Modelling the temporal variation in snow-covered area derived from satellite images for simulating/forecasting of snowmelt runoff in Turkey

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Abstract Monitoring the change of snow-covered area (SCA) in a basin is vitally important for optimum operation of water resources, where the main contribution comes from snowmelt. A methodology for obtaining the depletion pattern of SCA, which is based on satellite image observations where mean daily air temperature is used, is applied for the 1997 water year and tested for the 1998 water year. The study is performed at the Upper Euphrates River basin in Turkey (10 216 km^2). The major melting period in this basin starts in early April. The cumulated mean daily air temperature (CMAT) is correlated to the depletion of snow-covered area with the start of melting. The analysis revealed that SCA values obtained from NOAA-AVHRR satellite images are exponentially correlated to CMAT for the whole basin in a lumped manner, where R^2 values of 0.98 and 0.99 were obtained for the water years 1997 and 1998, respectively. The applied methodology enables the interpolation between the SCA observations and extrapolation. Such a procedure reduces the number of satellite images required for analysis and provides solution for the cloud-obscured images. Based on the image availability, the effect of the number of images on the quality of snowmelt runoff simulations is also discussed. In deriving the depletion curve for SCA, if the number of images is reduced, the timing of image analysis within the snowmelt period is found very important. Analysis of the timing of satellite images indicated that images from the early and middle parts of the melt period are more important.

Key words cumulative mean daily temperature; NOAA-AVHRR images; snow-covered area; snowmelt runoff; Turkey

Modélisation de la variation temporelle de la surface enneigée à partir d'images satellitaires pour la simulation/prévision de l'écoulement de fonte nivale en Turquie

Résumé Suivre l'évolution de la surface enneigée dans un bassin est d'une importance vitale pour la gestion optimale des ressources en eau, lorsque la contribution principale correspond à la fonte nivale. Une méthodologie d'obtention des courbes de diminution de la surface enneigée, qui s'appuie sur des observations satellitaires et qui utilise la température moyenne journalière de l'air, est appliquée à l'année hydrologique 1997 et testée pour l'année hydrologique 1998. L'étude est réalisée pour le bassin supérieur de l'Euphrate, en Turquie (10 216 km^2). La période principale de fonte dans ce bassin commence début avril. La température moyenne journalière cumulée de l'air (TMJC) est corrélée avec la réduction de la surface enneigée et avec le début de la fonte. L'analyse montre que les valeurs de surface enneigée obtenues à partir d'images satellitaires NOAA-AVHRR sont corrélées de manière exponentielle avec la TMJC du bassin dans sa globalité, avec des valeurs de R^2 respectivement égales à 0.98 et 0.99 pour les années hydrologiques 1997 et 1998. La méthodologie appliquée permet de réaliser des interpolations entre les observations de surface enneigée, ainsi que des extrapolations. Une telle procédure réduit le nombre d'images satellitaires nécessaires pour l'analyse et fournit une solution pour les images ennuagées. Compte tenu de la disponibilité des images, l'effet du nombre d'images

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sur la qualité des simulations d'écoulement de fonte nivale est également discuté. Si le nombre d'images est réduit, le calendrier des images par rapport à la période de fonte se révèle être très important pour la déduction de la courbe de réduction de la surface enneigée. L'analyse du calendrier des images satellitaires montre que les images correspondant au début et au milieu de la période de fonte sont plus importantes.

Mots clefs température moyenne journalière cumulée; images NOAA-AVHRR; surface enneigée; écoulement de fonte nivale; Turquie

INTRODUCTION

Snow and snowmelt runoff are major sources of water supply in mountainous regions, where the seasonal accumulation of snow pack is followed by lengthy melt periods that last for months. Accurate planning for agriculture, providing sufficient municipal water supply, efficient energy generation, recreation and effective flood mitigation depend greatly on the details of the snow melting process. Snowmelt runoff originates from the snow-covered areas (SCA). Snow cover and the equivalent amount of water volume stored supplies at least one-third of the water that is used for irrigation and the growth of crops worldwide (Steppuhn, 1981).

The high albedo of snow causes the reflection of a higher percentage of solar shortwave radiation, besides causing variations in the energy budget calculations. Moreover, the high heat capacity of snow cover isolates the soil surface from the atmosphere and slows down the warming process in spring. Thus, the ability to map the areal depletion of snow correctly is important for operational decision making (e.g. reservoir management); for correct specification of boundary conditions in numerical weather prediction models and for modelling atmospheric, hydrological and ecological processes (Simic *et al.*, 2004).

Remote sensing (RS) helps to determine the SCA from satellite images. The high reflectivity of snow in the visible bands of the electromagnetic spectrum enables the discrimination of snow from other non-snowy areas. Thus, RS is an indispensable tool for simulating and/or forecasting of snowmelt runoff and climate studies by the snow-covered area analysis it offers. A review of RS in snow hydrology is given by Rango (1993) and some applications are presented in Akyürek & Sorman (2002), Singh & Jain (2003), Bernier *et al*. (2003), Shaban *et al*. (2004), and Aouad-Rizk *et al*. (2005). Even though RS enables the determination of SCA on a daily basis, there may exist some missing dates in the determination of SCA, due either to the cost involved for image analysis or to the time duration required for satellite image processing. Moreover, cloud–snow confusion is one of the major impediments for snow classification. Certain types of clouds, such as cirrus, low stratus and small cumulus, are hard to discriminate from snow and ice-covered surfaces (Simpson *et al.*, 1998). Thus, in general, SCA is obtained for the cloud-free days during the melting period and interpolated in some way for the missing intermediate days. There is not a globally accepted method to fill out missing dates or to extrapolate for following days of SCA required for simulating or forecasting of snowmelt runoff.

