COMPARATIVE ANALYSIS OF VARIOUS SATELLITE PRODUCTS THROUGH HYDROLOGICAL MODELING

Cihan ÇOŞKUN

Master of Science Thesis

Department of Civil Engineering

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ABSTRACT

Master of Science Thesis

COMPARATIVE ANALYSIS OF VARIOUS SATELLITE PRODUCTS THROUGH HYDROLOGICAL MODELING

Cihan ÇOŞKUN

Anadolu University
Graduate School of Sciences
Department of Civil Engineering

Supervisor: Assoc. Prof. Dr. Aynur ŞENSOY ŞORMAN

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Majority of runoff is composed of snowmelt in the eastern part of Turkey, especially in mountainous areas. Monitoring of spatial and temporal change of snow covered area is difficult in hydrological and forecasting studies for such areas and the ground observation data are collected at a point and represent nearby area. Thus, satellites are preferred to follow the change in snow extent by taking of their spatial and temporal resolutions into consideration.

In this study, it is aimed to validate commonly used MODIS, MSG-SEVIRI and IMS satellite snow products against the data obtained from 50 ground observation stations in the eastern part of Turkey. However, the optic satellites are affected by cloudiness and different filtering techniques are applied to remove cloud cover. Validation analysis is applied to all steps of filtering and satellite data are compared depending on spatial and temporal resolutions. The stations are classified according to features for better comparative analysis of satellite data and ground observation data. Snow covered area graphics are determined using these three satellite data for Karasu and Murat Basins selected as study areas.

Snowmelt Runoff Model is used for hydrological modeling of basins since it takes snow covered area ratio in addition to precipitation and temperature as input. Impact studies of snow cover area derived by different satellites through conceptual hydrological model are interpreted. Furthermore, both hydrological model validation and runoff forecasting studies are applied with parameter sets determined in the calibration period. Deterministic Numerical Weather Prediction data are used for short-term (up until 2 days) runoff forecasting. As a result, a study including the satellite product validation, hydrological modeling and operational use in water resources management is applied.

Keywords: Snow Hydrology, MODIS, MSG-SEVIRI, IMS, Snowmelt Runoff Model (SRM), Hydrological Runoff Forecasting

ÖZET

Yüksek Lisans Tezi

ÇEŞİTLİ UYDU KAR ÜRÜNLERİNİN HİDROLOJİK MODELLEME İLE KARŞILAŞTIRMALI ANALİZİ

Cihan ÇOŞKUN

Anadolu Üniversitesi
Fen Bilimleri Enstitüsü
İnşaat Mühendisliği Anabilim Dalı

Danışman: Doç. Dr. Aynur ŞENSOY ŞORMAN

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Türkiye'nin doğu bölgelerinde, özellikle dağlık alanlarda akımın önemli kısmı kar erimesinden meydana gelmektedir. Bu bölgelerde kar erimesine bağlı yapılan hidrolojik modelleme ve tahmin çalışmalarında kar miktarının alansal ve zamansal olarak takip edilmesi zordur ve yer gözlem verileri yalnızca noktada ölçülmekte ve civarını temsil etmektedir. Bu sebeple, mekansal ve zamansal çözünürlükleri gözetilerek uydu görüntüleri kullanılması tercih edilmiştir.

Bu çalışmada, kar hidrolojisinde yaygın olarak kullanılan MODIS, MSG-SEVIRI ve IMS kar uydu ürünlerinin Türkiye'nin doğu bölgesinde bulunan 50 yer gözlem istasyonundan elde edilen veriler ile doğrulanması amaçlanmıştır. Ancak, kullanılan optik uydu ürünleri buluttan etkilenmektedir ve bu nedenle bulut etkisini azaltmak için harmanlama çalışması yapılmıştır. Harmanlama çalışmasının her basamağına doğruluk analizi uygulanmış ve uydu ürünleri kendi içerisinde zamansal ve mekansal özellikleri doğrultusunda karşılaştırılmıştır. Doğrulama çalışmasında noktasal yer gözlem verisi ile alansal uydu ürünlerinin daha iyi karşılaştırılabilmesi için istasyonlar farklı özelliklere göre sınıflandırılmıştır. Çalışma alanı olarak seçilen Karasu ve Murat Havzalarına ait karla kaplı alan grafikleri de yine bu üç farklı özellikteki uydular ile belirlenmiştir.

Havzaların hidrolojik modellemesi için yağış ve sıcaklık ile birlikte karla kaplı alan yüzdesini de değişken olarak alan Snowmelt Runoff Model (SRM) kullanılmıştır. Çeşitli uydulardan elde edilen karla kaplı alanların bu kavramsal hidrolojik model üzerindeki etki çalışmaları değerlendirilmiştir. Ayrıca, kalibrasyon döneminde belirlenen parametreler ile hem hidrolojik model doğrulaması hem de hidrolojik akım tahmin çalışması yapılmıştır. Hidrolojik akım tahmin çalışması için kısa vadeli (2 güne kadar) deterministik Sayısal Hava Tahmin verisi kullanılmıştır. Sonuç olarak, uydu ürünü doğrulaması, hidrolojik modelleme ve su kaynakları yönetiminde operasyonel kullanımın aynı anda gözetildiği bir çalışma gerçekleştirilmiştir.

Anahtar Kelimeler: Kar Hidrolojisi, MODIS, MSG-SEVIRI, IMS, Snowmelt Runoff Model (SRM), Hidrolojik Akım Tahmini

To my family and people who I am lucky to meet…

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ABBREVIATIONS AND SYMBOLS

AMSR-E	: Advanced Microwave Scanning Radiometer-Earth Observing System
AMSU	: Advanced Microwave Sounding Unit
ASCII	: American Standard Code for Information Interchange
AVHRR	: Advanced Very High Resolution Radiometer
CLM_SYP	: Climate / Synoptic Station
CM	: Combined
DEM	: Digital Elevation Map
DK	: Detrended Kriging
DMSP	: Defense Meteorological Satellite Program
DOD	: US Department of Defense
ECMWF	: The European Centre for Medium-Range Weather Forecasts
EO	: Earth Observation
EOS	: Earth Observation System
EOSDIS	: Earth Observing System, Data and Information System
ERS-SAR	: The European Remote Sensing-Synthetic Aperture Radar
ESA	: The European Space Agency
FMI	: The Finnish Meteorological Institute
EUMETSAT	: European Organization for the Exploitation Meteorological Satellites
FEWS	: Flood Early Warning System
GIS	: Geographical Information System
GMS	: Japanese Geostationary Meteorological Satellites
GOES	: Geostationary Operational Environmental Satellites
HDF-EOS	: Hierarchical Data Format-Earth Observation System
HRIT	: High Rate Image Transmission
H-SAF	: Satellite Application Facilities on Support to Operational Hydrology and Water Management
IMS	: Interactive Multisensor Snow and Ice Mapping System
METEOSAT	: European Geostationary Meteorological Satellites

MHE	: Moving Horizon Estimation
MM5	: Mesoscale Model 5
MODIS	: Moderate Resolution Imaging Spectroradiometer
MRT	: MODIS Reprojection Tool
MSG-SEVIRI	: Meteosat Second Generation-Spinning Enhanced Visible and Infrared Imager
NASA	: National Aeronautics and Space Administration
NATO	: The North Atlantic Treaty Organization
NDSI	: Normalized Difference Snow Index
NESDIS	: National Environmental Satellite, Data and Information Service
NIC	: National Ice Center
NOAA	: The National Oceanic and Atmospheric Administration
NSIDC	: National Snow and Ice Data Center
NWP	: Numerical Weather Prediction
P	: Precipitation
POES	: Polar Operational Environmental Satellites
Q	: Discharge
SCA	: Snow Covered Area
SE	: Snow Extent
SNOTEL	: Snow Telemetry Station
SRM	: Snowmelt Runoff Model
SRTM	: Shuttle Radar Topographic Mission
SWE	: Snow Water Equivalent
T	: Temperature
TIFF	: Tagged Image File Format
TM	: Thematic Mapper
TSMS	: The Turkish State Meteorological Service
USGS	: United States Geological Survey
UTM	: Universal Transverse Mercator
USAF	: US Air Force
WMO	: World Meteorological Organization

1. INTRODUCTION

1.1. Importance and Motivation of Study

Changing precipitation-runoff relationship and water demand based on increasing population highlights the need for the effective usage of water resources. Thus, planning and hydrological for reservoirs are becoming more of an issue. Effects of flood and drought could be minimized, early warning system could be developed and reservoirs could be operated more effectively with planning supported by hydrological modeling based on forecasting data.

Mean elevation of Turkey is around 1130 m and precipitation falls generally as snow in winter months, especially in the mountainous eastern part. Majority of runoff is composed of snowmelt in this region where important dam reservoirs are located. Euphrates River is a transboundary river that covers the largest catchment area in Turkey and fed mainly by snowmelt. In this study, Karasu Basin (E21A019) located on Upper Euphrates and Murat Basin (E21A022) located on Central Euphrates are selected as pilot sites. Euphrates Basin has the largest basin area of 127 304 km^2 and potential runoff turnout is 17% as the maximum ratio in Turkey. While it is important for national water resources management because of reservoirs within the boundaries of basin, it has international importance for being transboundary. Thus, modeling of precipitation-runoff and short-term deterministic forecasting provide opportunity not only in minimization effects of flood and drought but also effective water resources management.

Monitoring of daily changes in snow covered area is difficult in mountainous areas such as the eastern part of Turkey. In such cases, the data obtained from ground observation stations are point data and they represent only nearby area. Furthermore, satellites are preferred to follow the change in the snow covered area since operational availability of the ground observation is difficult. Thus, these data can be used both in hydrological modeling and forecasting studies.

1.2. Aim of Study

It is a question mark to that performances of satellites used as input to hydrological modeling and forecasting studies. Therefore, in this study, it is aimed to compare three different satellite products, Moderate Resolution Imaging Spectroradiometer (MODIS), Interactive Multisensor Snow and Ice Mapping System (IMS) and Meteosat Second Generation-Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI or SEVIRI), by analyzing the snow cover accuracy of the data against ground observations. Studies about validation could be found in international literature. However, satellite data are compared against ground observation or another satellite and the most commonly used three satellite data are investigated together in this study for the first time. These satellite products have different spectral, temporal and spatial characteristics, thus validation of selected satellite products are examined from several perspectives depending on their different properties.

In addition, impact assessment is applied by using these satellite products in hydrological modeling based on snowmelt. Snow covered area obtained by satellite data and hydro-meteorological data are used as input variables to hydrological model. Whereby, model performance is analyzed and it is aimed to determine precipitation-runoff relationship of Karasu and Murat Basins with this modeling.

Another objective of the study is to forecast the discharge in selected pilot areas. Use of Numerical Weather Prediction data in hydrological model is very limited in Turkey, so it is intended to predict the daily discharge with short-term deterministic weather forecast data. Operational implementation based on numerical weather forecasting is becoming crucial in the world and Numerical Weather Prediction data are used as input in hydrological modeling for daily runoff forecasting. Results of forecasting are compared against observation and performance is analyzed. The results of the study could support the operation policy of the reservoirs located on the downstream in order to optimize water resources management.

1.3. Guideline of Thesis

Thesis starts with the introduction chapter followed by presenting the study area, observation network and data used in the second chapter. Topographic properties of the study area, observation network and data are discussed in this part. The third chapter contains satellite information, deriving of snow covered area from satellite data, validation against ground observations and consistency analysis. In the fourth chapter, integrated structure of the hydrological model with an adjuvant platform is mentioned briefly. Furthermore, calibration and validation studies are given in this chapter. The fifth chapter incorporates the Numerical Weather Prediction data and integration of them with the hydrological modeling. In the last chapter, results are given briefly and it is touched upon the significance of the study for future studies.

2. STUDY AREA and DATA

2.1. Study Area

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.

The Euphrates which is the longest river of Western Asia has 2700 km length and 36.5 billion cubic meters flow potential (1236 km of Euphrates is within borders of Turkey) (Aytemiz and Kodaman, 2006). Important reservoirs and hydropower dams such as Keban, Karakaya, Atatürk, Birecik and Karkamış are seen in Figure 2.1, respectively.

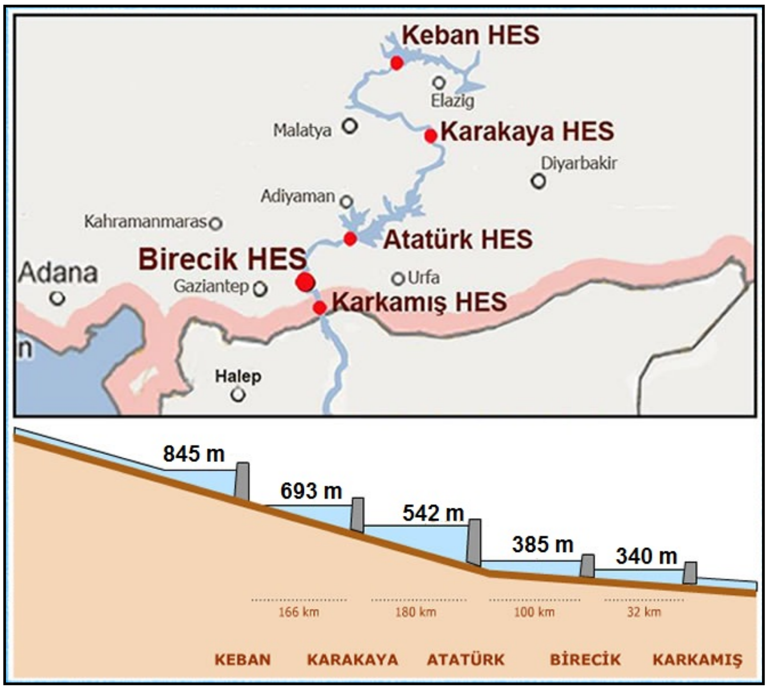

Figure 2.1. Reservoirs on Euphrates River (www.enerjiatlasi.com)

In this study, two headwater tributaries of Euphrates Basin named as Karasu Basin and Murat Basin are selected as test sites (Figure 2.2). One of the reasons of this selection is that both rivers are on the upstream of Euphrates and form it. The other reason is government agencies located on these areas to collect ground observation data.

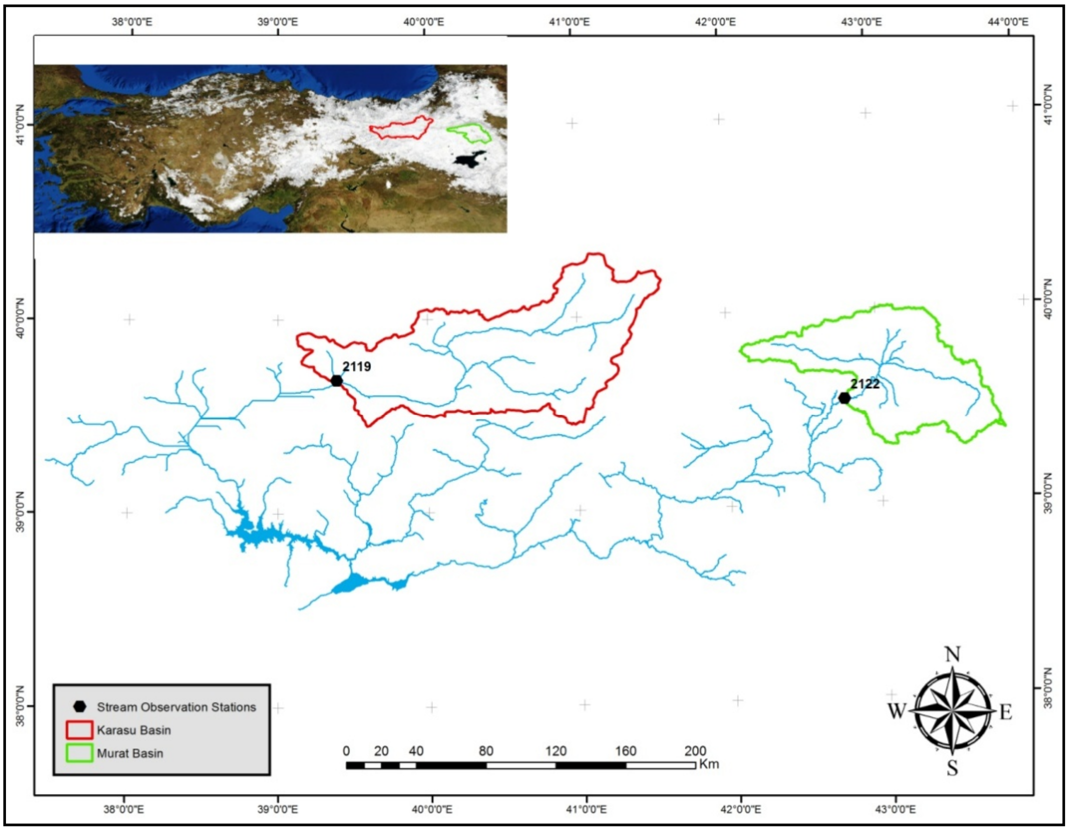

Figure 2.2. Location of Karasu and Murat Basins

Karasu Basin located between the 40°20’ East longitude and 39°50’ North latitude has a drainage area of 10350 km^2. Elevation range is from 1137 to 3521 m with a hypsometric mean elevation of 1983 m (Figure 2.3).

Murat Basin, the other tributary of Euphrates, is located on 43°10’ East longitude and 39°40’ North latitude. Basin drainage area is 5882 km^2 and elevation ranges from 1559 to 3508 m (Figure 2.3). Hypsometric mean elevation of Murat basin is 2125 m.

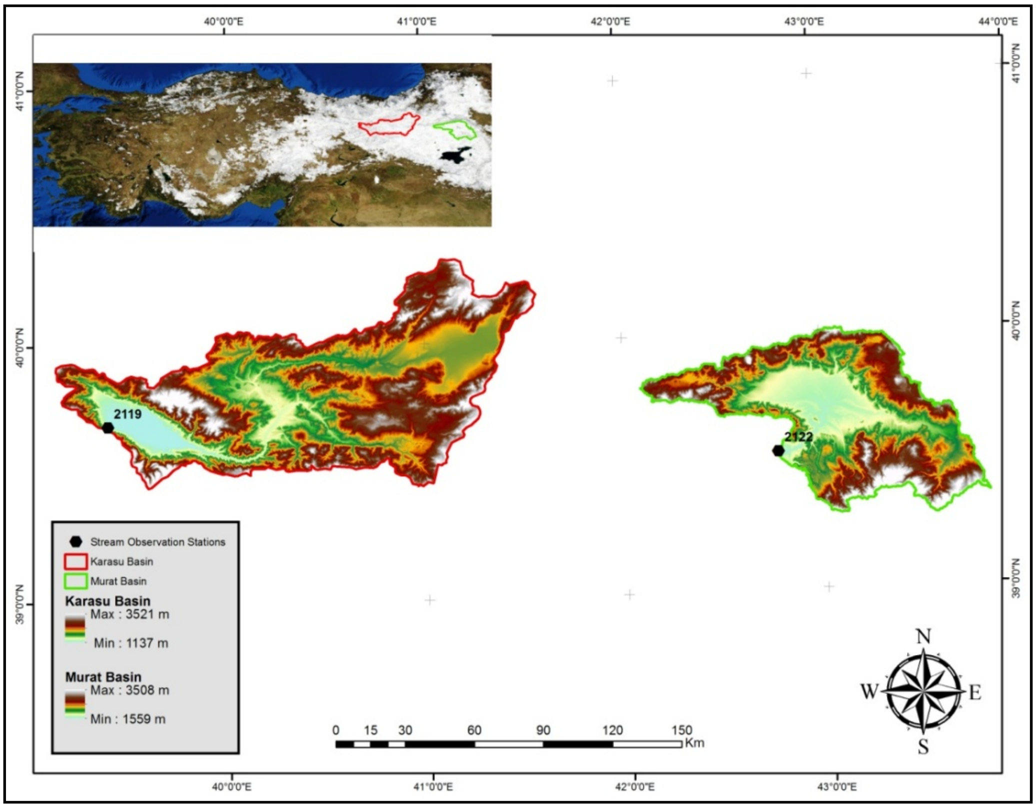

Figure 2.3. Elevation range of Karasu and Murat Basins

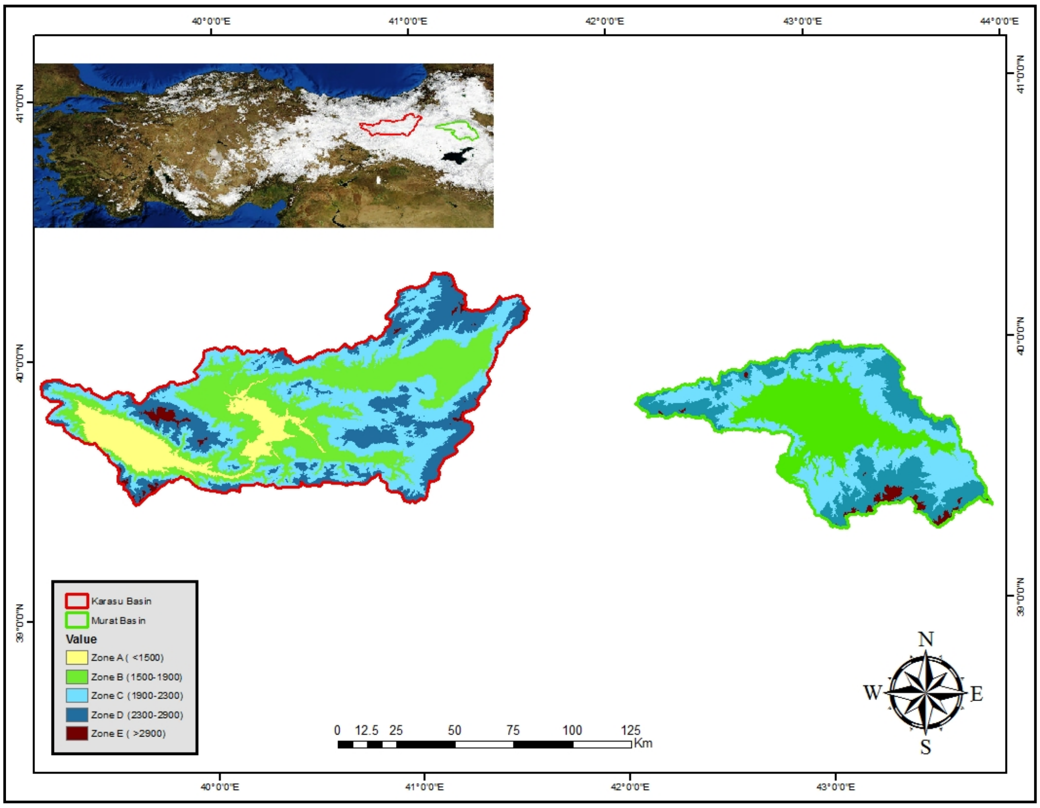

Figure 2.4. Elevation zones of Karasu and Murat Basins

Basins are divided into elevation zones with appropriate elevation ranges (400-600 m) to be used in hydrological modeling (Figure 2.4). Topographic properties of the basins with the respective elevation zones are given in Table 2.1 and Table 2.2.

Topographic properties of each basin are determined from the National Aeronautics and Space Administration (NASA) Shuttle Radar Topographic Mission (SRTM) 90 m Digital Elevation Data (srtm.csi.cgiar.org). Geographical Information System (GIS) platform is used with ArcMap program (ESRI ArcMap Version 10) to process SRTM. Similar zone elevation ranges are applied for both basins thus, Murat Basin does not have Zone A. Zone C has the largest area ratio in both basins. While Zone B has the second largest area ratio in Karasu Basin, Zone B and Zone D in Murat Basin have similar ratios. In both basins, Zone E has the smallest area (Table 2.1 & 2.2).

Table 2.1. Topographic properties of Karasu Basin and zones

Zone	**Elevation Range (m)**	**Area (km^2)**	**Area (%)**	**Hypsometric Mean Elevation (m)**
A	1137-1500	1105.86	10.68	1355
B	1501-1900	3300.42	31.89	1762
C	1901-2300	3513.63	33.95	2098
D	2301-2900	2275.13	21.98	2485
E	2901-3521	154.95	1.50	2993
All Basin	1137-3521	10350	100	1983

Table 2.2. Topographic properties of Murat Basin and zones

Zone	**Elevation Range (m)**	**Area (km^2)**	**Area (%)**	**Hypsometric Mean Elevation (m)**
B	1559-1900	1752.33	29.79	1744
C	1901-2300	2192.04	37.27	2069
D	2301-2900	1774.26	30.16	2513
E	2901-3508	163.37	2.78	3046
All Basin	1559-3508	5882	100	2125

In snowmelt, aspect has an important effect, so aspect maps of basins are derived using GIS platform (Table 2.3 and Figure 2.5). Basins show similar aspect properties in general. However, south aspect ratio is a bit more than north aspect ratio. The maximum aspect ratios of Karasu and Murat Basins are on southeast and southwest, respectively.

Table 2.3. Aspect ratios of Karasu and Murat Basins (%)

Aspect	Northeast	Southeast	Southwest	Northwest	Flat	North	South
Karasu	22.33	27.18	24.13	26.34	0.02	48.67	51.31
Murat	24.25	24.97	26.08	24.71	0.00	48.96	51.04

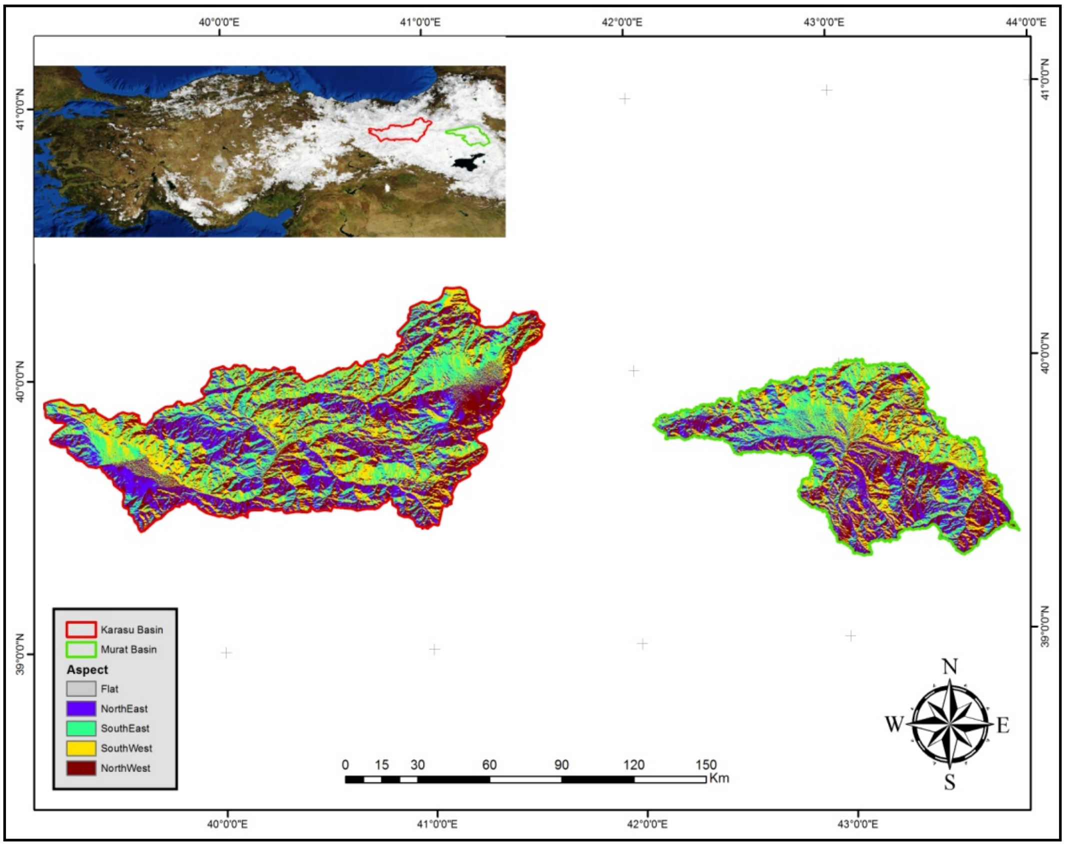

Figure 2.5. Aspect maps of Karasu and Murat Basins

The other important surface property is the slope of basin. About one half of each basin is over 15 percent slope (Table 2.4). Karasu Basin has a steeper slope compared to Murat Basin, 55 percent of area for Karasu Basin is over 15 percent slope while this area ratio is about 45 percent for Murat Basin. The slope ratios and elevation ranges of both basins show that the selected areas are on mountainous regions (Figure 2.6).

Table 2.4. Slope ratios of Karasu and Murat Basins (%)

Slope	Karasu	Murat
0-2	8.63	11.33
2-8	15.54	21.23
8-15	19.10	23.17
15-30	33.78	31.21
30-50	18.66	11.77
>50	4.28	1.30

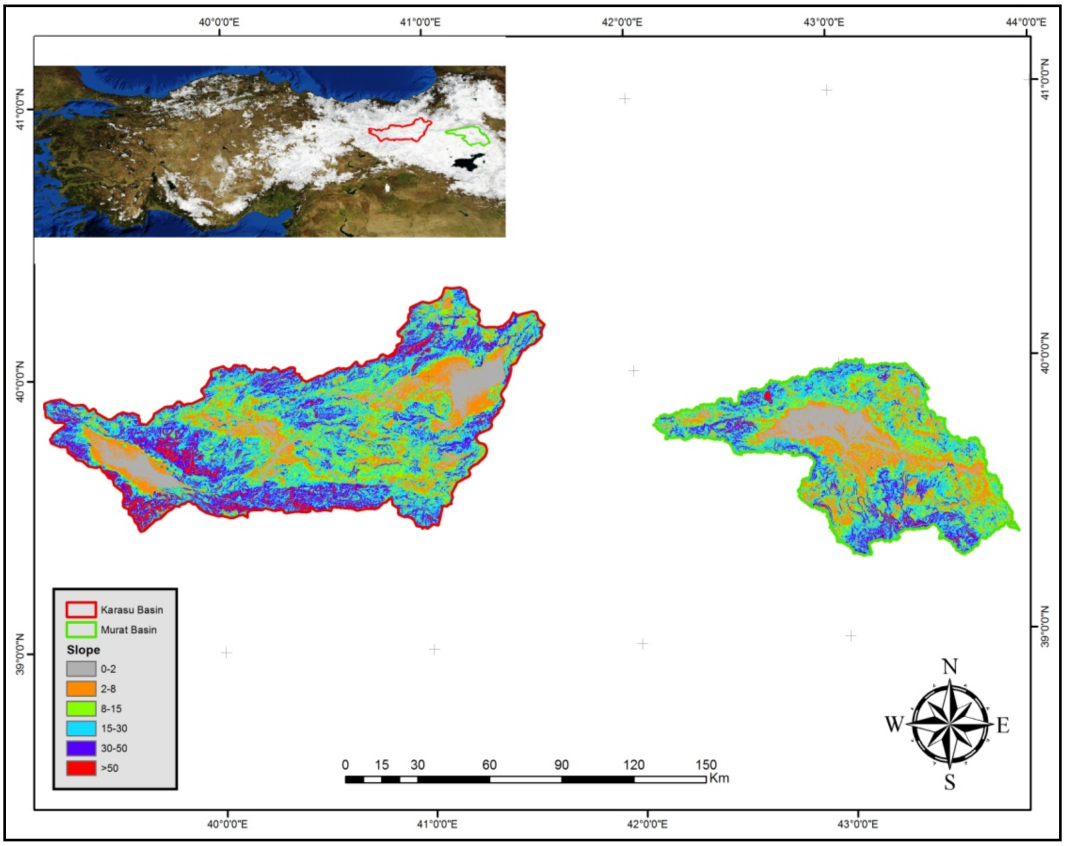

Figure 2.6. Slope maps of Karasu and Murat Basins

According to Corine land use classification product of European Environment Agency, land use of the basins is mainly agriculture, pasture and bare area with ratio of more than 90 % (www.eea.euraopa.eu; Table 2.5, Figure 2.7).

Table 2.5. Land use classes and ratios of basins (%)

Land Use Class	Karasu Basin	Murat Basin
Agricultural Area	31.50	36.11
Forest	3.50	0.02
Green Area	35.00	32.58
Bare Area	27.50	30.34
Urban	1.84	0.64
Water	0.66	0.31

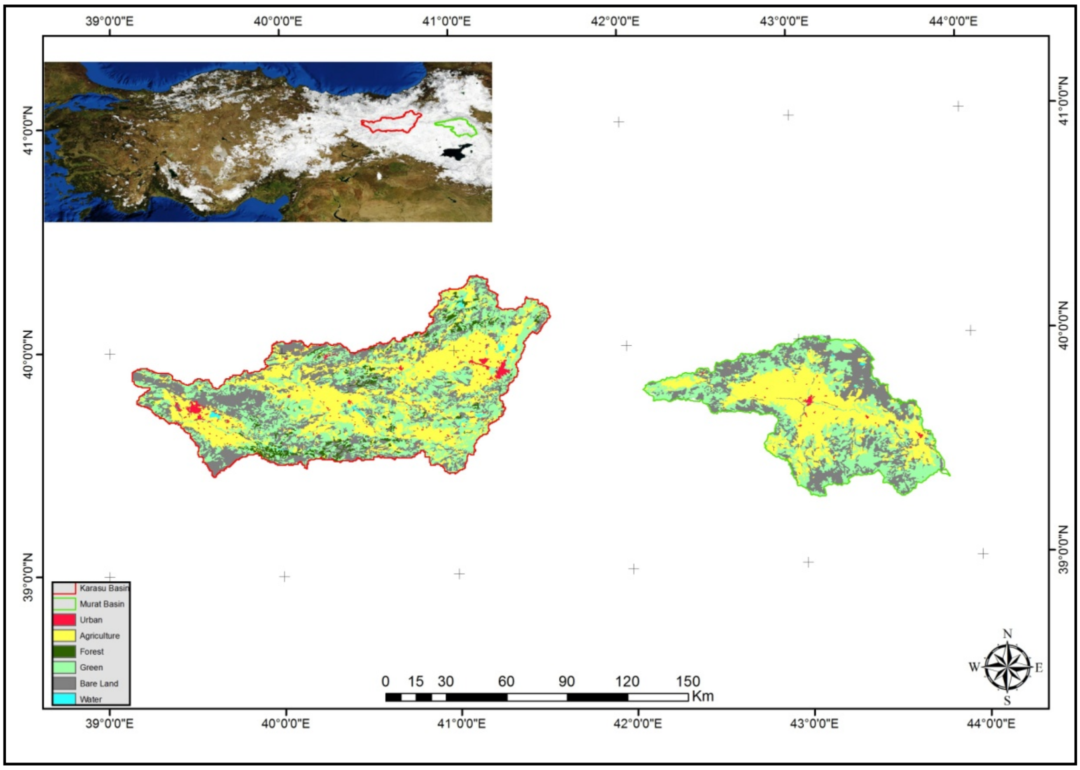

Figure 2.7. Land use maps of Karasu and Murat Basins

2.2. Research Activities in the Study Area

Hydrology science and applications cover management, assessment and forecasting of water quantity and quality. Hydrological data both for past and real-time are collected, stored and analyzed. Results are used to manage water resources against the hazards such as flood, drought, pollution, etc. Thus, availability of accurate, dependable and current data is an important prior condition (WMO, 1999).

