

# Using MODIS snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey

A. Emre Tekeli<sup>a,\*</sup>, Zuhale Akyürek<sup>b</sup>, A. Arda Şorman<sup>c</sup>, Aynur Şensoy<sup>c</sup>, A. Ünal Şorman<sup>a</sup>

<sup>a</sup>Department of Civil Engineering, Water Resources Lab., Middle East Technical University, Turkey

<sup>b</sup>Geodetic and Geographic Information Technologies, Middle East Technical University, Turkey

<sup>c</sup>Department of Civil Engineering, Anadolu University, Turkey

Received 16 December 2004; received in revised form 9 March 2005; accepted 12 March 2005

## Abstract

Water perhaps is the most valuable natural asset in the Middle East as it was a historical key for settlement and survival in Mesopotamia, “the land between two rivers”. At present, the Euphrates and Tigris are the two largest trans-boundary rivers in Western Asia where Turkey, Syria, Iran, Iraq and Saudi Arabia are the riparian countries. The Euphrates and Tigris basins are largely fed from snow precipitation whereby nearly two-thirds occur in winter and may remain in the form of snow for half of the year. The concentration of discharge mainly from snowmelt during spring and early summer months causes not only extensive flooding, inundating large areas, but also the loss of much needed water required for irrigation and power generation purposes during the summer season. Accordingly, modeling of snow-covered area in the mountainous regions of Eastern Turkey, as being one of the major headwaters of Euphrates–Tigris basin, has significant importance in order to forecast snowmelt discharge especially for energy production, flood control, irrigation and reservoir operation optimization.

A pilot basin, located on the upper Euphrates River, is selected where five automated meteorological and snow stations are installed for real time operations. The daily snow cover maps obtained from Moderate Resolution Imaging Spectroradiometer MODIS at 500 m resolution are compared with ground information for the winter of 2002–2003 both during accumulation and ablation and at accumulation stage for the winter of 2003–2004. The snow presence on the ground is determined from the snow courses performed. Such measurements were made at 19 points in and around the upper Euphrates River in Turkey and at 20 points in the upper portion of the pilot basin for the winters of 2002–2003 and 2003–2004, respectively. Comparison of MODIS snow maps with in situ measurements over the snow season show good agreement with overall accuracies ranging between 62% and 82% considering the shift in the days of comparison. The main reasons to have disagreement between MODIS and in situ data are the high cloud cover frequency in the area and the current version of the MODIS cloud-mask that appears to frequently map edges of snow-covered areas and land surfaces. The effect of elevation and land cover types on validation of MODIS snow cover maps is also analyzed. In order to minimize the cloud cover and maximize the snow cover, MODIS-8 daily snow cover products are used in deriving the snow depletion curve, which is one of the input parameters of the snowmelt runoff model (SRM). The initial results of modeling process show that MODIS snow-covered area product can be used for simulation and also for forecasting of snowmelt runoff in basins of Turkey.

© 2005 Elsevier Inc. All rights reserved.

**Keywords:** MODIS; Snow-covered area; Euphrates River; Remote sensing; Snowmelt runoff; Forecasting; Snowmelt runoff model (SRM)

## 1. Introduction

Snow-covered area is a fundamental parameter in the hydrologic cycle and climatology of the earth. Characteristic

high albedo reflectance of snow causes the snow surface to reflect much of the incoming solar radiation. With the high heat capacity of snow, snow cover insulates the soil surface from the atmosphere and slows down the warming process in spring. Thus, the snow has a direct impact on micro and macro atmospheric circulation models by affecting energy absorption and thermal heating of the basin. Snow cover and soil moisture are the most important variables in the heat

\* Corresponding author. Tel.: +90 312 210 54 46, +90 312 210 24 87; fax: +90 312 210 10 02.

E-mail address: [emret@metu.edu.tr](mailto:emret@metu.edu.tr) (A.E. Tekeli).

and water vapor exchange between earth and atmosphere. The presence of snow in a basin strongly affects moisture that is stored at the surface and is available for future runoff (Maurer et al., 2003). Therefore, monitoring of the seasonal snow cover is important for several purposes such as climatology, hydrometeorology, water use and control and hydrology, including flood forecasting.

Detection of snow-covered area from space has been used since the start of 1960s. Attention to snow-covered area was increased with the studies performed by Martinec (1975) and Rango and Martinec (1979). The main reason for using a spectral band in the visible part (0.4–0.7  $\mu\text{m}$ ) of the reflected solar radiation spectrum is associated with the high reflectance of snow at these wavelengths thus facilitating its detection. The attendant problems with the use of observations in the visible wavelengths are the obscuration of snow cover caused by clouds and vegetation cover. The Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua platforms has 36 selected, narrow spectral bands ranging in ground resolution from 250 to 1000 m. An algorithm has been developed to map snow cover at 500 m spatial resolution using MODIS observations by Hall et al. (2002). The 500 m spatial resolution results from using MODIS bands with demonstrated capability for detecting snow and separating snow from clouds.

Prior to the MODIS launch, the absence of ground truth against which to compare prototype MODIS snow-covered area classification necessitated reliance on images derived from other sensors such as Landsat in small catchments, in lieu of direct observations (Klein et al., 1998a; Maurer et al., 2003). This reduced the ability to make quantitative conclusions regarding snow-cover dynamics mainly because of the 16-day repeat of the Landsat satellite. The daily availability, easy access and the low costs make AVHRR data also a fundamental source of information for operational monitoring of snow-covered areas and, indirectly, of snow depth. However, AVHRR data need processing to classify the snow from the other features and the time that will be spent for image processing is not convenient for real time snowmelt runoff forecasting. MODIS/Terra Snow Cover Daily L3 Global 500 m Grid (MOD10A1) contains snow cover and they are ready to be used for snowmelt modeling. Another reason that MODIS is an improvement over AVHRR and why MODIS is used in this study is that its geolocation accuracy is much better. The geolocation accuracy for AVHRR is plus or minus one pixel whereas for MODIS it is roughly half a pixel for the 500 m product. Thus, for snowmelt modeling that can be significant because it is important to know if a snow-covered pixel is within a particular basin or not especially for hydrological models that use snow-covered area information as input variable such as snowmelt runoff model (SRM). Moreover, 500 m spatial resolution of MODIS enables more accuracy in comparing data to ground information. The mixed pixels (mixels) concept is highly reduced with respect to AVHRR

by a better spatial resolution and snow line is better captured. Furthermore, elevation, aspect, vegetation and land use effects can be better observed by the higher spatial resolution that MODIS snow cover maps have.

Snow-covered area monitoring gains more importance as the ratio of snowmelt runoff to the total annual flow increases. One of the major contributors of water to the Keban Dam is the Karasu River, which joins the Euphrates River at Keban Dam near the city of Elazığ, in the east part of Turkey. The Karasu Basin wherein 60–70% of the total runoff comes from spring, snowmelt runoff is tailor-made for snow cover analysis. Since Karasu Basin is headwaters of Euphrates River in Turkey, accurate simulation and forecasting of the snowmelt runoff is of vital importance for optimum water usage, storage and hydropower generation both for national and international uses.

One common problem that a scientist encounters in developing nations is the lack of informative data for the related study. Even if the data exist, quick, on-line and timely access to the data may be problematic. Since Turkey is a developing nation, the quick access to snow data, which is a must in operational snowmelt forecasting, is not possible yet. Snow measurements are mostly performed by snow courses by the governmental organizations mostly in 2–3-week periods. In these snow courses, snow water equivalent and snow depths are measured along a track. Furthermore, most of the courses are started mainly in November or December and they are abandoned by mid or end of March, when the snow ripens and starts to melt, even some snow may still remain in upper mountainous areas.

Turkey can be described as a country with abundant snow, however there is not yet an established continuous operational snow monitoring system. There exist some individual studies such as [Akyürek and Şorman (2002b), Şorman et al., (2001), Tekeli (2000) and Kaya (1999)]. Unfortunately, these studies are not suitable for operational purposes. Thus, the snow-covered area, which is the main input variable in major operational snowmelt runoff models, is needed by the researcher whose objective is basically snowmelt runoff prediction. MODIS or similar satellite images may be a useful solution for Turkey and as well as for most of the developing nations in this respect as one of the important elements in hydrologic, meteorological forecasting models. This is especially true relative to the MODIS snow products because they are produced on a daily basis and can be downloaded from the Internet for free.

Ongoing comparison of satellite derived snow maps and surface measurements is vital for improvement of snow mapping algorithms. Yet, a lack of ground measurements commonly results in two major limitations (Simic et al., 2004);

- the assessments are performed within small areas, which have available local surface measurements and/or
- the assessments are based on other satellite data.

