies. Agreement between indirect approaches used in this paper is an encouraging result that shows the reliability of the procedure where snow data is scarce. The results of correlation analysis between topographic and meteorological variables with snow cover indices suggested that elevation is the single most important variable on large-scale snow variability.

Keywords Critical temperature; mountainous basin; remote sensing; snow accumulation; snow persistence; snowmelt

Introduction

A significant portion of precipitation falls as snow in mountainous regions and snowmelt is the main source of surface-water supply, groundwater recharge and sometimes an additional factor in flood intensity. Snow cover represents the amount of water reserves in mountainous basins. The spatial and temporal variability of snow cover has received increasing attention in recent years (Elder *et al.* 1991; Kirnbauer *et al.* 1994; Doesken and Judson 1996; Bloschl 1999; Balk and Elder 2000; Skaugen *et al.* 2003). Factors causing heterogeneity of snow cover in mountainous regions include spatial variability in precipitation, temperature, solar radiation intensity on sloping surfaces, elevation, slope, aspect, wind, snow-holding capacity of the landscape, and drifting.

The disparate nature of snow distribution, an effect of both accumulation and melt, makes available data often inadequate for snow cover characterization. As Martinec and Rango (1981) stated, it is practically impossible to determine the areal distribution of water reserves stored in the snow cover of a mountain basin using conventional data because direct point

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measurements of the snow water equivalent (SWE) generally are scarce and extremely variable. In particular, in large-scale mountainous areas, access during the snowfall and melt period is difficult and sometimes impossible. Moreover, a snow survey in large basins is expensive, time-consuming and usually involves large errors. However, data on the timing, magnitude, and area of snow accumulation and melt is required for successful water resource management. As a result, in the case of snow data scarcity, indirect methods are needed for snow characterization.

The areal extent of the snow cover has long been recognized as an important hydrologic parameter related to both the average SWE and the snowmelt-derived runoff (Rango *et al.* 1977). Remote sensing is an indirect approach, which provides a reasonable way to monitor snow cover extent in time (Martinec and Rango 1987; Allen and Walsh 1993; Rango 1993; Jaagus 1997). The rate at which the snow cover depletes is inversely related to the SWE and the generated snowmelt runoff. Evaluation of snow reserves and its variability in space and time is very important for integrated water resources management, reservoir operation and river flow forecasting. In this research, Karun basin in south west of Iran was selected due to its large contribution of snowmelt to the Karun river. Extraction of snow cover accumulation and persistence indices in the study basin were addressed in this paper. It is, however, assumed that, using this methodology, important features of temporal variability of spatial snow cover distribution can be captured.

Relationships between snow cover and topographic characteristics of mountain basins have been studied recently (Lapen and Martz 1996; Tappeiner *et al.* 2001; Anderton *et al.* 2003). The work presented in this paper seeks to quantify a relationship between snow cover indices and terrain characteristics in a large-scale basin with scarce data.

Measured snow water equivalent (SWE) data are generally missing for large basins. Hydro-meteorological data analysis has been used as an indirect approach for this purpose. Investigation of critical temperature (US Army Corps of Engineers 1956; Martinec and Rango 1986; Roher *et al.* 1994; Kongoli and Bland 2000) and seasonal water balance (Rango and Martinec 1982; Ranzi *et al.* 1999) have been used for hydro-meteorological data analysis related to the snow hydrology research.

Two mentioned indirect approaches – remote sensing and hydro-meteorological data analysis – can be used to obtain more easily measurable variables, which is related to spatial and temporal variability of SWE.

The objective of this paper is to use the above approaches for understanding snow cover variability in space and time and snowmelt contribution to runoff. An improved understanding of these issues provides the basis for prioritizing areas of snow accumulation and persistence and its related process and finally zoning the area based on snow characteristics for water resources research and management purposes.

Methods and materials

Study area

The Karun basin is located in the southwest of Iran between 30°16′ to 32°39′ N latitude and 49°33′ to 52°0′ E longitude (Figure 1). The basin covers an area of approximately 24,141 m^2, with elevations between 800 and 4,400 m. The basin typically has cold winters with high precipitation and warm and dry summers. The mean annual precipitation of the area is about 650 mm. Precipitation pattern in this rugged area is exceedingly complex. Winter snowfall is particularly heavy at elevations over 2,500 m. The Poleshaloo hydrometric station, at the outlet of the basin with an elevation of 800 m, has recorded an average annual runoff of 328.5 $m^3\ s^{-1}$, corresponding to 429 mm of yearly runoff volume. Topography plays an important role in the temporal distribution of runoff because of snow reserves at higher altitudes. Peak flow generally occurs in the spring whereas maximum seasonal rainfall