In Turkey, various public organizations collect hydro-meteorological data. However, data stream is slow and unfortunately there is no common database. That hampers availability and process of data for research projects or non-public institutions. Also, topographic and meteorological conditions on high elevations in the eastern part of Turkey affect adversely to gather hydro-meteorological data. Majority of runoff in this region is contributed due to snowmelt. Therefore, observation of temporal and spatial variance of snow covered area and daily meteorological data takes an important role in hydrological modeling of mountainous part of Turkey. On the other hand, validation of satellite data sources is assessed against ground observations at snow meteorological stations.

Automatic stations are needed to increase the number and continuity of measurements, reliability of observations, and to design the most suitable system in research and development. For this purpose, snow measurements with a rather advanced technology have been started with NATO-Sfs project in 1996, in the Eastern Anatolia, Turkey. Automatic snow and meteorological stations were setup on high elevations in this part by guidance of a university and cooperation of State Hydraulic Works and Electrical Power Resources Survey and Development Administration in 1999.

Data collected with these projects and different hydrological models (SRM, SLURP, HEC-1) were applied in research studies by Kaya (1999), Uzunoğlu (1999), Şensoy (2000), Tekeli (2000), Beşer (2002), Şensoy (2005), Şorman (2005), Tekeli (2005). These studies contain not only model applications but also monitoring, data processing and analysis. Furthermore, atmospheric and hydrological models were integrated with Numerical Weather Prediction (NWP) data for the first time in Turkey.

Satellite Application Facilities on Support to Operational Hydrology and Water Management (H-SAF) project, which is financially supported by European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), was started in 2005. Turkey is a part of this project, in product generation (eg. snow recognition, fractional snow cover and snow water equivalent), validation of snow products with ground observations, calibration/validation studies with hydrological modeling and impact studies in the mountainous terrain of Europe.

Different scientific research projects were applied with financial aid of Anadolu University (BAP1207F117; BAP1307F284; BAP1404F149; BAP1505F459). It was aimed to reduce cloud ratio on satellite snow products in the eastern part of Turkey; validation of final products with ground observations; hydrological modeling to predict runoff for Karasu Basin. The other important projects on snow dominated basins in Turkey are TÜBİTAK (The Scientific and Technological Research Council of Turkey) supported 108Y161 & 113Y075. The objectives of the research projects are to forecast seasonal snow potential and daily runoff in Upper Euphrates Basin using field observations, satellite technologies, weather prediction data and hydrologic models; and to develop an operational hydrologic forecast system using Ensemble Prediction System and satellite data in snow dominated mountainous Fırat and Seyhan basins, respectively.

2.3. Observation Network and Hydro-meteorological Data

In this study, 50 meteorological observation stations operated by The Turkish State Meteorological Service (TSMS) and State Hydraulic Works are used for meteorological and snow data (Figure 2.8). 23 of them are snow telemetry (SNOTEL) and the other 27 are climate / synoptic stations (CLM_SYP). While data of CLM_SYP stations are in daily, data of SNOTEL are hourly or in higher temporal resolution. Also, SNOTEL stations are located on higher elevations in mountainous region generally since they have automatic data collection property.

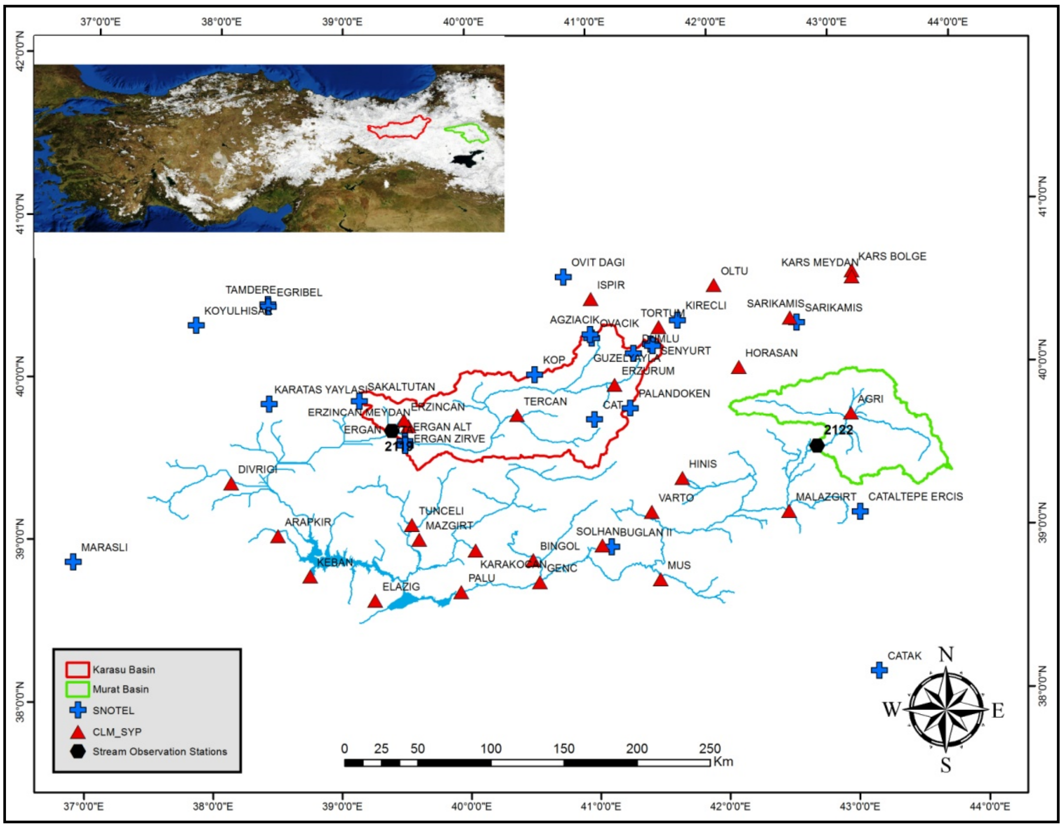

Figure 2.8. Observation network

Elevation range of stations is between 751 m and 2937 m (Figure 2.9) and distribution of observation network with topographic elevation is shown in Figure 2.10.

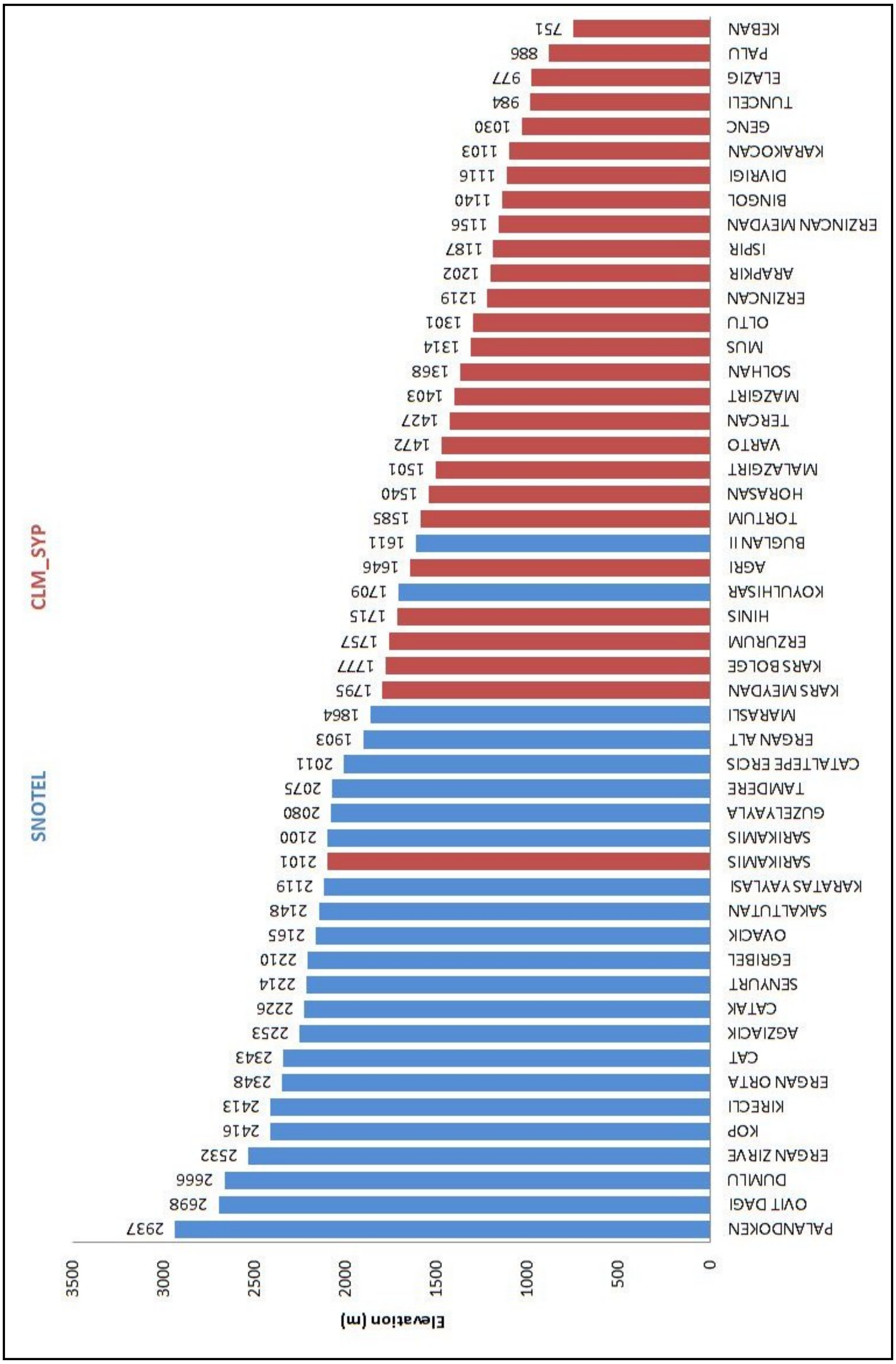

Figure 2.9. Altitudes of stations

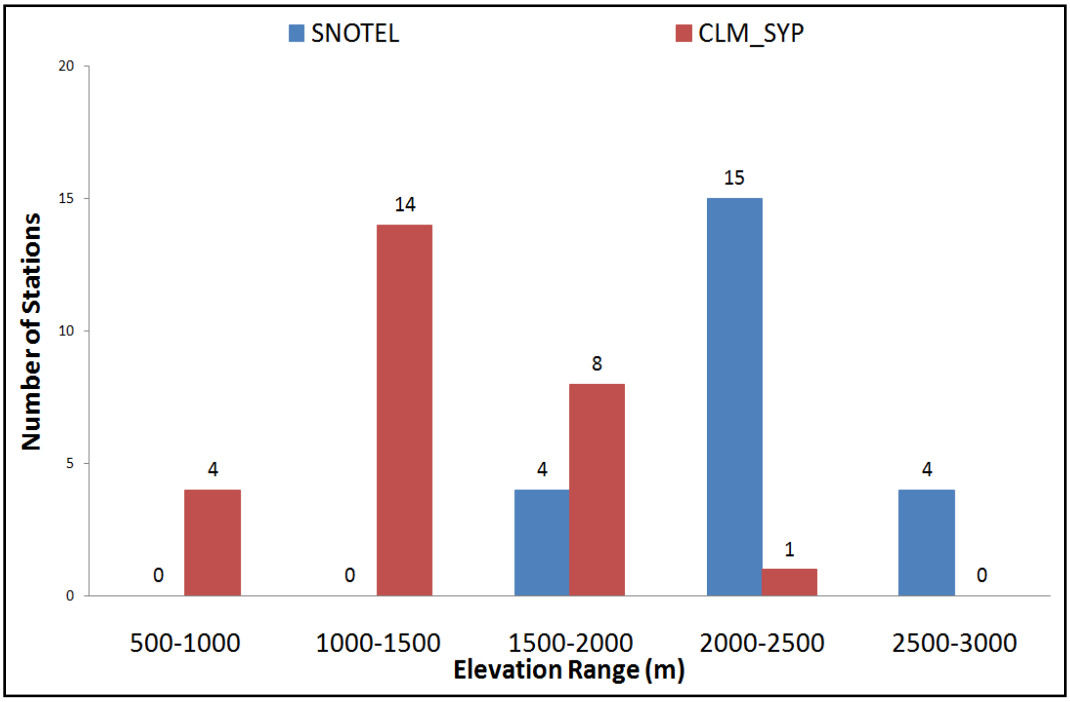

Figure 2.10. Histogram for elevation distribution of stations

SNOTEL stations are located generally on pasture, agriculture or bare areas. However, CLM_SYP stations are basically located on urban areas (Figure 2.11).

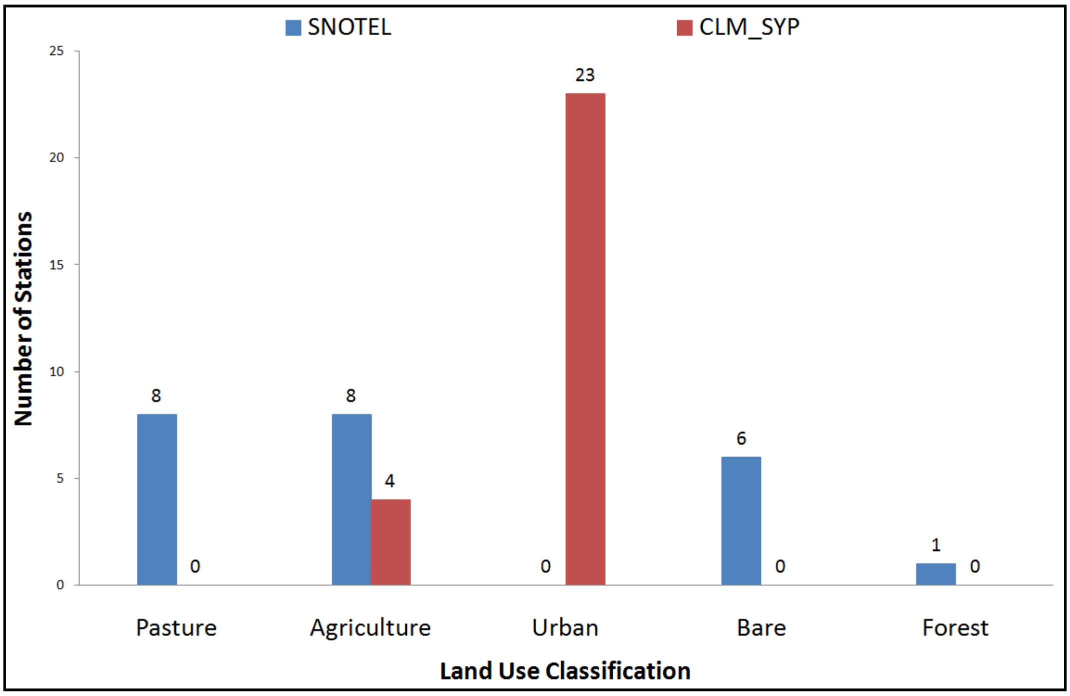

Figure 2.11. Land use distribution of observation network

Precipitation Data

Type of precipitation depends on air temperature. Thus, precipitation and temperature data should be taken into consideration together while interpreting snow accumulation.

Daily total precipitation data are provided by TSMS are processed to analyze monthly average and annual total precipitation values of 2008-2012 water years as given in Figure 2.12 and 2.13, respectively. According to Figures 2.12 and 2.13 based on monthly and annual averages, Sarıkamış station seems to receive more rain than other stations. However, Sarıkamış precipitation data for approximately two months in 2012 water year are missing, so annual total precipitation value is low in this year. Observations at Ağrı show high standard deviation for annual average precipitation for different seasons (Figure 2.13).

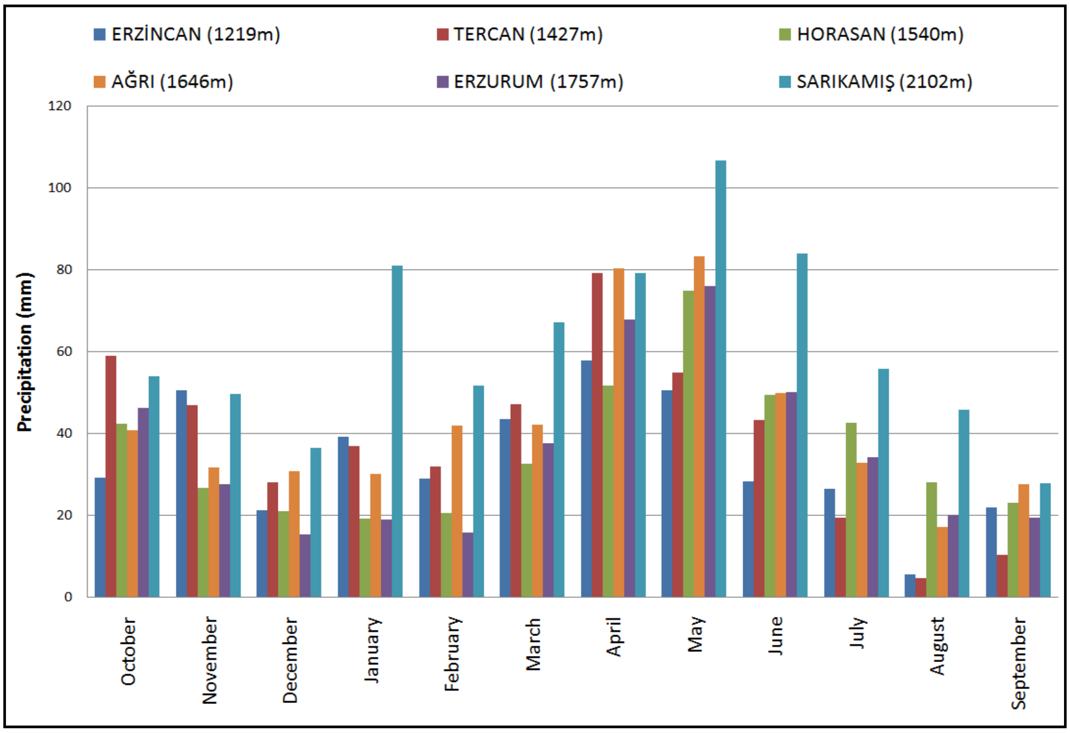

Figure 2.12. Monthly average precipitation data of stations (2008-2012)

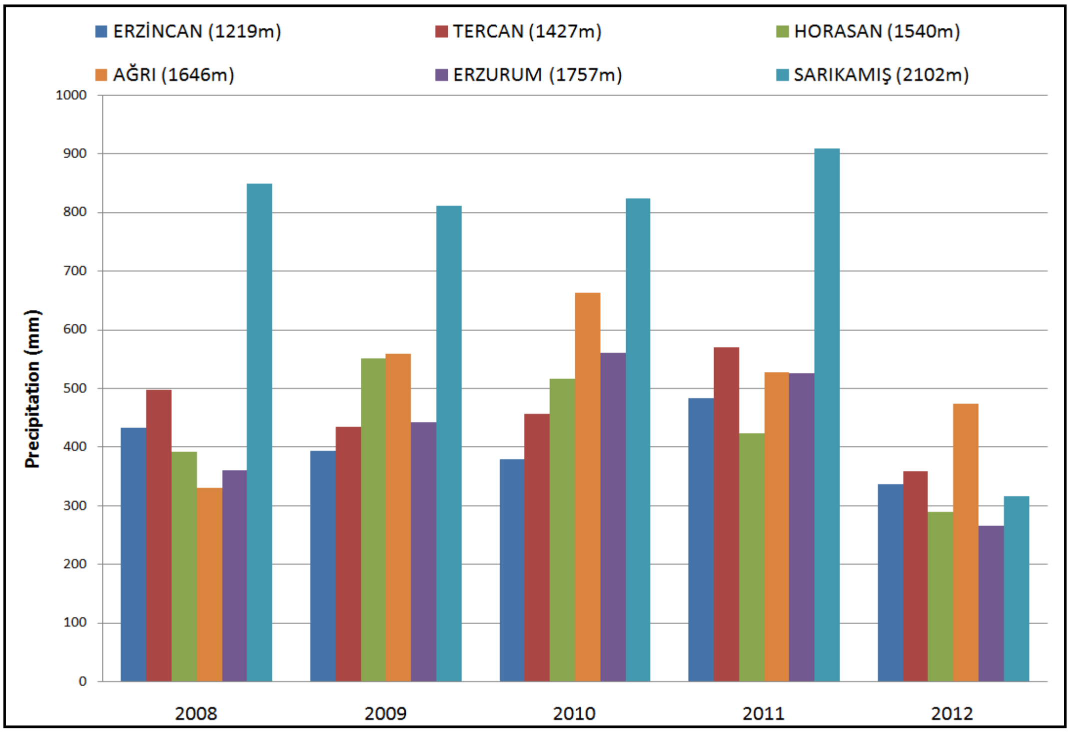

Figure 2.13. Annual total precipitation data of stations (2008-2012)

Air Temperature Data

Daily air temperature data provided by TSMS are processed and a sample of average air temperature data is given on a monthly and annual basis in Figures 2.14 and 2.15, respectively. Average temperature ranges between about -10 and 25^{0}C. Stations show similar trends as that the coolest month is January and the warmest month is July. Moreover, it can be seen that temperature increases while elevation decreases (Figure 2.14).

Furthermore, daily total precipitation and daily average temperature data are also used in hydrological modeling. For Karasu Basin, 15 meteorological stations close by basin are used to distribute temperature and precipitation by applying Detrended Kriging method (DK). Single station, Ağrı station within the boundaries of the basin (Figure 2.8), is used for hydrological modeling of Murat Basin.

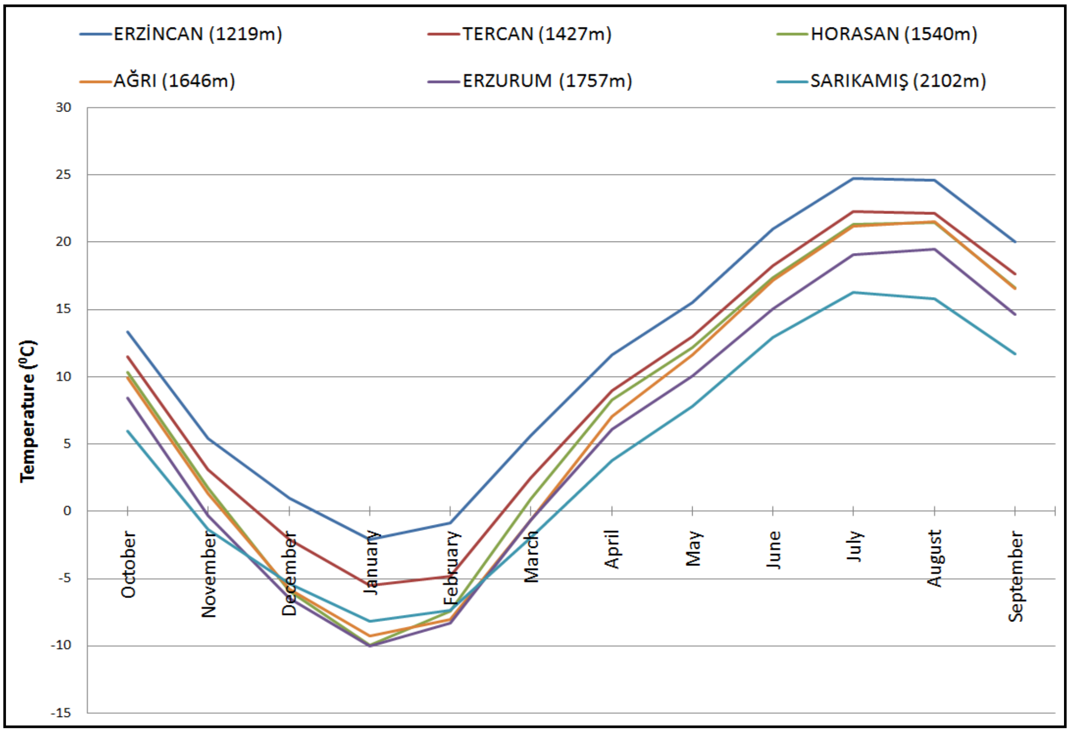

Figure 2.14. Monthly average temperature data of stations (2008-2012)

An annual average of air temperature data for the simulation period is provided in Figure 2.15. 2008, 2009 and 2012 water years show similar temperature trends; the warmest year is 2010 water year (Figure 2.15).

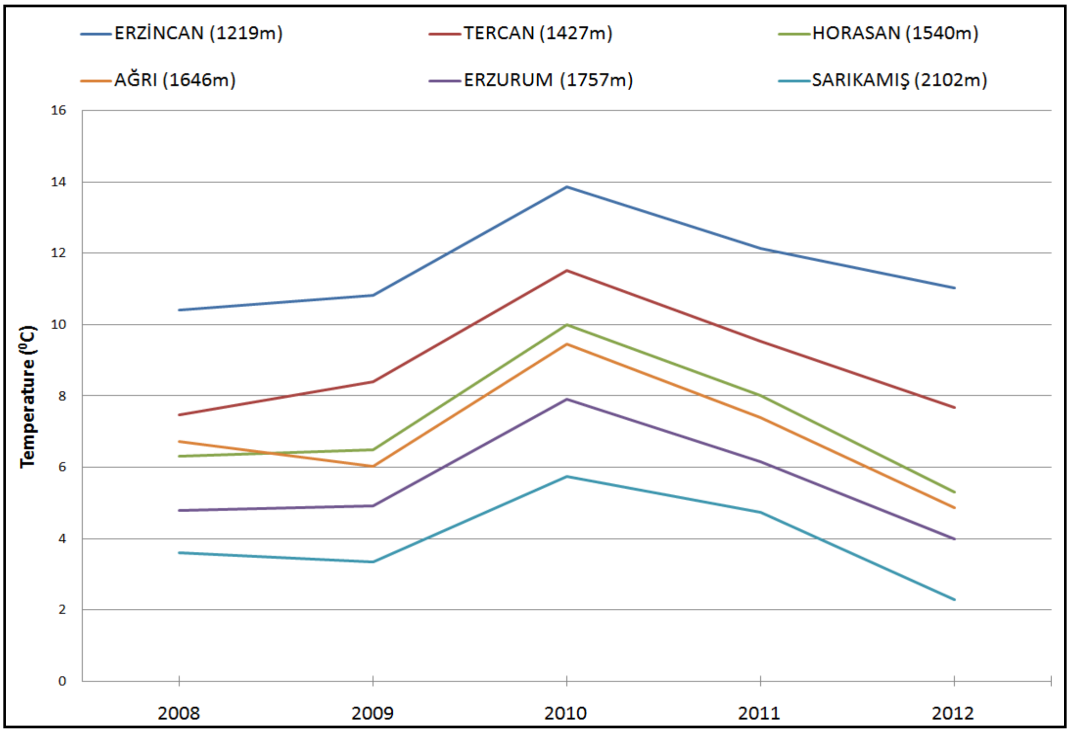

Figure 2.15. Annual average temperature data of stations (2008-2012)

Discharge Data

Karasu Basin and Murat Basin are controlled by stream gauging stations E021A019 and E021A022 (Figure 2.2 and 2.8), respectively. Snowmelt takes an important role in discharge contribution of these basins. According to the analysis of daily discharge data provided by State Hydraulic Works, long term records for Karasu Basin show that about 69% of annual total discharge consists of snowmelt during melt period (March-June for both basins). In the view of simulation period, between 2008 and 2012 water years, about 61% of annual total discharge comes into existence on snowmelt period for Karasu Basin (Figure 2.16). The same calculation on the long term runoff records of Murat Basin indicates that snowmelt discharge ratio is about 78%. The same ratio for the simulation period is approximately 77% (Figure 2.17).