The present study compares MODIS snow cover maps with the ground-based snow courses at some selected points in and around Karasu Basin, where snow depth and snow density are measured in order to yield snow water equivalent. The snow-covered area validation effort using MODIS products was performed during the winter of 2002–2003 for accumulation and ablation periods and during the winter of 2003–2004 for ablation period alone. It is also aimed to present the initial results of snowmelt modeling, where snow depletion curves derived from MODIS were used as input parameter.

## 2. Study area

The main study area is Karasu Basin (Fig. 1), which is the headwater of the Euphrates River. The basin is located in the eastern region of Turkey, for which the boundaries can be given by longitudes from 38°58'03" to 41°38'28" east and latitudes 39°23'18" to 40°24'26" north. The basin has a drainage area of 10215.7 km<sup>2</sup> with an elevation ranging from 1125 to 3487 m. The elevation range of the basin and the area around it can be seen from the digital elevation model, which is depicted in Fig. 2a. The main land cover is pasture, cultivated land and bare land. The long-term studies indicate that about 60–70% of the total annual volume of water comes during snowmelt season. The ratio was found as 64% and 70% for 1997 (Kaya, 1999) and 1998 (Tekeli, 2000) dry and wet water years, respectively (Fig. 3). The total runoff volume between March 1 and June 30 for 1997, 1998 and 2004 were  $1.72 \times 10^9$ ,  $2.41 \times 10^9$  and  $2.32 \times 10^9$  m<sup>3</sup>, respectively. Downstream in the Karasu Basin, there exist five big dams, some of which, namely Keban, Karakaya and Ataturk, are designed for flood control,

hydropower generation, irrigation and water supply. Thus, accurate snowmelt runoff estimation is very important for this area of interest.

The snow course measurements made by the government agencies in the east part of Turkey were also used in the analysis. The elevation data and the location of these individual observations are presented in Fig. 2a. Fig. 2b shows the location of the automated stations established in the basin by the project team.

## 3. Data and methodology

### 3.1. Snow data derived from MODIS

The approach used for obtaining the snow-covered area (SCA) maps from MODIS images employs the advantage of the fact that snow reflectance is high in the visible (0.5–0.7 μm) wavelengths and has low reflectance in the shortwave infrared (1–4 μm) wavelengths (Hall et al., 2001).

The MODIS snow-mapping algorithm is fully automated and is based on the normalized difference snow index (NDSI) and a set of thresholds (Hall et al., 2002). Based on NDSI and threshold values, snow cover pixels are separated from non-snowy areas using Eq. (1).

$$\text{NDSI} = \frac{\text{MODIS}_{B4} - \text{MODIS}_{B6}}{\text{MODIS}_{B4} + \text{MODIS}_{B6}} \quad (1)$$

To improve the snow mapping accuracy and to eliminate the spurious snow, a thermal mask is used. Using MODIS infrared bands 31 (10.78–11.28 μm) and 32 (11.77–12.27 μm), a split window technique (Key et al., 1997) is used to estimate ground temperature (Hall et

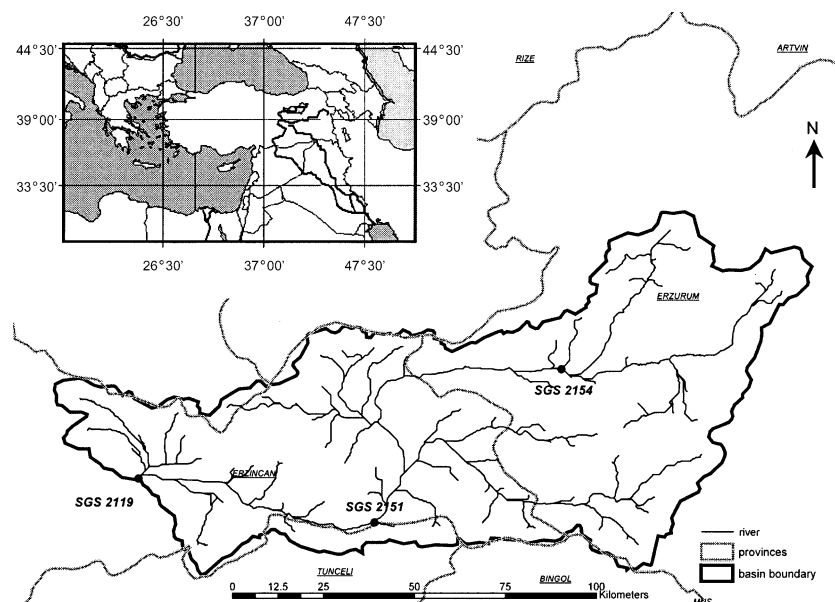


Fig. 1. Location of Karasu Basin (upper Euphrates River) in Turkey and the locations of stream gauges in the basin.

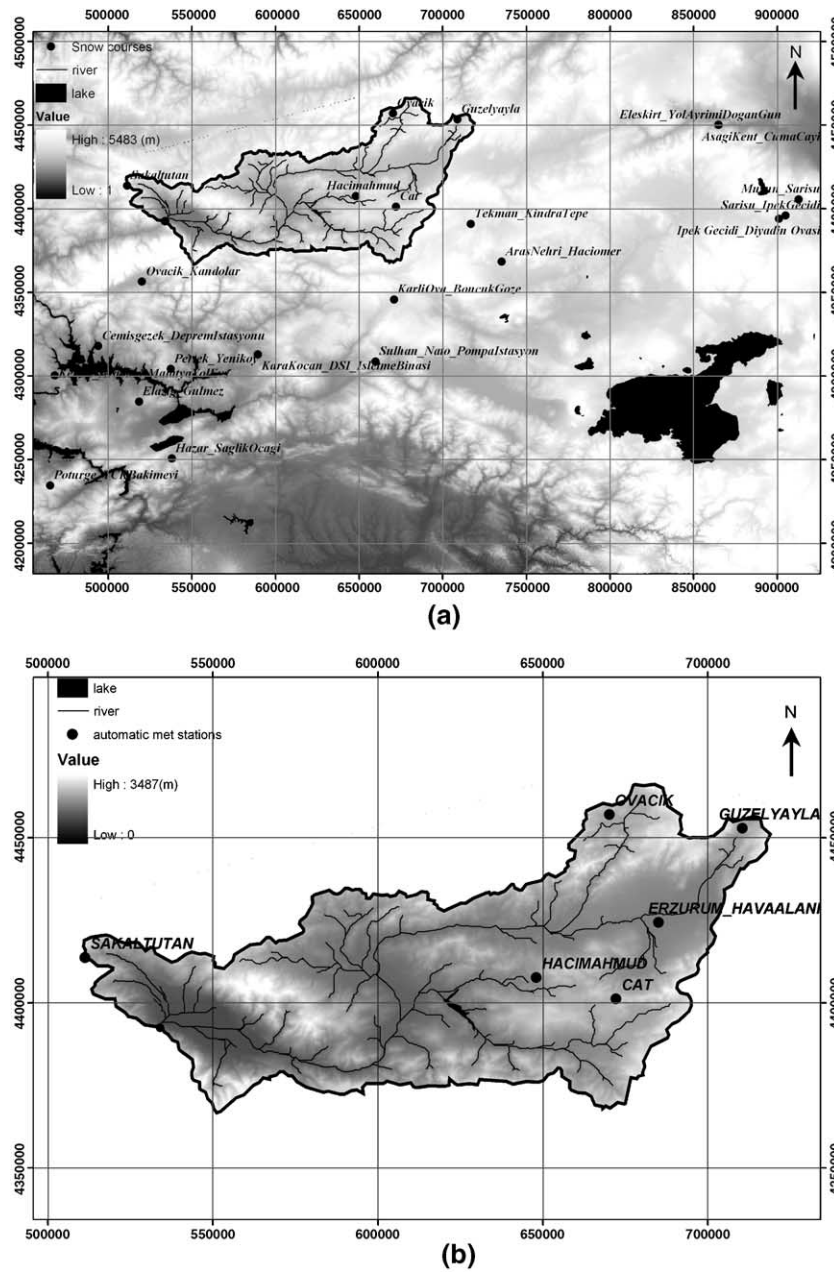


Fig. 2. Location of the snow courses on DEM of Turkey (a). Location of automatic stations on DEM of Karasu Basin (b).

al., 2002). If the temperature of a pixel is  $>283$  K then the pixel will not be mapped as snow (Riggs et al., 2003).

The production of MODIS snow cover maps start with a swath (scene) at nominal pixel resolution of 500 m and a nominal swath coverage of 2330 km (across track) by 2030 km (a long track) (Riggs et al., 2003). Then a 6-step procedure is followed for derivation of 6 different snow products. Except for the initial snow product, MOD10\_L2, each snow product in the sequence is produced using the preceding snow product as input (Riggs et al., 2003). All other MODIS products are spatial and/or temporal composites of individual snow observations from all daily

MOD10\_L2 products covering a particular area. The image type used in this study is MODIS/Terra daily snow cover Level 3, 500 m resolution product (MODIS/Terra Snow Cover Daily L3 Global 500m ISIN Grid-MOD10A1) in sinusoidal projection of Version 4. Product levels are used to indicate the spatial and temporal processing applied to the data. The daily level 3 snow product is the result of selecting an observation from the multiple observations mapped to cell of the MOD L2G product (Riggs et al., 2003). This version is supposed to have better cloud screening (Ackerman et al., 1998) and better snow determination in forest areas (Klein et al., 1998b) than earlier versions.