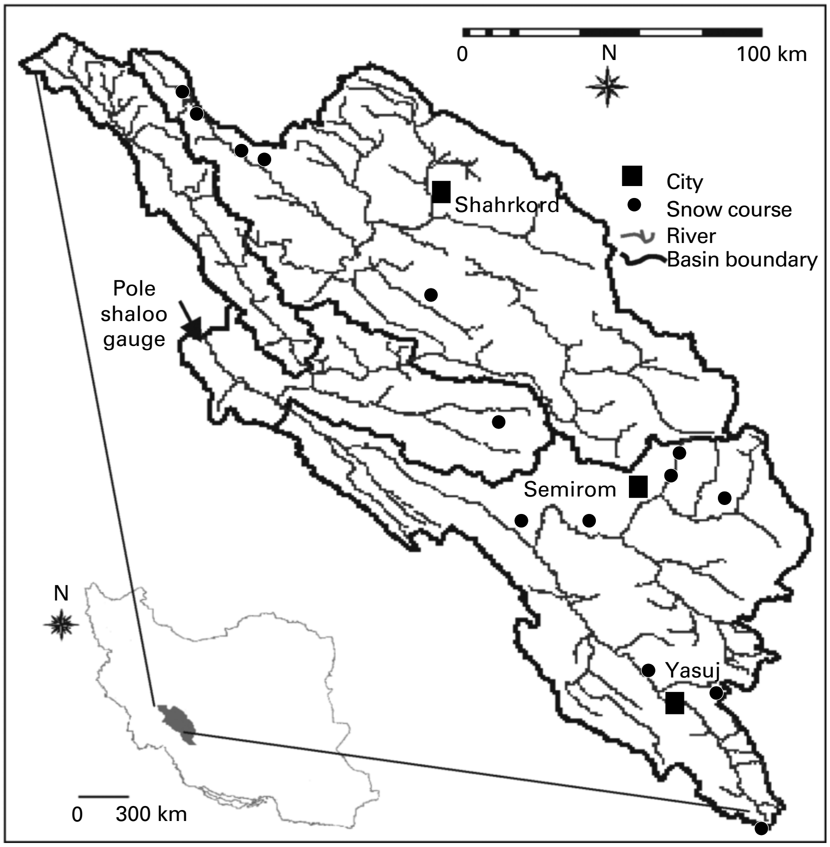

Figure 1 Location of Karun basin and its main sub-basins

occurs in the winter. Snowmelt typically commences in the middle of March or the beginning of April. Significant areas of this mountainous basin are subject to seasonal snow cover. The seasonal snow cover onset in autumn varies from late November to early January, while the date on which seasonal snow cover disappears may be as early as late March through to the end of June.

In this study, the basin was divided into several hydrological units based on the following criteria: (1) existence of a hydrometric station at the outlet of the unit, (2) coverage of a part of the highland area of the basin, (3) the units had to be hydrologically independent, and (4) the units should have relatively equal area. Such criteria were thought to be important in capturing snow cover variability and water resources planning and development. Figure 2 shows the selected hydrological units in the Karun basin.

Data collection

Over two hundred NOAA-AVHRR images corresponding to the November 1989 to August 1998 period were processed to estimate the extent of snow cover. This spatial data set is based on NOAA imagery of ~1 km resolution. Classification of snow, cloud cover and land was carried out based on the methodology presented by Simpson *et al.* (1998). Image enhancement and multi-spectral analysis were employed to filter out cloud cover using a relationship between snow cover and topography (Pourhmmat *et al.* 2004). Depending on the presence or absence of snow, a value of zero or one was assigned to each pixel. As a result,

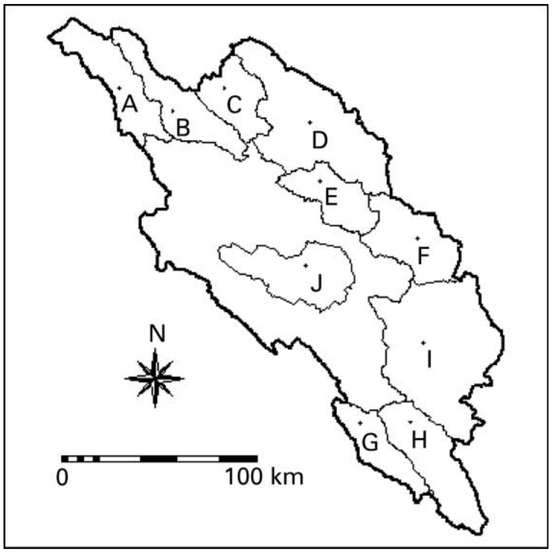

Figure 2 Hydrological units in the Karun basin

binary snow cover layers were extracted. The spatial storage and analysis was performed using ILWIS 3.1 (ITC 2001).