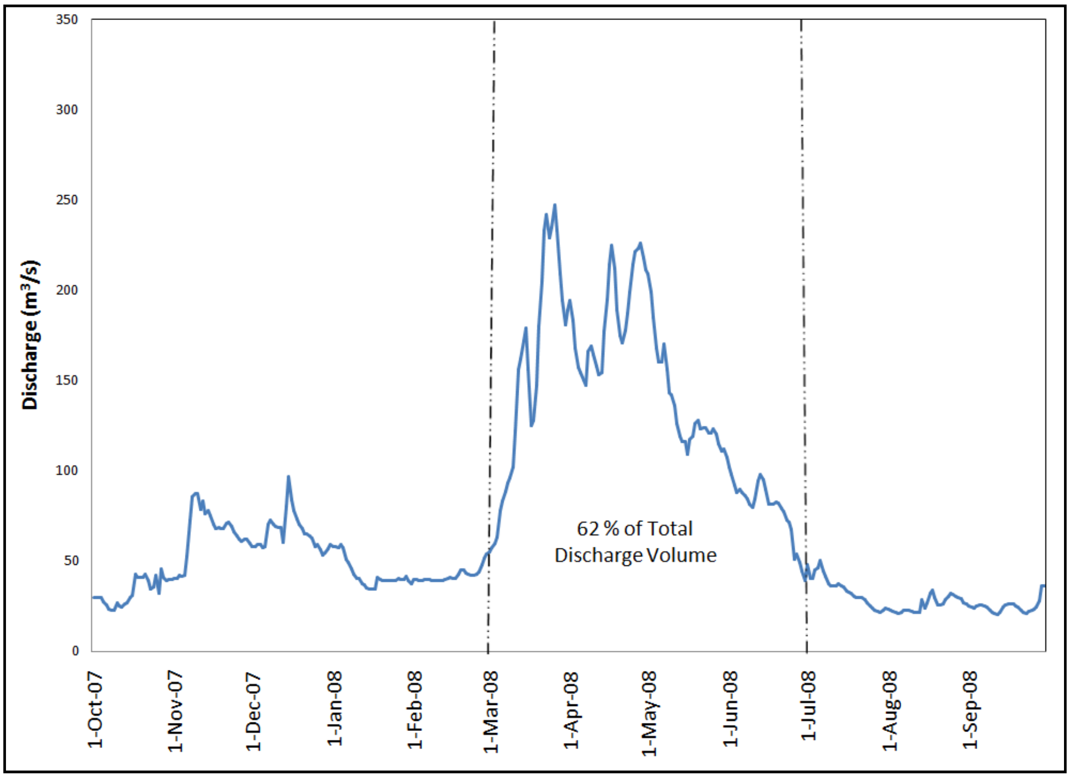

Figure 2.16. (a) Discharge of Karasu Basin in 2008 water year

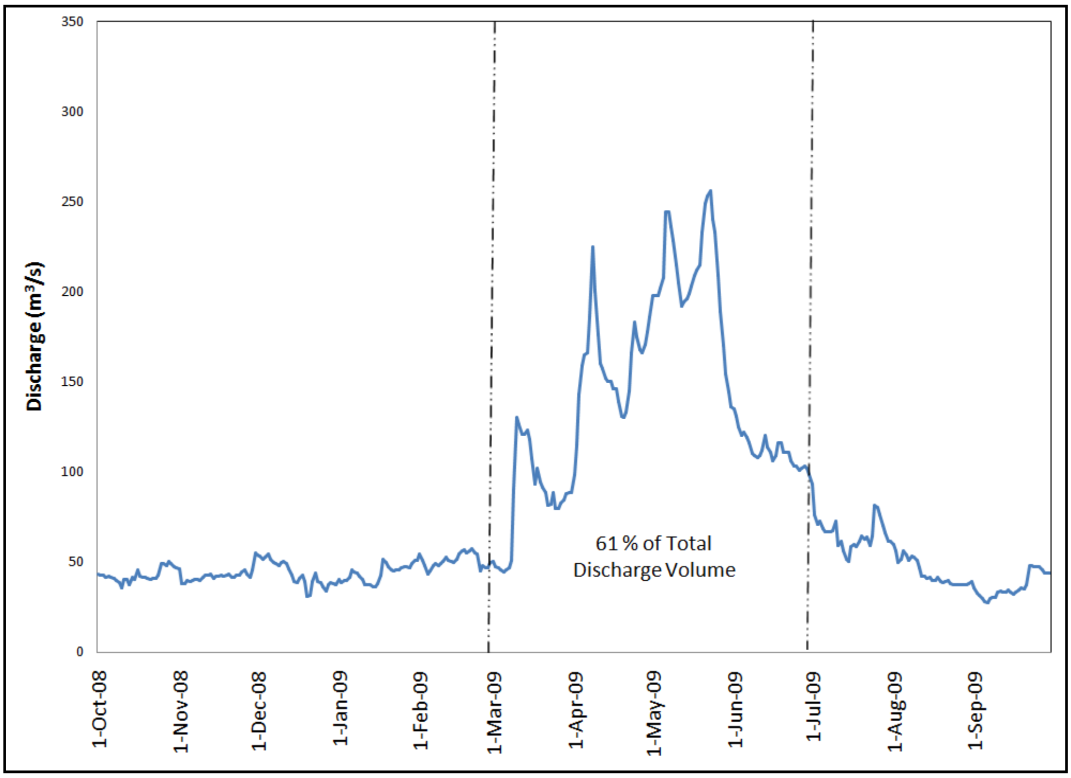

Figure 2.16. (b) Discharge of Karasu Basin in 2009 water year

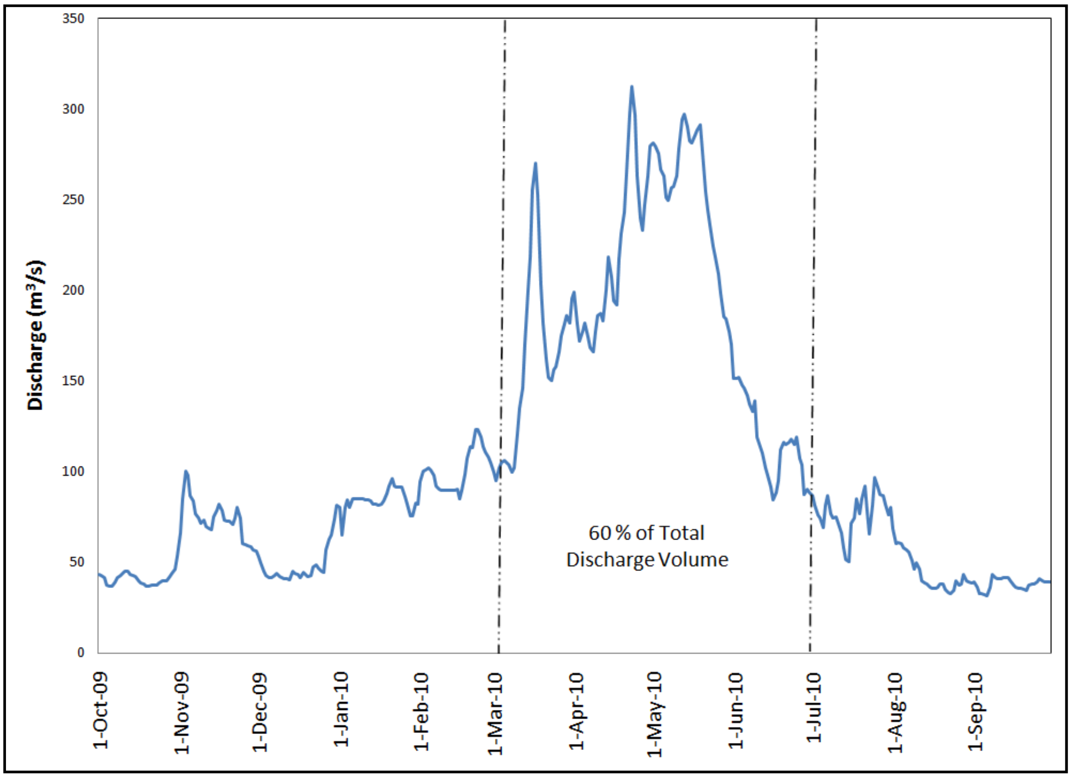

Figure 2.16. (c) Discharge of Karasu Basin in 2010 water year

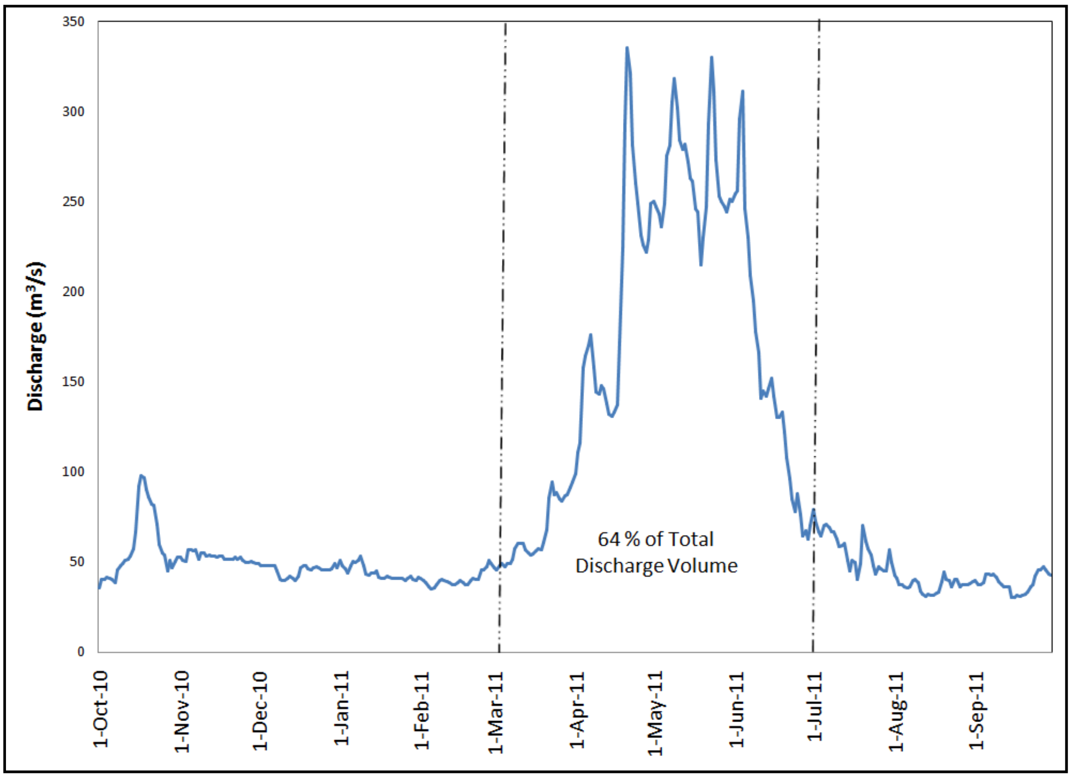

Figure 2.16. (d) Discharge of Karasu Basin in 2011 water year

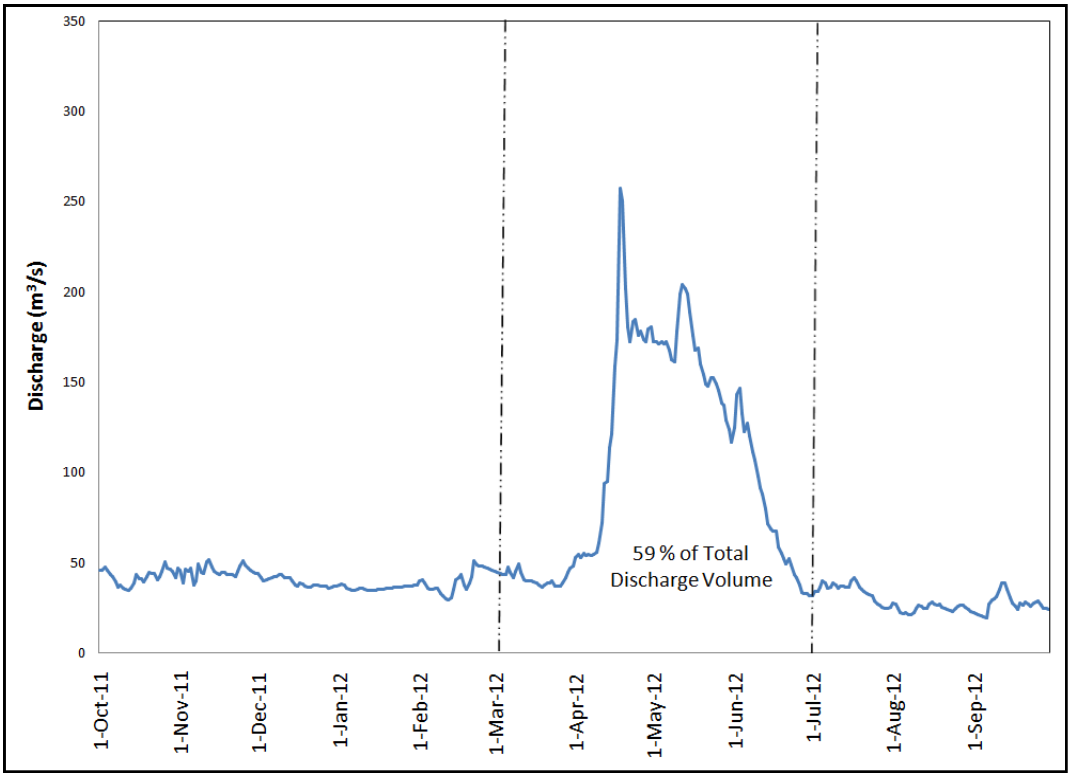

Figure 2.16. (e) Discharge of Karasu Basin in 2012 water year

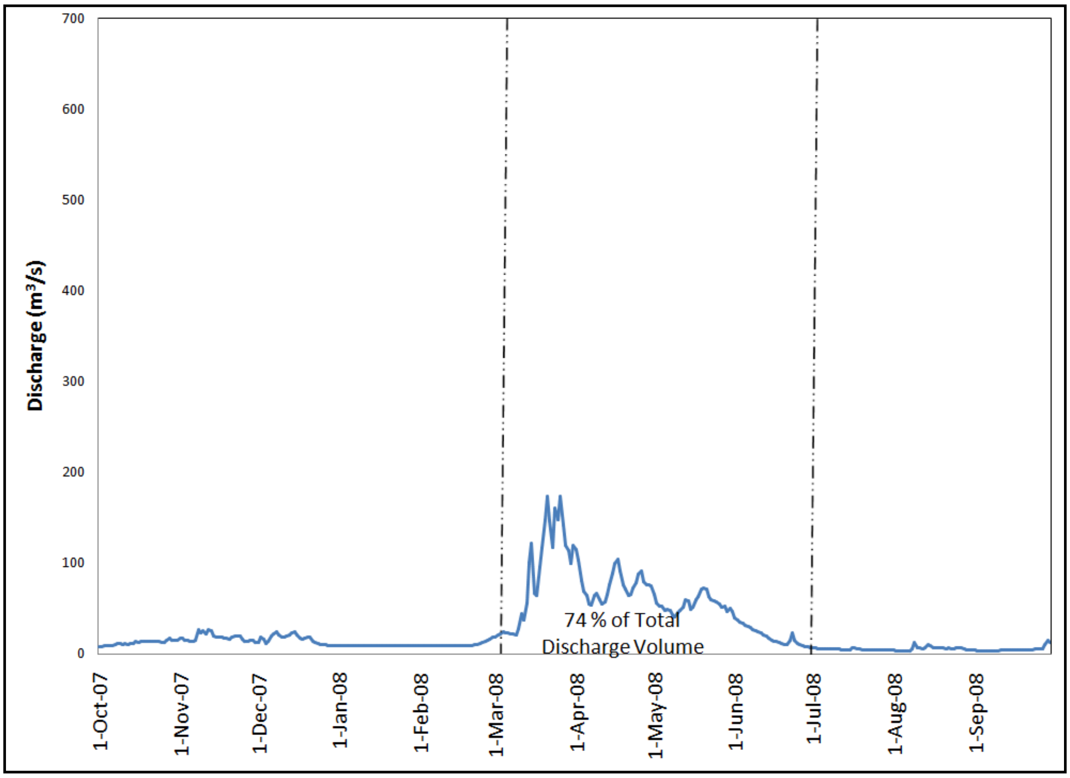

Figure 2.17. (a) Discharge of Murat Basin in 2008 water year

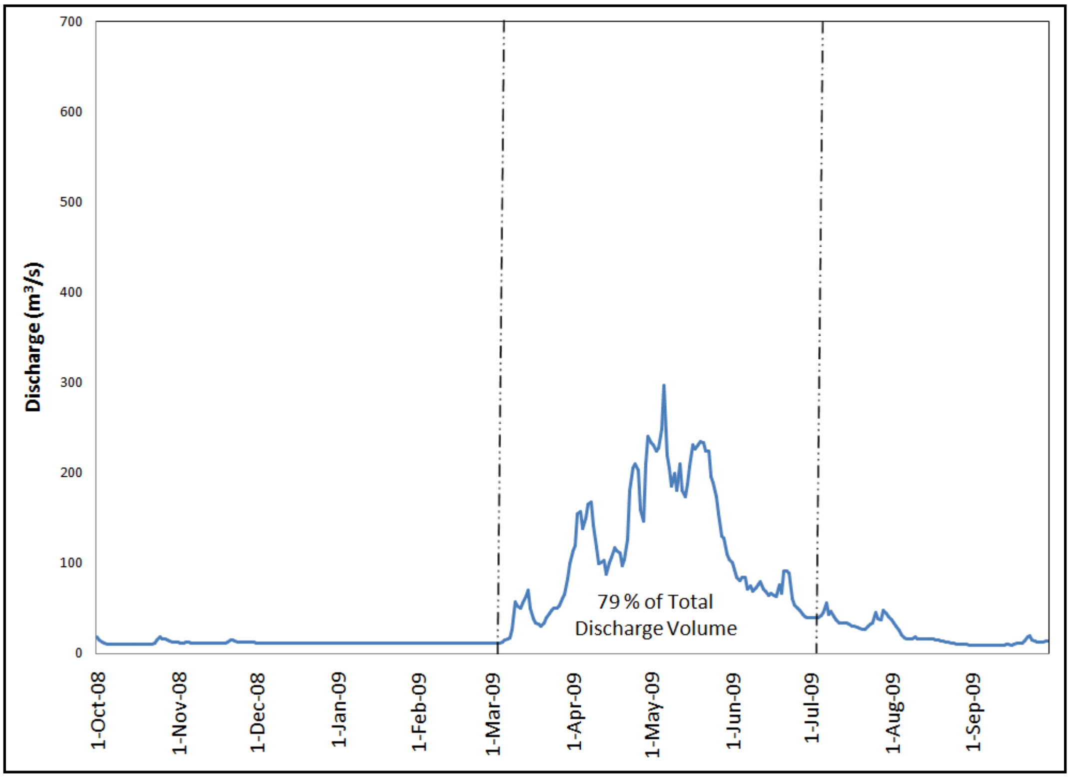

Figure 2.17. (b) Discharge of Murat Basin in 2009 water year

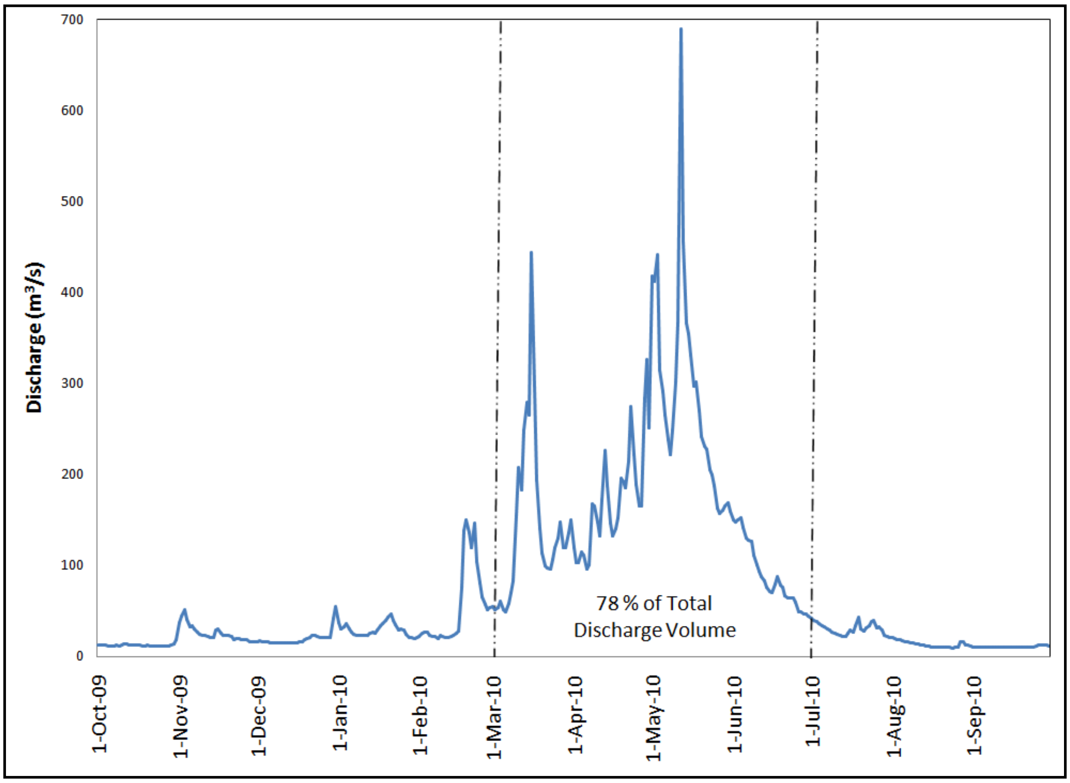

Figure 2.17. (c) Discharge of Murat Basin in 2010 water year

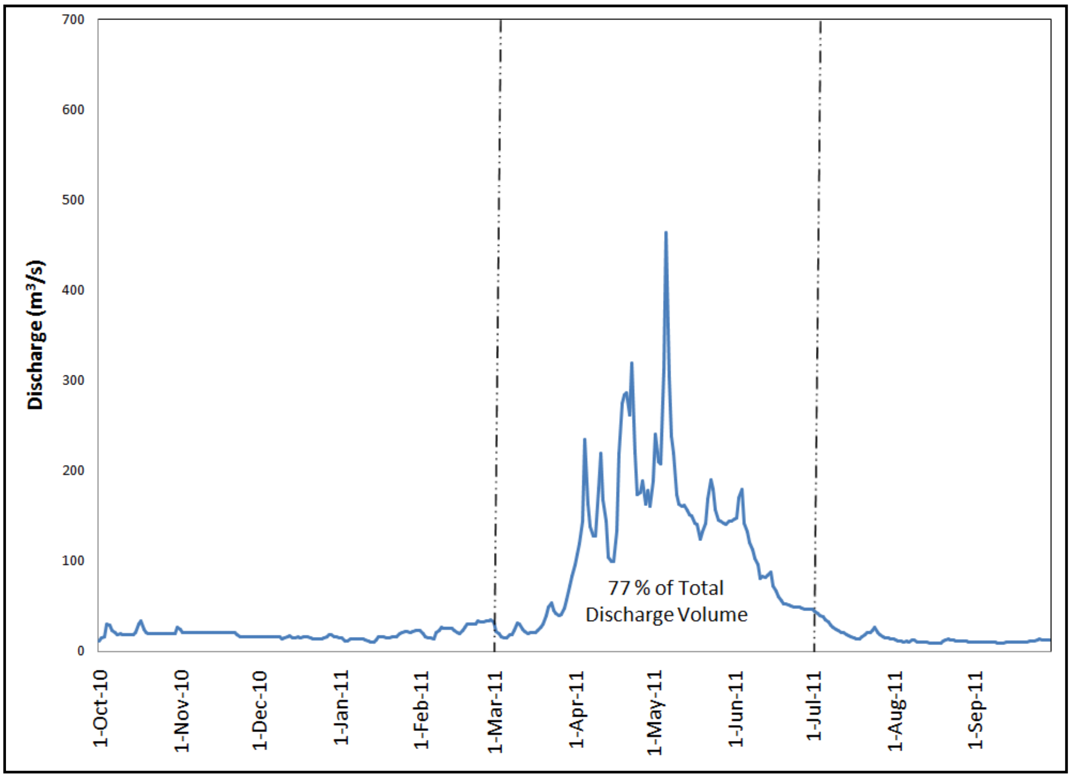

Figure 2.17. (d) Discharge of Murat Basin in 2011 water year

Snow Depth Data

In the study area, snow coarse measurements (depth and snow water equivalent) have been started using snow tube by government agencies since the mid 1960's. These records are available for once or twice a month and give information about snow potential of the basin. Since these measurements are not suitable to be used in hydrological modeling due to their temporal resolution, ultrasonic depth sensors were installed in stations.

A sample of continuous snow depth observation values (SNOTEL) recorded by ultrasonic depth sensors operated by TSMS and State Hydraulic Works are used for satellite data validation and provided in Figure 2.18. As can be seen in Figure 2.18, stations at lower elevations are affected less and for a limited time period by snowfall. Furthermore, a new snowfall is observed in the month of April, but snow cover duration is short since melting occurs quickly.

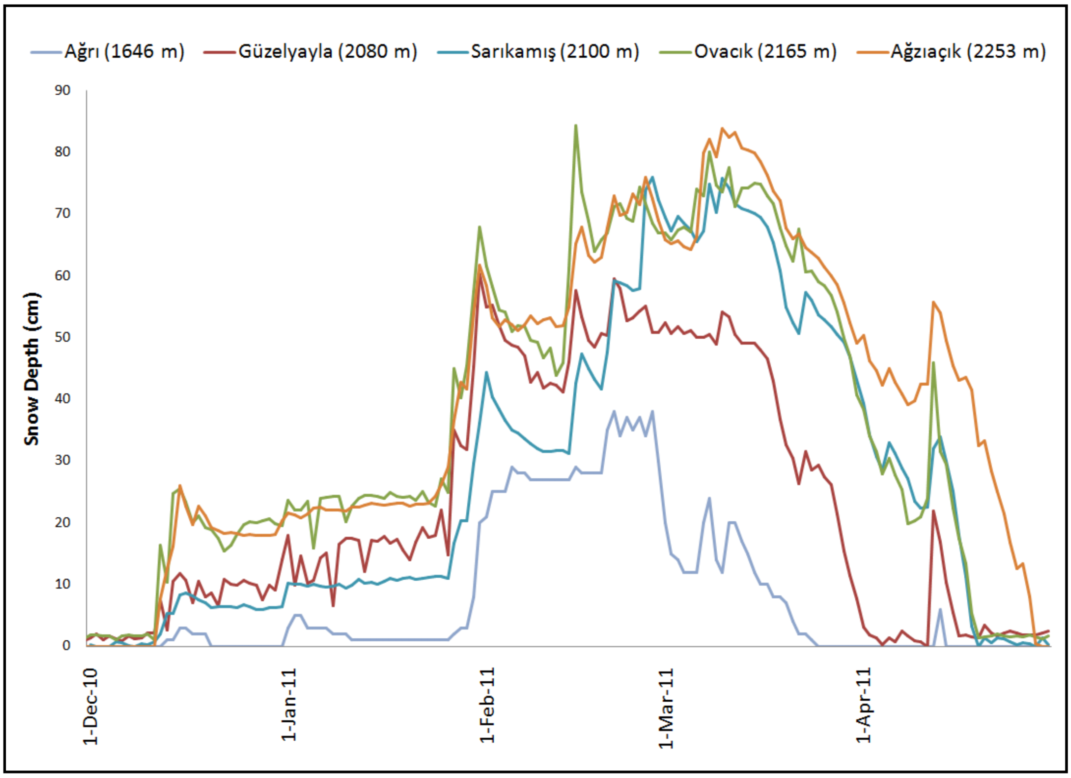

Figure 2.18. Snow depth from SNOTEL stations in 2011 water year

3. SATELLITE PRODUCTS and VALIDATION

3.1. Remote Sensing History in Snow Studies

Snowmelt is an important component of the hydrologic balance in many regions, especially mountainous areas. However, snow cover monitoring are particularly difficult in such areas because of the large spatial variability of snow characteristics and, often, limited availability of ground-based data. Satellite imagery is an attractive alternative compared to ground-based data, as the resolution and availability do not depend much on the terrain characteristics (Parajka and Blöschl, 2012).

Observation of temporal changes in the snow covered area is difficult with the ground observation stations since these stations record at a point and can only represent nearby area. Furthermore, satellite data are preferred to follow the time-dependent spatial change for snow hydrology and daily weather forecasting since snow has a very bright reflectance.

Accurate monitoring of global snow/ice cover is a key component in the study of climate and global change as well as daily weather forecasting. The Satellite Analysis Branch of National Environmental Satellite, Data and Information Service (NESDIS) first began generating Northern Hemisphere Weekly Snow and Ice Cover analysis charts from visible satellite imagery in November, 1966 (www.natice.noaa.gov).

In the 1970's, application of Earth Observation (EO) data in snow hydrology began. Rango et al. (1977) estimated the seasonal runoff contributed due to snowmelt in the Himalayan region by using EO data. Snow covered are in alpine catchments are mapped from satellite images with different sensors. Studies of mapping of snow and ice covered area by using EO data were summarized by Hall and Martinec (1975).

Martinec and Rango (1987) published a study about interpretation and utilization of areal snow cover area from satellites and usage of them in hydrological modeling. Many scientists such as Hu et al. (1993), Seidel et al

(1994), Baumgartner and Rango (1995), Rango (1996), Nagler and Rott (1997) did scientific studies about monitoring of snow covered area. However, results of method and application reached the large masses have started with HydAlp (Rott et al., 2000) and SnowTools (Guneriussen et al., 2000) projects in Europe.

One of the most important projects about satellite snow products in recent years is H-SAF and was established in 2005. The Development Phase covered 5 years, until September 2010, and was followed by a First Continuous Development and Operation Phase lasting 18 months, during which operations and dissemination of several products started. Second Continuous Development and Operation Phase will last until February 2017. Objectives of project are to provide new satellite-derived products from existing and future satellites with sufficient time and space resolution to satisfy the need of operational hydrology and to perform independent validation of the usefulness of the new products for fighting against flood, landslides, avalanches and evaluating water resources (www.hsaf.meteoam.it).

GlobSnow Projects coordinated by the Finnish Meteorological Institute (FMI) are one of the recent projects about snow studies. The European Space Agency (ESA) funded GlobSnow-1 project and it was active from 2008 to 2012. GlobSnow-1 resulted in two long-term datasets at the hemispherical scale. Information on two essential snow parameters: snow water equivalent (SWE) and areal snow extent (SE), were provided for a period of 33 years (1979-2012) and 17 years (1995-2012), respectively. GlobSnow-2 (2012-2014) was a direct continuation of the GlobSnow-1 project, which involved acquisition of the long-term satellite data records, development and adaptation of suitable algorithms, and the implementation of software for producing snow cover information at a global scale spanning decades (www.globsnow.info).

The other important project in recent years is SnowPex Project. It started in 2014 and continues. Project is an international collaborative effort, funded by the ESA, aiming to intercompare and evaluate satellite-based seasonal snow cover products of hemispheric to global extent in order to assess their accuracy, resolve possible discrepancies and elaborate guidelines for further improvement (snowpex.enveo.at).

In 21th century, remote sensing of snow covered area improved depending on developments in technology and satellite snow products in higher resolutions are available for hydrological modeling. Temporal resolution of these products is generally daily, however spatial resolution takes an important part. Thus, studies about different satellite monitoring in hydrological modeling and forecasting increases in number. Regional snow cover patterns are complementary to catchment runoff forecasting in connection with the structure and state of hydrologic processes in various watershed models (Grayson et al. 2002) and provide a very important source of information in recent regional climate and global change assessment studies (Pu et al. 2007).

Although satellite products obtained using remote sensing are practical and present larger areas in good spatial and temporal resolution, they should be validated because product accuracy is very important as in accessibility. The quality of satellite products are assessed against ground observation data in meteorological stations (Parajka and Blösch, 2006; Şorman et al., 2009; Yamankurt, E., 2010; Gao et al., 2012; Chen et al. 2012; Hancock et al., 2013; Byun and Choi, 2014; Berezowski et al., 2015). In this study, three different satellite snow products, namely MODIS (Moderate Resolution Imaging Spectroradiometer), MSG-SEVIRI (Meteosat Second Generation-Spinning Enhanced Visible and Infrared Imager) and IMS (Interactive Multisensor Snow and Ice Mapping System) are validated against ground observation data. These satellite products have different spectral, spatial and temporal properties where each of them is discussed in detail in the following parts. While IMS products have the longest history of monitoring snow and ice coverage, MSG-SEVIRI images provide the highest temporal frequency mainly because they are used for meteorological purposes. On the other hand, MODIS satellite images offer the best spatial resolution. MODIS and MSG-SEVIRI products are affected by cloudiness since they are optical satellites, but IMS provides clear-sky images because it is a blended product.

3.2. Remote Sensing of Snow Covered Area

3.2.1. MODIS Satellite Product

MODIS is an imaging spectroradiometer that employs a cross-track scan mirror collecting optics, and a set of individual detector elements to provide imagery of the Earth's surface and clouds in 36 discrete, narrow spectral bands from approximately 0.4 to 14.4μm (Barnes et al., 1998).

It is onboard two satellites, Terra and Aqua. Terra was first launched on 18 December 1999 and has started the observation on 24 February 2000. A second MODIS was deployed on the Aqua satellite on 4 May 2002 and has started the observation on 24 July 2002.

The MODIS instruments on Terra and Aqua image the same area on Earth at approximately 10:30 a.m. and 1:30 p.m. (local time), respectively. Together, the two overpass times (Terra in the morning and Aqua in the afternoon) allow the possibility of diurnal observations of snow, and the possibility to obtain more clear views of the surface, as clouds change in position and extent within a period of 3 hours (Hall and Riggs, 2007).

Snow data products are produced as a series of seven products. The sequence begins as a swath (scene) at a nominal pixel spatial resolution of 500 m with nominal swath coverage of 2330 km (across track) by 2030 km (along track, five minutes of MODIS scans). A summarized listing of the sequence of products is given in Table 3.1 (Riggs et al., 2006).

The mapping approach exploits the high reflectance in the visible and the low reflectance in the shortwave infrared part of the spectrum by the normalized difference snow index (NDSI) (Hall et al. 1995). The NDSI allows us to distinguish snow from many other surface features such as clouds that have high reflectance in both the visible and the shortwave infrared parts of the spectrum (Hall et al. 1998). The NDSI can usually separate cumulus clouds from snow, but it cannot always separate optically thin cirrus clouds (Hall and Riggs 2007). The NDSI calculation is based on MODIS bands 4 (0.55 μm) and 6 (1.6 μm).

However, Band 7 (2.1 μm) is used instead to calculate NDSI (Equation 3.1) for Aqua because of that Band 6 failed on Aqua platform after launch.

$$\mathrm{NDSI} = \frac{\mathrm{Band\ 4} - \mathrm{Band\ 6}}{\mathrm{Band\ 4} + \mathrm{Band\ 6}} \qquad \text{(Equation 3.1)}$$

Table 3.1. Summary of the MODIS snow data products (Hall and Riggs, 2007)

Earth Science Data Type	Nominal Data Array Dimensions	Spatial Resolution	Temporal Resolution	Map Projection
MOD10_L2 MYD10_L2	1354 km by 2000 km	500 m	Swath (scene)	None. (lat, long referenced)
MOD10_L2G MYD10_L2G	1200 km by 1200 km	500 m	Day of multiple coincident swaths	Sinusoidal
MOD10A1 MYD10A1	1200 km by 1200 km	500 m	Day	Sinusoidal
MOD10A2 MYD10A2	1200 km by 1200 km	500 m	Eight days	Sinusoidal
MOD10C1 MYD10C1	360^o by 180^o (global)	0.05^o	Day	Geographic
MOD10C2 MYD10C2	360^o by 180^o (global)	0.05^o	Eight days	Geographic
MOD10CM MYD10CM	360^o by 180^o (global)	0.05^o	Month	Geographic

***MOD**: EOS Terra Satellite, **MYD**: EOS Aqua Satellite

In this study, MODIS daily snow product with 500 m spatial resolution is obtained for the years 2008-2011. MODIS data are ordered free of charge through the Earth Observing System Data and Information System (EOSDIS) located at the NASA (reverb.echo.nasa.gov). MODIS imagery in Hierarchical Data Format (HDF-EOS) are merged into one (mosaic), transformed to a new geographical projection (UTM, WGS84) and adjusted for the area of interest in a different file format (Tagged Image File Format, TIFF) by MODIS Reprojection Tool 4.0 (MRT-4.0) (https://lpdaac.usgs.gov/tools/modis_reprojection_tool). There are ten classifications in MODIS snow algorithm but these classifications are reduced to three classifications (snow, cloud and land) in this study for simplifying the result presentation.

Even though snow has high reflectance in the visible and the shortwave infrared parts of the spectrum, clouds hinder data processing. Therefore, different filtering techniques are applied to MODIS data (Figure 3.1).

MODIS satellite data are acquired twice a day, MODIS/Terra in the morning and MODIS/Aqua approximately 3 hours later in the afternoon. The first step of filtering is to combine Terra and Aqua images (MODIS CM) (Figure 3.2). This allows a more clear view of the surface, as clouds change position and extent within a period of 3 hours. Then, temporal filter is applied to the combined imagery by going back in time of 3 (MODIS CM-3), 5 (MODIS CM-5) and 7 (MODIS CM-7) days respectively. A cloud covered grid cell is replaced with either snow or land if it is cleared during these time periods. In elevation filter (MODIS CM-7E), it is assumed that cloudy cells are snow above the snow elevation line and, on the contrary, cells are land below the land elevation line. These elevations vary during the season and defined by user. The range between snow and land line is called as the transition zone where cloudy cells may remain. Spatial filter (MODIS CM-7ES) changes the value of a cloud cell based on the situation of peripheral cells. Finally, the seasonal filter (MODIS CM-7ESA) clears all the remaining cloud obscureness assuming the cloudy cells are snow in a snow season and land during the off-season.