In this study, daily mean air temperature values are used to apply a methodology that would enable the determination of SCA, either for simulation or for forecasting of snowmelt runoff. The methodology is applied for the basin scale and promising results are obtained. The study also helps to find a way of reducing the number of satellite images required for deriving SCA and provides a solution to the cloud obscuring problem. The effects of image number on the snowmelt runoff simulation results are also evaluated.

METHODOLOGY

For forecasting and/or simulating snowmelt runoff, there exist numerous methodologies. These vary from the index methods to detailed energy balance approaches. Among the many index methods, the temperature index models are the most frequently used models in operational studies. In temperature index models, commonly, air temperature is used to estimate the snowmelt runoff. This is due to the fact that air temperature data are readily available from both climatological and operational hydrometeorological networks. Moreover, it is probably the best single index to represent areal snow cover change. The other main components of melt—short wave radiation, sensible and latent heat—show large variations due to topography and vegetation cover, and it is hard to obtain these data where hydrometeorological measurements are scarce. 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 & Gray, 1981).

The degree-day method is a temperature index method in which the total daily reduction of the water equivalent in the snowpack, M, is related to the difference between the daily average temperature and a base temperature, according to the formula:

$$M = a(T_a - T_b) \tag{1}$$

where a is the degree-day factor (cm °C^{-1} day^{-1}), T_a is the daily average and T_b the base temperature (°C) above which melting occurs. For cases in which $T_a < T_b$, no melt is produced. From the various applications of the degree-day method, it is known that a, the degree-day factor, is not a constant parameter but shows gradual increase as snow ripens and solar radiation increases.

The snowmelt runoff model (SRM) is a degree-day based temperature index model. It computes the water produced from snowmelt and rainfall, superimposes the values on the calculated recession flow, and transforms all together into daily discharge values (Martinec *et al.*, 1998). Despite the simplicity of the degree-day method, the reported studies prove its utility for simulation or forecasting of river discharges induced from snowmelt in SRM (Singh & Singh, 2001; Martinec *et al.*, 1998). The SRM is the main hydrological model used for snowmelt runoff computations in this study. Some over- and underestimations of the simulated/forecast discharges by SRM are expected, which may arise from the imperfections of the model parameters, variables and/or from the model structure. Since air temperature is just one component out of a group of snowmelt driving factors, such an outcome is normal. However, the studies performed worldwide, over 100 basins in 25 countries, prove the utility of the SRM in hydrological studies (Seidel & Martinec, 2004).

Temperatures within the watershed begin to increase starting from the lowest elevation towards the high altitudes as the spring months start and progress to summer. Snow retreats from the lowest towards higher elevations with the increase of temperature in the basin. Thus, the existence of a relationship between SCA and mean daily air temperature is certain. A procedure for evaluating the depletion of snow-covered area using mean air temperature was tested and it was found that depletion of SCA is exponentially correlated with cumulative mean air temperature (Singh *et al.*, 2003).

STUDY AREA

Karasu basin, the headwaters of Euphrates River in Turkey, is selected as the study area. Figure 1 shows the location of the basin in Turkey, the river network in the basin and the major dams on the Euphrates River. The basin has a drainage area of 10 216 km^2 and ranges in altitude from 1125 to 3487 m (Table 1). The main land cover types are shrub, grass and bare land. Long-term studies indicate that about 60–70% of the total annual volume of water arrives in the basin during the snowmelt season. From the ratios of 64% for 1997 (Kaya, 1999) and 70% for 1998 (Tekeli, 2000), these years were defined as average and wet years, respectively, based on the long-term river discharge volume analysis of 1954–1987 (Table 2 and Fig. 2). In the downstream of Karasu basin, there are two large dams, namely Keban and Karakaya dams, which are designed for hydropower generation, irrigation and water supply (Fig. 1). Therefore, accurate snowmelt runoff estimation in terms of rate of discharge and volume is very important for the area of interest.

The study is performed by using the data from the water years 1997 and 1998. The dates with satellite images are shown in Table 3 with the SCA percentages. The SCA data were obtained from Kaya (1999) for 1997 and from Tekeli (2000) for 1998 water