Twenty years of monthly hydro-meteorological data including precipitation, temperature and runoff from 1979 to 1999 were gathered. Data from some of the gauges were discarded because of prolonged periods of missing or doubtful records. Finally, 25 rain gauges, 22 temperature gauges and 13 hydrometric stations were selected on the basis of reliability and completeness of records. Hourly precipitation, temperature and snowfall from 1987/8 to 1998/9 were available from four synoptic stations within the basin.

There are thirty-two snow courses in the basin, which were established by the Khuzestan Water and Power Authority. These sites are normally visited at the time of maximum snow accumulation to provide an index of snow pack conditions for operational purposes during the spring–summer period. The distribution of the snow courses is uneven and only 14 stations have generally reliable historical measurements including some missing data in the period of 1984/5 to 1997/8. Some of the snow courses are located too far from the roads. Only one snow survey team conducts the measurement each year. Therefore, the time lag between the first measurement and the last one is about twenty days. As a result, records are not consistent and reliable in all snow courses. Figure 1 depicts the location of the active snow course network within the Karun basin. Most of the snow courses are located at intermediate elevations, i.e. between 1,500 and 2,500 m above mean sea level. Only a few active courses are located above 2,500 m. Because of operational difficulties and costs, in high elevation areas above 3,000 m, there is no snow course. Unfortunately, due to the discontinuity, inconsistency, missing and short records, this data set could not be used in this research.

Remotely sensed data analysis

Many samples may be required to provide a reliable mean snow depth and SWE due to large spatial variations. This can be expensive and time consuming, and may not be practical in large-scale basins. Satellite remote sensing has been increasingly advocated for monitoring surface processes over time. Remotely sensed data that simply shows areas with and without snow cover can be extremely valuable in assessing the variability of snow cover and the amount of water present in the form of snow. Temporal monitoring of snow cover could be used as an indirect approach for estimation of snow characteristics. In this research, three snow cover indices are introduced based on temporal series of snow cover observations during snowfall and snowmelt seasons, as well as the time of maximum snow depth.

Snow cover accumulation index. The accumulation of snow cover usually begins at higher elevations of the basin, and continues at lower elevation through the accumulation period. During the accumulation period, the variations of snow depth over the basin area show the combined effects of the terrain and meteorological factors. Periodic monitoring of snow-covered area during the snowfall season using satellite images enables one to determine the frequency of snow cover observation for different parts of the basin. Snow cover accumulation index (SCAI) can be derived by the summation of raster binary snow maps in snowfall season divided by the number of maps during the period of observation as follows:

$$SCI = \left[\frac{1}{N}\sum_{1}^{N} Smap_t\right] \times 100 \qquad (1)$$

where:

SCI: snow cover index (%),

$Smap_t$: rasterized binary snow cover map at time t, and

N: number of snow cover maps during observation period.

Selection of maps was based on having at least one suitable map every two weeks during the snowfall season. As a result, 52 snow cover layers in the snowfall season (from late autumn to winter) during 1989 to 1998 were identified. The pixel size of snow cover layers was changed from 1,100 (m) to 250 (m) using the re-sampling function in GIS to increase the resolution of summation operation.

Maximum snow cover accumulation index. Snow sampling in a mountainous basin is generally carried out at the time of maximum snow depth. Spatial pattern of snow cover variability at this time corresponds to the maximum probability of snow cover observation, which can be useful for snow survey planning. In Karun basin, snow sampling is generally planned from mid-February to mid-March each year. This period is believed to be the time of maximum snow depth accumulation in the area. A map of maximum snow cover accumulation index (MSCAI) can be derived by the summation of selected binary snow cover maps at the time of maximum snow depth divided by the number of observations (ten years).

Snow cover persistence index. The factors affecting snow cover depletion are extremely complex and include the interrelationships between terrain and meteorological conditions during the melt period. If the disappearance of the snow cover is monitored during the melting period, its persistence pattern and spatial distribution over a region can be determined. Snow cover persistence index (SCPI) can be derived by the summation of binary snow cover maps in snowmelt season divided by the number of maps during the period of observation. Selection of snow cover layers was carried out similar to the case of SCAI. A total of 31 maps were selected during the snowmelt season (through spring until early in the summer).

Hydro-meteorological data analysis

Due to the lack of sufficient SWE measurements in the region, indirect methods based on hydro-meteorological data must be applied to determine spatial and temporal variability of snow cover characteristics. In this study, critical temperature was derived and a seasonal water balance equation was applied for evaluation of potential snow cover extent and estimation of average annual SWE, respectively.