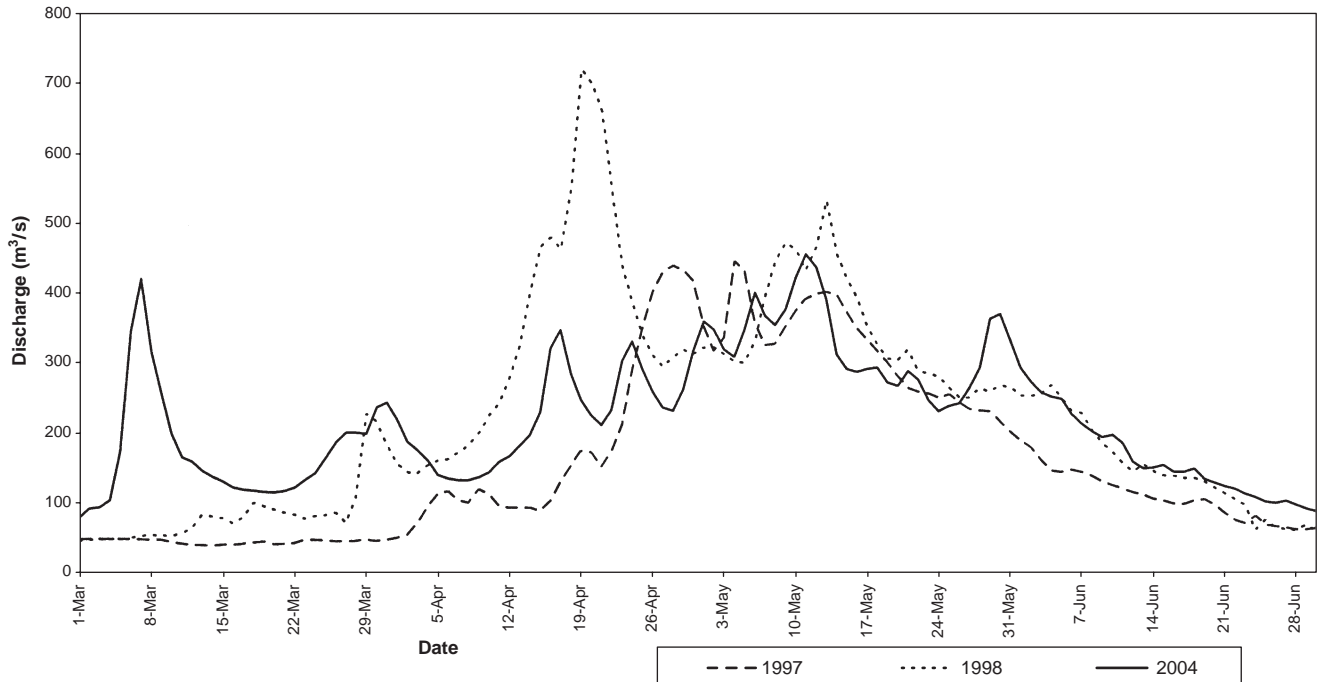


Fig. 3. Discharges observed at SGS 2119 between March 1–June 30 1997, 1998, and 2004.

Like other MODIS products, MOD10A1 products are being produced and they are distributed by the NASA Distributed Active Archive Center (DAAC) located at the National Snow and Ice Data Center (NSIDC). Since the study area in Turkey is between two scenes namely, h21v04 and h21v05, two images needed to be digitally stitched together. MODIS Reprojection Tools version 3.0a (MRT, 2003) was used to tile the images together. The tiled images were then reprojected to World Geodetic System 1984 (WGS84), Universal Transverse Mercator (UTM) Zone 37 with a cell size of 500 m.

### 3.2. Ground data

#### 3.2.1. Data belonging to December 2002–April 2003 period

Snow cover maps of MODIS were compared with the ground data collected in and around the basin. The ground data collection was comprised primarily of two forms of data. The first one was comprised of snow courses data existent for a long period and the second data set was comprised of automated snow pillow and meteorological stations existing since 1998 (Şorman et al., 2002).

The first data set involves the measurement of snow depth, snow density, and snow water equivalent on specific dates of the periodic field trips. The second data set includes the automated measurements of snow water equivalent, snow depth, snow density and some other meteorological variables, which are necessary for snow-melt runoff modeling using energy-based models, in two

hourly averages. These automated stations were designed and constructed by the project team from Middle East Technical University, Water Resources Research Center and funded by the State Planning Organization of Turkey.

The former type of ground data collection is generally restricted to lower elevation zones. On the contrary, the second ones were tried to be located in the relatively higher elevations of the mountainous terrain.

The distribution of the snow courses performed in the winter of 2002–2003 and the location of the automated stations in the basin can be seen in Fig. 2a,b, respectively. Dates with the ground truth obtained from snow courses and automated snow measurement stations in winter 2002–2003, December through April, can be seen in Table 1 and Table 2. Dates from automated snow pillows and meteorological stations were not given specifically since they continuously store data in every 2 h as averages of the measurements made by sensors every 30 s.

#### 3.2.2. Data belonging to March 2004

A similar study was performed for the winter of 2003–2004 water year for four specific dates between March 22 and 25, in which 20 points were gathered around Guzelyayla automated meteorological and snow station in the Kırkgöze sub-basin, located in the upper right region of the basin under study. The main focus in analyzing the dates of March 22–25, 2004, which is the ablation stage, was to assess the spatial variation of MODIS-derived snow cover. Fig. 4 shows the distribution of 20 points in the study area.

Table 1  
Dates and names of ground observations and the dates of analyzed MODIS images

Ground observation	Snow course measurement (elevation)	Dates of MODIS images	Ground observation	Snow course measurement (elevation)	Dates of MODIS images
24/12/2002	Yol Ayrımı (1679 m)	24/12/2002			17/2/2003
		25/12/2002			18/2/2003
		26/12/2002	19/2/2003	Hacı Omer	19/2/2003
27/12/2002	Diyadin Ovası (2009 m)	27/12/2002	19/2/2003	Gulmez (1354 m)	
		28/12/2002	19/2/2003	Tekman Kindıra Tepe	
		29/12/2002			20/2/2003
30/12/2002	Tekman Kindıra Tepe (2050 m)	30/12/2002			21/2/2003
30/12/2002	Hacı Omer (1920 m)	31/12/2002			25/2/2003 <sup>a</sup>
		1/1/2003			26/2/2003
		2/1/2003	27/2/2003	Yeni Koy	27/2/2003
3/1/2003	Hazar Sağlık Ocagi (1297 m)	3/1/2003	27/2/2003	Yol Ayrımı	
		4/1/2003	28/2/2003	Hazar Sağlık Ocagi	28/2/2003
		5/1/2003	28/2/2003	Diyadin Ovası	
6/1/2003	Yol Ayrımı	6/1/2003	28/2/2003	Musun (1738 m)	
7/1/2003	Hacı Omer	7/1/2003			1/3/2003
7/1/2002	Tekman Kindıra Tepe				2/3/2003
		8/1/2003	3/3/2003	Gulmez (1354 m)	3/3/2003
		9/1/2003			4/3/2003
		10/1/2003	5/3/2003	Boncuk Goze	5/3/2003
10/1/2003	NATO Pompa Ist. (1525 m)		5/3/2003	NATO Pompa Ist.	
10/1/2003	Arapgir Yol Kavsagi (1158 m)		5/3/2003	DSI işletme bakımevi (1091 m)	
		11/1/2003	6/3/2003	TCK Bakımevi (1796 m)	6/3/2003
14/1/2003	Yeni Koy (1498 m)		7/3/2003	Yol Ayrımı	7/3/2003
14/1/2003	Kandolar (1251 m)		7/3/2003	Hazar Sağlık Ocagi	
		15/1/2003 <sup>a</sup>			
16/1/2003	Diyadin Ovası (2009 m)	16/1/2003			11/3/2003
17/1/2003	Yol Ayrımı	17/1/2003			12/3/2003
		21/1/2003	13/3/2003	Yeni Koy	13/3/2003
22/1/2003	Boncuk Goze (1772 m)	22/1/2003	13/3/2003	Kandolar	
22/1/2003	NATO Pompa Ist.		13/3/2003	Hacı Omer	
23/1/2003	Hacı Omer	23/1/2003	13/3/2003	Tekman Kindıra Tepe	
23/1/2003	Tekman Kindıra Tepe		14/3/2003	Diyadin Ovası	14/3/2003
		24/1/2003			15/3/2003
		26/1/2003 <sup>a</sup>	24/3/2003	NATO Pompa Ist.	24/3/2003
		27/1/2003 <sup>a</sup>	25/3/2003	Boncuk Goze	25/3/2003
28/1/2003	Yeni Koy	28/1/2003 <sup>a</sup>	26/3/2003	Yeni Koy	26/3/2003
28/1/2003	Kandolar		26/3/2003	Diyadin Ovası	
		29/1/2003 <sup>a</sup>			27/3/2003 <sup>a</sup>
		30/1/2003 <sup>a</sup>			28/3/2003
		2/2/2003			29/3/2003
		3/2/2003			30/3/2003
4/2/2003	Hacı Omer	4/2/2003	31/3/2003	Kandolar	31/3/2003
4/2/2003	Tekman Kindıra Tepe		31/3/2003	Yol Ayrımı	
		5/2/2003			
		6/2/2003			
		16/2/2003 <sup>a</sup>			

<sup>a</sup> MODIS images are not analyzed for automated stations.