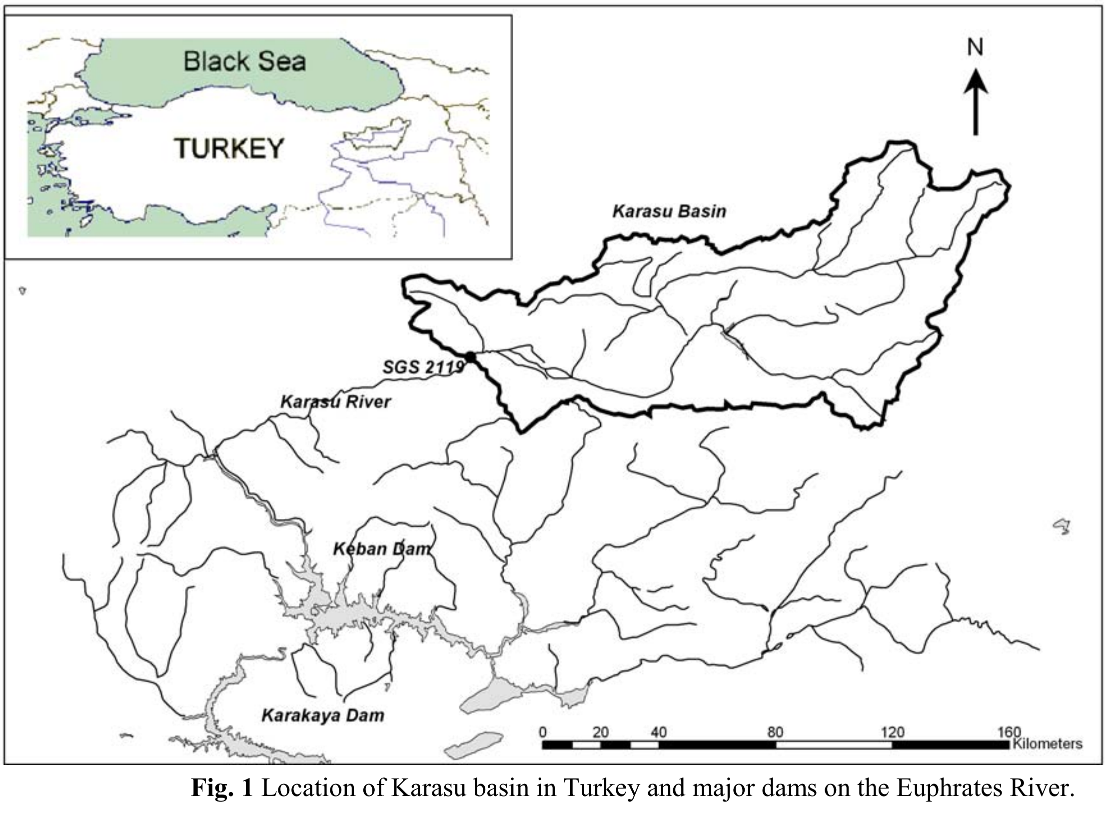

Fig. 1 Location of Karasu basin in Turkey and major dams on the Euphrates River.

Table 1 Elevation zones of Karasu basin.

Zone	Elevation range (m)	Area (km^2)	Area (%)	Hypsometric mean elevation (m)	Mean slope (%)
A	1125–1500	1123.2	11	1352	6.1
B	1500–1900	3268.5	32	1751	11.5
C	1900–2300	3459.3	34	2097	18.1
D	2300–2900	2196.8	21	2482	21.3
E	2900–3487	167.9	2	2989	26.3
Whole basin	1125–3487	10215.7	100	1977	15.5

Table 2 Long-term (1954–1987) river discharge volume analysis.

Water year	Total discharge volumes (1 March–31 June) (m^3)
1997	1.71×10^9
1998	2.41×10^9
Long-term mean (1954–1987)	$\mathbf{1.77 \times 10^9}$

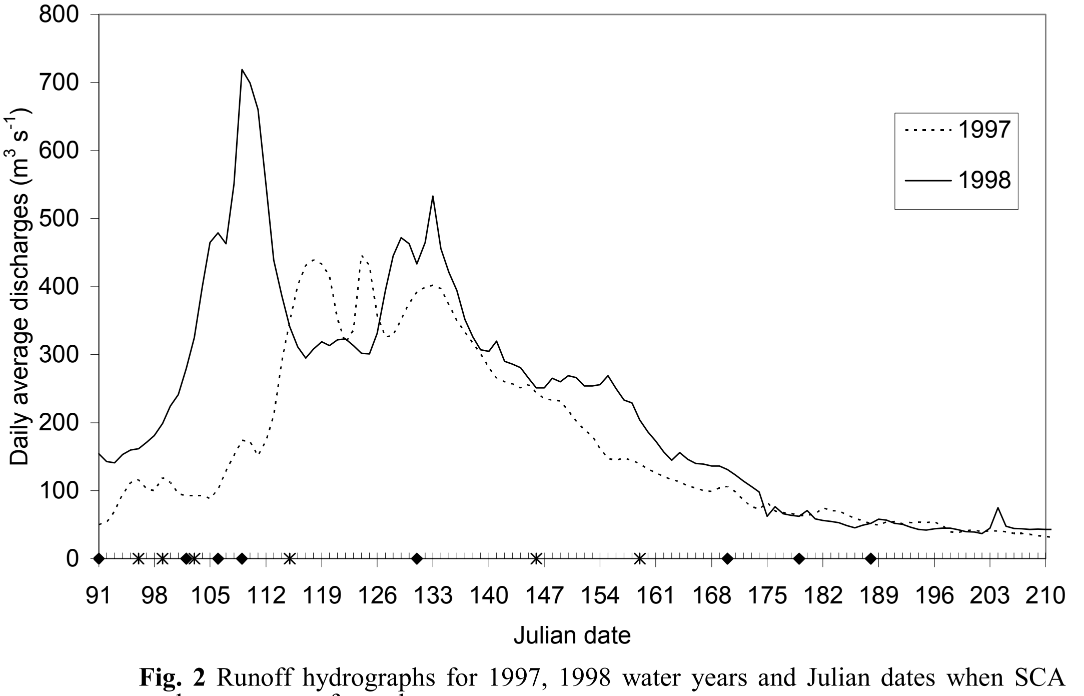

Fig. 2 Runoff hydrographs for 1997, 1998 water years and Julian dates when SCA analyses were performed.

years. For both years, NOAA-AVHRR satellite images, with 1.1 km × 1.1 km spatial resolution, were used for the determination of SCA.

Mean daily air temperatures were obtained from the meteorological stations in and around the basin (Fig. 3). The temperature data availability for 1997 and 1998 water years from the above-mentioned stations are presented in Table 4. The point temperature values obtained from the stations were then interpolated throughout the basin using either kriging or de-trended kriging, based on the analysis performed on these point values (Başbuğ, 1999). The Spatially Distributed Hydrometeorological Variables

Table 3 Dates of satellite images used for the study and the SCA in percentages for the elevation zones.