Critical temperature. Some studies show that surface air temperature is as reliable as any other variables used for differentiating between rain and snow (US Army 1956). Also, spatial variation of air temperature is generally more reliable than other meteorological variables in mountainous regions, due to its reasonable correlation with elevation. Many studies suggest that the snowfall temperature, which is known as the critical temperature (T_c), is normally greater than 0°C, but can vary depending on climate, geographic location and season (Kongoli and Bland 2000). US Army Corps of Engineers (1956) suggested T_c is in the range of 0.5–1°C, whereas Martinec and Rango (1986) referred to maximum values as high as 5.5°C. Roher *et al.* (1994) determined T_c values between 0 and 1.5°C in Switzerland. In this study, T_c was determined by analyzing hourly simultaneous records of SWE, rainfall and temperature recorded at synoptic stations in the region. Values of SWE, rainfall, and air temperature were extracted on a daily basis.

The relationship between daily average air temperature and cumulative amount of rainfall and SWE was used to determine T_c. The procedure is shown for Kouhrang synoptic station in Figure 3. This graph can be helpful to estimate a range of temperatures with corresponding chance of snowfall and rainfall observation. In other words, each observation of precipitation with corresponding mean temperature in a synoptic station was analyzed. In this procedure, percentages of SWE in total precipitation were varied from 0–100%. Then for each temperature record, we obtained the corresponding amounts of rain and SWE. After sorting the data based on the temperature, we plotted Figure 3 using cumulative rain and SWE on the *y* axis. When all of the precipitation is snow, curves of cummulative rain and SWE overlay each other. As shown in Figure 3, below the temperature of −2.5°C all precipitation is in the form of snowfall. The line of accumulated SWE reaches an asymptotic value at a daily average air temperature of 5°C. This means that all of the precipitation is in the form of rain for a daily average air temperature above 5°C. In regions where temperature is between −2.5°C and 5°C, rain, snow or a mixture of both could occur. To account for the uncertainty of the exact critical temperature, we used the median value of air temperature for T_c in all stations. The average values of T_c for all stations in the entire region is equal to 2.4°C.

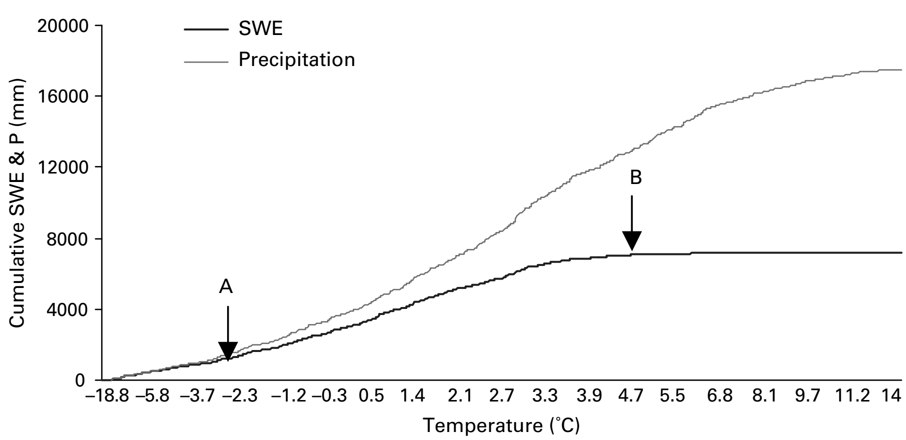

Figure 3 Relationship between daily air temperature and cumulative precipitation and snow water equivalent (SWE) at Kouhrang synoptic station

There is a strong relationship between mean air temperature of the snowfall season and elevation in the Karun basin (Figure 4). Therefore, the areas, which are potentially subject to snow-free, snow-covered and snowfall-melt based on T_c, can be classified using winter lapse rate and digital elevation model (DEM).

Seasonal water balance. In areas of snow accumulation, water stored in the snowpack causes a time delay between precipitation and runoff. One may use the water balance equation to indirectly estimate the average basin SWE. The water balance equation quantitatively balances runoff against precipitation, change in snowpack water equivalent, and losses (US Army Corps of Engineers 1956). The total SWE can be finally computed as the residual when other terms in the water balance equation are known from observations and simulations (Ranzi *et al.* 1999). A seasonal water balance model was used for estimating the average SWE at the time of maximum accumulation for the entire basin or any sub-basins. The snowmelt season was considered to be from the beginning of March up to the end of summer. The water balance model may be expressed as follows (Rango and Martinec 1982):

$$(H_w + P)C = R \tag{2}$$

where:

H_w: average basin water-equivalent of the snowpack at the start of the melting period (cm),

P: precipitation in the basin during snowmelt season(cm),

C: average runoff coefficient, and

R: total runoff depth during the snowmelt season (cm).

Basin precipitation in the snowmelt season was computed based on a simple relationship between seasonal precipitation and elevation. Average runoff coefficient and total runoff during the snowmelt period can be easily computed based on discharge data for each year. Period of precipitation and runoff data was twenty years from 1979/80 to 1998/9. Estimation of the SWE using the above water balance model provided the means for ranking hydrological units with respect to snowmelt contribution to the total runoff.