### 3.2.3. Elevation and land cover data

In order to investigate how the accuracy of MODIS snow maps vary by elevation and vegetation type, elevation data and land cover information were obtained. Elevation data

for Karasu Basin were derived from 1/250,000 scaled topographic maps. For the east part of Turkey, in addition to the elevation data belonging to the snow courses, SRTM30-arc seconds data were used.

Table 2  
Additional MODIS images analyzed for automated stations

Automated stations	Hacimahmud	Güzelyayla	Ovacık	Sakaltutan	Çat
Elevation (m)	1965	2065	2130	2150	2340
Dates of MODIS images	13/4/2003, 14/4/2003, 15/4/2003, 16/4/2003, 17/4/2003, 18/4/2003, 19/4/2003, 20/4/2003, 21/4/2003, 22/4/2003, 23/4/2003, 24/4/2003, 25/4/2003, 26/4/2003, 27/4/2003, 28/4/2003, 29/4/2003, 30/4/2003				

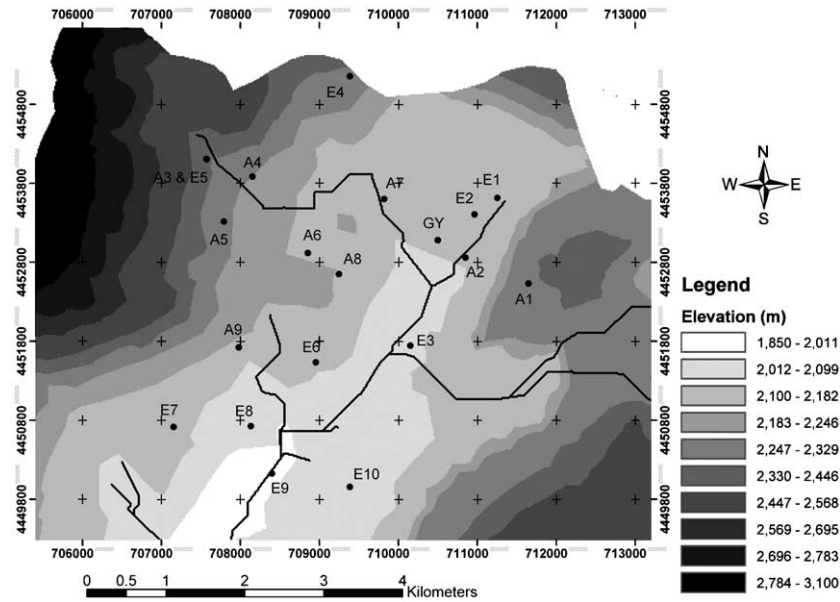


Fig. 4. The locations of the snow measurements on the dates of March 22–25, 2004.

The land cover information was obtained from a previous study (Akyürek & Şorman, 2002a), where the land cover types were obtained from medium-resolution image, using a multi-level classification technique based on knowledge-based segmentation of Landsat images. The level of the land use/cover classification was determined according to CORINE land cover classification scheme.

3.3. Method of analysis

Ground observations were compared to all MODIS grid cells falling within a radius of 1500 m of each individual observation site. If 50% or more of all cloud-free grid cells within 1500 m radius were classified as snow by MODIS then the site was considered to be snow-covered for comparison purposes. A snow depth of 25.4 mm was used as a threshold to indicate snow presence at the surface (Maurer et al., 2003). During the analysis it was also observed that cloud covering frequency was high. Therefore

if the grid cell was cloud obscured in the date of ground truth, the images acquired few days before and few days after the ground data date were analyzed. It was accepted as matched if there exists a snow-covered grid cell within 1 or 2 days before or after the date of ground observation. The matched and the undetermined due to cloud-obscured pixels of MODIS snow cover maps with the ground data were analyzed according to the elevation classes. The results are presented in Table 3. The matched with MODIS indicates that MODIS identifies snow and snow was recorded at the station, the undetermined due to cloud-obscured pixels of MODIS indicates that MODIS identifies cloud, but snow was recorded at the station. Since no direct conclusion about the surface can be made in cloud-obscured observations, it can be said that neither MODIS snow map classification is wrong nor the algorithm fails to detect snow in some cases. Unfortunately, it is thought that including undetermined due

Table 3  
Summary of analyses of MODIS images performed for winter 2002–2003 (December–March) at snow courses and automated stations with respect to elevation zones

Elevation zones	Number of observations	Matched with MODIS	Undetermined due to cloud	Matched (%)
A (1125–1500 m)	16	11	5	68.75
B (1500–1900 m)	15	13	2	86.67
C (1900–2300 m)				
Snow courses	17	11	6	64.71
Automated stations	228	73	155	32.02
D (2300–2900 m)				
Automated station	57	22	35	38.59

Table 4  
Summary of analyses of MODIS images for winter 2002–2003

Ground truth data	MODIS classification (on the date of ground observation)		
	Snow	Undetermined due to cloud	Matched (%)
Snow	61	37	62.24
Ground truth data	MODIS classification (one day shift from the date of ground observation)		
	Snow	Undetermined due to cloud	Matched (%)
Snow	70	28	71.43
Ground truth data	MODIS classification (two-day shift from the date of ground observation)		
	Snow	Undetermined due to cloud	Matched (%)
Snow	80	18	81.63

to cloud-obscured pixels in matched percentages would not be correct. The summary of the analysis for water year 2002–2003 is presented in Table 4 indicating the matched percentages in terms of percentage ratio and the discussion is done in Section 4.

Similar analysis was performed for the winter period during March of 2003–2004 at the ablation period for 4 days, of which 20 ground truth data were collected for those dates. The analyses are summarized in Table 5.

### 3.4. Brief description on snowmelt modeling

Several snowmelt forecasting models have been developed to suit specific needs and hydrologic conditions. These are either data intensive and/or complex to handle. Very few models can handle varied hydrologic conditions in general. The popular ones are SAARR (1972), SRM (Martinec, 1975), RMS (Leavesley, 1983) and UBC (Quick & Pipes, 1997) (Rao et al., 1996). Among many models, snowmelt runoff model (SRM), which uses the snow cover information as input, has been the most widely used one both in simulation and forecasting (Ferguson, 1999; Hall & Martinec, 1985; Rango & Martinec, 1979; Rango & van Katwijk, 1990; WinSRM, 2003).

SRM or variations of it were applied over 100 basins in 25 countries at latitudes 32–60 °N, 33–54 °S with basin sizes varying from <1 to 120,000 km<sup>2</sup> and documented in about 80 scientific journals (Seidel & Martinec, 2004).

Table 5  
Analyses performed for winter 2003–2004 March (ablation period)

Location	22/3/2004	23/3/2004	24/3/2004	25/3/2004
A1	S	S	C	S
A2	S	S	C	S
A3	S	S	S	S
A4	S	S	S	S
A5	S	S	C	S
A6	S	S	C	S
A7	S	S	C	S
A8	S	S	C	S
A9	S	S	C	S
E1	S	S	C	S
E2	S	S	C	S
E3	S	S	C	S
E4	S	S	C	S
E5	S	S	S	S
E6	S	S	C	S
E7	C	S	C	S
E8	C	S	C	S
E9	S	S	C	S
E10	S	S	C	S
E11	S	S	C	S
Guzelyayla	S	S	S	S
Ovacik	S	S	C	S
Cat	S	S	S	S
Hacimahmud	C	C	L	L
Sakaltutan	N/A	N/A	N/A	N/A
Match (%)	21/24 (87.50)	23/24 (95.83)	5/24 (20.83)	23/24 (95.83)

S: snow, C: cloud, L: land, and N/A: not applicable.

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

Based on the input values, SRM computes the daily stream flow for a lag time of 18 h by;

$$Q_{n+1} = [c_{sn}a_n(T + \Delta T)S_n + c_{Rn}P_n]A100000 / 86400(1 - k_{n+1}) + Q_n k_{n+1}. \tag{2}$$

According to Eq. (2), the daily average discharge on day  $n + 1$  is computed by summation of snowmelt and precipitation that contributes to runoff with the discharge on the preceding day.