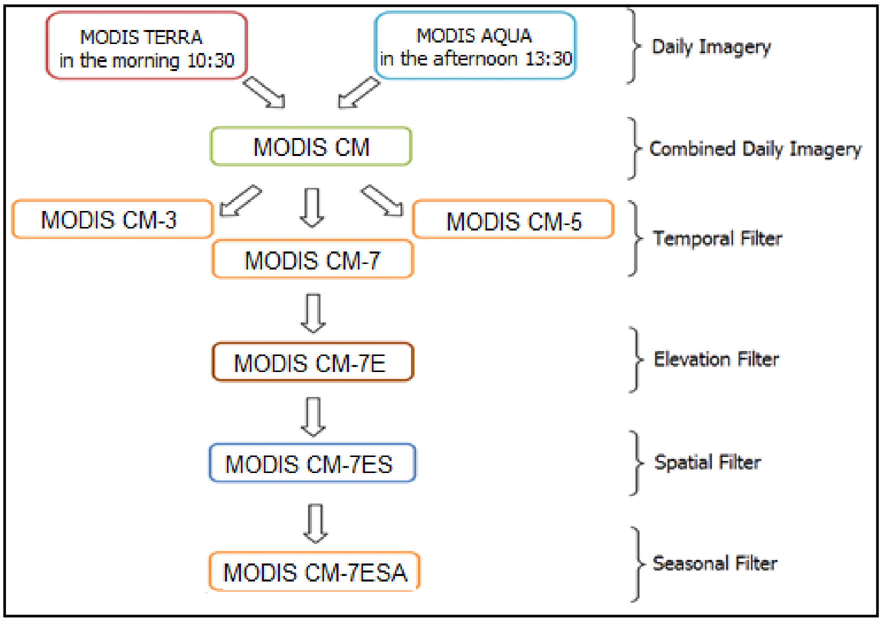

Figure 3.1. Flowchart of filtering daily MODIS data (Yamankurt, 2010)

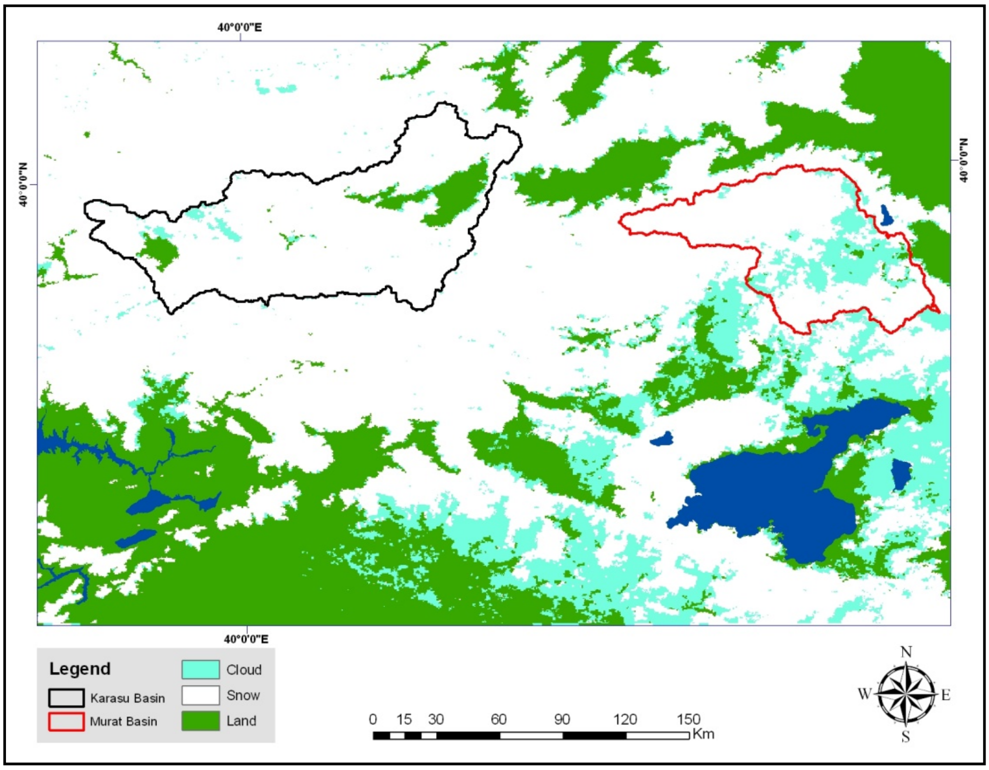

Figure 3.2. MODIS CM imagery for 25 February 2009

3.2.2. MSG-SEVIRI Satellite Product

The main Meteosat Second Generation (MSG) instrument is called the Spinning Enhanced Visible and Infrared Imager (SEVIRI). It, also named Meteosat-9 or MSG-2 and was launched on 21 December 2005. It builds up images of the Earth's surface and atmosphere in 12 different wavelengths once every 15 minutes, compared to three wavelengths once every 30 minutes for the comparable instrument on earlier Meteosat satellites. The imaging spatial resolution is 3 km at nadir and degrades to 5 km over Europe. MSG-SEVIRI data are produced between 08:00 and 15:45 GMT, making 32 individual images per day. If at least there ones of 32 images are snow, the cell is produced as snow.

MSG-SEVIRI is a geostationary satellite scanning the whole hemisphere, requires the inclusion of visible, near-infrared and thermal parts of the spectrum, at the same time as the essential spectral content for adequate snow-cover extent monitoring. The high temporal resolution and wide aerial coverage of SEVIRI imagery make it a good choice for observing rapidly changing phenomena, such as for fog monitoring, tracking cloud movements or snow-cover mapping (Bertrand et al. 2008, Cermak and Bendix 2008, Sürer and Akyürek 2012).

The Turkish State Meteorological Service (TSMS) has been receiving MSG-2 data for more than eight years in high rate image transmission (HRIT) data format. The HRIT data are converted to hierarchical data format and used in the product generation chain at the TSMS. Of the 12 spectral channels, four have been used mainly in the snow recognition algorithm development. The central wavelengths and channel numbers of these bands are given in Table 3.2.

Table 3.2. SEVIRI channels used in the snow recognition algorithm (Sürer and Akyürek, 2012)

Channel No.	Central Wavelength (µm)	Description
1	0.635	Visible (VIS0.6)
3	1.640	Near infrared (NIR1.6)
4	3.900	Shortwave infrared (IR3.9)
9	10.800	Infrared (IR10.8)

The data are produced between longitude 25^{o} W – 45^{o} E and latitude 25^{o} – 75^{o} N (Figure 3.3). Mountainous areas and flat/forest areas show different phsyical properties; thus the use of a mountain mask is required. In order to generate this mountain mask, a 1-km spatial resolution GTOPO (digital elevation map, DEM) developed by United States Geological Survey (USGS) is used. The definition of a mountainous area is based on the mean altitude and standard deviation of the slope within 5km×5km pixels (Lahtinen et al., 2009). The algorithm for mountain mask generation is as follows;

- $\mu \geq 1000$ m
- $\mu \geq 700$ m and $\sigma \geq 2$ degree
- $\mu \geq 500$ m and $\tau \geq 800$ m

where μ is mean elevation, σ is standard deviation of slope and τ is range between minimum and maximum elevations, which is the difference between maximum and minimum elevation in the mesh.

In this study, similar to the application on MODIS product, different filtering techniques are applied to every daily SEVIRI product in order to remove cloud cover. Applied filters are temporal, spatial and seasonal filters, respectively. Temporal filter is applied to the combined imagery by going back in time of 3 (SEVIRI -3), 5 (SEVIRI -5) and 7 (SEVIRI -7) days as in filtering process of MODIS, respectively. Elevation filter is not applied since product is composed of irregular cells. Spatial filter (SEVIRI -7S) changes the value of a cloud cell based on the situation of peripheral cells. Finally, the seasonal filter (SEVIRI -7SA) clears all the remaining cloud obscureness assuming the cloudy cells are snow in a snow season and land during the off-season (Figure 3.4).

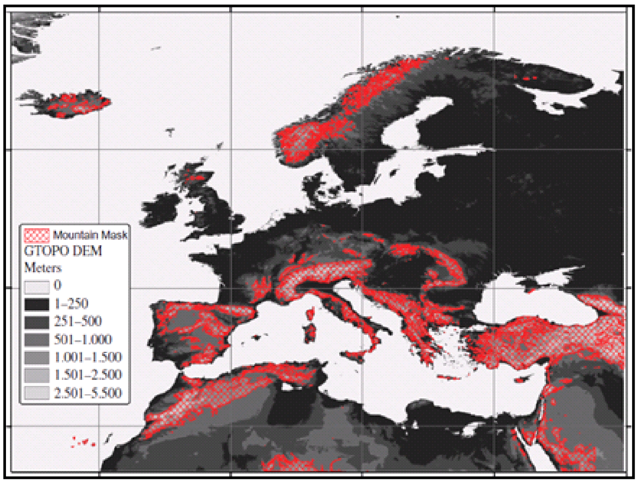

Figure 3.3. SEVIRI domain shown with mountain mask (Sürer and Akyürek, 2012)

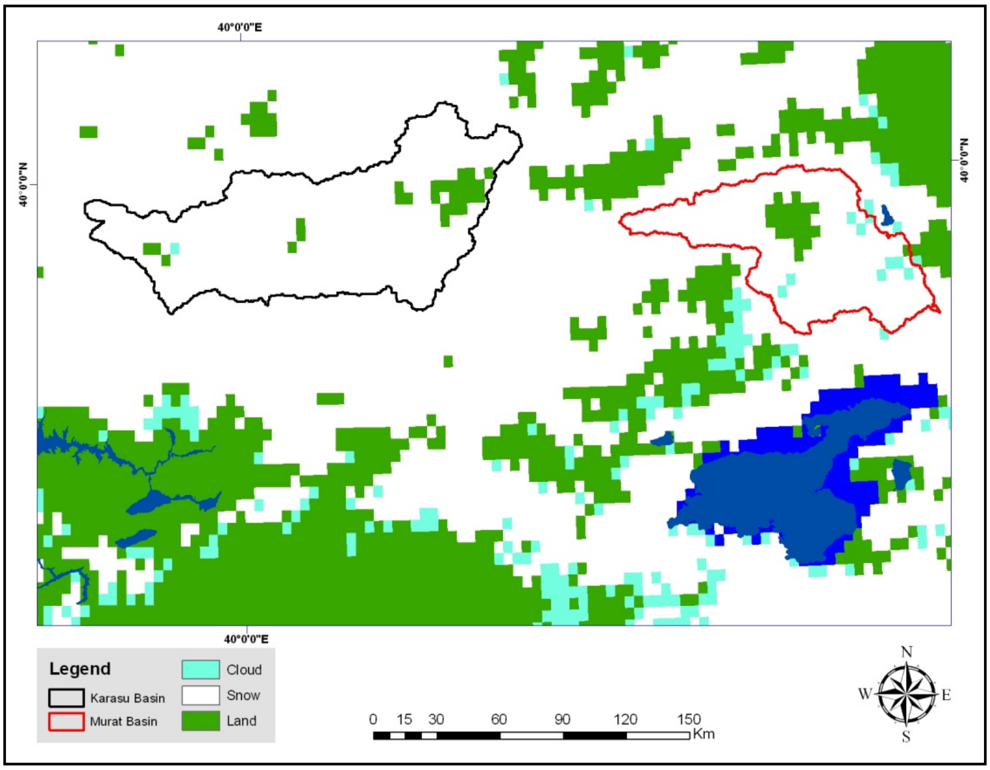

Figure 3.4. MSG-SEVIRI imagery for 25 February 2009

3.2.3. IMS Satellite Product

The National Oceanic and Atmospheric Administration / National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) has the longest record history of monitoring snow and ice coverage with the Interactive Multisensor Snow and Ice Mapping System (IMS) since 1966.

The IMS was designed to allow meteorologists to chart snow cover interactively on a daily basis using a variety of data sources within a common geographic system (Helfrich, 2007). The original input satellite data sources were outlined as NOAA polar orbiters (POES), NOAA geostationary (GOES) data, Japanese Geostationary Meteorological Satellites (GMS), European Geostationary Meteorological Satellites (METEOSAT), Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), Advanced Microwave Sounding Unit (AMSU), US Department of Defense (DOD) polar orbiters, and Defense Meteorological Satellite Program (DMSP). Indirect satellite sources also include a weekly National Ice Center (NIC) chart and the US Air Force (USAF) daily snow depth and ice cover product and various radars, models, surface observations, webcams and charts (Ramsay, 1998). The IMS product is provided in clear-sky imagery as a result of usage of different satellites and instruments.

The Polar and Geostationary Operational Environmental Satellite programs (POES/GOES) operated by NESDIS provide invaluable visible and infrared spectral data in support of these efforts. Clear-sky imagery from both the POES and the GOES sensors show snow/ice boundaries very well; however, the visible and infrared techniques may suffer from persistent cloud cover near the snowline, making observations difficult (Ramsay, 1995). The microwave products (DMSP and the AMSR-E, Advanced Microwave Scanning Radiometer-Earth Observing System) are unobstructed by clouds and thus can be used to produce clear-sky imagery. In operational use, clear-sky imagery without cloud facilitates snow studies.

There are three versions of IMS product. Initial release of data set at is named as Version 1.1 and this version provided the product in 24 km spatial resolution weekly from 04 February 1997 to 22 February 2004. Second release (Version 1.2) provided from 23 February 2004 to 02 December 2014 has 4 km spatial resolution and daily in temporal. The last and newest release is Version 1.3 and provided since 03 December 2014 in 1 km spatial resolution and daily. Different sensors and instruments are used as input to obtain IMS product in clear-sky. Thus, used sensors and instruments may be different in each version (Table 3.3).

Northern Hemisphere Weekly Snow and Ice Cover analysis charts derived from the visible imagery first was generated by the Satellite Analysis Branch (SAB) in November, 1966. The spatial and temporal resolutions of the analysis are 190 km and 7 days, respectively. However, errors caused by resolutions in the National Meteorological Center's Numerical Weather Prediction models (Mitchell, 1993), customer needs and expectations at a higher resolution caused to derive a new surface imagery product which has spatial resolution in 24 km on per day. This chart has been produced since February, 1997 by SAB meteorologists.

One of the important changes happened in February, 2004 and spatial resolution was improved to 4 km. Since this time, both products (4 km and 24 km in spatial resolution) are available from National Snow and Ice Data Center (NSIDC) to provide continuance of current studies started before. Besides these improvements, a new development occurred in 2014 year and a satellite product in 1 km spatial resolution is available from December, 2014.

In this study, IMS daily snow product (Version 1.2) with 4 km spatial resolution is obtained for the years 2008-2011. IMS data are ordered free of charge through the NSIDC located at NOAA. IMS imageries are available in TIFF and American Standard Code for Information Interchange (ASCII) formats. TIFF format is used for providing convenience on GIS platform. Furthermore, the product has their projection information within the GeoTIFF file itself instead of in an extra file as a result of improvement in Version 1.3. In this study, product data are clipped in smaller frame including study area because original product has all Northern hemisphere and it is difficult to process. However, there is no need to apply any filtering techniques to output data of IMS since it is obtained as clear-sky imagery as a result of product algorithm (Figure 3.5).

Table 3.3. Sensors/Instruments used as input in IMS (nsdic.org/data/docs/noaa)

Sensor or Source	Platform or Organization	Version of Data this Applies to
ACNFS sea ice area fraction and sea ice thickness	NIC	1.3
AMSR-2	GCOM-W	1.3
AMSU	NOAA POES Satellites (15 - 18), Aqua, EUMETSAT MetOp-A	1.1, 1.2, 1.3
ASCAT	EUMETSAT MetOp-A	1.3
ATMS (MIRS based)	S-NPP	1.3
Automated snow detection layers	NESDIS and NCEP	1.1, 1.2, 1.3
AVHRR	NOAA POES Satellites (14 - 19), EUMETSAT MetOp-A	1.1, 1.2, 1.3
Canadian snow analysis	Environment Canada	1.3
GFS daily snow depth	NCEP	1.3
GMS Imager	JMA GMS-5 (Himawari 5)	1.1, 1.2
GOES Imager	NOAA GOES Satellites (9, 10, 11, 13)	1.1, 1.2, 1.3
Hourly surface weather reports	METAR	1.3
MODIS	Aqua and Terra	1.2, 1.3
MTSAT-1R Imager	JMA MTSAT-1R (Himawari 6)	1.2
MTSAT-2 Imager	JMA MTSAT-2 (Himawari 7)	1.3
MVIRI	MFG	1.1, 1.2
Radar	Various radar published from Europe, Japan, China, South Korea, Canada, or U.S.	1.3
SAR	Radarsat-2	1.3
SAR (C-band)	Sentinel-1A	1.3
SEVIRI	MSG	1.3
SNODAS	NOHRSC	1.1, 1.2, 1.3
SSM/I	DMSP Satellites	1.1, 1.2, 1.3
SSMIS	DMSP Satellites	1.2, 1.3
U.S. Air Force Snow and Ice Analysis Product	USAF	1.1, 1.2, 1.3
Various weather reports, ice charts, and snow depth reports	In situ data from U.S. and other foreign countries	1.3
VIIRS Binary Snow Cover EDR	NASA Goddard	1.3
VIIRS Sea Ice Characterization EDR	NASA Goddard	1.3
VIIRS (visible channels 1,2,3, IR channel 15, day/night bands)	S-NPP Satellites	1.3
Weekly sea ice analysis and ice edge	NIC	1.1, 1.2, 1.3

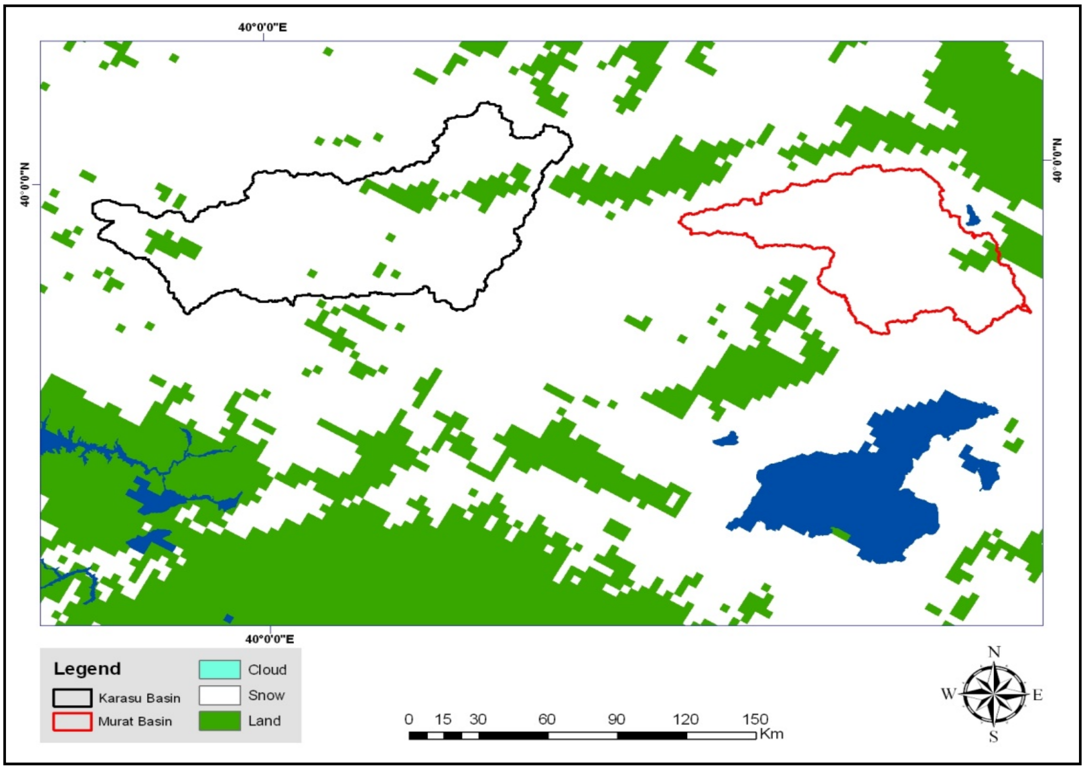

Figure 3.5. IMS imagery for 25 February 2009

3.3. Validation and Comparative Analysis of Satellite Products

Usage of satellite products is increasing in water resources management; however, testing of algorithm accuracy is still limited, especially in mountainous areas. With this motivation, in this study, three different satellite products are validated against ground observation stations in the eastern part of Turkey for 2011 water year. The reason for choosing 2011 water year arises from the highest data availability of ground stations in the region. There are 50 observation stations, elevations ranging from 751-2937 m, measuring at least daily snow depth. Out of these, 23 of them are SNOTEL stations and the other 27 are CLM_SYP stations (Figure 2.7). Hence, there is approximately a balanced distribution between the two station categories showing variation in elevation and land-use characteristics.

In 2011 water year, a total of 18152 point data are collected from 50 observation stations, 98 point data are considered missing data mainly due to station failure. 76.60% of these are land ($snow_{depth}$ = 0 cm), 1.93% is fractional snow ($snow_{depth}$ = 1-3 cm), 21.47% is snow ($snow_{depth} \geq$ 4 cm) and these ratios are given in the first column (Total) in validation tables.

MODIS and MSG-SEVIRI cannot serve clear-sky images as IMS product since they are optic satellites. Thus, different filtering techniques are applied to MODIS and MSG-SEVIRI satellite products and each filtering step is validated separately (Table 3.4 and 3.5). Validation results of IMS are shown in Table 3.6.

MODIS/Terra and MODIS/Aqua have similar results; land accuracy is 63.62% and 57.63%, respectively (Table 3.4). The land accuracy is the ratio of number of land data in satellite product (e.g. 8847 for MODIS/Terra) to that of ground observation (13905). In the calculation of this ratio, there is cloud effect (36.30% for MODIS/Terra), but when disregarding the cloud, land accuracy is computed as 99.88% (8847/8858). Land accuracy increases after CM filter application since some of cloudy cells are removed. On the other hand, the most efficient filter is the first step of temporal filtration. After CM-3 filter, the accuracy ratio is increased to 93.43% and, after all clouds are removed, land accuracy becomes 98.82% in final product.

Similar to land accuracy, same computing method is applied for snow accuracy. The snow accuracy is the ratio of number of snow data in satellite product (e.g. 1121 for MODIS/Terra) to that of ground observation (3897). Snow accuracy ratios in MODIS/Terra and MODIS/Aqua are quite low. However, cloud ratios of land and snow in Terra are lower than that of Aqua due to difference in overpass times of platforms. The most efficient filter is temporal filter since majority of clouds are removed here. After removing all cloud, snow accuracy increases to 93.56% (Table 3.4 and Figure 3.8).

Fractional snow means that snow depth is below 4 cm. This class is considered to prevent uncertainties in transition zones and disregard patchy snow nearby observation station. Depending on removal of cloud, land and snow accuracies increase and in the final product, land and snow accuracies in fractional snow are 61.43% and 38.57%, respectively.

Daily product of MSG-SEVIRI is combined data of 32 images obtained once every 15 minutes in a day. The land accuracy is 37.35% and this ratio is below MODIS CM product (Table 3.5). The reasons of that are spatial resolution and cloud ratio due to product algorithm. In final product, all cloud cannot be removed because of missing data in summer season. Thus, filtering algorithm accepts the missing data as cloudy data. Some data are available in summer season. However, continuity of the products is important becasue temporal filtering needs consecutive day data. If all of the missing data is regarded as land, land accuracy in final production is 97.08%.

Snow accuracy of daily MSG-SEVIRI is 50.04% and this ratio is higher than MODIS CM product since the cloud ratio in snowy days of MSG-SEVIRI is lower than MODIS CM. In final product, the snow accuracy after cloud removed is 91.12% (Table 3.5 and Figure 3.8). The reason of 0.03% cloud in final product, results from a missing satellite image on 11 October 2010 when there is snow on ground but filtering algorithm keeps it as cloud.

Fractional snow accuracy is in half shares for land and snow. Moreover, there is no cloud or missing data in this condition period.

IMS product does not need cloud filtering because of being a blended product of various satellites. The core product (final product at the same time) of IMS has 97.64% land accuracy and 95.53% snow accuracy (Table 3.5 and Figure 3.8). Also, fractional snow accuracy is 60%.

If accuracies in final products are compared, IMS product has the highest snow and fractional snow accuracy against ground observation data (Figure 3.8). However, the highest land accuracy ratio is of MODIS. The ground observation stations are classified as CLM_SYP and SNOTEL concerning the effects such as elevation, land-use and micro-climate. The stations in both classes are validated against ground observation data, separately and accuracy tables are given below (Table 3.7 and 3.8). In addition to these tables, snow cloud ratio and snow accuracy after cloud removed graphics are plotted in each filtering for CLM_SYP, SNOTEL and all stations (Figure 3.6, 3.7 and 3.8).

Table 3.4. Validation results of MODIS product against ground observation data in 2011

Ground Observations	Total	MODIS/Terra			Accuracy After Cloud Removed	MODIS/Aqua			Accuracy After Cloud Removed	MODIS CM			Accuracy After Cloud Removed
	18152	Land	Snow	Cloud		Land	Snow	Cloud		Land	Snow	Cloud	
Land (D_S = 0)	13905	8847	11	5047	99.88%	8013	21	5871	99.74%	9852	27	4026	99.73%
	76.60%	63.62%	0.08%	36.30%		57.63%	0.15%	42.22%		70.85%	0.19%	28.95%	
Fractional Snow (D_S = 1-3 cm)	350	20	16	314	44.44%	24	14	312	36.84%	32	22	296	40.74%
	1.93%	5.71%	4.57%	89.71%		6.86%	4.00%	89.14%		9.14%	6.29%	84.57%	
Snow (D_S >= 4 cm)	3897	18	1121	2758	98.42%	17	965	2915	98.27%	25	1420	2452	98.27%
	21.47%	0.46%	28.77%	70.77%		0.44%	24.76%	74.80%		0.64%	36.44%	62.92%	

Ground Observations	Total	MODIS CM-3			Accuracy After Cloud Removed	MODIS CM-5			Accuracy After Cloud Removed	MODIS CM-7			Accuracy After Cloud Removed
	18152	Land	Snow	Cloud		Land	Snow	Cloud		Land	Snow	Cloud	
Land (D_S = 0)	13905	12992	70	843	99.46%	13457	98	350	99.28%	13615	121	169	99.12%
	76.60%	93.43%	0.50%	6.06%		96.78%	0.70%	2.52%		97.91%	0.87%	1.22%	
Fractional Snow (D_S = 1-3 cm)	350	126	62	162	32.98%	171	86	93	33.46%	191	102	57	34.81%
	1.93%	36.00%	17.71%	46.29%		48.86%	24.57%	26.57%		54.57%	29.14%	16.29%	
Snow (D_S >= 4 cm)	3897	92	2761	1044	96.78%	166	3177	554	95.03%	221	3387	289	93.87%
	21.47%	2.36%	70.85%	26.79%		4.26%	81.52%	14.22%		5.67%	86.91%	7.42%	

Ground Observations	Total	MODIS CM-7E			Accuracy After Cloud Removed	MODIS CM-7ES			Accuracy After Cloud Removed	MODIS CM-7ESA			Accuracy After Cloud Removed
	18152	Land	Snow	Cloud		Land	Snow	Cloud		Land	Snow	Cloud	
Land (D_S = 0)	13905	13675	121	109	99.12%	13740	142	23	98.98%	13741	164	0	98.82%
	76.60%	98.35%	0.87%	0.78%		98.81%	1.02%	0.17%		98.82%	1.18%	0.00%	
Fractional Snow (D_S = 1-3 cm)	350	196	103	51	34.45%	215	124	11	36.58%	215	135	0	38.57%
	1.93%	56.00%	29.43%	14.57%		61.43%	35.43%	3.14%		61.43%	38.57%	0.00%	
Snow (D_S >= 4 cm)	3897	235	3500	162	93.71%	247	3583	67	93.55%	251	3646	0	93.56%
	21.47%	6.03%	89.81%	4.16%		6.34%	91.94%	1.72%		6.44%	93.56%	0.00%	

* **D_S** means snow depth

Table 3.5. Validation results of MSG-SEVIRI product against ground observation data in 2011

Ground Observations	Total	SEVIRI			Accuracy After	SEVIRI -3			Accuracy After	SEVIRI -5			Accuracy After
	18152	Land	Snow	Cloud	Cloud Removed	Land	Snow	Cloud	Cloud Removed	Land	Snow	Cloud	Cloud Removed
Land (D_S = 0)	13905	5194	182	8529	96.61%	6895	337	6673	95.34%	7102	374	6429	95.00%
	76.60%	37.35%	1.31%	61.34%		49.59%	2.42%	47.99%		51.08%	2.69%	46.24%	
Fractional Snow (D_S = 1-3 cm)	350	61	95	194	60.90%	140	156	54	52.70%	161	169	20	51.21%
	1.93%	17.43%	27.14%	55.43%		40.00%	44.57%	15.43%		46.00%	48.29%	5.71%	
Snow (D_S >= 4 cm)	3897	119	1950	1828	94.25%	258	3181	458	92.50%	306	3407	184	91.76%
	21.47%	3.05%	50.04%	46.91%		6.62%	81.63%	11.75%		7.85%	87.43%	4.72%	

Ground Observations	Total	SEVIRI -7			Accuracy After	SEVIRI -7S			Accuracy After	SEVIRI -7SA			Accuracy After
	18152	Land	Snow	Cloud	Cloud Removed	Land	Snow	Cloud	Cloud Removed	Land	Snow	Cloud	Cloud Removed
Land (D_S = 0)	13905	7120	389	6396	94.82%	7168	396	6341	94.76%	7190	406	6309	94.66%
	76.60%	51.20%	2.80%	46.00%		51.55%	2.85%	45.60%		51.71%	2.92%	45.37%	
Fractional Snow (D_S = 1-3 cm)	350	173	174	3	50.14%	174	174	2	50.00%	175	175	0	50.00%
	1.93%	49.43%	49.71%	0.86%		49.71%	49.71%	0.57%		50.00%	50.00%	0.00%	
Snow (D_S >= 4 cm)	3897	337	3498	62	91.21%	343	3509	45	91.10%	346	3550	1	91.12%
	21.47%	8.65%	89.76%	1.59%		8.80%	90.04%	1.15%		8.88%	91.10%	0.03%	

Table 3.6. Validation results of IMS product against ground observation data in 2011

Ground Observations	Total	IMS		Accuracy
	18152	Land	Snow	
Land (D_S = 0)	13905	13577	328	97.64%
	76.60%	97.64%	2.36%	
Fractional Snow (D_S = 1-3 cm)	350	140	210	60.00%
	1.93%	40.00%	60.00%	
Snow (D_S >= 4 cm)	3897	182	3715	95.33%
	21.47%	4.67%	95.33%	

If accuracies of CLM_SYP and SNOTEL stations are compared for all satellite products, it is clear to see that SNOTEL has higher ratio than CLM_SYP. Various reasons such as elevation and land-use can cause this difference (Table 3.7 and 3.8).

SNOTEL stations are generally located above 1500 m and majority of them are on 2000-2500 m range (Figure 2.9). However, CLM_SYP stations except for Sarıkamış are located below 1800 m (Figure 2.8). The bigger part of CLM_SYP stations is in range of 1000-1500 m and this range is mainly in transition zone. Therefore, snow is not stable for long term and cloud ratio is higher here and snow accuracy is lower here due to these reasons.

The other important reason is land-use since CLM_SYP stations are generally located on urban area. Thus, microclimate effect occurs on CLM_SYP stations. Contrary to that, there is no any SNOTEL station on urban area. They are distributed on pasture, agriculture and bare areas. Microclimate effect became important during the validation of satellite snow products.

In both classes, combined filter removes approximately 10% of clouds in MODIS. As can be seen from Figure 3.6, 3.7 and 3.8, temporal filter is the most efficient filter to remove clouds. However, this filter causes a lower decrease in the accuracy (~ from 98 to 96) for nival areas (on SNOTEL stations), but a more significant drop (~ from 96 to 86) on the transition zone (CLM_SYP stations).