Results and discussion

Zoning the area based on snow charactiristics

Hydrological units depicted in Figure 2 were used as a basis for zoning the basin, based on the results of indirect approaches including remote sensing, critical temperature analysis and water balance model.

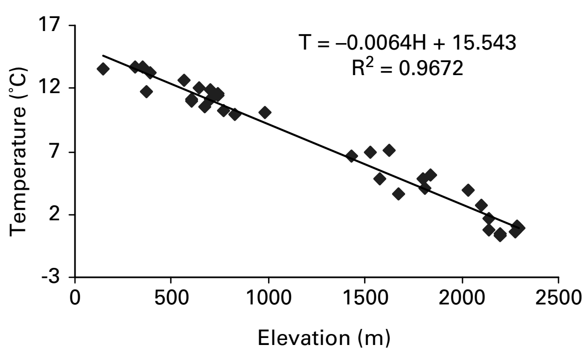

Figure 4 Mean air temperature lapse rate of snowfall season in the Karun basin

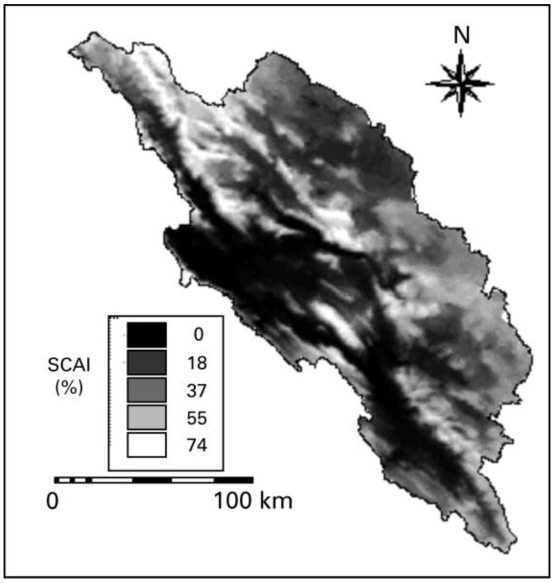

Figure 5 Spatial pattern of snow cover accumulation index (SCAI) in percent in the Karun basin

Ranking areas based on SCAI, MSCAI and SCPI. Spatial patterns of SCAI, MSCAI and SCPI in the Karun basin are shown in Figures 5, 6 and 7, respectively, where lighter shading represent areas with more frequent snow cover observations. The snow indices indirectly represent areas of different snow depth and SWE during specific temporal scales. A high frequency of snow observation or a long persistence of snow cover in localized areas indicates either reduced snowmelt energy input or a large original SWE, or interaction of both during snowfall and snowmelt seasons. Weighted average percentages of SCAI, MSCAI and SCPI in each hydrological unit were estimated by overlaying the boundary of hydrological units and spatial snow cover indices in the GIS. As can be seen in Table 1,

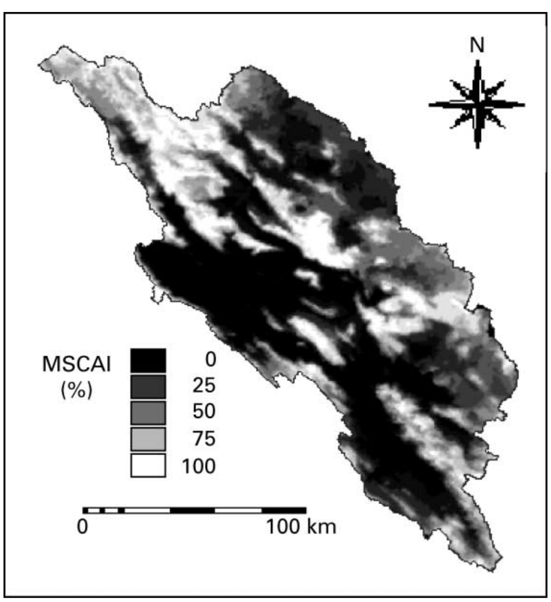

Figure 6 Spatial pattern of maximum snow cover accumulation index (MSCAI) in percent in the Karun basin