Snowmelt from the preceding date is found by multiplication of the degree day factor,  $a$ , ( $\text{cm } ^\circ\text{C}^{-1} \text{d}^{-1}$ ), zonal degree days ( $T + \Delta T$ ) ( $^\circ\text{C}$ ) and the snow-covered area percentage ( $S$ ). To determine the percentage that contributes to runoff, the result of the above multiplication is further multiplied with  $c_s$ , snowmelt runoff coefficient and the total area of the zone,  $A$  ( $\text{km}^2$ ).

Measured/forecasted precipitation is multiplied by  $c_p$ , rainfall runoff coefficient and the zonal area to calculate the precipitation contributing to runoff. Discharge computed on preceding date is multiplied by recession coefficient ( $k$ ) to calculate the effect on today's runoff. Eq. (2) is applied to each zone of the basin when the model is applied in semi-distributed manner, the basin is subdivided into zones, and then the discharges are summed up. SRM adjusts the input data if lag time other than 18 h is used (WinSRM, 2003).

For accuracy assessment of the model performance, Nash and Sutcliffe efficiency statistic  $NSE$  ( $R^2$ ) (Eq. (3)) and volume difference  $D_v$  (%) (Eq. (4)) are used.

$$R^2 = 1 - \frac{\sum_{i=1}^n (Q_i - Q'_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2} \tag{3}$$

where

- $Q_i$ : measured daily discharge
- $Q'_i$ : computed daily discharge
- $\bar{Q}$ : average measured discharge of the season under study
- $n$ : number of daily discharge values

$$D_v[\%] = \frac{V - V'}{V} * 100 \tag{4}$$

where

- $V$ : measured yearly or seasonal runoff volume
- $V'$ : computed yearly or seasonal runoff volume.

$R^2$  approaches to 1 as the root mean square prediction error decreases to zero. Volume difference ( $D_v$ ), which is the percentage difference between the observed and simulated/forecasted mean or total discharge, reduces to zero as the observed and modeled values approach to each other.

SRM was successfully applied to upper Euphrates Basin for simulation of water years 1997 and 1998 by Kaya (1999) and Tekeli (2000). The accuracies obtained from the above studies are determined, varying from 0.95 to 0.85 for  $R^2$  and 0.56–9.3 for  $D_v$ , respectively.

#### 4. Analysis of the results and discussions

##### 4.1. The comparison of MODIS snow maps with ground truth observations in 2002–2003

For a limited validation of the MODIS snow product, comparisons between MODIS snow cover and in situ snow depth were made at automated stations and snow courses. Since point observations are being compared to a spatially integrated satellite measurement around each station site, some errors in these comparisons are expected. The snow cover maps were obtained for the dates where ground data exist and the validation was performed according to the elevation zones for winter 2002–2003 (Table 3). The matched percentage was less than 50% where the comparison was done by using automated stations. The undetermined due to cloud was due to high cloud cover frequency in the upper elevation zones.

It is shown in Table 4 that the matched percentages increased from 62.24% to 81.63% as 1 or 2 days ahead or after images of the date with ground data were searched. The images after and before of the date with ground data can be a possible solution to the cloud obscure problem associated with the use of optic instruments acquiring reflected solar radiation observations. Thus, the main problem faced in forming Table 4 was the cloud obscured pixels leading to undetermined classifications.

The error matrix, which is a widely used technique to assess the accuracy of remotely sensed data through comparisons with reference data, was prepared. However, the validation captures omission errors (there is snow but it is missed by the image) but not commission errors (no snow on the ground and image is showing snow). The original MODIS image for the date January 17, 2003 was obtained. The MODIS/Terra snow cover map and the original image are depicted in Fig. 5. When these two images are compared through visual interpretation, it is seen that the edges of the snow-covered areas and land surfaces are mapped as cloud. This appears to be caused by a problem in the current version of the MODIS cloud-mask that appears to frequently map edges of snow-covered areas and land surfaces. This may be due to lower fraction of snow or shallow snow depth in the

affected grid cells. Therefore in order to remove these problems, the cloud identification algorithms must be improved.

For the ablation period of March, 2004, the accuracy was more than satisfying based on the presented data in Table 5. Among 96 observations, 74 observations mapped as snow or land by MODIS agreed with the ground measurements with a matched ratio of 77.08%. As the individual dates were analyzed the matched percentages increased to 87.5%, 95.83% and 95.83% for the dates 22, 23 and 25 of March 2004 which can be considered as relatively clear sky. For the image belonging to March 24, 2004, which is cloud-covered, the matched percentage reduced to 20.83%. Thus, it can be said that MODIS snow map algorithm correctly captures the presence of snow on the ground surface if the image is cloud-free or clear sky conditions exist for the pixel in which there is ground truth. The values are quite in agreement with Hall et al. (1998) and Klein and Barnett (2003). In the former, correct classification accuracies were defined as 99% for grid cells having vegetation coverage <50% and 98% for grid cells with vegetation coverage >50%, whereas in the second study, MODIS snow cover maps were 88% in agreement with the SNOTEL measurements.

##### 4.2. The variation of MODIS snow maps with topography and land use

In order to examine how snow is mapped by the approach according to elevation, percentage of cloud-free observations mapped as snow by MODIS was obtained and shown in Fig. 6. Examination of percentage of observations where grid cells were mapped as snow by MODIS highlights the spatial pattern where snow is mapped by the approach used in snow classification. MODIS maps more at higher elevations, namely at C and D zones, less than 30% of the time (Fig. 7). This case is in agreement with the elevation bias problem of binary snow classification methods. Pixels with patchy snow cover tend to be mapped as non-snow-covered. This case will result in underrepresented snow-covered area in lower parts of the basins with rough topography. On the other hand, mostly snow-covered pixels (>50% or so) will be mapped as completely snow-covered. Consequently, the snow-covered area in higher parts of the basin will be overrepresented.

When the aspect distribution was analyzed, it was observed that for NE and NW slopes, MODIS maps more snow less than 45% of the time compared to SE and SW slopes. It maps more snow less than 30% of the time on SE and NW slopes. The areal percentages of each aspect class for elevation zones C and D are given in Fig. 8.

According to the land cover classes, MODIS maps more snow on pasture less than 30% of the time and it maps more snow on the cultivated areas less than 20% of the time (Table 6).

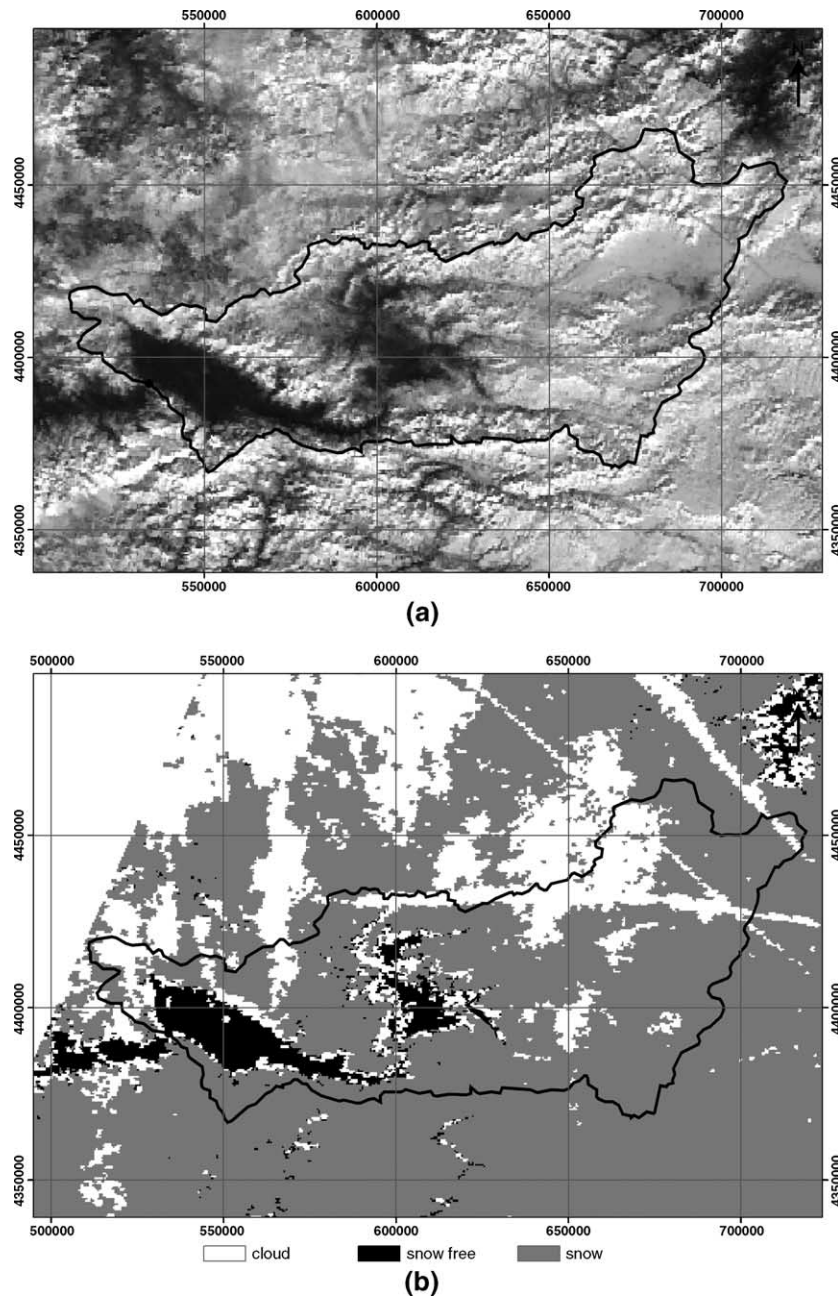


Fig. 5. Original MODIS/Terra image for 17.01.2003 (a). MODIS/Terra Snow Cover Daily L3 Global 500 m map for 17.01.2003 (b).