Image number	Date	Zone A	Zone B	Zone C	Zone D	Zone E
Water year 1997:						
1	1 April	58.2	96.30	100.00	100.00	100.00
2	12 April	16.3	78.80	98.80	100.00	100.00
3	16 April	8.5	69.90	98.40	100.00	100.00
4	19 April	7.1	61.30	96.20	100.00	100.00
5	11 May		5.20	17.20	89.50	100.00
6	19 June			3.00	22.60	83.70
7	24 June			1.90	14.30	68.50
8	7 July				2.80	33.70
Water year 1998:						
1	6 April	0.52	38.48	93.19	99.45	100.00
2	9 April	0.50	19.93	78.72	98.31	100.00
3	13 April	0.42	5.20	49.21	90.97	99.69
4	25 April	0.22	2.93	26.39	77.45	99.35
5	26 May				3.26	25.53
6	8 June				0.42	20.65

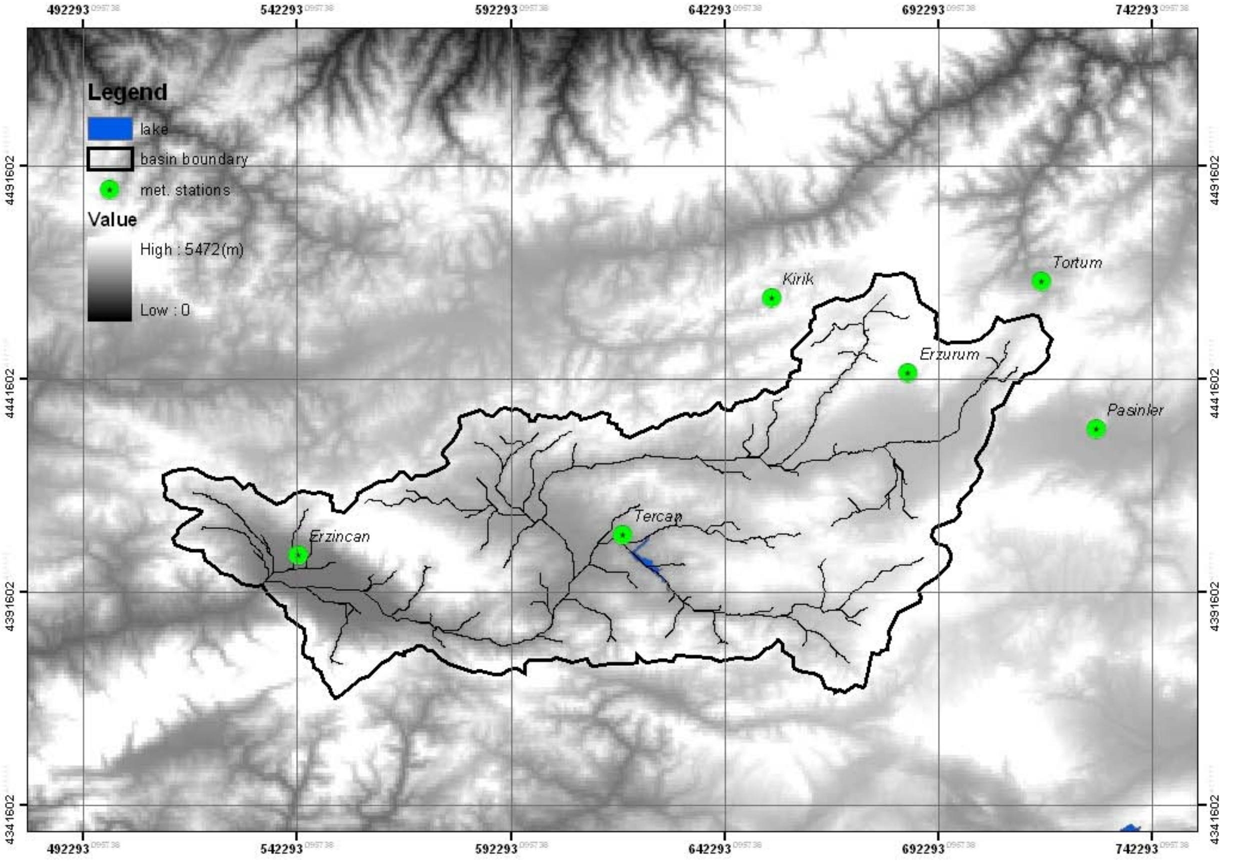

Fig. 3 Location of meteorological stations in and around Karasu basin.

(SPAM) program developed by Garen *et al.* (1994) can be used for this purpose**.** In this study, the SPAM program is used for interpolation of temperature from the point measurements throughout the basin in daily time series.

Table 4 Availability of temperature data for water years 1997 and 1998.

Meteorological station names	April		May		June		July	
	1997	1998	1997	1998	1997	1998	1997	1998
Erzincan (1218 m)	×	×	×	×	×	×	×	
Tercan (1425 m)	×	×	×	×	×	×	×	
Tortum (1602 m)		×		×		×		
Pasinler (1660 m)	×	×		×	×	×	×	
Erzurum (1758 m)	×	×	×	×	×	×	×	
Kırık (2075 m)	×						×	

The SPAM program requires a digital elevation model (DEM) of the area under study. Spatial interpolation is performed by dividing the variability into vertical and horizontal components. In de-trending, a linear regression of elevation *versus* the hydrological variable is fit to each data set. For estimation of the de-trending line, Garen *et al.* (1994) suggest the use of least absolute deviations regression for daily precipitation and least squares for daily temperature data. Residuals from this regression are used in the kriging calculations. Kriging handles the horizontal interpolation. Distances among the stations and distances between stations and grid cells are used to calculate the kriging weights. In the present version of the program used, de-trending is related to orographic influence, i.e. for precipitation the values are expected to increase with elevations, whereas for temperature the values are expected to decrease. If such a condition cannot be satisfied, only the interpolation by pure kriging in the horizontal dimension is performed.

An overlay analysis within the geographic information systems is used to determine the mean temperatures of the basin from the distributed temperature values provided as outputs by SPAM. These mean temperature values are related to the SCA variation within the basin.

APPLICATION

Based on the findings in Kaya (1999) and Tekeli (2000), the depletion of SCA in Karasu basin with cumulative mean air temperature (CMAT) on a daily basis for the corresponding dates is given in Fig. 4 for 1997 and 1998 water years. An exponential relationship between SCA and CMAT can be assumed (cf. Fig. 5), in the form:

$$Y = A \times \exp(-BX) \qquad (2)$$

For the present case, Y denotes the SCA and X stands for the CMAT, whereas, A and B are the coefficients to be determined. The exponential fit to variation of SCA with respect to CMAT can be seen in Fig. 5 and the computed coefficients in equation (2) are given in Table 5.