Table 3.7. Validation results of CLM_SYP stations in 2011

CLM-SYP

	Ground Observations	Total	MODIS CM-7ESA			Accuracy After Cloud Removed
MODIS		9855	Land	Snow	Cloud	
	Land (D_s = 0)	8682	8609	73	0	99.16%
		88.10%	99.16%	0.84%	0.00%	
	Fractional Snow (D_s = 1-3 cm)	274	177	97	0	35.40%
		2.78%	64.60%	35.40%	0.00%	
	Snow (D_s >= 4 cm)	899	136	763	0	84.87%
		9.12%	15.13%	84.87%	0.00%	

	Ground Observations	Total	SEVIRI -7SA			Accuracy After Cloud Removed
SEVIRI		9855	Land	Snow	Cloud	
	Land (D_s = 0)	8682	5008	242	3432	95.39%
		88.10%	57.68%	2.79%	39.53%	
	Fractional Snow (D_s = 1-3 cm)	274	132	142	0	51.82%
		2.78%	48.18%	51.82%	0.00%	
	Snow (D_s >= 4 cm)	899	90	809	0	89.99%
		9.12%	10.01%	89.99%	0.00%	

	Ground Observations	Total	IMS		Accuracy
IMS		9855	Land	Snow	
	Land (D_s = 0)	8682	8455	227	97.39%
		88.10%	97.39%	2.61%	
	Fractional Snow (D_s = 1-3 cm)	274	111	163	59.49%
		2.78%	40.51%	59.49%	
	Snow (D_s >= 4 cm)	899	90	809	89.99%
		9.12%	10.01%	89.99%	

Table 3.8. Validation results of SNOTEL stations in 2011

SNOTEL

	Ground Observations	Total	MODIS CM-7ESA			Accuracy After Cloud Removed
MODIS		8297	Land	Snow	Cloud	
	Land (D_s = 0)	5223	5132	91	0	98.26%
		62.95%	98.26%	1.74%	0.00%	
	Fractional Snow (D_s = 1-3 cm)	76	38	38	0	50.00%
		0.92%	50.00%	50.00%	0.00%	
	Snow (D_s >= 4 cm)	2998	115	2883	0	96.16%
		36.13%	3.84%	96.16%	0.00%	

	Ground Observations	Total	SEVIRI -7SA			Accuracy After Cloud Removed
SEVIRI		8297	Land	Snow	Cloud	
	Land (D_s = 0)	5223	2182	164	2877	93.01%
		62.95%	41.78%	3.14%	55.08%	
	Fractional Snow (D_s = 1-3 cm)	76	43	33	0	43.42%
		0.92%	56.58%	43.42%	0.00%	
	Snow (D_s >= 4 cm)	2998	256	2741	1	91.46%
		36.13%	8.54%	91.43%	0.03%	

	Ground Observations	Total	IMS		Accuracy
IMS		8297	Land	Snow	
	Land (D_s = 0)	5223	5122	101	98.07%
		62.95%	98.07%	1.93%	
	Fractional Snow (D_s = 1-3 cm)	76	29	47	61.84%
		0.92%	38.16%	61.84%	
	Snow (D_s >= 4 cm)	2998	92	2906	96.93%
		36.13%	3.07%	96.93%	

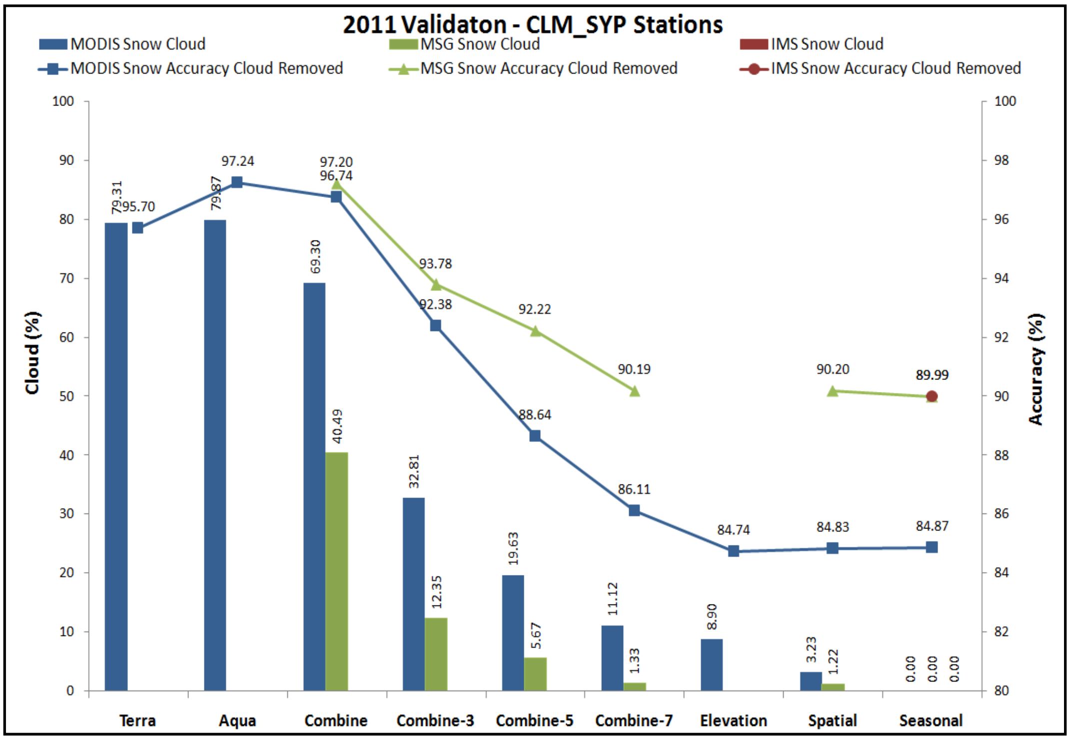

Figure 3.6. Snow cloud and accuracy ratios of CLM_SYP stations in 2011

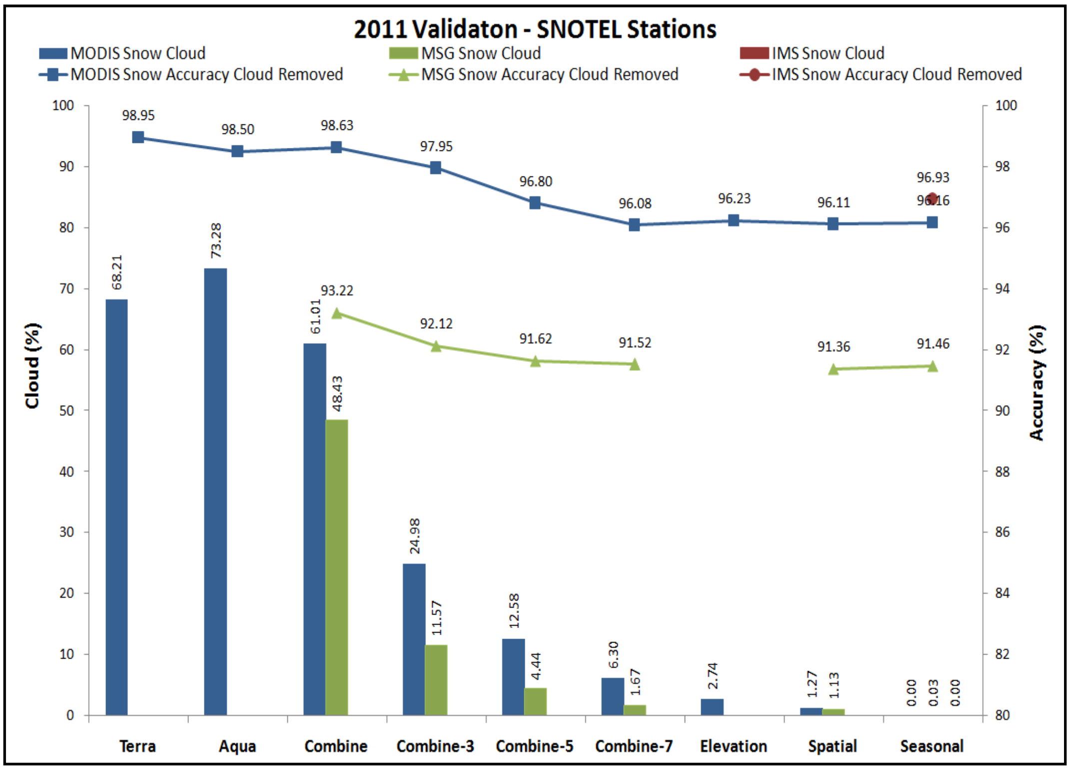

Figure 3.7. Snow cloud and accuracy ratios of SNOTEL stations in 2011

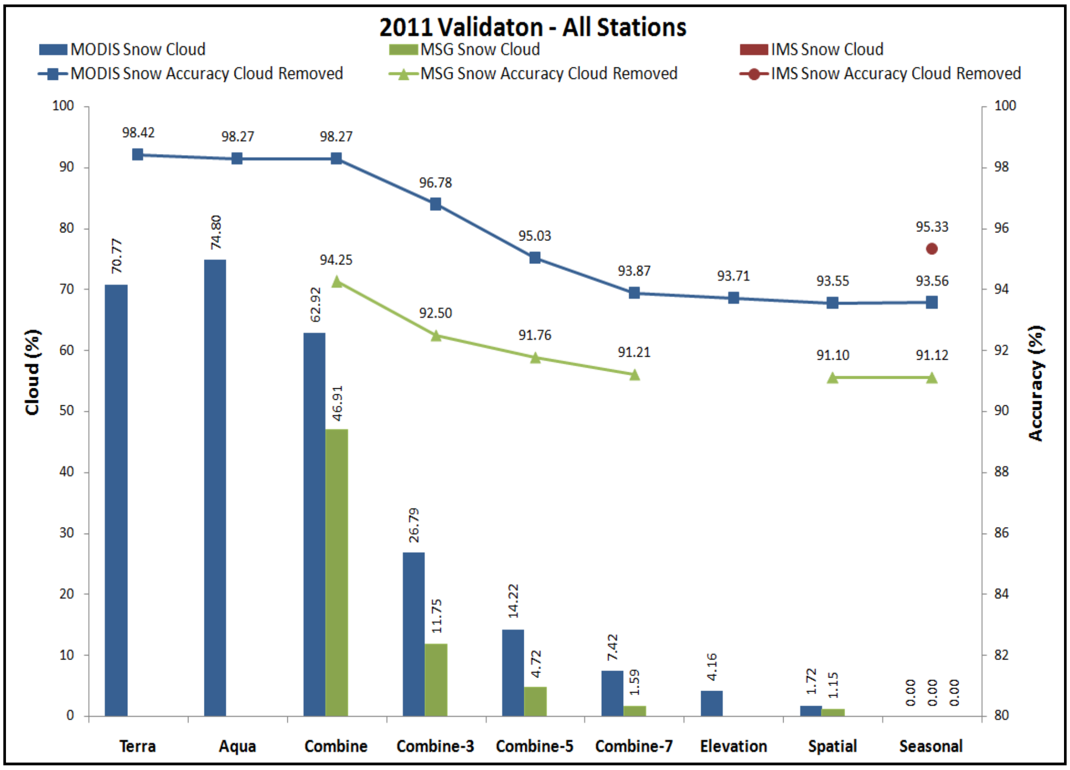

Figure 3.8. Snow cloud and accuracy ratios of all stations in 2011

While filtering removes cloud on MODIS and MSG-SEVIRI products, it reduces accuracies. Therefore, filtering effects are interpreted where Figure 3.9, 3.10 and 3.11 show number of errors arising from algorithm and filtering steps on all stations for MODIS, MSG-SEVIRI and IMS snow products. These errors show the number of days there is a mismatch between satellite snow product and ground observation for each station in 2011 snow season.

The majority of errors occur in temporal filter for MODIS data while substantial amount of clouds are removed by this filter (Figure 3.9). Stations located in the range of 1200-1400 m (between Arapkir and Mazgirt) have elevation filter errors. Spatial and seasonal filters give generally rise to error in the range of 1500-2000 m (between Malazgirt and Cataltepe) since snow does not occupy a consistent place in spatially. Moreover, the number of error arising from spatial filtering in MODIS product is higher than that of MSG-SEVIRI most probably due to higher spatial resolution.

Approximately half of MSG-SEVIRI product errors originate from the raw MSG-SEVIRI product (algorithm error), whereas the other half occur from the filtering process. Similar to MODIS, the bigger part of errors occur in temporal filter. Contrary to MODIS, spatial filter does not cause many errors because the majority of clouds are removed until this filter (Figure 3.10).

In IMS, filtering is not applied and errors are occurred by product algorithm (Figure 3.11). The majority of errors occur in the range of 1200-1650 m (between Ispir and Ağrı) where snow does not stay on ground for a long time.

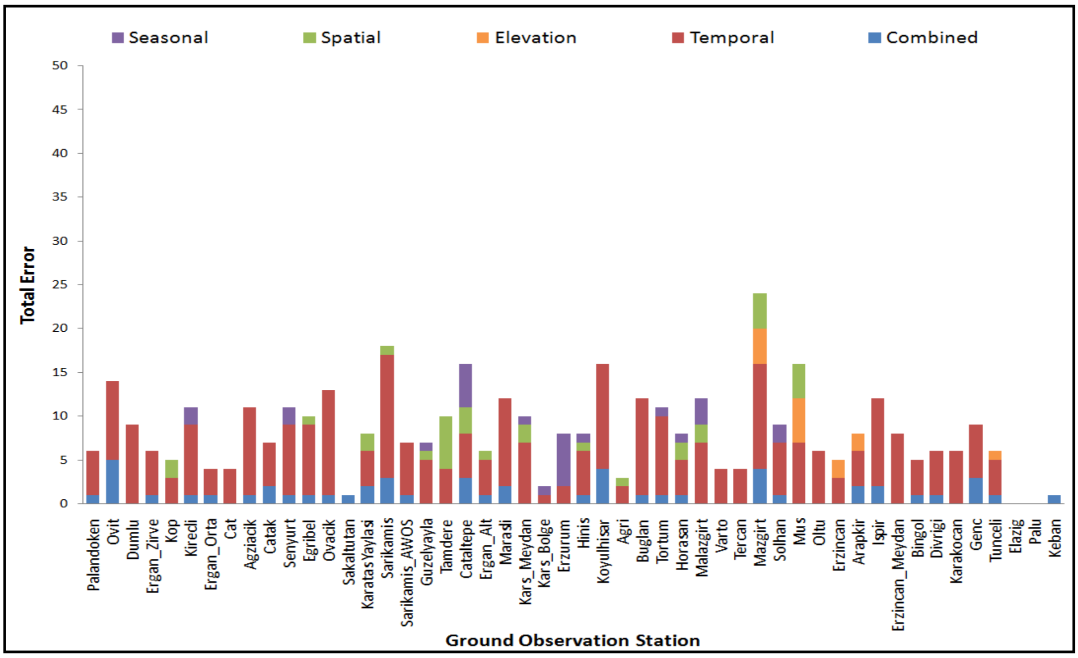

Figure 3.9. Number of errors arising from each filtering for MODIS satellite product

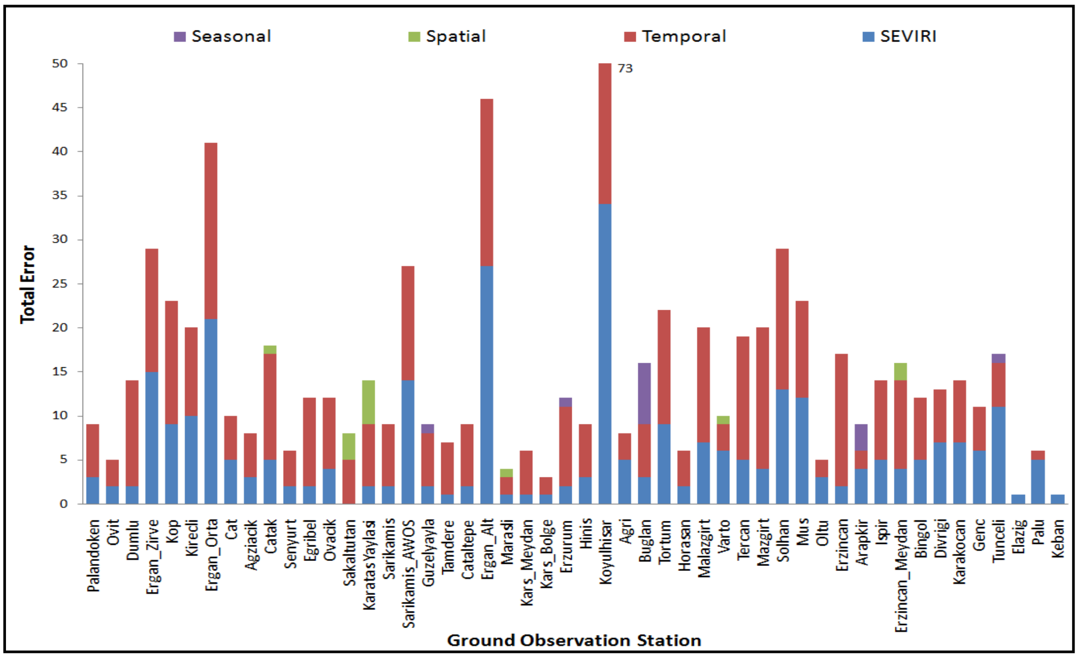

Figure 3.10. Number of errors arising from each filtering for MSG-SEVIRI satellite product

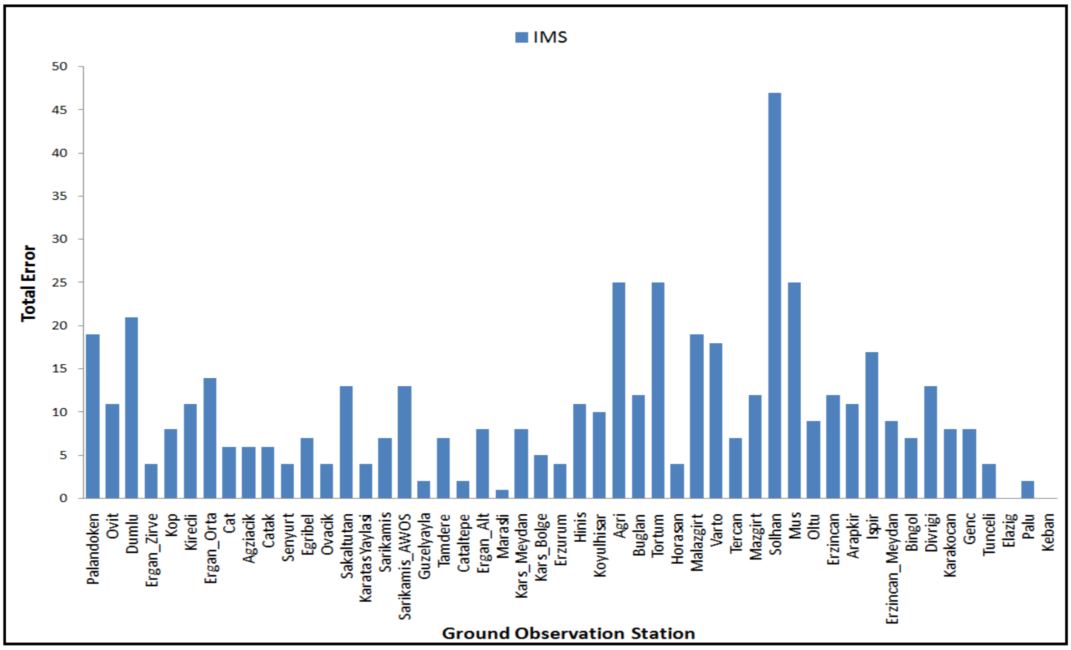

Figure 3.11. Number of errors for IMS satellite product

The other study on errors is to classify them as omission and commission. Omission error is that satellite data is provided as land where ground observation data is snow; on the contrary, commission error is that satellite data is snow where ground observation is land.

MSG-SEVIRI has most notably high omission errors (Figure 3.12). Its errors generally are on elevations higher than 1700 m (higher than Koyulhisar). Koyulhisar station has the maximum omission error since station is located in a forest area. Omission errors of MODIS and IMS data are distributed through stations and there is no significant trend.

In commission error, MSG-SEVIRI and IMS satellite data have similar results due to their spatial resolution (Figure 3.13). Errors for them are generally on elevations lower than 1700 m (Ağrı and lower) and the stations here are CLM_SYP stations affected by microclimate since they are located on urban areas. Differently from this trend, errors of Ergan_Zirve, Ergan_Orta and Ergan_Alt stations are arising from variable topography (high elevation difference in short distance). Also when snow depth data of these stations are interpreted, it becomes obvious that, blowing snow effect from higher to lower elevations is significant.

In general, errors of MODIS data are distributed independently of elevation and other effects since its spatial resolution is higher than the othersMSG-SEVIRI data have both omission errors on high elevations and commission errors on low elevations. Errors of IMS data are generally on low elevations as commission.

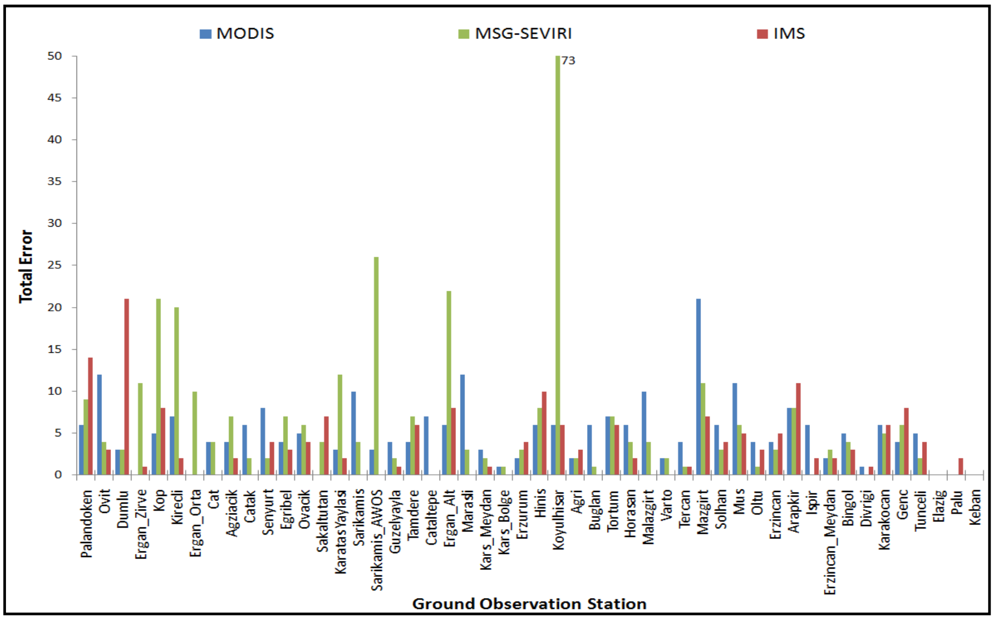

Figure 3.12. Snow-Land (Omission) errors

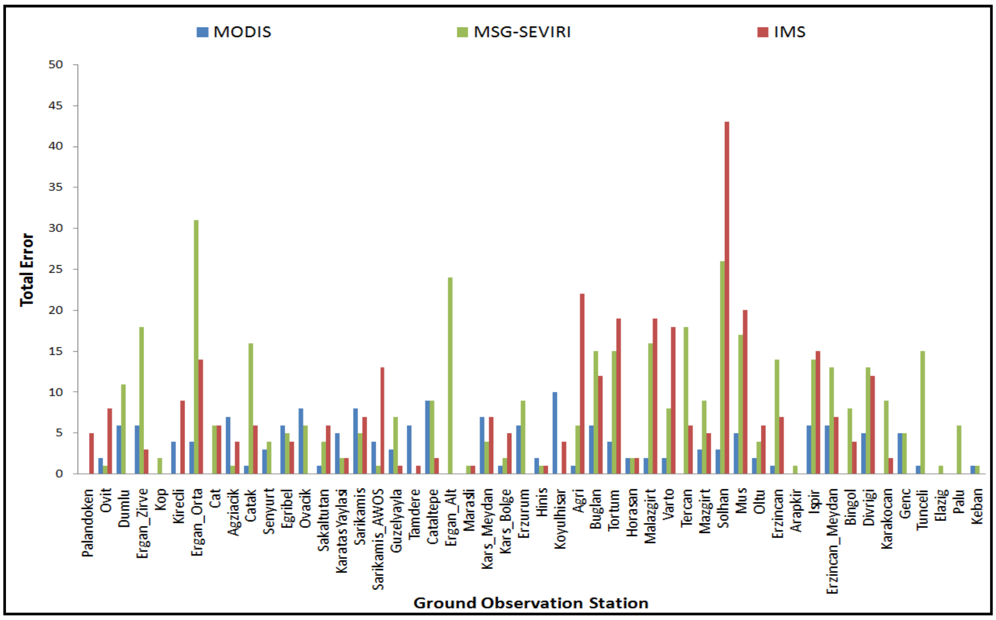

Figure 3.13. Land-Snow (Commission) errors

3.4. Snow Covered Area Graphics

After the validation of satellite products against ground observation data, snow covered area (SCA) graphics of the study areas are created between 2008 and 2011 water years. SCA graphics of Karasu Basin for each year are shown in Figure 3.14 – 3.17. Similarly, SCA graphics of Murat Basin are given in Figure 3.18 – 3.21. These figures show the time-dependent spatial change of snow extent basinwide. However, SCA graphics are calculated for all satellite products for each elevation zone and basins since hydrological model needs zonal SCA data.

In Karasu Basin, accumulation period generally starts in November. However, in 2011 water year, it starts late in December (Figure 3.17). Depletion generally starts in March and melting period finishes in the last days of May. 2010 water year is different from the others since the basin is not covered by snow for a long period (Figure 3.16). The other interesting event in 2011 water year is the second SCA peak occurring in April (Figure 3.17). However, snow cover duration is short since melting occurs quickly.

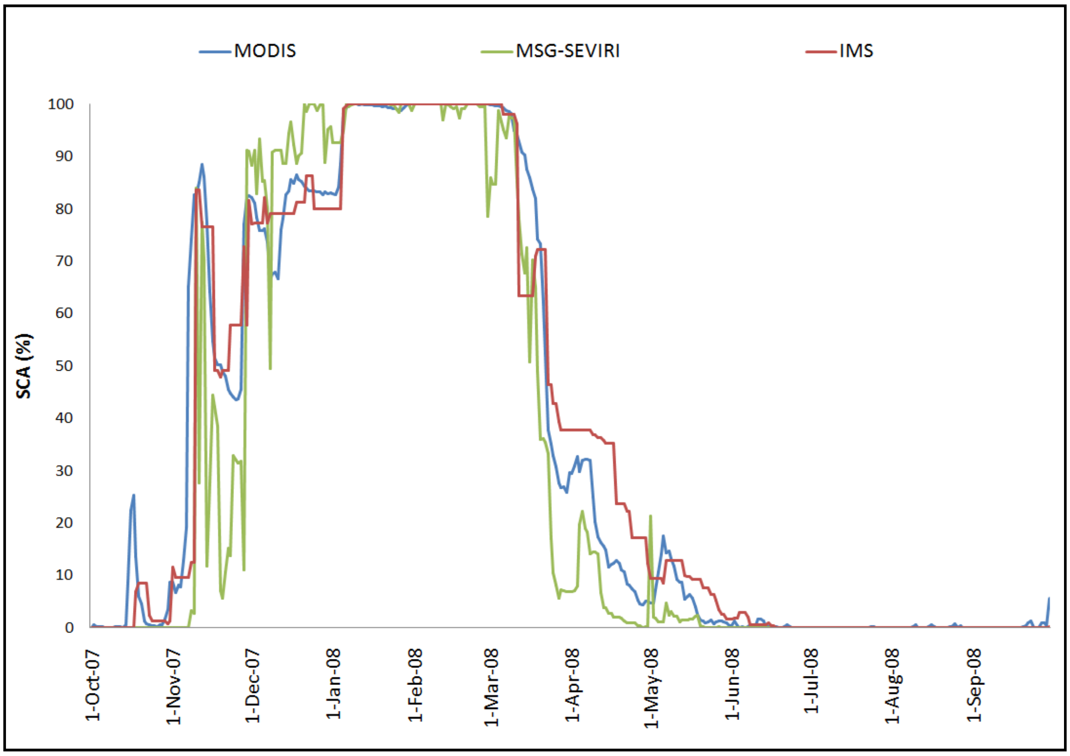

Figure 3.14. SCA graphics of each satellite product for Karasu Basin in 2008 water year

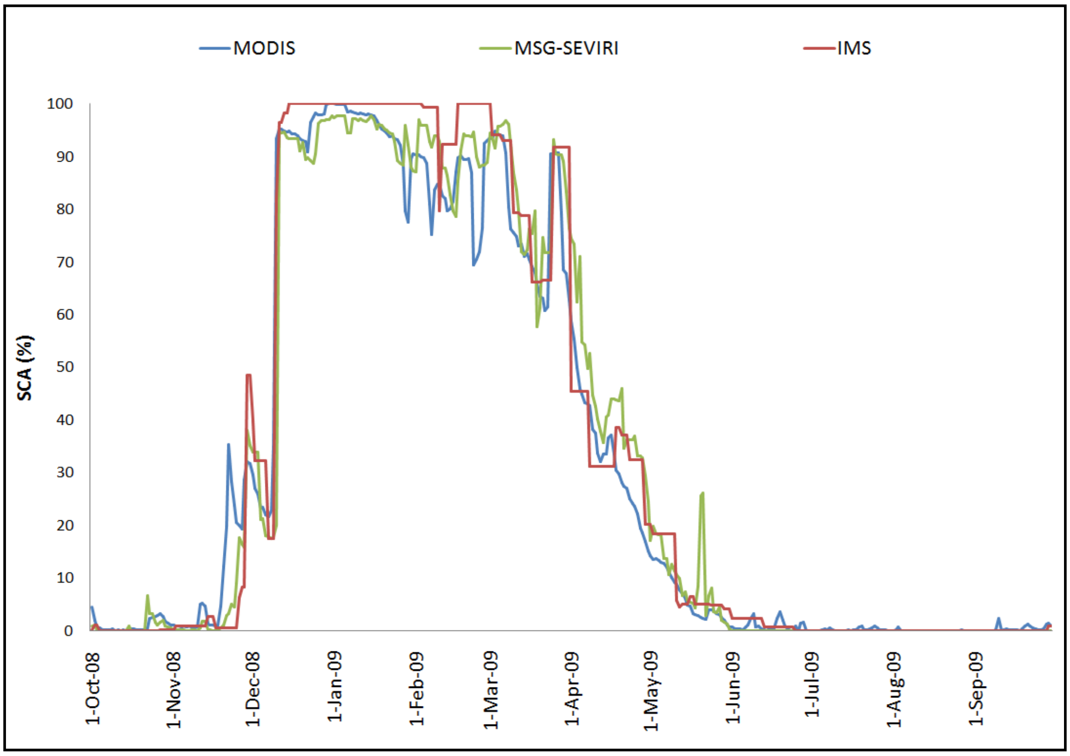

Figure 3.15. SCA graphics of each satellite product for Karasu Basin in 2009 water year

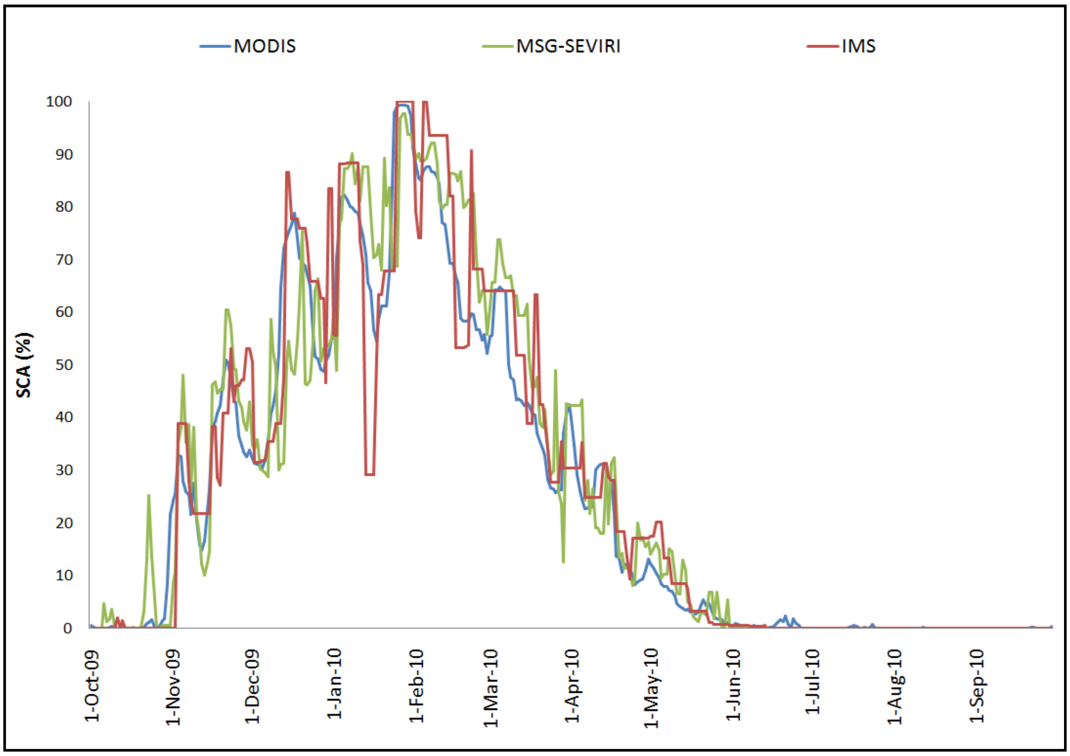

Figure 3.16. SCA graphics of each satellite product for Karasu Basin in 2010 water year

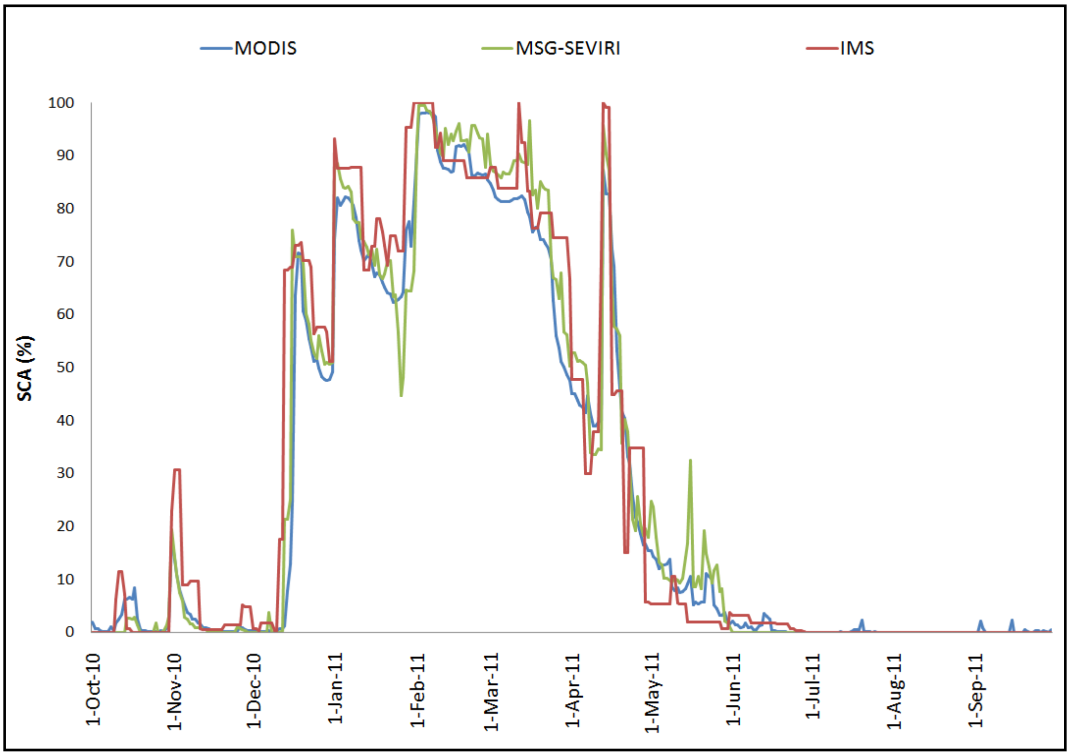

Figure 3.17. SCA graphics of each satellite product for Karasu Basin in 2011 water year

The other study area, Murat Basin, has similar accumulation and melting periods with Karasu Basin. Accumulation generally occurs in November or December. Depletion starts in March and takes approximately three months until the beginning of June (Figure 3.18 – 3.21).