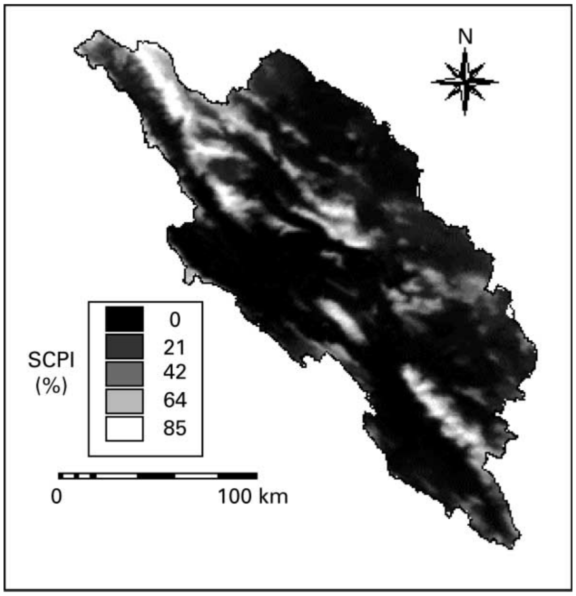

Figure 7 Spatial pattern of snow cover persistence index (SCPI) in percent in the Karun basin

hydrological units B, A, F and C are the most important areas with respect to the SCAI and MSCAI. Moreover, units B, A and C have maximum percentage of snow cover persistence in the melt season. The minimum percentage of SCAI, MSCAI and SCPI can be observed in hydrological units J, G and D, respectively.

Ranking areas based on snow cover potential. Areas with potential of snow-free, snow-covered and snowfall-melt were classified using T_c and winter lapse rate. For this purpose, DEM and winter lapse rate (Figure 4) were used to classify the area with temperature below 0°C as snow-covered zone, areas with temperatures between 0–2.4°C as snowfall-melt zone and areas with temperature higher than 2.4°C as snow-free zone during snowfall season. The spatial pattern of different snow zones is shown in Figure 8. The snow-covered zone represents the area where precipitation occurs as snow and it will not melt until the end of the snowfall season. This area will participate in snowmelt runoff generation in spring and summer. Snowfall-melt zone is an area with the possibility of snowfall and snowmelt in the

Table 1 Ranking of the hydrological units based on snow characteristics

Hydrological unit	Snowmelt (mm)	Snow cover indices (%) SCAI	MSCAI	SCPI	Snow cover potential area (%)	Overall rank
A	213	53	64	21	31	2
B	514	62	64	38	64	1
C	149	51	53	11	41	4
D	76	33	28	2	20	8
E	207	48	47	8	45	5
F	132	52	57	4	61	3
G	58	28	25	2	15	9
H	211	37	37	9	40	7
I	178	39	41	7	53	6
J	135	19	16	3	15	10

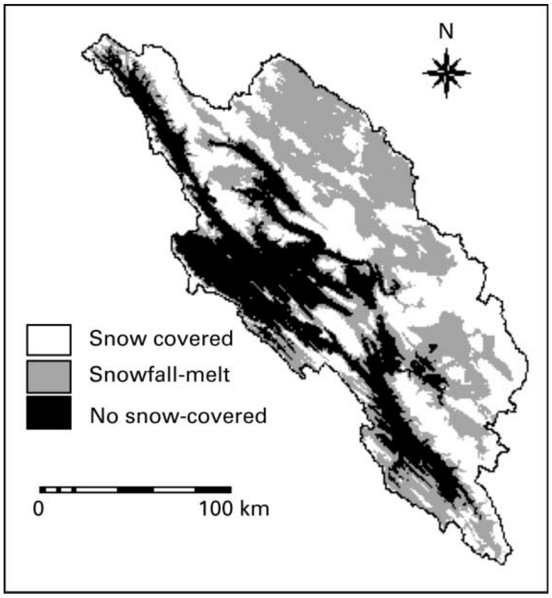

Figure 8 Spatial pattern of snow cover potential zone based on the critical temperature

snowfall season. Finally, snow-free zone is an area where, on average, precipitation during the snowfall may occur only as rain. The percentage of the area of snow cover in hydrological units was estimated in GIS. As shown in Table 1, hydrological units B and F have more than 60% of their total area as snow-covered area during snowfall season. On the contrary, hydrological units G, J and D have the minimum percentage of snow-covered area.

Ranking areas based on contribution of snowmelt to runoff. The average SWE in the sub-basins are listed in Table 2. These sub-basins have sufficient hydro-meteorological data including monthly precipitation and runoff and were estimated using the water balance as in Equation (2). As a result, snowmelt runoff can be approximated considering runoff coefficient. Average annual depth of snowmelt runoff in Karun basin was estimated at

Table 2 Physiographic characteristics of subbasins and the corresponding estimated snowmelt (mm)

Sub-basin	Area (km^2)	Elevation (weighted average) (m)	Area higher than elevation (%) 2000 (m)	2500 (m)	3000 (m)	Snowmelt (mm)
Armand	9942	2433.8	93.4	39.7	9.1	111.5
Barez	8999.7	2311.9	80.4	32.6	6.1	133.1
Batari	860.8	2201.1	85.7	14.1	0.1	189.1
Dehkadeh	203.5	2673.9	100	80.2	15.1	390.3
Kata	4027.7	2465	94.7	42.8	7.1	101
Morghak	2146.4	2181.5	61.5	28.9	8.3	357.3
Pole Shaloo	24141	2297.9	79.1	32.5	7.2	152.5
Shahmokhtar	890.2	2366.6	87.4	41.2	3.1	225.9
Solekan	2288.6	2524.7	100	47.5	6.1	45.3
Patave	2800	2298.9	78.8	28.8	5.9	173.7
Tangzard	1045	2561.9	100	56.5	4.8	40.5
Bashmalek	169.3	1264.8	13.4	6.3	0	17.1
Gooshepol	99	2556.2	86.1	51.3	25.8	516.1