#### 4.3. Comparison of MODIS snow cover maps with automated station data in April 2003

The spring snowmelt was also studied for MODIS images of April 2003 (18 days) at four automated stations in the experimental basin in Turkey. The summary of the performed study can be seen in Table 7. “S” and “C” stand for snow- and cloud-covered grid cells in the MODIS image where “L” designates the grid cells detected as bare land. MODIS images very well caught the dates in which snow was removed from the ground. Data obtained from the automated stations indicate the removal of snow from the ground for April 9, 13, 20 and 25 for Hacimahmud,

Guzelyayla, Ovacik and Cat stations, respectively. In MODIS images, “L” was detected in 14th April for Guzelyayla, 28th April for Ovacik and 30th April for Cat station. Sakaltutan station was not operating in that time period. The reason for the delay in detection of land for Ovacik and Cat stations can be due to high cloud cover as can be seen in Table 7.

At Hacimahmud station, the MODIS image on date 28th April showed “S” again. It was surprising since that grid cell was defined as “L” for April 13, 14, 20 (see Table 7). When data from the Hacimahmud station was investigated in a more detailed manner, it was seen that snow depth and snow water equivalent values showed an increase in the date

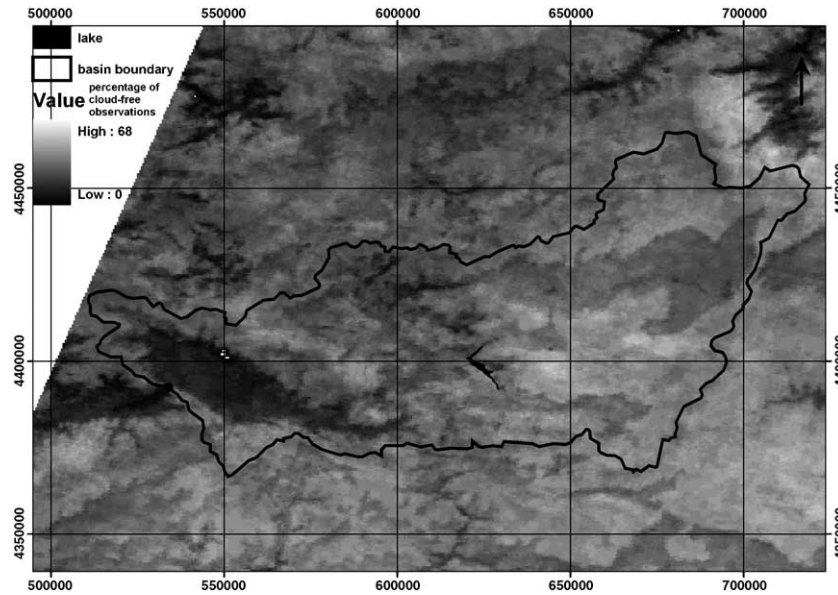


Fig. 6. Percentage of cloud-free observations mapped as snow on a per grid cell basis by MODIS over the winter 2002–2003.

mentioned. Recorded snow depth was 7.44 cm, satisfying the range proposed by Simic et al. (2004) (>25.4 mm) and that of Maurer et al. (2003) (>1cm). Thus the existence of snow in that grid cell was possible. It may be a late spring snowfall that affected the lower elevations of the basin.

4.4. Discussion on model application

In this study, in order to provide the snow-covered area inputs for the SRM, MODIS\_8 daily snow cover

products were used to minimize the cloud cover and maximize the snow cover extent. Even though 1–2-day shift methodology was used in validation of MODIS daily snow cover maps, MOD10A1 could have been used by the same methodology in providing the snow-covered area input for SRM. The lack of ground data required by the methodology for year 2004 did not allow the use of MOD10A1 in the snowmelt modeling. Since maximum snow cover is a more useful parameter than minimum or average snow cover when MODIS data are used because

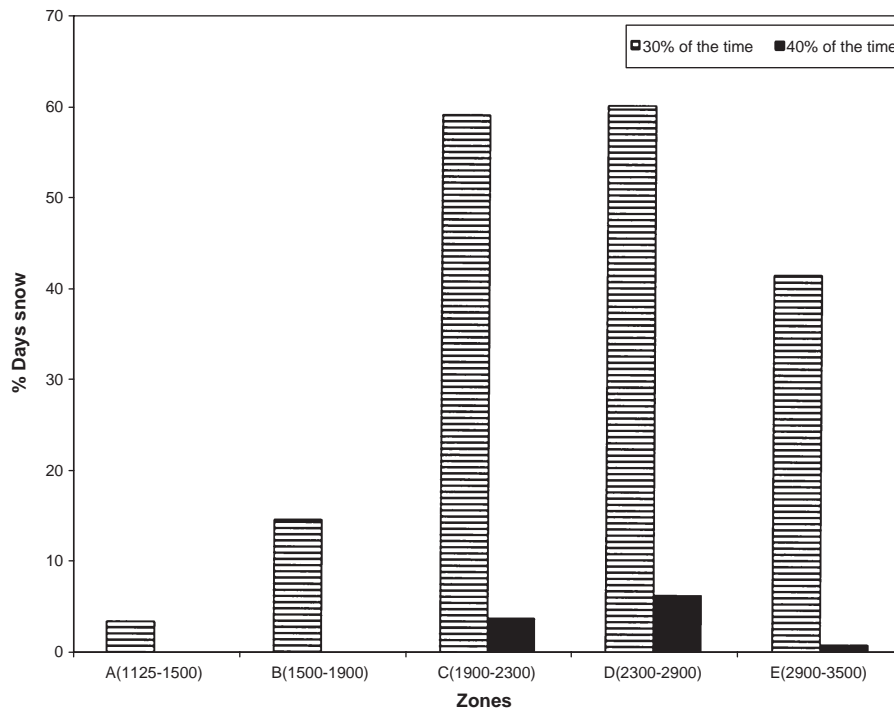


Fig. 7. The distribution of MODIS mapped snow percentages of the time with respect to elevation zones.

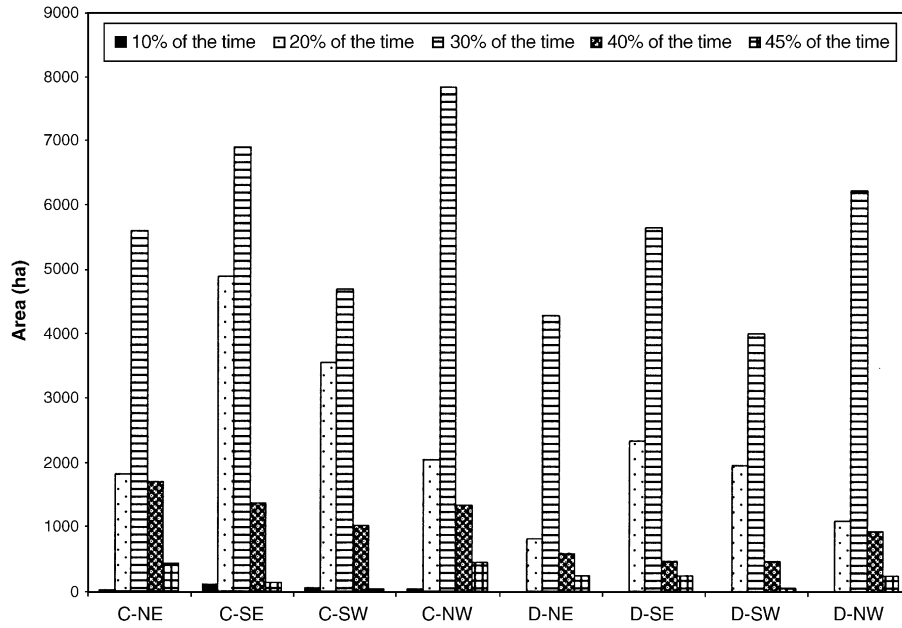


Fig. 8. The distribution of MODIS mapped snow percentages of the time with respect to aspect classes for elevation zones C and D.

cloud cover often prevents a meaningful average amount of snow to be calculated (Hall et al., 2002), MOD10A2 were used in model application. The snow depletion curves belonging to each elevation class were obtained from MODIS snow products for the ablation period of 2004 (Fig. 9). Daily values of SCA between the MODIS observations were derived from linear interpolation based on the accumulated temperature values obtained from numerical weather model forecasts of Mesoscale Model Version 5 (MM5) valid for the  $t+24$  h. The other model variable, precipitation was also obtained from forecasts of Mesoscale Model Version 5 (MM5).