If the SCA graphics are interpreted for different satellite images, IMS shows abrupt changes both on the accumulation and depletion seasons (somewhat like a ladder formation) most probably due to the data combination of various spatial resolution satellites under cloud cover. MODIS and MSG-SEVIRI show a more smooth change in the snow extent even though both images have different spatial resolutions. An interesting point is noticed for MSG-SEVIRI images, whereby SCA never reaches 100% during the snow season when other images show full snow cover. This problem is more pronounced in Murat Basin (except for 2008 water year). When MSG-SEVIRI data are viewed day by day, some of the cells remain as land pixels throughout all the water year. These cells seem to correspond to urban areas (cities) hence the problem with MSG-SEVIRI data is either related with the spatial resolution (although IMS has similar spatial resolution without such results) or the snow algorithm itself.

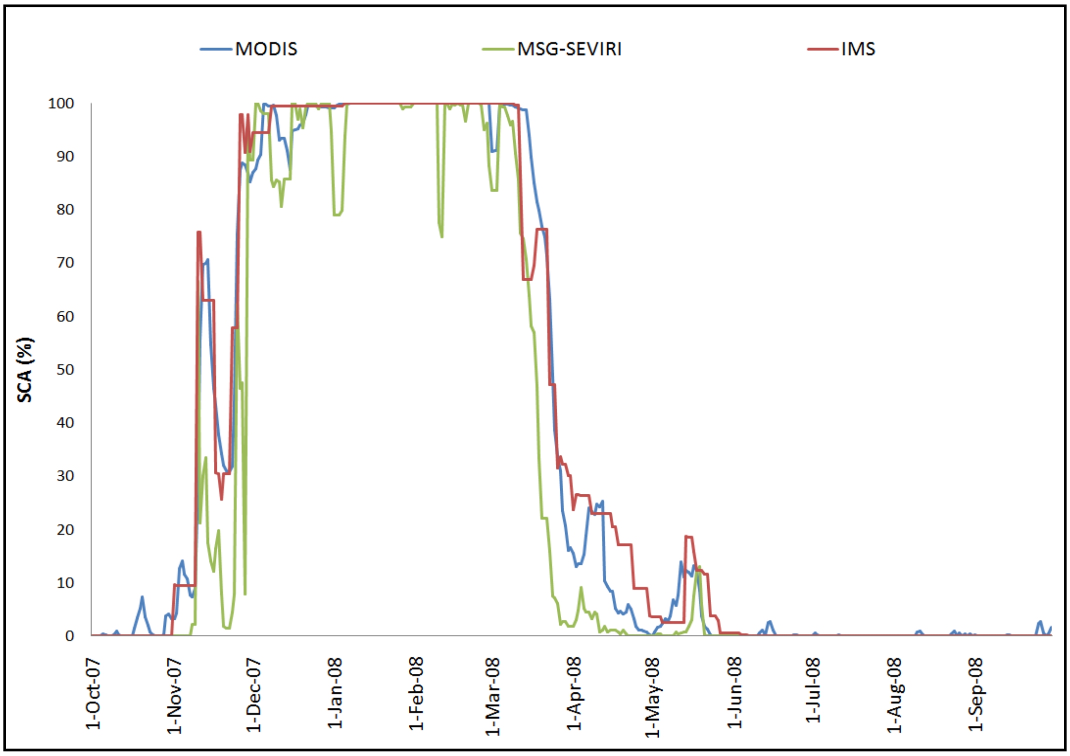

Figure 3.18. SCA graphics of each satellite product for Murat Basin in 2008 water year

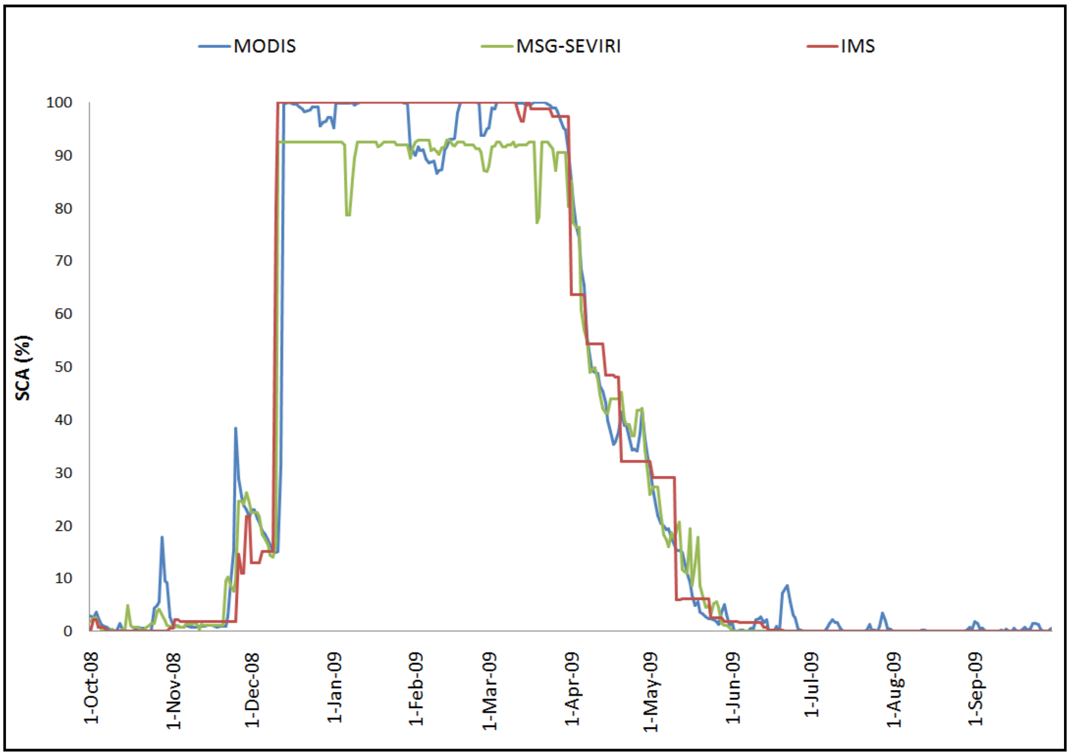

Figure 3.19. SCA graphics of each satellite product for Murat Basin in 2009 water year

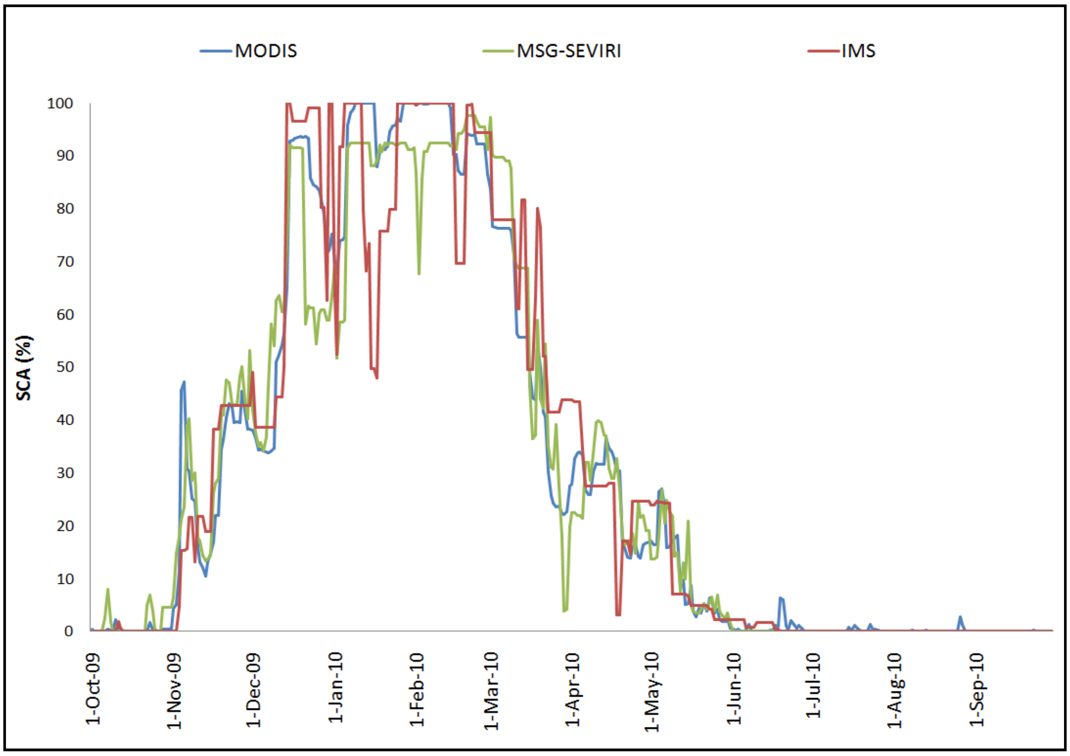

Figure 3.20. SCA graphics of each satellite product for Murat Basin in 2010 water year

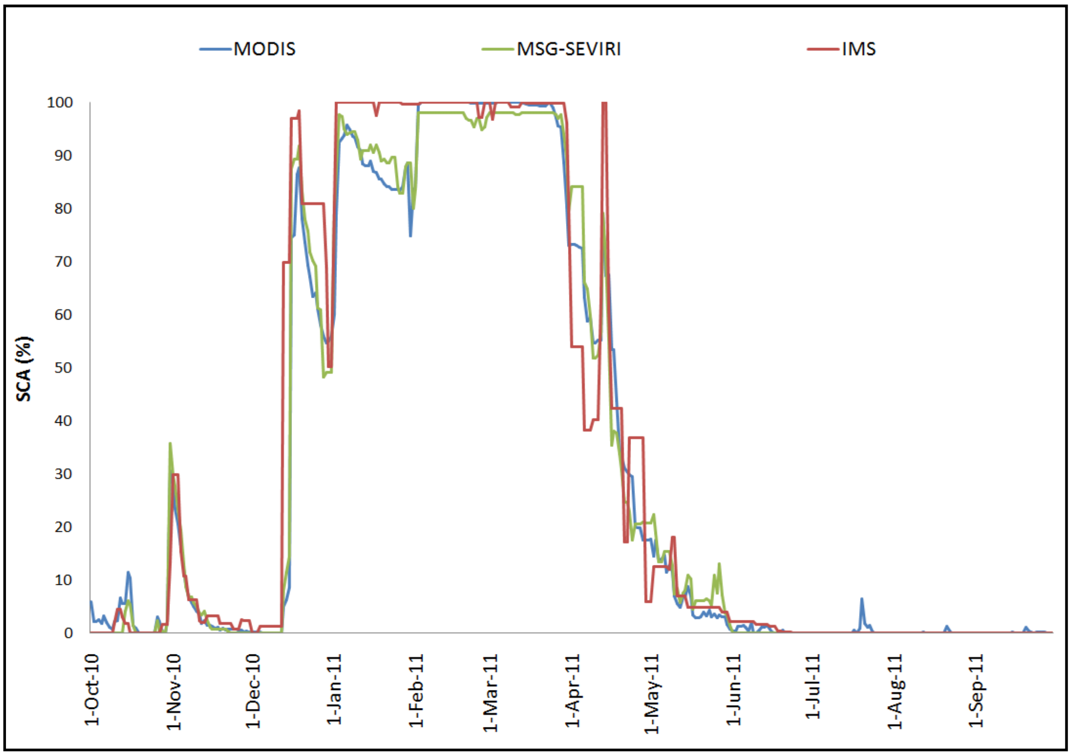

Figure 3.21. SCA graphics of each satellite product for Murat Basin in 2011 water year

Event-based SCA Graphics

Various events for both basins are considered in three different periods to interpret relation between SCA derived by satellite snow products and ground observation snow depth data. SCA curves are cloud free, but daily cloud cover is presented in order to give an idea about daily cloudiness. Thus, first event (mid December 2010) represents snow accumulation period in Karasu and Murat Basins and it is obvious that, IMS product responds simultaneously with ground observation data as a result of being a blended product (Figure 3.22 and 3.23). However, MODIS and MSG-SEVIRI respond late because of cloud problem during snowfall period.

In Event 2 (end of December and January), IMS and MSG-SEVIRI satellite products change with snowfall in the same time, but MODIS responds late similar to Event 1 because of cloudiness problem (1 January 2011). Then, especially in Murat Basin, IMS does not show any change while MODIS and MSG-SEVIRI changes smoothly depending on snow depth changes (Figure 3.24 and 3.25). Figure 3.25 corroborates this problem of IMS with that SCA of IMS is still 100 % while snow depth in Ağrı Station (1646 m, corresponds to B zone of Murat Basin) depletes. However, SCA ratios of MODIS and MSG-SEVIRI decreases correspond to snow depth changes.

In Event 3 (end of March and beginning of April), IMS shows sudden decrease in snow depletion period similar to Event 2 (Figure 3.26 and 3.27) and cannot respond depletion smoothly as MODIS and MSG-SEVIRI. It keeps snow extent for a while in spite of depletion in snow depth, and then shows sudden change. However, MODIS and MSG-SEVIRI respond smoothly and concurrently to the decrease of snow depth.

Events show that IMS has a problem about abrupt change even though it has similar spatial resolution with MSG-SEVIRI. The reason of that may be due to spatial resolution of one of the component satellites in blended product algorithm. However, outstanding point of IMS is to change simultaneously with snowfall in accumulation period. Here, the disadvantage of MODIS and MSG-

SEVIRI satellites attracts notice; they respond late to snowfall because of cloud problem in snow accumulation period. While snow depth on ground station increases, snow extent of MODIS and MSG-SEVIRI cannot increase since cloud amount is high in snowfall period.

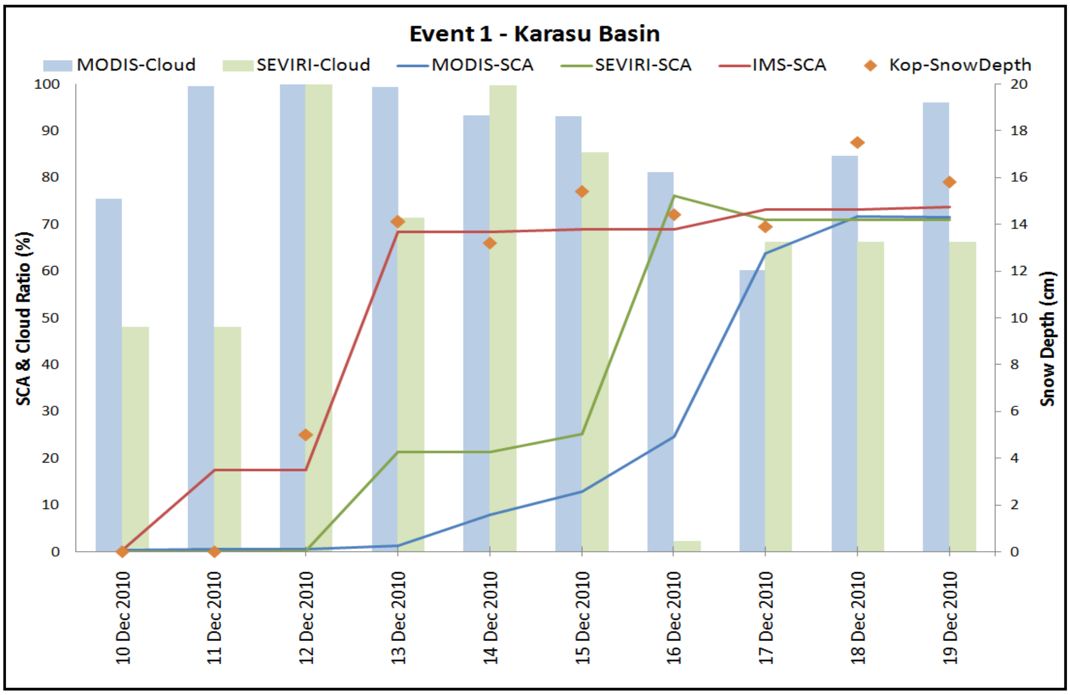

Figure 3.22. Karasu Basin snow accumulation event in 2011 water year

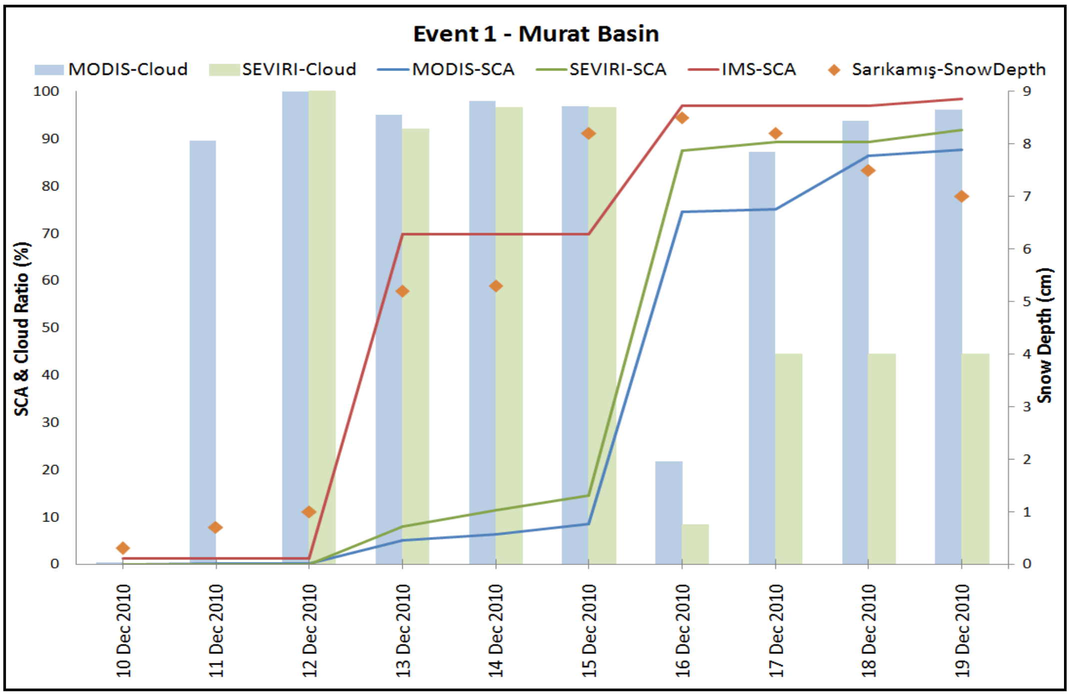

Figure 3.23. Murat Basin snow accumulation event in 2011 water year

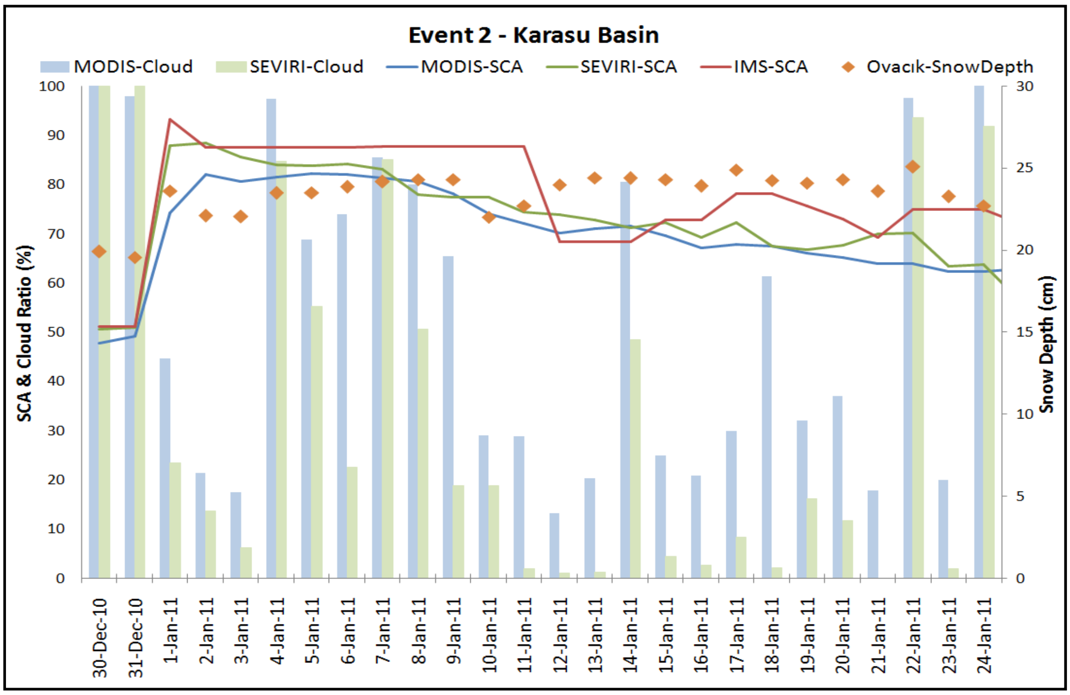

Figure 3.24. Karasu Basin snow season event in 2011 water year

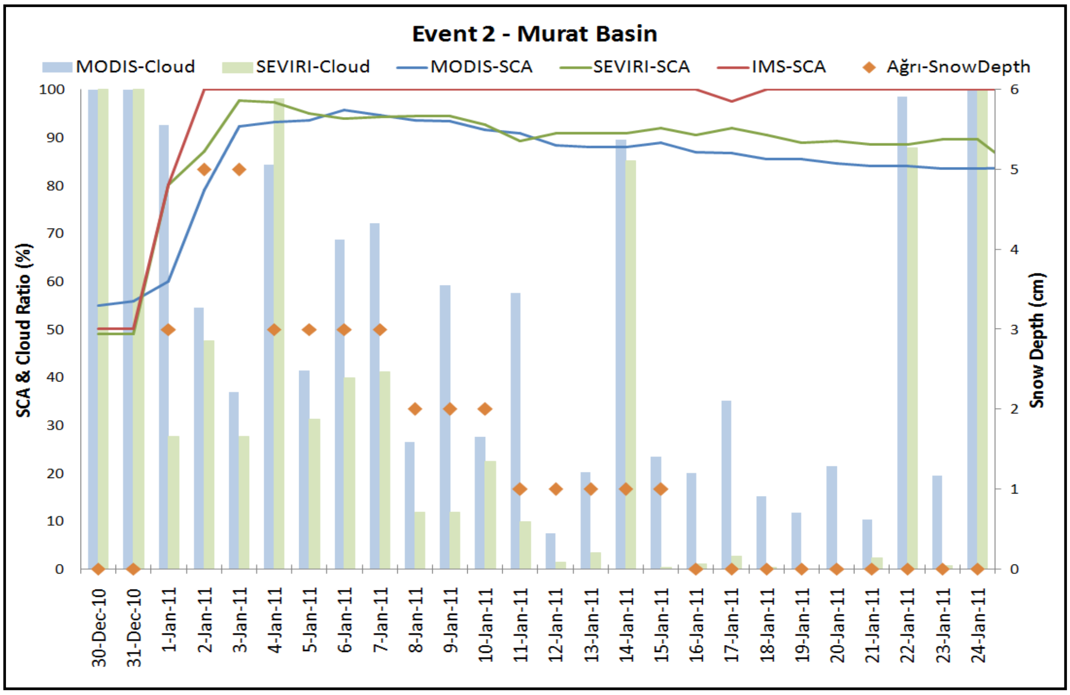

Figure 3.25. Murat Basin snow season event in 2011 water year

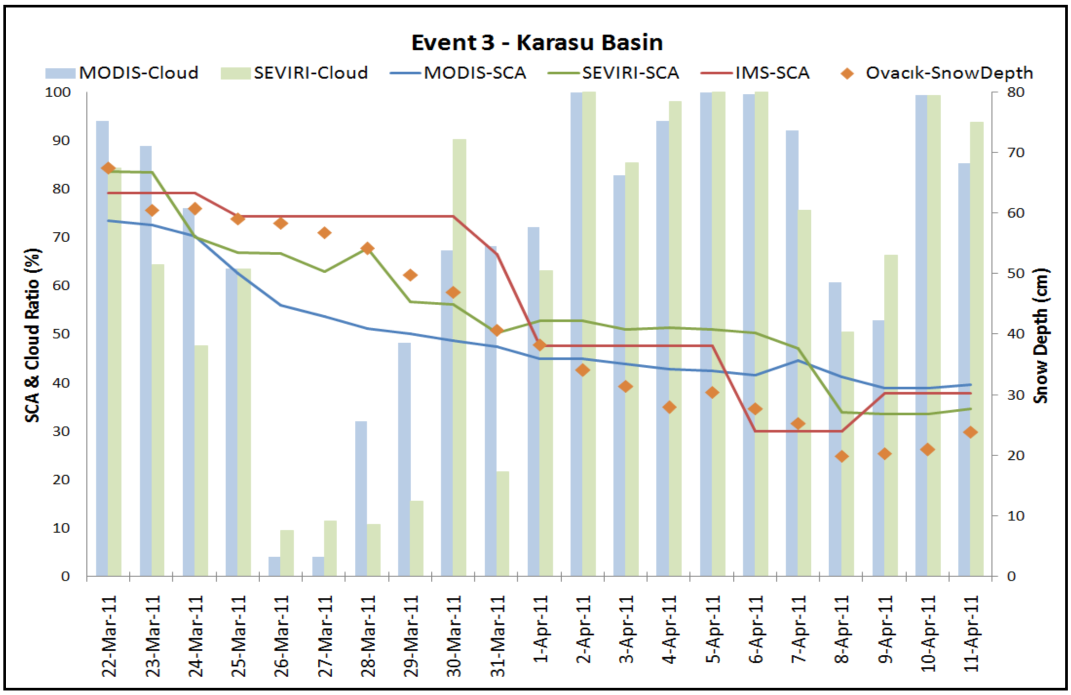

Figure 3.26. Karasu Basin snow depletion event in 2011 water year

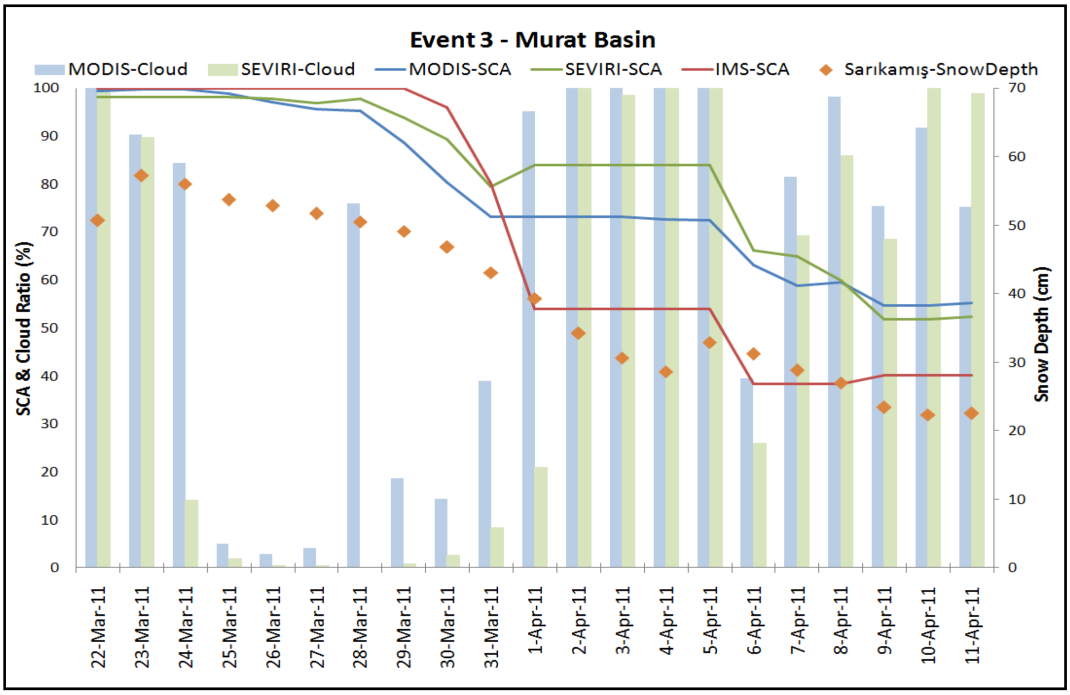

Figure 3.27. Murat Basin snow depletion event in 2011 water year

4. HYDROLOGICAL MODELING

Accurate estimation of discharge from snowmelt in mountainous regions is important to manage water resources efficiently for hydropower generation, irrigation and flood mitigation purposes. Various hydrological models have been used for runoff simulation and/or forecasting in snow-dominated mountainous basins around the world. Hydrological models can be various types as physical based, conceptual and deterministic models. According to spatial discretisation, hydrological models are classified as lumped, semi-distributed and distributed models. Lumped models represent the complete hydrological system as a homogeneous unit. Fully-distributed models are employed to calculate values at specific grid locations in a hydrological system. Semi-distributed or semi-lumped models lie between lumped and distributed models. Selecting one out of the hydrological models is not easy since each model has various advantages and disadvantages. In this study, Snowmelt Runoff Model (SRM) is selected since it takes SCA as an additional variable into consideration and has a good representation of snow areal extend in mountainous basins as a semi-distributed conceptual hydrological model.

4.1. Snowmelt Runoff Model (SRM)

The Snowmelt Runoff Model (SRM) is a semi-distributed conceptual model using temperature index method. The model takes into account the daily total precipitation, the daily average air temperature and daily snow cover area along with other catchment-specific parameters (Martinec, 1975; Martinec et al., 2008). The SRM, which is also termed as Martinec-Rango model, can be applied to mountain basins of various sizes and elevations (Butt and Bilal, 2011).

The SRM (Martinec et al., 2008) is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff component. It has also been applied to evaluate the effect of climate change on seasonal snow cover and runoff. SRM was developed by Martinec (1975) for small European basins. After the progress in satellite remote sensing of snow cover, SRM has been applied to larger basins. Contrary to the original assumptions, there appear to be no limits for application in regard to the basin size and the elevation range. Also, a dominant role of snowmelt is not a necessary condition. To date, the model has been applied by various agencies, institutes and universities. More than 80% of these applications have been performed by independent users (Martinec et al., 2008).

It is known that the effect of global climate change on hydrologic systems, especially on mountain snow and glacier melt, can modify the timing and amount of runoff in mountainous watersheds (Abudu et al., 2012). SRM can be used to simulate the daily streamflow of a snowmelt season or in a year, to provide short-term and seasonal runoff forecasts, and to evaluate the potential effect of climate change on the seasonal snow cover and runoff (Seidel et al., 1998,; Prasad and Roy, 2005; Martinec et al., 2008; Rango et al., 2008; Immerzeel et al., 2009; Rango et al., 2013; Sharma et al., 2013).

Snow cover area (SCA) data are significant input to the SRM, thus consistency and availability of satellite snow products are important. The remote sensing can provide spatial and temporal variability of snow cover information (Nagler, 2008). The high reflectivity of snow in the visible bands of the electromagnetic spectrum enables the discrimination of snow from other non-snowy areas. In remote sensing, numerous sensors have been used to map snow cover. Some of the most important and widely used sensors includes Landsat 5 Thematic Mapper (TM), NOAA-AVHRR, European Remote Sensing-Synthetic Aperture Radar (ERS-SAR), IMS and MODIS. SRM is applied with various satellite products by Gomez-Landesa and Rango (2002), Li and Williams (2008), Immerzeel et al. (2009), Butt and Bilal (2011), Abudu et al. (2012), Aggarwal et al. (2014), He et al. (2014), Kult et al. (2014), Qiu et al. (2014). In Turkey, SRM is applied in various research studies (Kaya, 1999; Tekeli et al. 2005; Gözel, 2011; Şensoy and Uysal, 2012).

Even though various satellite products are used in different studies of SRM for various purposes, there is not enough literature on the comparison of various satellite products in one study. Thus, this study presents a comparative analysis of various satellite products through SRM hydrological modeling. Since SRM is a semi-distributed hydrological model, satellite snow products should be provided as zonal input in modeling (Figure 4.1).

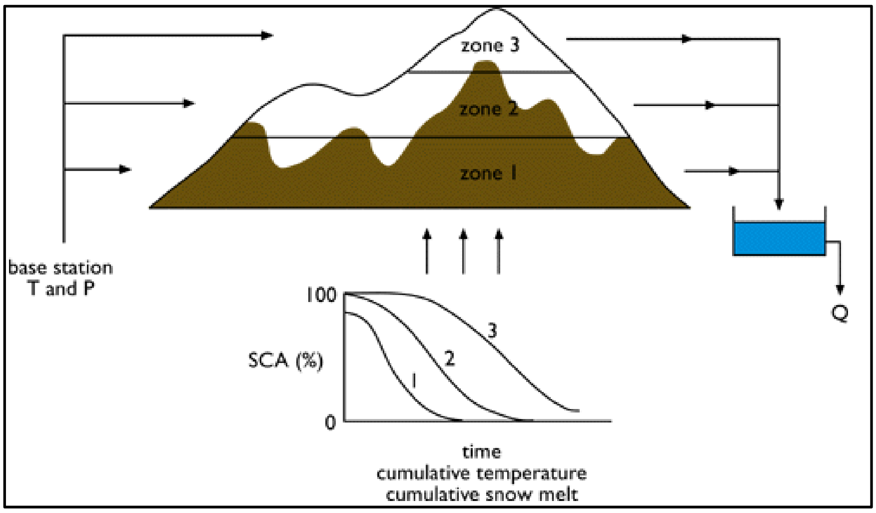

Figure 4.1. SRM model structure (Martinec, 2008)

Formula of SRM is based on the following equation (Martinec, 2008)

$$Q_{t+1} = [c_{St} \cdot a_t (T_t + \Delta T_t) S_t + c_{Rt} P_t] \cdot (A \cdot 10000 / 86400) \cdot (1-k_{t+1}) + Q_t k_{t+1}$$

(Equation 4.1)

where:

t : stands for day

Q : average daily discharge [m^3/s].