The high R^2 values in Table 5 support the preliminary assumption of an exponential relationship between SCA and CMAT. This exponential relationship can be explained on the basis of distribution of snow in the basin (Singh *et al.*, 2003). As discussed by Singh & Kumar (1997), increase of snow depth with elevation would result in thinner and low-density snow packs at the lower elevations and thicker and

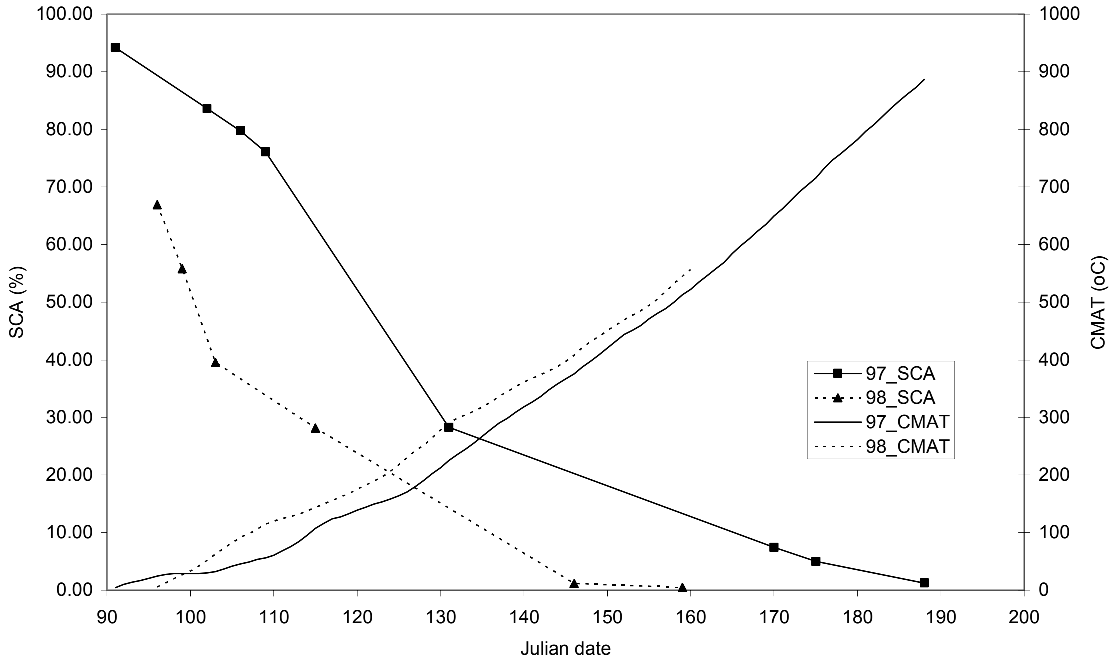

Fig. 4 Variation of snow covered area and cumulative mean temperature with time in Karasu basin for water years 1997 and 1998.

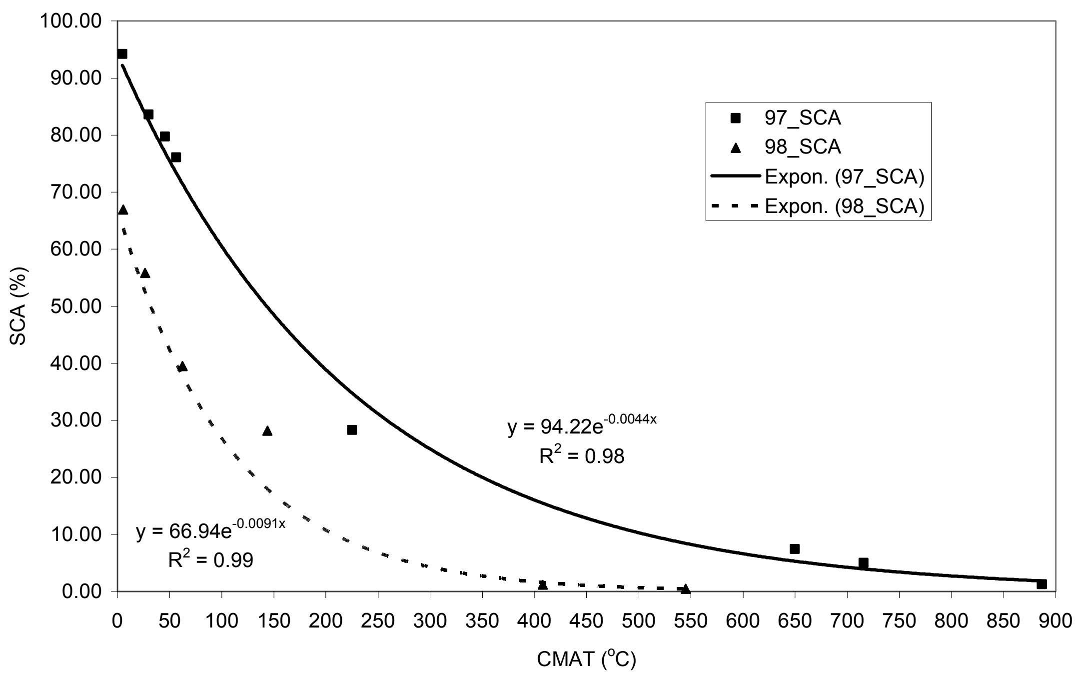

Fig. 5 Exponential fit to variation of SCA and CMAT for water years 1997 and 1998.

denser ones at the higher altitudes. This case is in agreement with the data gathered from the automated snow and meteorological stations distributed at different elevations in the Karasu basin.

At the start of spring, SCA in the basin is reduced by retreating of the snow line from the lower elevations of the basin towards the higher areas. The retreat rate is

Table 5 Coefficients and R^2 values for the 1997and 1998 ablation periods.