Using the snow depletion curves obtained from MODIS\_8 day snow cover maps, runoff was forecasted at the basin outlet SGS 2119 from April 1 to April 15, 2004 using SRM with the calibrated model parameters, obtained from model applications in 1997 and 1998 water year simulations. Fig. 10 shows the forecasted discharge with the measured one. The accuracy assessment parameters, volume difference ( $D_v$ ) and coefficient of determination ( $R^2$ ), were

obtained as  $-8.88\%$  and  $-0.94$ , respectively. The result statistics can be accepted as promising since the runs were performed using the model parameters that do not represent the hydrometeorological characteristics of the water year under study. The long-term mean of the annual runoff volume for SGS 2119 was calculated as  $1.77 \times 10^9 \text{ m}^3$ . Both years 1997 and 1998 do not represent the mean runoff volume and the shapes of the hydrographs are also different from each other. Parameters that were optimized for catching the early peak of the 1998's runoff might have resulted the overestimation during the climbing limb of the hydrograph. The over prediction may also stem from the use

Table 6  
The distribution MODIS mapped snow percentages with respect to land cover

Land cover	Area (ha)	Days snow					
		10%		20%		30%	
		(ha)	%	(ha)	%	(ha)	%
Built-up	4622.4	4.41	0.1	559.17	12.1	107.19	2.32
Cultivated	59,520.02	33.75	0.06	7026.7	11.81	3454.83	5.8
Pasture	519,326.7	1080.81	0.21	18,906.55	3.64	47,930.1	9.23
Bare land	376,397.5	11,395.4	3.03	21,094.6	5.6	24,373.3	6.48
Water	2224.8	0	0	51.39	2.31	129.51	5.82

Table 7  
Summary of analyses for April 2003 at automated stations

Date	Hacimahmud	Guzelyayla	Ovacik	Cat
13 April 2003	L	S	S	S
14 April 2003	L	L	S	S
15 April 2003	C	C	C	C
16 April 2003	C	C	C	C
17 April 2003	C	C	C	C
18 April 2003	C	C	C	C
19 April 2003	C	C	C	C
20 April 2003	L	C	C	C
21 April 2003	C	C	C	C
22 April 2003	C	C	C	C
23 April 2003	C	C	C	C
24 April 2003	C	C	C	C
25 April 2003	C	C	C	C
26 April 2003	C	C	C	C
27 April 2003	C	C	C	C
28 April 2003	S	C	L	C
29 April 2003	C	L	C	C
30 April 2003	L	C	C	L

S: snow, C: cloud, and L: land.

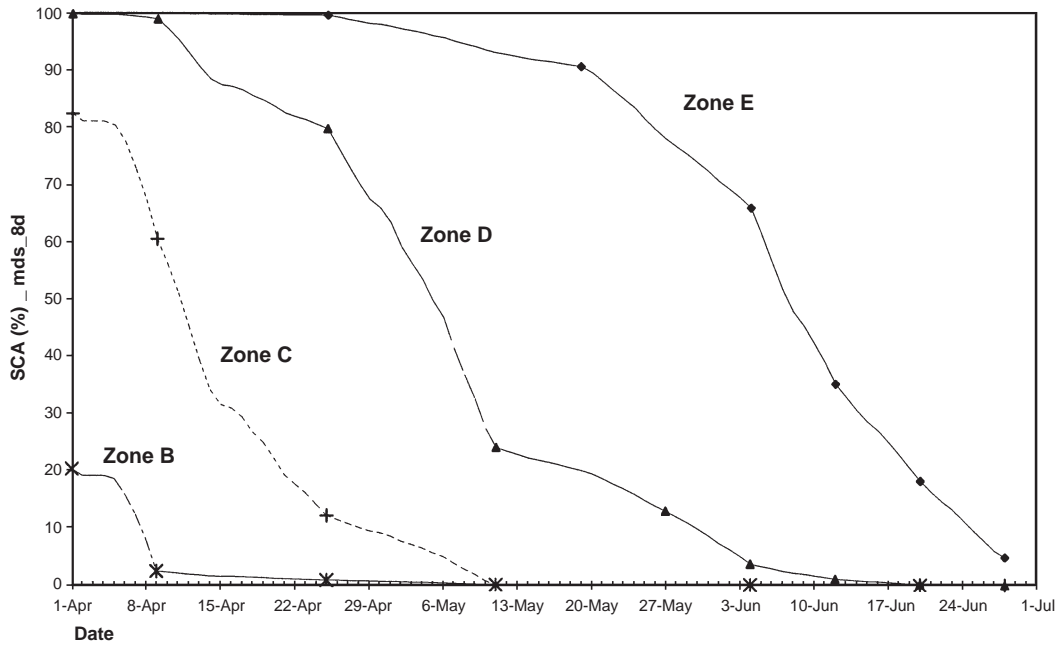


Fig. 9. Snow depletion curves obtained from MODIS snow products.

of forecasted precipitation and temperature values. These ( $t+24$  h) forecasted values should be compared with the observed values.

**5. Conclusions**

Snow cover has importance in various sciences ranging from climatology to hydrology. It gains more importance in hydrology especially in basins where most of the annual

discharge comes from the spring melt of snow in addition to rainfall amount. Snow cover applications include the determination of the snow reserves up to modeling the melt for prevention of the floods. Thus, quick and accurate information about the snow coverage is very important for operational forecasting and/or simulating the water resources applications.

In this paper, daily snow cover maps of MODIS (MOD10A1) were compared for winter of 2002–2003 for accumulation and ablation and for ablation period in March

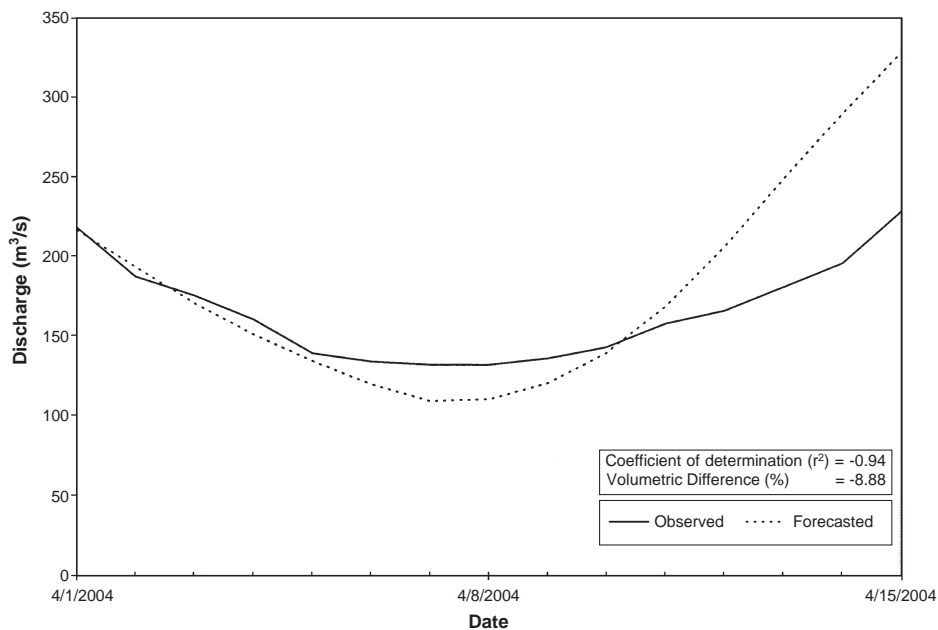


Fig. 10. Forecasted and measured discharge values at SGS 2119 from April 1, 2004 to April 15, 2004.

2004 separately. The matched percentages of the MODIS snow maps in comparison with ground measurements in the non-cloud-covered grid cells were provided. The matched percentages increased from 62% to 82% as one performed the analysis on the date of ground observation and including 2-day shift. The high frequency of cloud cover is the main reason of the reduced matched percentages. In the validation studies, mainly the omissions error checks could be performed since the snow courses were performed at places where there was actually snow on the ground surface. Thus commission errors could not be provided. Even though the error matrix is not provided, a small study based on the automated stations data was performed, indicating the possible commission errors. It is seen that higher number of automated stations is needed for commission error studies. For both years it is found that MODIS determines the snow-covered areas satisfactorily in the basins located at the eastern part of Turkey, which is a rough terrain of the country under study.