T : daily mean temperature [$^oC \cdot d$].

Δ T : the adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [^oC d].

P : precipitation contributing to runoff [cm].

S : ratio of the snow covered area (SCA) to the total area [%].

A : area of the basin or zone [km^2].

c : runoff coefficient expressing the losses as a ratio (runoff/precipitation), with c_S referring to snowmelt and c_R to rain. The runoff coefficient accounts for the losses, which are the difference between the available water volume (snowmelt + rainfall) and the outflow from the basin. At the start of the snowmelt season, losses are usually very small because they are limited to evaporation from the snow surface, especially at the high elevations. When some soil becomes exposed and vegetation grows, more losses must be expected due to evapotranspiration and interception. Towards the end of the snowmelt season, direct channel flow from the remaining snowfields may prevail which leads to a decrease of losses and to an increase of the runoff coefficient.

a : degree-day factor [cm $^{o}C^{-1}d^{-1}$]. The degree-day can change according to the changing snow properties during the snowmelt season.

k : recession coefficient indicating the decline of discharge in a period. Analysis of historical discharge data is usually a solution to determine k. Thus, longer historical discharge data give a representative recession coefficient of the basin.

There are additional internal model parameters to be used in the calculation algorithm of the model. T_{CRIT} is one of them and means the critical temperature. It determines whether the measured or forecasted precipitation is rain or snow. SRM needs the critical temperature only in order to decide whether precipitation immediately contributes to runoff (rain), or, if $T< T_{CRIT}$, whether snowfall took place. In this case, SRM automatically keeps the newly fallen snow in storage until it is melted on subsequent warm days. The other parameter is Rainfall Contributing Area (RCA). It can be treated in two ways. In the initial situation (option-0), it is assumed that rain falling on the snowpack early in the snowmelt season is retained by the snow which is usually dry and deep. Rainfall runoff is added to snowmelt runoff only from the snow-free area. At some later stage, the snow cover becomes ripe and parameter is switched to option-1. Then, if rain falls on this snow cover, it is assumed that the same amount of water is released from the snowpack so that rain from the entire zone area is added to snowmelt. Furthermore, precipitation threshold is selected to change recession calculations. This value can be different according to the rainfall-recession characteristics of selected basin. With no threshold, the recession coefficient will be continuously decreased, and SRM is likely to overestimate the runoff. By putting the threshold higher than the highest daily precipitation, SRM will probably underestimate the sharp runoff peaks from heavy rainfall.

4.2. Integrated Model Structure of FEWS-SRM

SRM is integrated with Flood Early Warning System (Delft-FEWS) platform to make it possible to integrate and manage different sources of data (satellite, in situ, numerical weather prediction data). Delft-FEWS is a sophisticated collection of modules designed for building an operational water management system, customized to the specific requirements of individual organizations. Originally designed for hydrological forecasting and warning, Delft-FEWS is now also being applied for day-to-day operational management, real-time control and forecasting and warning in other disciplines, i.e. water quality and navigation. Delft-FEWS is free software and can be downloaded on the relevant website (oss.deltares.nl/web/delft-fews).

Delft-FEWS platform enables the SRM to estimate runoff coefficients automatically. Runoff coefficients are time-dependent and change depends on loss conditions. Thus, estimation of coefficients is difficult and Moving Horizon Estimation (MHE) approach is adapted to the hydrological model for automatic estimation of parameters.

Delft-FEWS platform provides a simplicity in missing data process by interpolating the missing ones in time series data which is suitable to interpolate, such as daily air temperature, snow covered area. That is to say, Delft-FEWS platform enables user to interpolate missing data or make any mathematical process during model application.

Another advantage of Delft-FEWS is to enable the long-term simulation. While a year is allowed to be simulated in original SRM program in one simulation, the longer continuous period can be simulated in FEWS-SRM (integration of Delft-FEWS platform and SRM hydrological model). This makes a continuous time series simulation in calibration and validation period.

Accuracy of the model performance is evaluated with different performance criteria. Nash and Sutcliffe Efficiency (Equation 4.2), Correlation Coefficient (Equation 4.3), Volume Difference (Equation 4.4) and Root Mean

Square Error (Equation 4.5) are used for accuracy assessment of the model performance. The equations are provided below.

$$\text{NSE} = 1 - \frac{\sum_{t=1}^{T} (Q_O - Q_S)^2}{\sum_{t=1}^{T} (Q_O - \bar{Q}_O)^2} \qquad \text{(Equation 4.2)}$$

$$R^2 = \frac{\sum_{t=1}^{T} (Q_O - \bar{Q}_O)(Q_S - \bar{Q}_S)}{\sqrt{\sum_{t=1}^{T} (Q_O - \bar{Q}_O)^2 (Q_S - \bar{Q}_S)^2}} \qquad \text{(Equation 4.3)}$$

$$D_V (\%) = \frac{V_O - V_S}{V_O} \text{ x } 100 \qquad \text{(Equation 4.4)}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{T} (Q_O - Q_S)^2}{T}} \qquad \text{(Equation 4.5)}$$

where Q_O and Q_S are observed and simulated discharges. $\bar{Q}_O$ and $\bar{Q}_S$ are mean of observed and simulated discharges, respectively. T stands for total duration with defined as daily time steps. Besides, V_O and V_S is observed and simulated seasonal runoff volume, respectively.

4.3. Parameter Estimation

Parameter estimation is an application to determine parameter values by making an analogy between model output and observation data in calibration period. Good performance depends on consistency of parameters as much as data accuracy. Sensitivity of parameters should be well known for a good validation and forecasting performance. Furthermore, model parameters should be in physically acceptable limits.

Runoff coefficients are estimated automatically in FEWS platform. However, the other parameters are estimated manually by the user. Thus, user’s experience and knowledge about the sensitivity of parameters are important in the estimation step. Besides, parameter set determined in the estimation period is used to validate and/or forecast the other years. Hence, uncertainty and subjectivity should be minimized in the determination of parameter sets as much as possible.

In this study, an external automatic optimization methodology is adapted to the model to estimate runoff coefficients. An objective function is defined to minimize differences of observed and simulated discharges and rate of parameters according to weights of variables. The general formula is based on the following equation;

$$J = \sum_{t=1}^{N} (W_{Q}(\Delta_{Qt})^2 + W_{Cs}(Cs_{t} - Cs_{t+1})^2 + W_{CR}(C_{Rt} - C_{Rt+1})^2) \quad \text{(Equation 4.6)}$$

where W_Q, W_{Cs}, W_{Cr} are weights of discharge and runoff coefficients (snowmelt and rainfall) in the objective function, respectively. Δ_{Qt} is the difference between observed and simulated discharge and ($C_{St} - C_{St+1}$) and ($C_{Rt} - C_{Rt+1}$) are the rate of runoff coefficients snowmelt and rainfall at time t, respectively. Here, the aim is to minimize the difference since large differences between consecutive runoff coefficients is not preferred in regard to physical meaning of parameters.

Runoff coefficients are calibrated independently for each satellite (MODIS, MSG-SEVIRI and IMS) while the other parameters are kept constant for different satellite products.

Recession coefficients of a basin are determined with analysis of historical discharges. Thus, long record of discharge data gives more accurate representation for recession. Degree-day factor and T_{CRIT} are determined according to the results of previous modeling studies for the selected basins (Kaya, 1999; Tekeli et al. 2005; Gözel, 2011; Şensoy and Uysal, 2012).

Since the accuracy assessments of satellite products are almost identical, it is not easy to select one of the satellite products. Therefore, hydrological validation study and resolution of satellites are considered to be important factors to select one of the more practically used satellite products.

In this study, 2008-2010 water years are used in the calibration period for all satellite products and 2011-2012 water years are used in validation with estimated parameter sets. However, observed discharge of 2012 water year for Murat Basin is not available; thus, only 2011 water year is used for validation. Considering input data, same observed temperature and precipitation values are used for all simulations with different satellite data; only SCA data show a change according to different satellite snow products.

In calibration study for Karasu Basin, modeling of runoff with different satellite products gives similar results (Figure 4.2), but model parameter estimation using MODIS satellite product gives slightly better performance (Table 4.1). In winter months of 2008 year, all simulated discharges are below the observed discharge. While runoff modeling with MODIS and MSG-SEVIRI products gives a similar trend with observed discharge, IMS gives higher results in the melting period. Parameter estimations of 2009 and 2010 water years give better performances for all products. Nevertheless, during the low flows in summer months of 2008 and 2009 water years, there is an overestimation in model results.

In Murat Basin, modeling studies give similar results (Figure 4.3) while modeling with MSG-SEVIRI product has slightly better performance (Table 4.1) in the overall period. While observed discharge is increasing in 2008 water year, a time lag is observed in simulated discharges. Simulation with MSG-SEVIRI cannot catch the peak flow in this year. Simulation of 2009 gives a better agreement with observed discharges. There are two important observed peak flows in 2010, these are 444 m^3/s and 689 m^3/s, respectively. In the first peak, simulation with IMS results in a more consistent estimate of observed peak flow than others. Simulated discharges with IMS, MODIS and MSG-SEVIRI satellite products are 370 m^3/s, 305 m^3/s and 290 m^3/s, respectively. The second peak flow is the highest observed discharge in the simulation period of study. Even though simulations of all satellite products give similar values to each other, they all underestimated the peak flow since extreme difference between consecutive runoff coefficients is not preferred.

In comparison of area and hydro-meteorological properties of basins, Karasu has a larger basin area than Murat Basin and hydro-meteorological properties are similar for them. However, the observed peak discharge in Murat Basin is quite high than Karasu Basin in the month of April, 2010 water year, so it causes to think trueness of this peak discharge.

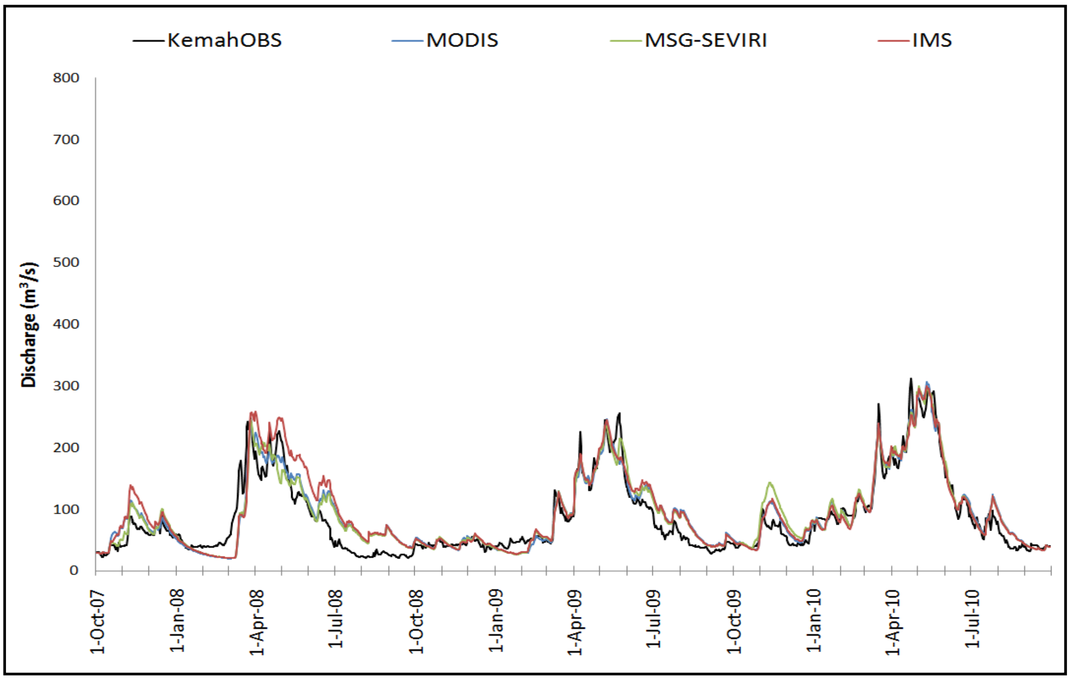

Figure 4.2. Calibration period of Karasu Basin (2008-2010)

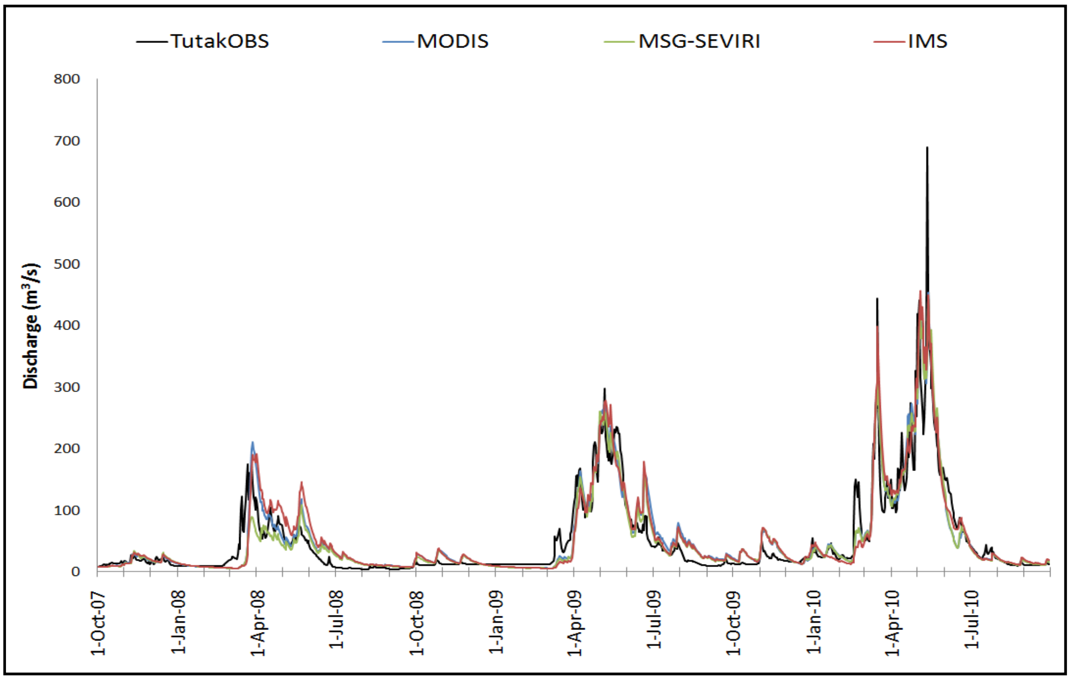

Figure 4.3. Calibration period of Murat Basin (2008-2010)

Table 4.1. Accuracy assessment for the calibration period

	Karasu Basin (2008-2010)				**Murat Basin (2008-2010)**			
Satellite Product	**NSE**	**R^2**	**D_V**	**RMSE**	**NSE**	**R^2**	**D_V**	**RMSE**
MODIS	0.88	0.89	-7.68	22.22	0.85	0.86	-8.67	27.7
MSG-SEVIRI	0.87	0.89	-8.2	22.54	0.86	0.87	-2.28	26.11
IMS	0.82	0.86	-12.38	26.6	0.82	0.84	-11.42	30.1

4.4. Validation Study

Validation study shows the accuracy of parameters determined in the estimation period. These parameters can be used not only for validation period but also for forecasting study. Parameter set determined in the calibration period is used to validate 2011-2012 water years in Karasu Basin and 2011 water year in Murat Basin. Runoff coefficients (c_S and c_R) are calculated as the average of coefficients in three calibration years. The other parameters such as degree-day, T_{CRIT} are used with predetermined values.

Validation performance assessment for the two basins is given in Table 4.2. Difference in simulated discharges occurs both due to different SCA and runoff coefficients parameters estimated in calibration study for each satellite product because they are calibrated independently for each one.

In Karasu Basin, simulation of discharges for all satellite data provides an overestimation. Volume differences in Table 4.2 point out this in addition to graphics in Figure 4.4. Validation studies with MODIS and MSG-SEVIRI products resulted in similar overestimation in 2011 water year. Since same observed temperature and precipitation data are used for all satellite data, the reason of this difference is basically the estimated runoff coefficients. While runoff coefficients in simulations with MODIS and MSG-SEVIRI are higher, that of simulation with IMS has the lowest values in the month of April, 2011. Thus, accuracy assessment of simulation with IMS gives better performance results than that of MODIS and MSG-SEVIRI data in 2011 water year. However, performance decreases for IMS and MSG-SEVIRI when 2011 and 2012 water years are validated as continuous time series. Correlation coefficient shows that trends of all simulations are similar to each other.

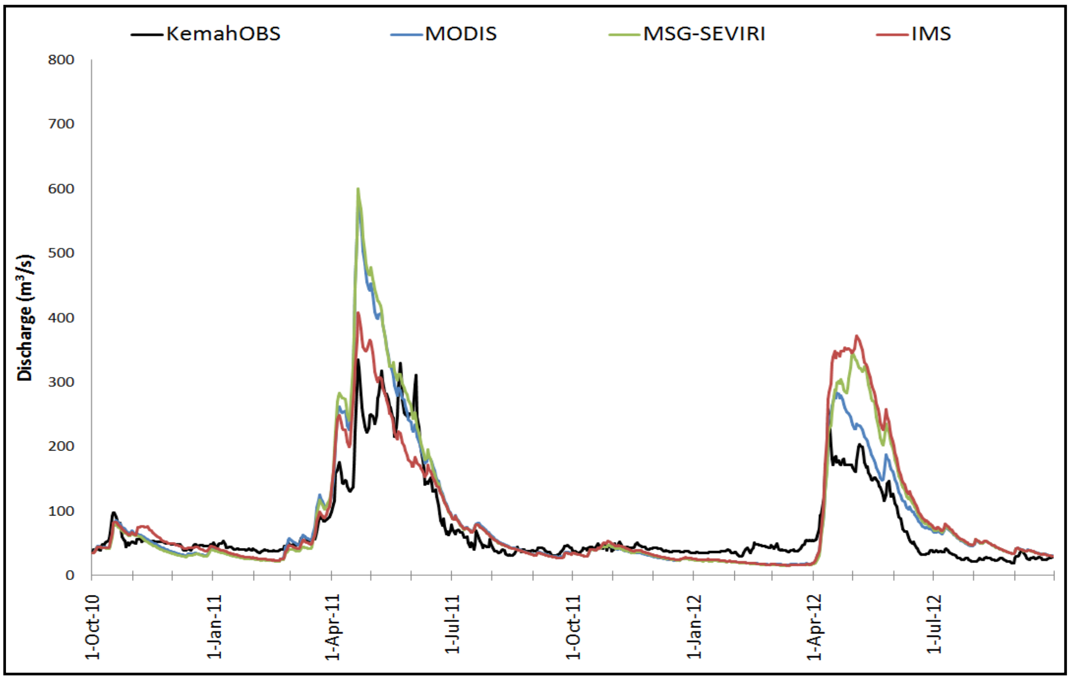

Figure 4.4. Validation period of Karasu Basin (2011-2012)

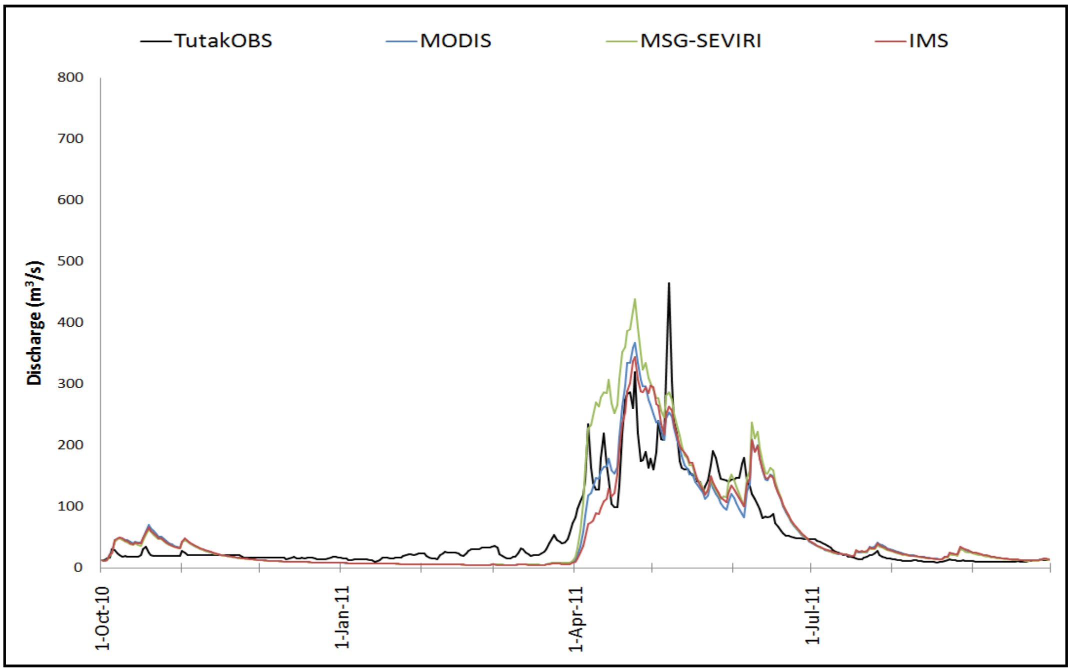

Figure 4.5. Validation period of Murat Basin (2011)

Table 4.2. Accuracy assessment for the validation period

	Karasu Basin (2011-2012)				Murat Basin (2011)			
Satellite Product	**NSE**	**R^2**	**D_V**	**RMSE**	**NSE**	**R^2**	**D_V**	**RMSE**
MODIS	0.49	0.87	-18.76	46.80	0.76	0.80	-2.02	33.05
MSG-SEVIRI	0.24	0.86	-25.49	57.27	0.58	0.81	-18.03	43.86
IMS	0.44	0.78	-20.17	49.33	0.75	0.78	-0.14	34.06

It is obvious that, Murat Basin has better accuracy performance than Karasu Basin in validation study while they have similar results in the calibration period. In Murat Basin, accuracies of modeling with MODIS and IMS data are statistically similar (Table 4.2). However, MSG-SEVIRI simulation gives low performance, again. This may be due to snow mapping algorithm of MSG-SEVIRI and not to monitor full snow extent. The highest peak discharge is underestimated because of the penalty in coefficients change in the objective function (Figure 4.5). Low flow in winter months is most notably since none of simulation responses sufficiently here. The reason is precipitation occurs in the form of snowfall and temperature is generally below zero till April. Since SRM does not have a separate soil moisture routine, model cannot provide base flow in continuous simulation and runoff values decrease with recession depending on discharge of previous day.

According to hydrological model results applied for a very limited time period both for calibration and validation; for Karasu Basin, MODIS snow product provides similar performances in both validation years (2011 and 2012). While IMS product provides two extreme NSE results with 0.79 and -0.59 for 2011 and 2012 water years, respectively, MSG-SEVIRI performances are low for both years. For Murat Basin, performances are higher compared to Karasu Basin; however MSG-SEVIRI gives slightly lower performance. The experience on MODIS shows a better performance for other validation years. The availability of three products limit the calibration period and this might reduce the validation performance of products through modeling. According to these results, MODIS and IMS could be preferable for hydrological applications in large basins such as Karasu and Murat Basins.

5. RUNOFF FORECASTING SYSTEM

Changing precipitation-runoff relationship and water demand based on increasing population indicate a need for effective usage of water resources. Thus, planning and forecasting supported by hydrological modeling are becoming more of an issue. Effects of flood and drought could be minimized, early warning system could be developed and reservoirs could be operated more efficiently with hydrological runoff forecasting. As a result of these necessities, Numerical Weather Prediction (NWP) data are provided as input to hydrological models for decision support in flood, hydropower and reservoir management (Anderson et al. 2002, Jasper et al. 2002, Westrick et al. 2002, Jonsdottir and Porarinsson 2004, Kunstmann and Stadler 2005, Nagler et al. 2008, Şorman et al, 2009, Tekeli et al. 2005, Nagler et al. 2008, Abudu et al. 2010, Şensoy and Uysal 2012, Yücel et al. 2015).

5.1. Numerical Weather Prediction Data

Numerical Weather Prediction is focused on taking current observations of weather and processing these data with computer models to forecast the future state of weather. Knowing the current state of the weather is just as important as the numerical models processing the data. Current weather observations serve as input to the numerical models through a process known as data assimilation to produce outputs of temperature, precipitation, and hundreds of other meteorological elements from the oceans to the top of the atmosphere (www.ncdc.noaa.gov). In other words, NWP is the name given to technique used to forecast the weather from its present, measured state up to several days ahead. Table 5.1 shows the range and classification of NWP data.

Table 5.1. NWP data according to range and classification

Range	Classification
Short Range Weather Forecast (0 / 2-3 days)	Deterministic Prediction System
Medium Range Weather Forecast (2-3 days / 2 weeks)	
Long Range Weather Forecast (more than 2 weeks)	Probabilistic Prediction System

In Turkey, Turkish State Meteorological Services (TSMS) is the responsible government organization for providing weather forecasts both in quantitative and qualitative form. Since Turkey is one of the member states of the European Centre for Medium-Range Weather Forecasts (ECMWF), forecast data received from ECMWF by TSMS are used as boundary conditions to Mesoscale Model 5 (MM5) / Weather Forecast and Research (WRF) (Figure 5.1 & 5.2) modeling system developed by Pennsylvania State University/National Center for Atmospheric Research (www.mmm.ucar.edu/mm5) to generate finer resolution forecast products both temporally and spatially to the end users. The weather prediction data was served as MM5 until the end of 2012, and then WRF designed as the successor of MM5 and includes all capabilities available within the MM5.

Hydrological models can provide forecasted discharge using these NWP data. Accuracy of hydrological forecasting system is associated with the accuracy of NWP data. As the accuracy of forecast data increases, performance of hydrological forecasting system is expected to increase. Therefore, accuracy of input variables plays a significant role in hydrological forecasting system.

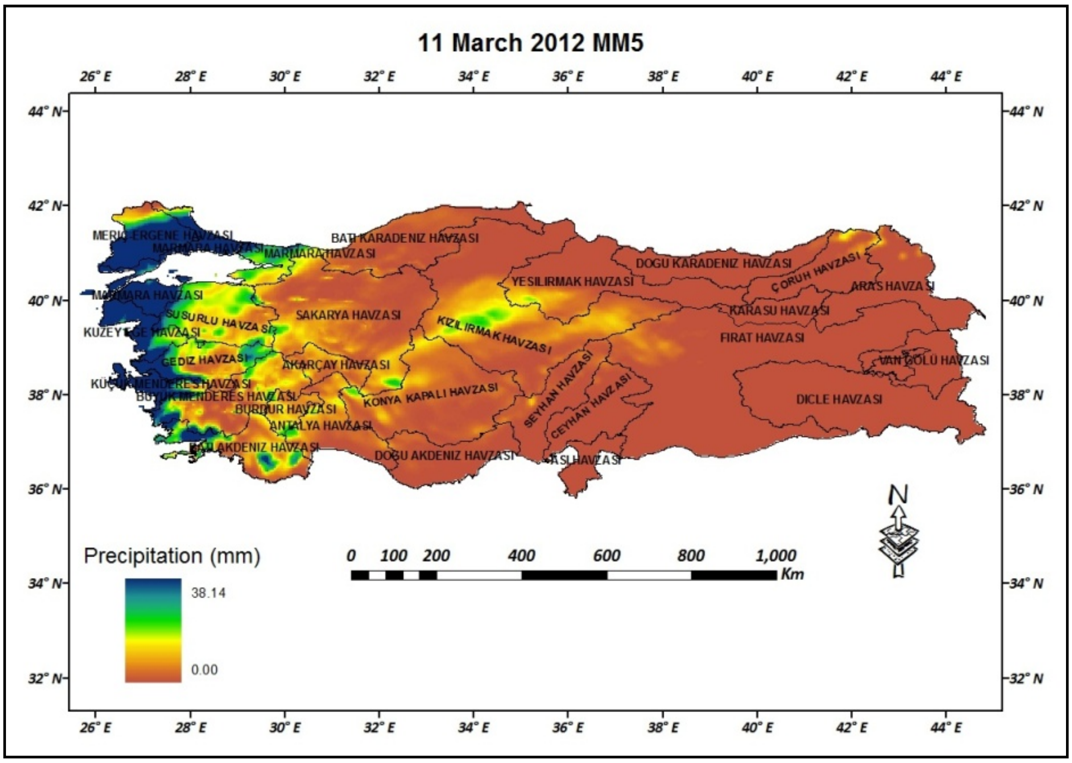

Figure 5.1. Turkey MM5 precipitation data (11 March 2012)

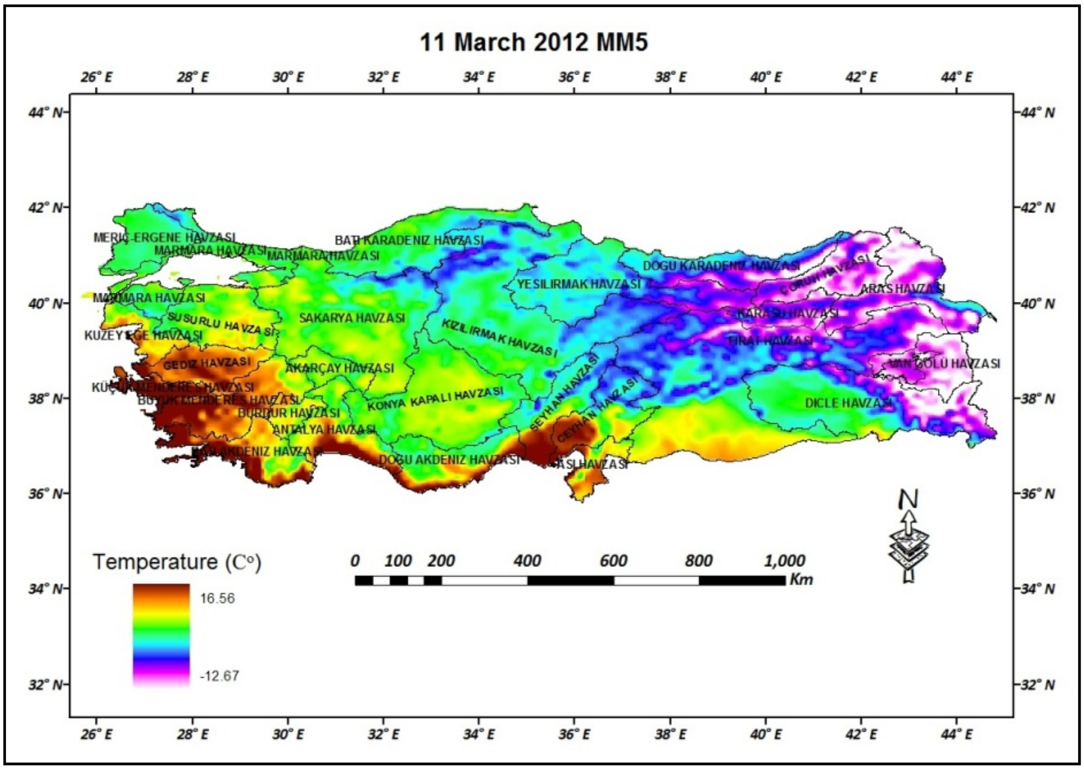

Figure 5.2. Turkey MM5 temperature data (11 March 2012)

In this study, MM5 daily average air temperature and daily total precipitation data having 4.5 km spatial resolution and 1-2 day lead time projections are provided as input to SRM hydrological model for runoff forecasting during 2011-2012 water years for Karasu Basin and 2011 water year for Murat Basin.

Before directly providing MM5 data into the hydrological model, bias correction is applied to MM5 temperature data to increase the consistency of prediction and observation data. Linear scaling method is used for the bias correction. A linear relationship between prediction and observation data is defined first. Then, the defined relationship is applied to prediction data of the other years. Both data series have the same average at the end of the bias correction process. These relationships are given in Figure 5.3 – 5.5 and Table 5.2 – 5.4 for both basins. As can be seen, there is a good correlation between observation and NWP data and bias correction reduces errors. The average of raw weather prediction temperature data is higher than that of observation data for Karasu Basin while average of raw weather prediction data is lower than that of observation data for Murat Basin. However, bias correction cannot be applied to MM5 precipitation data since there is no linear relationship between observed and MM5 precipitation data, and correction may increase uncertainty in precipitation data.