Melt season	A	B	R^2	*SWE* (mm) (1 April)
1997	94.22	0.0044	0.98	172
1998	66.94	0.0091	0.99	282

reduced as the thicker and denser snow packs are reached at the higher altitudes towards the end of the melting period. Rapid melting of snow, and thus the quick disappearance of SCA in lower elevations, was reported by Kattelman (1997). Gupta *et al*. (1982) derived a logarithmic relationship between SCA and the volume of seasonal snowmelt runoff for Himalayan basins. These studies support the exponential relationship between SCA and CMAT used in this study. An exponential relationship implies that initial increments in temperature lead to higher changes in the snow-covered area than later increments in temperature of the same magnitude (Singh *et al.*, 2003).

As can be seen in Table 5 the A values of equation (2) vary for each year since this value is dependent on the initial percentage of snow cover in the basin. In the same table, averages of data (gathered all around the basin where snow exists on the indicated date) show 172 mm snow water equivalent (*SWE*) for 1 April 1997 and 282 mm for 1 April 1998. Although, higher *SWE* for 1998 foresees a slower reduction, the fast depletion in 1998 caused the B coefficient to be higher than in 1997. Another reason may arise from the variation in intensity and composition of winter precipitation. Moreover, the snowmelt/thawing mechanism and early melting observed in early April 1998, might have caused faster depletion.

Snow-covered area is one of the major inputs to some major operational snowmelt runoff models for simulating or forecasting river discharges. Besides, SCA has great importance in numerical weather prediction models.

The study performed here can mainly be used for the following purposes:

- Interpolating and simulating of SCA;
- Extrapolating and forecasting of SCA; and
- Snow-covered area sensitivity analysis.

Interpolating and simulating of SCA

As the relationship between SCA and CMAT is derived, the SCA values for the missing dates can be found by using the obtained relationship. In this way, SCA between the observation times can be interpolated and the depletion of the SCA from the basin can be simulated. The simulated values can be used as input into a snowmelt runoff model (SRM) (Martinec *et al.*, 1998) to obtain the simulated discharges, or used to update and/or improve a model such as HBV (Engest *et al.*, 2003).

As a typical interpolation example, for the year 1997, the images for 16 April, 11 May and 19 June (image numbers 3, 5 and 6) were removed from the available images. Based on the remaining images (image numbers 1, 2, 4, 7 and 8, see Table 3), a new exponential relationship was derived. The comparison of the new exponential fit with the observed values is given in Fig. 6. A similar analysis was conducted for the water year 1998, in which the images for the 9 and 13 April, and 26 May were

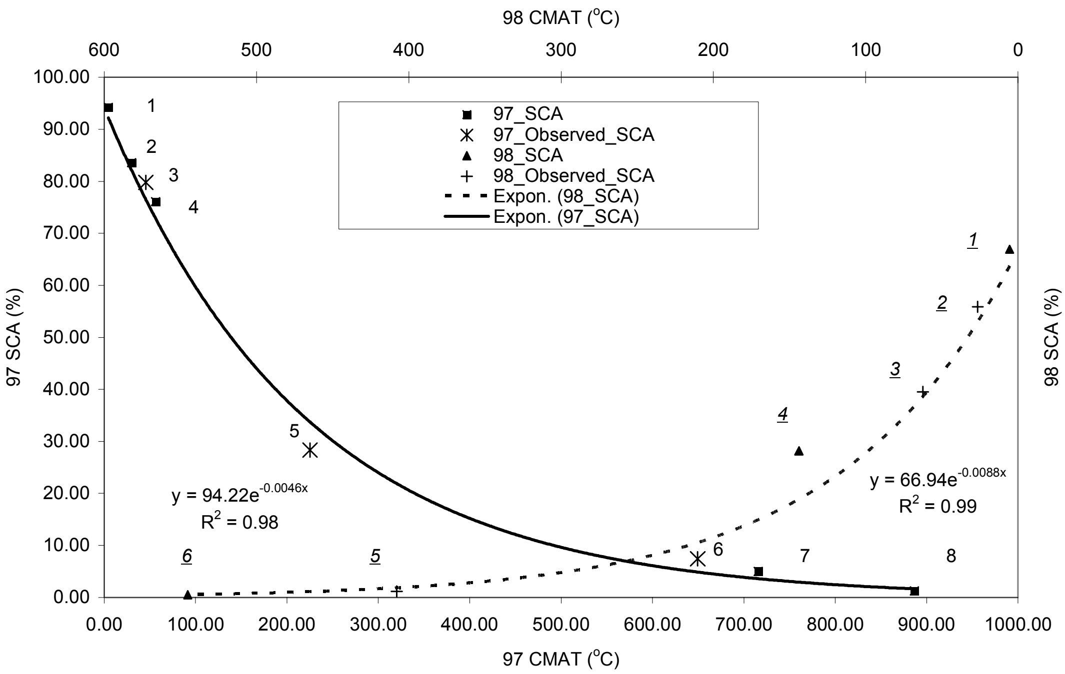

Fig. 6 Exponential fit to variation of observed SCA and CMAT for water year 1997 (16 April [3], 11 May [5] and 19 June [6] values are interpolated) and water year 1998 (9 [*2*], 13 April [*3*] and 26 May [*5*] values are interpolated). The numbers 1 to 8 indicate the image numbers given in Table 3 and the numbers *1* to *6* (underlined and italic) indicate the image numbers given in Table 3 for the 1998 water year.

removed. Figure 6 also represents the exponential relationship and the observed values for 1998 on the *y*-axis on the right side. The selection of the removed points was based on the analysis performed by the available images and the observed discharges at the basin outlet (SGS 2119 in Fig. 1), trying to omit images, one at the beginning, one in the middle and one at the end of the melting season. Since the *A* coefficient in equation (2) depends on the initial snow cover percentage, it stayed the same. However, there occurs a slight change in the *B* values in equation (2) that indicate the depletion according to the number of the images used in deriving the equation.