Upscaling from point to pixel size and limited spatial coverage are two concepts that hinder the study performed here. Therefore the validation of MODIS snow maps through comparisons with higher-resolution satellite images must be also performed.

MODIS\_8 daily snow cover products (MOD10A2) were used to model the snowmelt in the ablation period of 2004. The reason for using 8-day snow cover maps instead of daily ones was the fact that there was no ground truth data that might have increased the accuracy of the daily image. However, in 8-day snow cover maps there is the possibility that the cloud contaminated grid cells might have determined as cloud-free and correctly classified. Performed forecasting studies show that it seems expedient to use MODIS snow maps in prediction of the magnitude and timing of snowmelt runoff contributing large volumes of flows to reservoirs. The hydrograph shape might have been affected by the elevation bias of the MODIS snow-mapping algorithm, which may underrepresent the snow cover in lower elevation regions and overrepresent in the higher elevation ranges. This may be overcome by the fractional snow-covered area studies of the MODIS data, which forms a future task of the further studies. Nevertheless, it is believed that optimum use, operation and management of the water resources in the study area can be improved by using MODIS imagery coupled with suitable snowmelt models providing critical and sensitive input parameters in order to forecast the magnitude and timing of snowmelt runoff accurately during spring months of the year.

Use of either daily or 8-day snow cover maps lead to a further study which would be on the sensitivity analysis of MODIS snow cover maps on runoff simulations and/or forecasts. Such a study would give an idea about the timing and number of images to be used in simulations and/or forecasts. The results might be compared with findings in Tekeli et al. (in press).

It is hoped this study would be a pioneer for the developing Middle East countries for which water is very crucial and scarce.

## Acknowledgments

A. Emre Tekeli would like to express his great appreciation to Dr. Dorothy Hall of NASA/Goddard Space Flight Center who gave us the courage to tackle such a study. Thanks are also sent to Hüsni Demir who helped to perform various analyses during the study. The authors thank the VIIIth Regional Directorate and General State Hydraulic Works for their assistance before and during the site studies. The MODIS snow cover maps were obtained from NASA Distributed Active Archive Center (DAAC) located at the National Snow and Ice Data Center (NSIDC).

## References

- Ackerman, S. A., Strabala, K. I., Menzel, P. W. P., Frey, R. A., Moeller, C. C., & Gumley, L. E. (1998). Discriminating clear sky from clouds with MODIS. *Journal of Geophysical Research*, 103(D24), 32141–32157.
- Akyürek, Z., & Şorman, Ü. (2002a). Accuracy assessment of a Landsat assisted land-cover mapping. Case study: City of Erzurum and its vicinity—Turkey. *3rd International Symposium Remote Sensing of Urban Areas, Istanbul, Turkey, 11–13. June, 2002*, 2 (pp. 529–536).
- Akyürek, Z., & Şorman, A. Ü. (2002b). Monitoring snow covered areas using NOAA-AVHRR data in the eastern part of Turkey. *Hydrological Sciences Journal*, 47(2), 243–252.
- Ferguson, R. I. (1999). Snowmelt runoff models. *Progress in Physical Geography*, 23, 205–227.
- Hall, D. K., & Martinec, J. (1985). *Remote sensing of ice and snow*. New York: Chapman Hall Ltd. 189 pages.
- Hall, D. K., Foster, J. L., Verbyla, D. L., Klein, A. G., & Benson, C. S. (1998). Assessment of snow cover mapping accuracy in a variety of vegetation-cover densities in central Alaska. *Remote Sensing of Environment*, 66, 129–137.
- Hall, D. K., Riggs, G. A., Salomonson, V. V. (2001) Algorithm theoretical basis document (ATBD) for the MODIS snow and sea ice mapping algorithms, Available at: [http://modis.gsfc.nasa.gov/data/atbd/atbd\\_mod10.pdf](http://modis.gsfc.nasa.gov/data/atbd/atbd_mod10.pdf)
- Hall, D. K., Riggs, G. A., Salomonson, V. V., DiGirolamo, N. E., & Bayr, K. J. (2002). MODIS snow cover products. *Remote Sensing of Environment*, 83, 181–194.
- Kaya I. (1999). Application of snowmelt runoff model using remote sensing and geographic information systems, *Master of Science Thesis*, Water resources laboratory, Civil Engineering Department, Graduate School of Natural and Applied Sciences, Middle East Technical University.
- Key, J. R., Collins, J. B., Fowler, C., & Stone, R. S. (1997). High latitude surface temperature estimates from thermal satellite data. *Remote Sensing of Environment*, 61, 302–309.
- Klein, A. G., & Barnett, A. (2003). Validation of daily MODIS snow cover maps of the Upper Rio Grande River Basin for the year 2000–2001 snow year. *Remote Sensing of Environment*, 86, 162–176.
- Klein, A. G., Hall, D. K., & Seidel, G. A. (1998a). Algorithm intercomparison for accuracy assessment of the MODIS snow-mapping algorithm. 55th Annual Eastern Snow Conference. New Hampshire, June 2–3: Jackson.

- Klein, A. G., Hall, D. K., & Riggs, G. A. (1998b). Improving snow cover mapping in forests through the use of a canopy reflectance model. *Hydrological Processes*, *12*, 1723–1744.
- Leavesley, G. (1983). *Precipitation runoff modeling system*. Denver, Colorado, USA: USGS Publ User manual.
- Martinec, J. (1975). Snowmelt runoff model for streamflow forecasts. *Nordic Hydrology*, *6*, 145–154.
- Maurer, E. P., Rhoads, J. D., Dubayah, R. O., & Lettenmaier, D. P. (2003). Evaluation of the snow covered area data product from MODIS. *Hydrological Processes*, *17*, 59–71.
- MRT. (2003) Available at: <http://lpdaac.usgs.gov/landdaac/tools/modis/index.asp>
- Quick, M. C., & Pipes, A. (1997). *UBC Watershed Model*, *Hydrological Sciences Bulletin*, *XXII*.
- Rao, S. V. N., Ramasastri, K. S., & Singh, R. N. P. (1996). A simple monthly runoff model for snow dominated catchments in Western Himalayas. *Nordic Hydrology*, *27*(4), 255–274.
- Rango, A., & Martinec, J. (1979). Application of a snowmelt runoff model using Landsat data. *Nordic Hydrology*, *10*, 225–238.
- Rango, A., & Van Katwijk, V. (1990). Development and testing of a snowmelt runoff forecasting technique. *Water Resources Bulletin*, *26*, 135–144.
- Riggs, G. A., Barton, J. S., Casey, K. A., Hall, D. K., Salomonson, V. V. (2003). MODIS Snow products user guide for collection 4 data products Available at: <http://modis-snow-ice.gsfc.nasa.gov/userguides.html>
- SAARR. (1972). *Stream flow synthesis and reservoir regulation*. Portland, Oregon: US Army Corps of Engineers, North Pacific.
- Seidel, K., & Martinec, J. (2004). *Remote sensing in snow hydrology*. Springer.
- Simic, A., Fernandes, R., Brown, R., Romanov, P., & Park, W. (2004). Validation of VEGETATION, MODIS and GOES+SSM/I snow-cover products over Canada based on surface snow depth observations. *Hydrological Processes*, *18*, 1089–1104.
- Şorman, A. Ü., Uzunoğlu, E., & Kaya, I. (2001). Applications of SRM and SLURP models in eastern Turkey using remote sensing and geographic information systems. In M. Owe, K. Brubaker, J. Ritchie, & A. Rango (Eds.), *Proceedings Santa Fe symp. April 2000. Remote sensing and hydrology 2000*. IAHS Publication No 267 (pp. 81–86).
- Şorman, A. A., Tekeli, A. E., & Şorman, A. Ü. (2002). Application of snowmelt runoff models by RS/GIS Techniques over the Central Asia and Turkey, XXII. Nordic hydrological conference. *Nordic Association for Hydrology-Nordic Hydrological Programme NHP Report no 47, vol. 1* (pp. 161–173).
- Tekeli, A. E. (2000). Integration of remote sensing and geographic information systems on snow hydrology modeling, Master of Science Thesis, Water Resources Laboratory, Civil Engineering Department, Graduate School of Natural and Applied Sciences, Middle East Technical University.
- Tekeli, A. E., Akyürek, Z., Şensoy, A., Şorman, A. A., Şorman, A. Ü. (in press). Modeling the temporal variation in snow cover area on sub-basin scale for simulating/forecasting of snowmelt runoff in Turkey, *Hydrological Sciences Journal*, *50*(4).
- WinSRM. (2003). *WinSRM users manual*, Available at: <http://hydrolab.arsusda.gov/cgi-bin/srmhome>