152.5 mm. Therefore, snowmelt runoff comprises about 50% of the annual total runoff in this mountainous basin. To study the regional pattern of SWE and contribution of snowmelt to runoff, a relationship between several physiographic indices and the estimated snowmelt depth was developed using stepwise multiple regression analysis. The most accurate regional model was used to estimate the snowmelt depth of all hydrological units, depicted in Figure 2. The regression analysis indicated that the best correlation was between snowmelt depth (mm) and per cent area higher than 3000 m. This relationship is significant at the 99% confidence level and R^2 is equal to 0.61:

$$S = 17.41(PA_h) + 56.54 \qquad (3)$$

where:

S: average annual snowmelt depth (mm) and

PA_h: per cent area higher than 3000 m.

Equation (3) was used to estimate the average annual snowmelt (mm) in all hydrological units (Figure 2) and the results are also shown in Table 1. It shows that units B and A have the highest average annual snowmelt runoff and units G and D have the lowest.

Correlation between topography and snow cover indices

The association of spatial and temporal characteristics of snow cover, namely SCAI, MSCAI and SCPI, with topography and meteorological variables was examined for the study basin. Relationship between snow cover indices and mean air temperature in snowfall season (MATSS), mean air temperature of melting season (MATMS), elevation, slope and aspect were investigated. Geomorphometric variables, including elevation, aspect and slope, were extracted from the 250 m pixel size DEM. Layers of MATSS and MATMS were developed using lapse rate of snowfall and snowmelt seasons and the DEM. Table 3 gives the correlation matrix of these topographic indices with SCAI, MSCAI and SCPI. SCAI, MSCAI and SCPI are highly correlated with elevation, MATSS and MATMS. Also, a negatively correlated snow cover–temperature relationship was observed. Regarding the extraction of MATSS and MATMS layers using DEM, there is an inter-correlation between these layers, which is shown in Table 3. This suggested that topography has the most important influence on the snow accumulation during snowfall season. Furthermore, it appears that spatial patterns of snow melting were largely dominated by the elevation. Therefore, temperature was omitted from the rest of the analysis. Correlation between snow cover indices with aspect and slope were weak, which illustrates that, at large scale, snow cover indices cannot be adequately modeled with aspect or slope individually. To examine the influence of slope,

Table 3 Correlation matrix of snow cover indices with topographic and meteorological variables

	SCAI (%)	MSCAI (%)	SCPI (%)	Elevation (m)	Aspect (°)	Slope (%)	MATSS (°C)	MATMS (°C)
SCAI	1							
MSCAI	0.94	1						
SCPI	0.62	0.67	1					
Elevation	0.78	0.76	0.69	1				
Aspect	−0.04	0.12	−0.04	−0.01	1			
Slope	0.06	−0.04	0.25	0.12	−0.04	1		
MATSS	−0.78	−0.76	−0.69	−1	0.01	−0.12	1	
MATMS	−0.78	−0.76	−0.69	−1	0.01	−0.12	1	1
Weighted average	36	40	9	2297.9	169.4	26.2	0.8	12.6
Std.	25	33	17	469.5	103.8	24.1	3	3.2

aspect and elevation on snow cover indices, a random line sampling technique in GIS was used. As a result, a similar spatial data set from all the above layers was extracted. Using this method, a data set with 3896 samples (pixel number with corresponding values) was prepared. Multiple linear and nonlinear stepwise regression models were used to examine relationships between snow cover indices and topographical variables. These relationships are shown in Table 4. The proposed models were tested based on the test sample data set, which was extracted using other series of random line sampling. Validation pixels (3708 test pixels) were not used for estimating the model parameters. Model performance is shown in Table 4, using mean absolute error (MAE) and root mean absolute error (RMAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}[z(x_i) - \hat{z}(x_i)] \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[z(x_i) - \hat{z}(x_i)]^2} \quad (5)$$

where:

n: number of data observations,

$z(x_i)$: observed values, and

$\hat{z}(x_i)$: estimated values.

As can be seen in Table 4, only in the case of SCAI and MSCAI, the correlation coefficient and model accuracy was slightly improved by including slope gradient and aspect. In the case of SCPI models, better accuracy can be achieved only when elevation is used as the independent variable.