Extrapolating and forecasting of SCA

Using the exponential relationship derived, the depletion of SCA can be forecast once the forecast temperature values are obtained. As an example, the depletion of SCA for 7 July 1997 was forecast based on the temperature values and using all the remaining seven satellite images (see Fig. 7). To see the effect of the number of available images on the accuracy of the forecast values, 24 June and 7 July 1997 were forecast using the remaining six satellite images. As the number of images was reduced, the exponential fits were recalculated each time. Table 6 summarizes the procedure followed for both 1997 and 1998. Even though it cannot be clearly stated that the increase in number of images reduced the percentage differences between the observed and forecast SCA values, it can be seen from Table 6 that, as the time period of forecast increases, the forecast of SCA values later in the time period get worse. Thus to get better estimates of further forecasts, the exponential fits should be updated with the latest available SCA image.

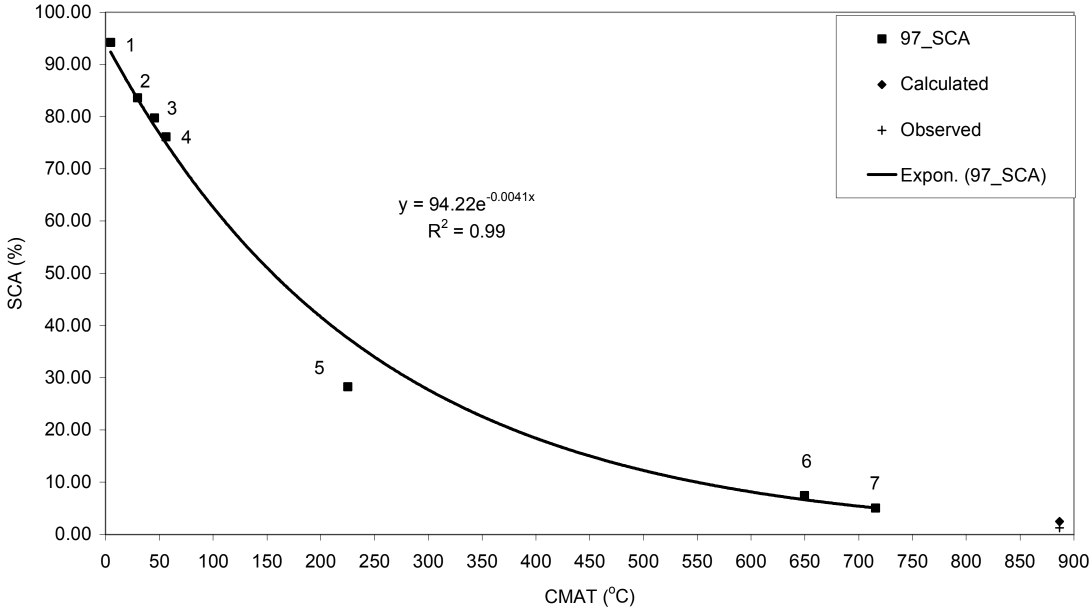

Fig. 7 Exponential fit to variation of SCA and CMAT for water year 1997 (extrapolating for 7 July 1997– Julian date 188).

Table 6 Effect of image availability on the forecast accuracy for 1997 and 1998 water years.

Image numbers used*	Date of forecast SCA	*A*	*B* ($\times 10^{-3}$)	R^2	Extrapolated SCA	Observed SCA	Difference in %
1,2,3,4,5,6,7	7 July 1997	94.22	–4.1	0.99	2.49	1.26	–97.62
1,2,3,4,5,6	7 July 1997	94.22	–4.1	0.98	2.49	1.26	–97.62
	24 June 1997				5.01	5.02	0.19
1,2,3,4,5	7 July 1997	94.22	–5.2	0.99	0.94	1.26	25.40
	24 June 1997				2.28	5.02	54.58
	19 June 1997				3.21	7.44	56.85
1,2,3,4	7 July 1997	94.22	–3.8	0.98	3.24	1.26	–157.14
	24 June 1997				6.21	5.02	–23.71
	19 June 1997				7.98	7.44	–7.26
	11 May 1997				40.04	28.31	–41.43
1,2,3,4,5	8 June 1998	66.94	–9.4	0.97	0.40	0.50	20.00
1,2,3,4	8 June 1998	66.94	–6.4	0.95	2.05	0.50	–310.00
	26 May 1998				4.92	1.20	–310.00
1,2,3	8 June 1998	66.94	–8.1	0.98	0.81	0.50	–62.00
	26 May 1998				2.46	1.20	–105.00
	25 April 1998				20.86	28.19	26.26

*The numbers indicate the image number for water years 1997 and 1998 given in Table 3.

Snow-covered area sensitivity analysis

The effect of number of satellite images on runoff simulations using the Snowmelt Runoff Model, SRM, (Martinec *et al.,* 1998) was studied. Such an analysis would give an idea about the cost-benefit relationship for remote sensing imagery in snowmelt modelling as well as SCA sensitivity analysis. Before performing such an analysis, the SRM parameters were set to get an acceptable hydrograph shape and an accurate discharge volume. Such a set-up would enable one to see the effect of SCA on the SRM model simulations and remove the uncertainties that may arise from the model itself or from the selected model parameters. As the set-up is achieved, all the model variables and parameters are kept constant except the SCA input information.

To perform this analysis, the number of images used and their timing were changed and new exponential fits were found. Based on the new relationships, SCA for each case was recalculated and inserted into the SRM model. The SRM simulations were compared with respect to goodness of fit and percentage deviation statistics.

Table 7 shows the model runs performed based on the image availability, goodness of fit and percentage deviation statistics for the water year 1997. It results from Table 7 that no simple monotonic relationship between the number of images and quality of simulations exist. It is also observed that the percentage deviations increase as some of the images were excluded from the analysis. This is in good agreement with findings obtained by Male & Gray (1981), who stated, "For operational purposes, the total area of snow cover has been found to be a good index for improving runoff forecasts." It is also seen that the timing of snow cover maps has effects on both goodness of fit (R^2) and percentage deviation statistics (D_v). For the model runs 3 and 4, which have the same number of images, both D_v values are quite different: 1.86 and 2.14, respectively. For runs 2 and 6, each of which has five images in the analysis, the resulting different R^2 and D_v values demonstrate the importance of the image timing.

Table 7 Model runs performed based on the image availability and statistics (R^2 and D_v) for the 1997 water year.

Model run	Image numbers used	Measured runoff: Volume (10^6 m^3)	Measured runoff: Average (m^3 s^{-1})	Computed runoff: Volume (10^6 m^3)	Computed runoff: Average (m^3 s^{-1})	Goodness of fit (R^2)	Percentage deviation (D_v)
1	All 8 images are used	1639.60	193.64	1607.68	189.87	0.96	1.95
2	1, 2, 6, 7, 8	1639.60	193.64	1553.41	183.46	0.94	5.26
3	1, 2, 4, 5, 6, 7, 8	1639.60	193.64	1609.12	190.04	0.96	1.86
4	1, 2, 3, 5, 6, 7, 8	1639.60	193.64	1604.49	189.49	0.96	2.14
5	1, 2, 3, 4, 7, 8	1639.60	193.64	1538.61	181.71	0.93	6.16
6	1, 2, 3, 4, 8	1639.60	193.64	1189.67	140.50	0.68	27.44

The largest deviations were seen between model runs 2 and 5 relative to previous runs (1, 3, 4). A higher volumetric difference was expected from model run 2, but analysis showed that image number 3 did not have much effect on the simulations. Starting from model runs 4 and 5, the volumetric differences began to increase. This showed the importance of the images 4, 5 and 6 for the simulation studies. A further analysis was performed to see the removal effect of images 5, 6 and 7. Such a simulation gave the worst R^2 and D_v. This last analysis showed the importance of images 5, 6 and 7 for runoff simulations. When model runs 4, 5 and 6 are combined, the importance of the images 4, 5, 6 and 7 are easily seen. It can be observed from Table 3 that the dates of these images are falling in the main melting period where the decline of snow-covered area is the steepest.

DISCUSSIONS AND CONCLUSION

Snow-covered area has direct impact on hydrological and meteorological model studies. For meteorological studies, it affects the energy budget calculations with its high albedo. For hydrology, SCA is directly related to snow reserves, flood mitigation, optimum operation of water resources and hydropower production. Deriving the relationship between SCA and the above mentioned outputs is very important for the rarely studied basins with rough topography and high elevation ranges, e.g. eastern Turkey. Satellite images such as NOAA-AVHRR provide the information related to SCA. But the cloud obscuring problem degrades the use of satellites with optical sensors.

Air temperature has been found as a dominating and most readily found meteorological parameter in snow hydrology. Thus the relationship between SCA and mean daily air temperature was sought. An exponential relation was found between SCA and cumulative mean daily air temperature (CMAT) resulting in R^2 values of 0.98 and 0.99 for the water years 1997 and 1998, respectively. The exponential relationship resulted in different constants for each year. This was due to the variation of snow pack and climate conditions from year to year and the initial distribution of snow cover, initial snow water equivalent, meteorological conditions and the melt/thawing mechanism that the snow pack is subjected to. Comparison of B values with those of Singh *et al.* (2003) shows that B values computed in this study are somewhat higher. The higher B values can be explained by the comparison of the cumulated air temperature values 600–900°C *vs* 2500–3000°C. Thus, the variation of B values between different years can be attributed to the annual differences in winter precipitation both in intensity and composition, initial snow water content, meteorological conditions and the melt/thawing cycles that the snow pack is subject to. Even though, using a set of constant values A and B may give some idea about SCA variation for a different year, it would be wise to update them with the conditions of the snow year at hand. Hence, for projection it is necessary to update the model with the latest satellite image.

The results in extrapolation of SCA show that the dates of the SCA are more important than the number of images in the extrapolation. The images for 11 May 1997 and 13 April 1998 are very important in forecasting the SCA in an accurate way. The date 11 May can be considered as the mid-point in the snowmelt period, whereas 13 April is early in the snow melting process. However considering the characteristics of the 1998 water year as being a wet season, this condition placed more importance on the images for April, when an early peak occurred.

A monotonic relation between the number of snow cover maps and the quality of snowmelt runoff simulations could not be achieved. Still, the performed analysis reveal that the simulation accuracies get better as the number of images is increased. The studies suggest that if there are fewer images (2 or 3) to be used in deriving SCA, the timing within the snowmelt period is very important (HYDALP, 2000). In this study, the images for the early and middle parts of the snowmelt period are found important for image timing. These findings are in agreement with HYDALP(2000).

As a conclusion, the proposed methodology is found to be suitable both for interpolating the SCA values based on observed air temperature values and for extrapolating based on forecasted air temperatures for the water years showing average characteristics. The calculated values of SCA could be used as input to snowmelt runoff models (e.g. SRM) either for simulating or forecasting river discharges or used for improving the runoff simulations. The quality of simulation/forecast can be increased as later and newer snow cover maps are used.

The methodologies such as that applied in this study are good for the average conditions but not so good for wet or dry conditions. Therefore, uncertainty analysis in simulating and forecasting of SCA would be helpful in modelling the situations that do not obey the average expectations. The uncertainty concept can also be applied in the determination and use of variables A and B for a water year different from the one for which they were calculated.

Acknowledgements The authors would like to thank anonymous reviewers for their valuable comments and remarks.

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Received 5 August 2004; accepted 4 May 2005