Practical implications

Zoning the Karun basin based on snow characteristics in this study has several practical applications for management of water resources. As illustrated in Figures 1 and 2, there is no snow course in unit A. This is while hydrological unit A is the second most important part of the basin with respect to snow cover indices and snowmelt runoff (Table 1). This suggests the need to setup snow gauges in that particular hydrological unit. In Karun basin there are no telemetric snow gauges. If a plan for completion of the existing snow measurement network is to be devised, zoning the basin can be used for site selection of snow gauges.

Snow cover indices proposed in this research can be used for practical purposes such as dam site selection and drought management and planning. If SCAI is high in a hydrological

Table 4 Relationships between snow cover indices and topographical variables

Model	R^2	S.E.	MAE	RMSE
$SCAI = a_1H^{0.5} + c$	0.766	0.1550	0.135	0.164
$SCAI = a_1H^{0.5} + a_2As^{0.5} + c$	0.767	0.1547	0.134	0.163
$SCAI = a_1H^{0.5} + a_2As^{0.5} + a_3As^{2}S^{0.5} + c$	0.768	0.1545	0.134	0.163
$MSCAI = a_1H^{0.5} + c$	0.734	0.222	0.183	0.225
$MSCAI = a_1H^{0.5} + a_2S^{0.5} + c$	0.737	0.221	0.182	0.226
$MSCAI = a_1H^{0.5} + a_2S^{0.5} + a_3S^{2}As^{0.5} + c$	0.739	0.221	0.180	0.224
$SCPI = a_1H^{2} + c$	0.790	0.104	0.084	0.109
$SCPI = a_1H^{2} + a_2H + c$	0.857	0.087	0.060	0.095
$SCPI = a_1H^{2} + a_2S^{0.5} + a_3S^{2}As^{0.5} + c$	0.814	0.097	0.224	0.263

H is elevation (m), S is slope gradient (%), As is slope aspect (°), $a_1,\ldots,a_3$ are regression coefficients and c is constant coefficient. All regression were significant at $P < 0.001$. Number of sample data points and test sample were 3896 and 3708 pixels, respectively unit, it means that snow cover observation during snowfall season is frequent. Also, high values of MSCAI and SCPI shows that more snow reserves may be available through the spring and summer in that particular unit. As an example, SCAI, MSCAI and SCPI in unit F are 52%, 57% and 4%, respectively. Although frequency of snow cover observation during snowfall season and snow accumulation at the start of snowmelt season is high in this hydrological unit, a low percentage of SCPI shows that snow cover will disappear early in the spring. Therefore, unit F is a good candidate for water supply planning by dam construction to regulate the riverflow during low flow seasons. On the other hand, hydrological units B, A and C have high values of SCAI, MSCAI and SCPI. So not only is the frequency of snow accumulation during snowfall season high, but also more snow reserves could be available through the spring and summer in those units. With respect to the high percentage of SCPI in the above units, snowmelt naturally contributes to the runoff during a low flow season. Consequently, there is no priority for drought management planning and dam construction projects in these particular hydrological units.

Summary and conclusions

Snow cover accumulation and persistence indices were extracted using satellite images. The approach can be seen as an indirect qualitative assessment of snow cover variability in space and time. Long term monitoring of snow cover variability is crucial for assessing the snow cover dynamics. In spite of uncertainties in extracting usable information from data, they provide realistic estimates of snow cover area in the times when ground snow measurements are not feasible. Using remotely sensed data, a temporal mapping of the same area of the basin can be obtained. Observations taken at certain time intervals yield important information on changes of spatial patterns of accumulation and persistence of snow. Developing distributed snow cover indices may contribute to the understanding of snowmelt processes. Specifically, snow cover indices may assist in developing concepts for spatially distributed hydrological snowmelt models in large-scale mountainous basins.

Correlation analysis between topographic and meteorological variables with snow cover indices was conducted in this research. The results suggested that elevation was the single most important variable describing large-scale snow variability. Regression models similar to the ones presented in this study can be applied to predict the spatial pattern of snow accumulation and persistence in other basins.

This study demonstrates how remotely sensed data can complement ground hydro-meteorological measurements to simulate the spatial and temporal variations of snow cover characteristics and zoning in a mountainous basin. The procedure that was developed for zoning a large mountainous basin uses different but related approaches. As such, hydrological units with different levels of priority regarding snow characteristics can be ranked. Frequency of snow cover observations using remote sensing, potential of snowfall and snow-covered area using meteorological analysis and contribution of snowmelt to runoff based on the hydrologic water balance equation were also used in this study. Consequently, a picture representing snow characteristics in the scale of subbasins was presented.

Agreement between three indirect approaches for zoning the area, regarding the highest and lowest ranking of hydrological units, was observed in this study. This is an encouraging result that shows the reliability of indirect approaches for the situation of snow data scarcity.

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