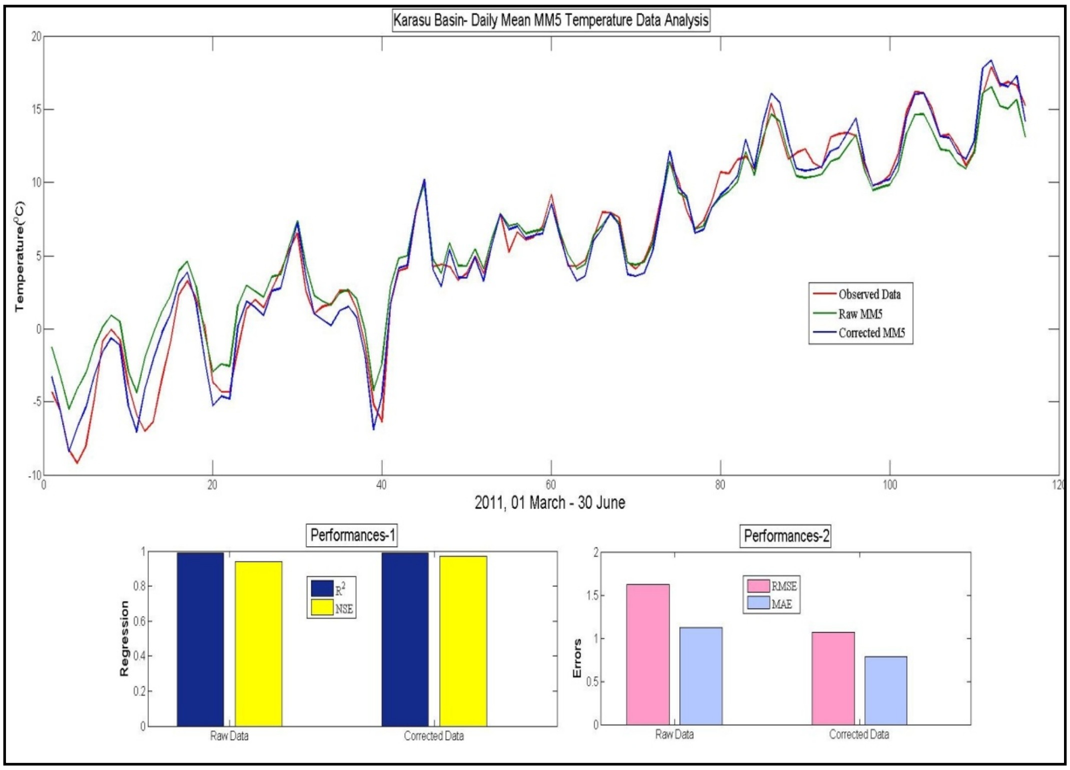

Figure 5.3. MM5 temperature data for Karasu Basin in 2011

Table 5.2. MM5 temperature comparison analysis of Karasu Basin in 2011

Karasu 2011 (116 days)	Minimum Temperature (^{0}C)	Average Temperature (^{0}C)	Maximum Temperature (^{0}C)
Observed Data	-9.20	5.82	17.86
Raw Data	-5.51	6.22	16.53
Corrected Data	-8.42	5.82	18.35

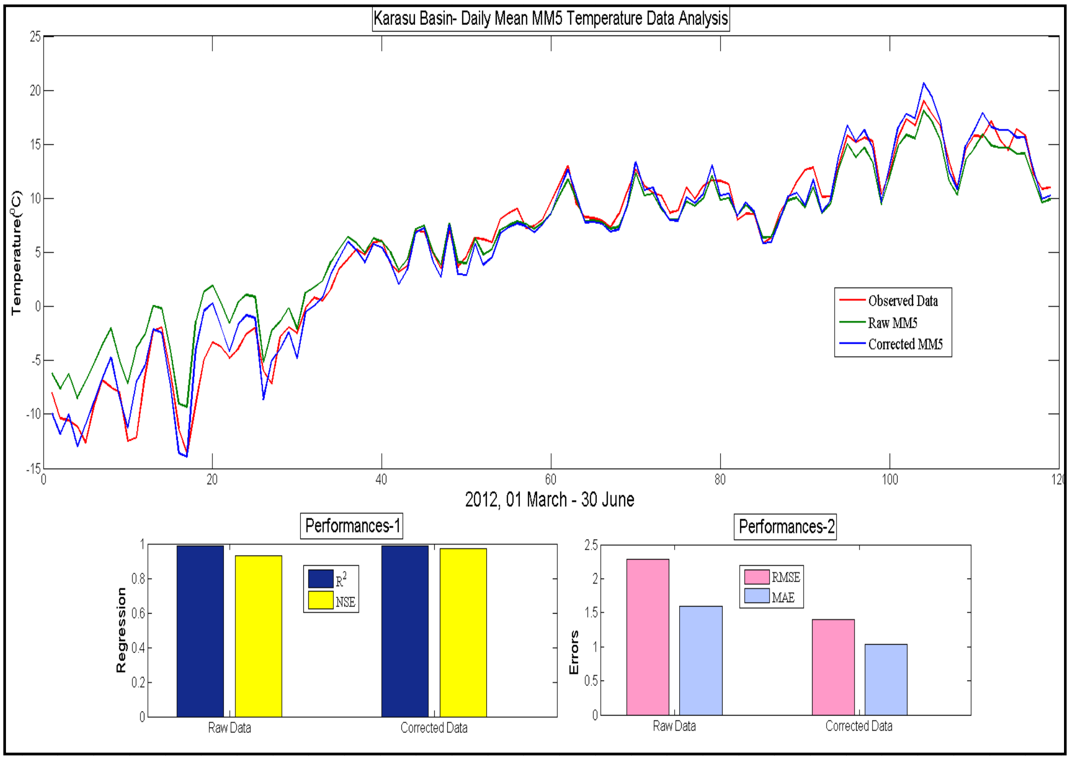

Figure 5.4. MM5 temperature data for Karasu Basin in 2012

Table 5.3. MM5 temperature comparison analysis of Karasu Basin in 2012

Karasu 2012 (119 days)	Minimum Temperature (^0C)	Average Temperature (^0C)	Maximum Temperature (^0C)
Observed Data	-13.72	5.57	19.00
Raw Data	-9.32	6.15	18.10
Corrected Data	-13.92	5.57	20.62

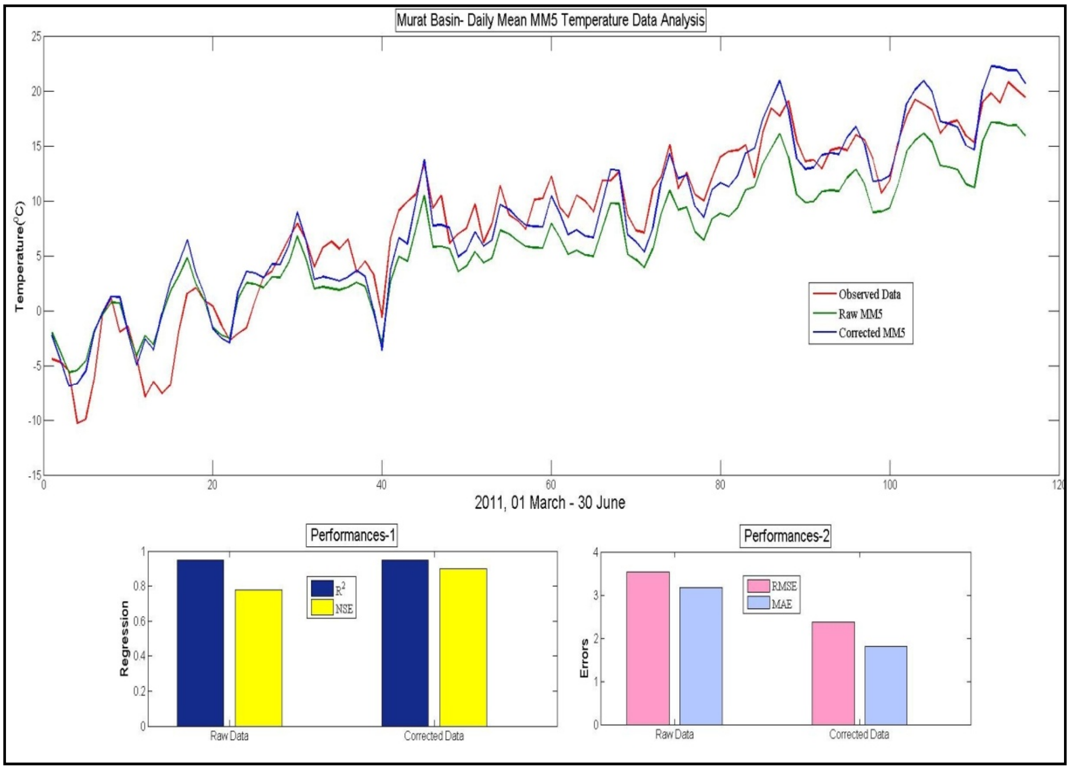

Figure 5.5. MM5 temperature data for Murat Basin in 2011

Table 5.4. MM5 temperature comparison analysis of Murat Basin in 2011

Karasu 2012 (116 days)	**Minimum Temperature (^{0}C)**	**Average Temperature (^{0}C)**	**Maximum Temperature (^{0}C)**
Observed Data	-10.30	8.39	20.80
Raw Data	-5.62	6.31	17.13
Corrected Data	-6.87	8.39	22.22

5.2. Runoff Forecasting using FEWS-SRM

Bias corrected NWP data are integrated into SRM on FEWS platform for discharge forecasting. Different than the simulation model structure, in the forecasting model structure, discharge of one of the previous days is determined with data assimilation. The number of days backwards is optional for user and it determines the initial state for the discharge. Then, discharges are simulated for the first lead time using observed meteorological data, and later on, one (Q_1) and two (Q_2) lead time discharges are forecasted.

Discharges of 2011 and 2012 water years are forecasted for Karasu Basins and 2011 water year for Murat Basin. While MSG-SEVIRI satellite data are not used since they give low performance in hydrological validation study, MODIS and IMS satellite data are used in forecasting.

Similar to hydrological validation, forecasting with IMS data gives better result and performance (Figure 5.6 and Table 5.5) for the year 2011 in Karasu Basin. Coefficient of determination (R^2) and NSE performance for both satellite data for one or two lead time of forecast are slightly better for IMS. Volume differences are negative for both cases and RMSE of forecasting with MODIS is higher than that of IMS. Performances decrease for the second day of forecast due to increased uncertainties in NWP with the lead time.

The opposite way round, in Karasu Basin for 2012 water year, forecasting with MODIS gives better performance than that with IMS data as seen in Figure 5.7 and Table 5.5. NSE performance of forecasting with MODIS is higher than that of IMS. However, in similar to 2011 water year, coefficients of determination of forecasts with both satellite data are similar to each other. Furthermore, volume difference of forecasting with IMS is higher, so RMSE for forecasting with IMS is higher than forecasting with MODIS.

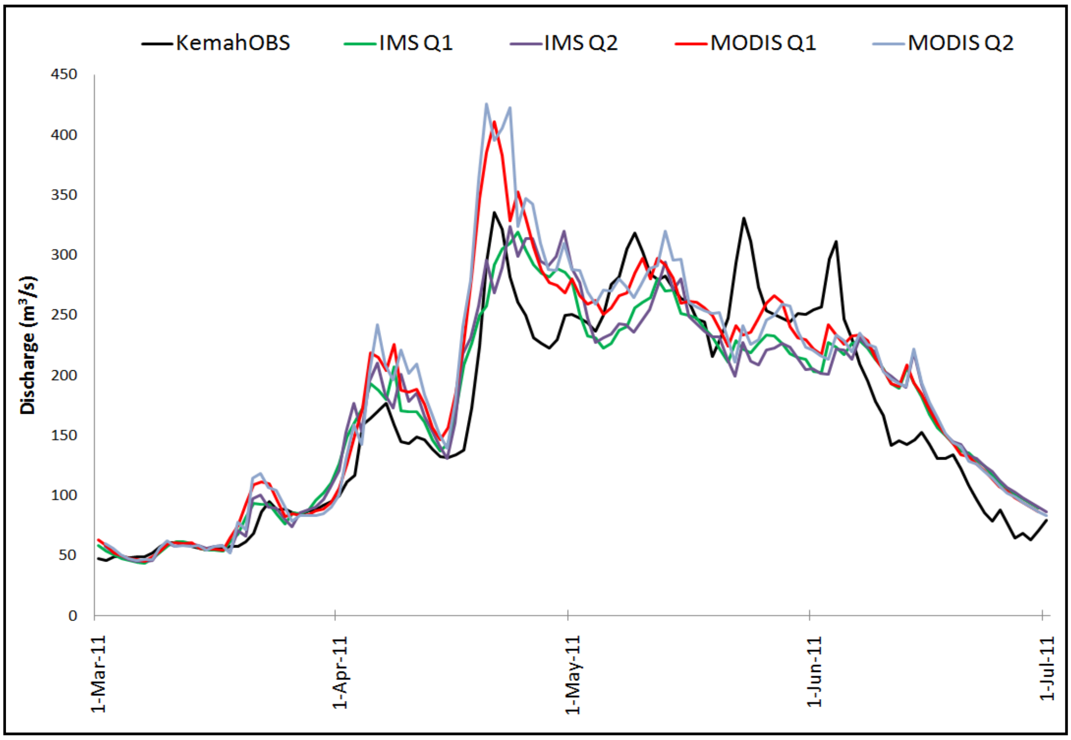

Figure 5.6. Forecasting study of Karasu Basin in 2011

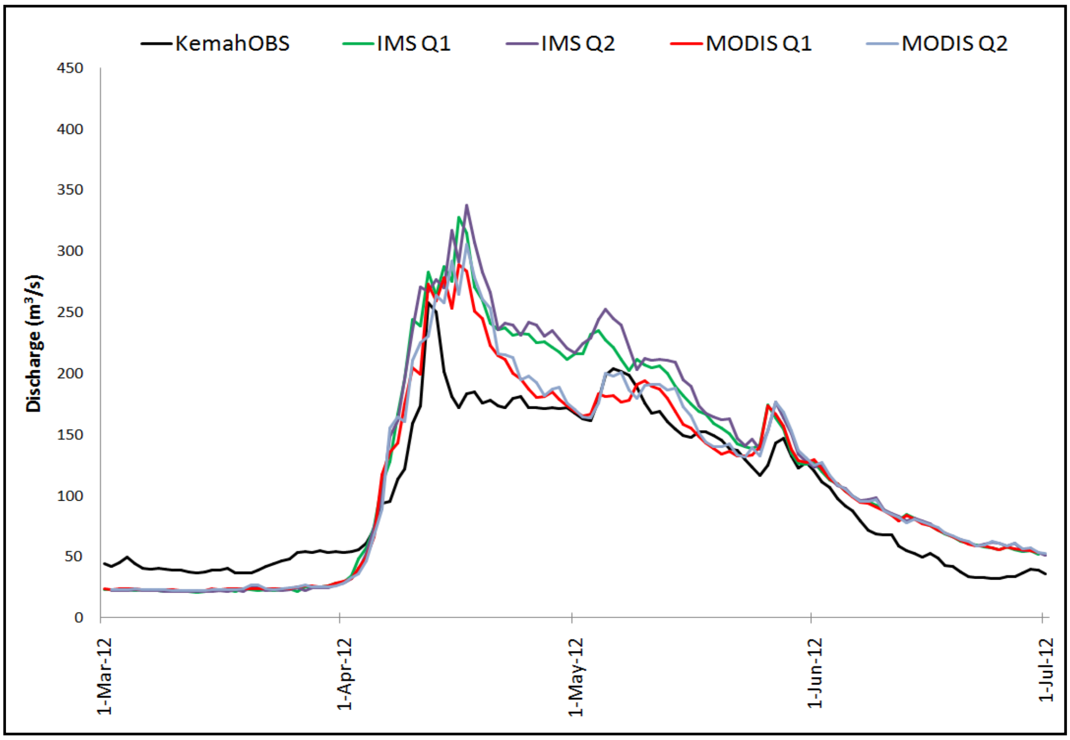

Figure 5.7. Forecasting study of Karasu Basin in 2012

Table 5.5. Accuracy assessment of forecasting simulation for Karasu Basin (2011-2012)

	Performance	IMS Q1	IMS Q2	MODIS Q1	MODIS Q2
2011	**NSE**	0.85	0.80	0.81	0.73
	R^2	0.85	0.85	0.86	0.81
	Dv (%)	-2.40	-3.33	-9.41	-11.60
	RMSE	34.40	39.11	38.21	45.67
2012	**NSE**	0.59	0.49	0.79	0.74
	R^2	0.91	0.91	0.89	0.88
	Dv (%)	-17.79	-21.67	-7.74	-10.45
	RMSE	38.83	43.65	27.86	31.22

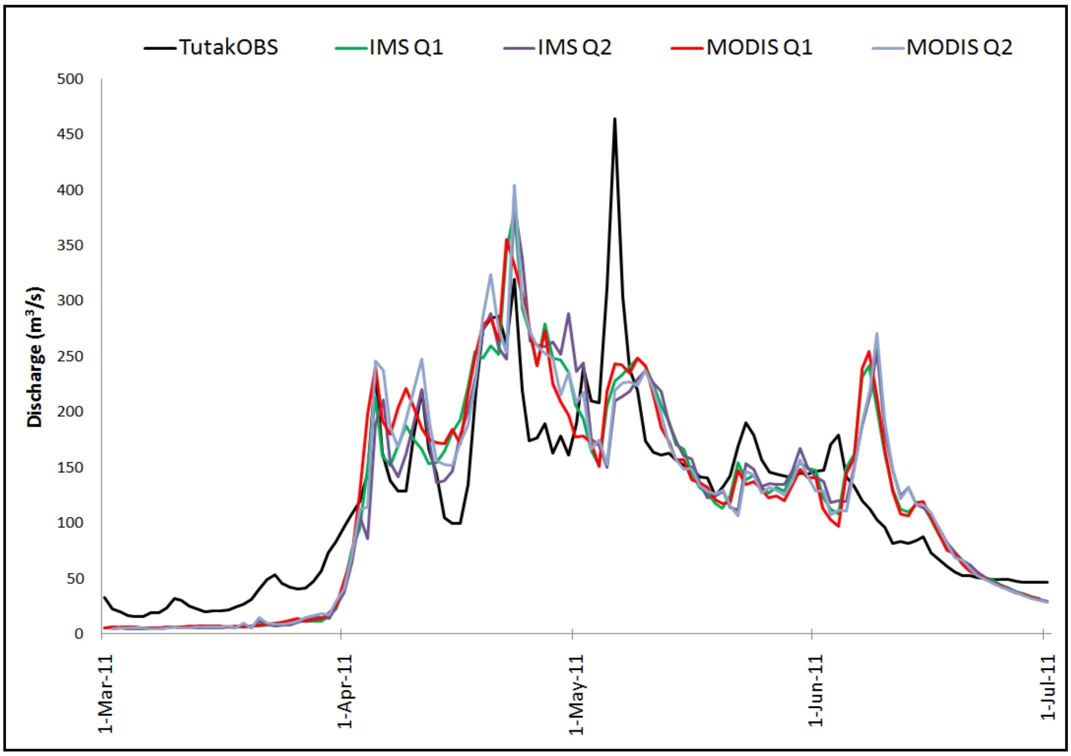

Figure 5.8. Forecasting study of Murat Basin in 2011

Table 5.6. Accuracy assessment of forecasting simulation for Murat Basin (2011)

	Performance	IMS Q1	IMS Q2	MODIS Q1	MODIS Q2
2011	**NSE**	0.65	0.61	0.66	0.63
	R^2	0.72	0.72	0.73	0.71
	Dv (%)	-0.57	-0.99	-1.11	-1.47
	RMSE	48.53	50.92	47.96	49.60

In Murat Basin, forecasted discharges with IMS and MODIS satellite data give approximate results in similar to hydrological validation study (Figure 5.8 and Table 5.6). Regression analysis and RMSE of forecasting studies with different satellite data are almost identical for both basins.

For both basins, forecasting studies have performance similar to hydrological models, thus one of MODIS or IMS can be used in such large basins in forecasting studies.

6. CONCLUSION

Snowmelt is an important component of the hydrological balance in many regions, especially mountainous areas. However, snow cover monitoring is particularly difficult in such areas because of the large spatial variability of snow characteristics and, often, limited availability of ground based data. Furthermore, ground observations represent point or just nearby area. Thus, satellite imagery is an important tool to monitor large snow extent and properties. In this study, satellite products from MODIS, MSG-SEVIRI and IMS in different spectral, temporal and spatial resolutions are used firstly in validating ground observation data and then in hydrological modeling/forecasting.

The selected three satellite snow products in different resolutions are validated with the records of 50 ground observation stations located in the eastern part of Turkey. MODIS and MSG-SEVIRI are affected by cloudiness since they are optical satellites, thus stepwise filtering techniques are applied to remove cloud. On the contrary, IMS provides clear-sky images because of being a blended product of several satellites and ground observations. According to the validation analysis, it can be stated that the most efficient filtering step is temporal filter to remove cloud but at the same time resulting in the highest trade off from accuracy. In the final cloud-free product, the accuracy performance order from high to low follows as IMS (95.33%), MODIS (93.56%) and MSG-SEVIRI (91.12), all showing a high accuracy level above 90%.

If the validation results are analyzed more in depth, it is seen that ground observation station classification as SNOTEL and CLM_SYP does point out interesting results. For example, SNOTEL accuracies are higher compared to CLM_SYP stations most probably due to more stable snow cover at the higher elevations as well as less microclimate effect from urban areas (since most of the CLM_SYP stations are located in urban areas). Also different satellite snow products indicate variable omission-commission errors. While MODIS shows a relatively stable error performance among observation stations, IMS gives high commission errors for low elevation stations (CLM_SYP) and MSG-SEVIRI leads to large errors in omission for high elevation stations (SNOTEL) and also in commission for low elevation stations (CLM_SYP). These error performances may be attributed mainly to spatial resolution and stable snow cover.

Considering the continuous daily snow cover area graphics during accumulation and depletion period of snow, MODIS product displays a more steady change compared to the others. This is mainly because of the powerful snow algorithm of the optical sensor, robust cloud filtering methodology as well as the finer spatial resolution of the product. Although built and used for meteorological conditions, MSG-SEVIRI optical product performs well overall, but shows high fluctuations at times most probably related to its algorithm and spatial properties. IMS, although a blended product that gave the best validation accuracy, sometimes depicts abrupt changes in snow extent especially during the depletion period. But it also performs quite well to catch the timing of new snow events. These conditions may well be explained by the product's course spatial resolution but blended property.

As a conclusion of the validation analysis, all three satellite snow products show high accuracy (above 90%) for the selected eastern region of Turkey. But it may be feasible to use IMS if the area of interest shows long durations of cloud cover during the snow season or if the basin relief is relatively low which makes the area prone to large number of transition events (area cover changes from snow to land many times in the snow season). Otherwise, for smaller basins MODIS could be preferred due to more sensitive spatial resolution. Also, IMS products may be preferable for the accumulation stage whereas, the optical satellites could be more appropriate during the melting period. Hence, basin area, elevation range, cloud cover duration, meteorological factors, timing and image availability for the region can play an important role for the selection of best satellite product.

Once the accuracy of satellite snow products using ground data are validated, their usability in hydrological models for simulation and forecasting is evaluated. The Snowmelt Runoff Model, a semi-distributed conceptual model taking into account daily snow covered area is utilized with three different satellite snow products. Parameter sets determined in calibration period between 2008-2010 water years are used for hydrological validation in 2011 and 2012 water years. The results show that MODIS and IMS give better performance than MSG-SEVIRI in hydrological modeling in both catchments but especially for Murat Basin.

After model calibration/validation, runoff forecasting is implemented using 1-2 day deterministic Numerical Weather Prediction data together with MODIS and IMS snow products only since MSG-SEVIRI had a low performance in hydrological modeling. Forecasts with both snow products provide similar performance and as expected 1-day forecasts gave slightly higher results than 2-day values due to less uncertainty in the weather conditions. Hence it can be concluded that, MODIS or IMS products can be employed as snow input data for hydrological modeling/forecasting in large basins such as the ones exemplified in this study.

On the overall, this study demonstrates the comparative analysis of three satellite snow products with different properties, impact studies of these products in hydrological modeling and their operational use in runoff forecasting for a more efficient water resources management in the selected region. Apparently, it is difficult to choose the best snow product since each one has advantages and disadvantages according to its properties. Although IMS and MODIS products gave slightly better results both in product validation and hydrological modeling, it would be more convincing to apply the methodology to a longer time period and to other watersheds when the data is available preferably including extreme water years.

REFERENCES

Abudu, S., Cui, C., Saydi, M. and King, J. P. (2012), *Application of snowmelt runoff model (SRM) in mountainous watersheds: A review*, Water Science and Engineering, 2012, 5(2): 123-136.

Aggarwal, S. P., Thakur, P. K., Nikam, B. R. and Garg V. (2014), *Integrated approach for snowmelt runoff estimation using temperature index model, remote sensing and GIS*, Current Science, Vol. 106, No. 3.

Anderson, M. L., Chen, Z. Q., Kavvas, M. L. and Feldman A., (2002), *Coupling HEC-HMS with atmospheric models for prediction of watershed runoff*, Journal of Hydrologic Engineering, **7**(4), 312-319.

Aytemiz, L. and Kodaman, T. (2006), *Sınır aşan sular kullanımı ve Türkiye – Suriye ilişkileri*, TMMOB Su Politikaları Kongresi. Turkey

BAP-1207F117 (2012-2014), *Türkiye'nin dağlık Doğu bölgelerinde harmanlanan uydu görüntüleriyle bulut azaltma yöntemleri ve doğrulaması*, Anadolu Üniversitesi, Eskişehir.

BAP-1307F284 (2013-2015), *Hidrolojik ensemble tahmin sisteminin uygulanması*, Anadolu Üniversitesi, Eskişehir.

BAP-1404F149 (2014-2015), *Kar erimesine bağlı akımların yapay sinir ağları ile modellenmesi*, Anadolu Üniversitesi, Eskişehir.

BAP-1505F459 (2015-2017), *Çeşitli kar uydu görüntülerinin karşılaştırmalı tutarlılık analizi ve kısa vadeli operasyonel hidrolojik tahmin sisteminde değerlendirme*, Anadolu University, Eskişehir

Barnes, W. L, Pagano, T. S. and Salomonson, V. V. (1998), *Prelaunch characteristics on the moderate resolution imaging spectroradiometer (MODIS) on EOS-AM1*, IEEE Transactions on Geoscience and Remote Sensing, 36, 1088–1100.

Baumgartner, M. F. and Rango, A. (1995), *A microcomputer based alpine snowcover analysis system (ASCAS)*, Photogrammetric Engineering and Remote Sensing, 61 (12), 1475-1486.

Berezowski, T., Chormanski, J. and Batelaan, O. (2015), *Skill of remote sensing snow products for distributed runoff prediction*, Journal of Hydrology, 524, 718-732.

Bertrand, C., Gonzalez, L., Ipe, A., Clerbaux, N. and Dewitte, S. (2008), *Improvement in the GERB short wave flux estimations over snow covered surfaces*, Advances in Space Research, 41 (11), 1894–1905.

Beşer, Ö. (2002), *The use of SSM/I for snow mapping over the eastern part of Turkey*, Master of Science Thesis, Middle East Technical University, Graduate School of Natural and Applied Sciences, Ankara.

Butt, M. J. and Bilal, M. (2011), *Application of snowmelt runoff model for water resource management*, Hydrological Process, 25, 3735-3747.

Byun, K., and Choi, M., (2014), *Uncertainty of snow water equivalent retrieved from AMSR-E brightness temperature in northeast Asia,* Hydrological Process, 28 (7), 3173–3184.

Cermak, J. and Bendix, J. (2008), *A novel approach to fog/low stratus detection using Meteosat 8 data,* Atmospheric Research, 87 (3–4), 279–292.

Chen, H., Xiang, T., Zhou, X., and Xu, C. Y. (2012), *Impacts of climate change on the Qingjiang Watershed's runoff change trend in China*, Stochastic Environmental Research and Risk Assessment, 26, 847-858.

Gao, H., Birkett C. and Lettenmaier D. P. (2012), *Global monitoring of large reservior storage from satellite remote sensing*, Water Reourse Research, 48.

Gómez-Landesa, E. and Rango, A. (2002). *Operational snowmelt runoff forecasting in the Spanish Pyrenees using the Snowmelt Runoff Model,* Hydrological Processes, 16, 1583-1591.

Gözel, E. (2011), *Modeling of seasonal snow water potential and daily discharges in the Upper Euphrates Basin*, Master of Science Thesis, Anadolu University, Graduate School of Science, Eskişehir.

Grayson, R. B., Blöschl, G., Western, A. and McMahon, T. (2002). *Advances in the use of observed spatial patterns of catchment hydrological response*. Advances in Water Resources, 25, 1313–1334.

Guneriussen, T., Bjerke, P. L., Hallikainen, M., Hiltbrunner, D., Johnsen, H., Jaaskelainen, V., Kolberg, S. A., Koskinen, J., Maltzer, C., Pullianen, J., Sand, K., Solberg, R. Standley, A. and Wiesmann, A. (2000), *Research and Development of Earth Observation Methods for Snow Hydrology, SnowTools Final Report*, NORUT Report, 431/47-00.

Hall, D. K. and Martinec, J. (1985), *Remote sensing of ice and snow*, Chapmen and Hall, London, 189.

Hall, D. K., Riggs, G. A. and Salomonson, V. V. (1995). *Development of methods for mapping global snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data*, Remote Sensing of Environment, 54, 127– 140.

Hall, D. K., Foster, J. L., Verbyla, D. L., Klein, A. G. and 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. and Riggs, G. A. (2007), *Accuracy assessment of the MODIS snow products*, Hydrological Processes, 21, 1534-1547.

Hancock, S., Baxter, R., Evans, J. and Huntley, B. (2013), *Evaluating global snow water equivalent products for testing land surface models*, Remote Sensing of Environment, 128, 107–117.

He, Z. H., Parajka, J., Tian, F. Q. and Blöschl, G. (2014), *Estimating degree-day factors from MODIS for snowmelt runoff modeling*, Hydrology and Earth System Sciences, 18, 4773-4789.

Helfrich, S. R, McNamara, D., Ramsay, B. H., Baldwin, T. and Kasheta T. (2007), *Enhancements to, and forthcoming developments in the interactive multisensor snow and ice mapping system (IMS)*, Hydrological Process, 21, 1576–1586.

Hu, X., Bailey, J. O., Barret, E. C. and Kelly, E. J. (1993), *Monitoring snow area and depth with integration of remote sensing and GIS*, International Journal of Remote Sensing, 14, 17, 3529-3268.

Immerzeel, W. W., Droogers, P., de Jong, S.M. and Bierkens, M. F. P. (2009), *Large-scale monitoring of snow cover and runoff simulation in Himalayan river basin using remote sensing*, Remote Sensing of Environment, 113, 40-49.

Jasper, K., Gurtz, J. and Lang, H., (2002), *Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model*. Journal Hydrology, 267, 40–52.

Jonsdottir, J. F. and Şorarinsson, J. S., (2004), *Comparison of HBV models driven with weather station data and with MM5 meteorological model data*, Orkustofnun Hydrological Services, Report No. OS-2004/017.

Kaya, I. (1999), *Application of Snowmelt Runoff Model using remote sensing and geographic information systems*, Master of Science Thesis, Middle East Technical University, Graduate School of Natural and Applied Sciences, Ankara.

Kult, J., Choi, W. and Choi, J. (2014), *Sensitivity of the snowmelt runoff model to snow covered area and temperature inputs*, Applied Geography, 55, 30-38.

Kunstmann, H. and Stadler, C. (2005), *High resolution distributed atmospherichydrological modeling for Alpine catchments,* Journal of Hydrology, 314, 105–124.

Lahtinen, P., Erturk, A. G., Pulliainen, J. and Koskinen, J. (2009), *Merging flat/forest and mountainous snow products for extended European area*, International Geoscience Remote Sensing Symposium., 2, 563–566.

Li, X. and Williams, M. W. (2008), *Snowmelt runoff modeling in an arid mountain watershed, Tarim Basin, China*, Hydrological Process, 22, 3931-3940.

Martinec, J. (1975), *Snowmelt runoff model for streamflow forecasts*, Nordic Hydrology, 6, 145- 154.

Martinec, J. and Rango, A. (1987), *Interpretation and utilization of areal snow cover data from satellites*, Annals of Glaciology, 19, 166-169.

Martinec, J., Rango, A., and Roberts, R. T. (2008), *Snowmelt Runoff Model (SRM) User's Manual*, 19-39, New Mexico State University Press., New Mexico.

Mitchell, K. E., DiMego, G. J. and Black, T. L. (1993), *Case study on the impact of improved snow cover and sea ice on wintertime forecasts of NMC's regional NGM and Eta models*, Preprints, 13th Conference of Weather Analysis and Forecasting, American Meteorological Society, Vienna, VA, 516–517.

Nagler, T. and Rott, H. (1997), *The application of ERS-1 SAR for snowmelt runoff modeling,* In: M.F. Baumgartnet, G.A. Schultz, and A.I. Johnson (eds), 55th Scientific Assembly of the International Association of Hydrological Sciences, Rabat, Morocco, 28-30 April, 1997 (IAHS Publication No.242, pp. 119-126).

Nagler, T., Rott, H., Malcher, P. and Muller, F. (2008), *Assimilation of meteorological and remote sensing data for snowmelt runoff forecasting,* Remote Sensing of Environment, 112, 1408–1420.

Parajka, J. and Blöschl, G. (2012), *MODIS-based snow cover products, validation, and hydrologic applications*, In: Multiscale Hydrologic Remote Sensing: Perspectives and Applications (N. B. Chang & Y. Hong, eds). CRC Press, Taylor & Francis Group, Boca Raton, FL, 185–212.

Prasad, V. H. and Roy, P. S. (2005), *Estimation of snowmelt runoff in Beas Bas*in*, India*, Geocarto International, 20(2), 41-47.

Pu, Z., Xu, L. and Salomonson, V. V. (2007), *MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau*, Geophysical Research Letters, 34, L06706.

Qiu, L., You, J., Qiao, F. and Peng, D. (2014), *Simulation of snowmelt runoff in ungauged basins based on MODIS: a case study in the Lhasa River basin*, Stochastic Environmental Research and Risk Assessment, 28, 1577–1585.

Ramsay, B. H. (1995), *An overview of NOAA/NESDIS's interactive multisensor snow and ice mapping system*, Proceedings of 1995 First Moderate Resolution Imaging Sprectroradiometer MODIS Snow and Ica Workshop, Greenbelt, MD, National Aeronautics and Space Administration Conference Publication 3318, 23-27.

Ramsay B. H. (1998), *The interactive multisensor snow and ice mapping system*, Hydrological Processes, 12, 1537–1546.

Rango, A., Salomonson, V. V. and Foster, J. L. (1977), *Seasonal streamflow estimation in the Himalayan region employing meteorological snowcover observations*, Water Resources Research, 13 (1), 109-112.

Rango, A. (1996), *Spaceborne remote sensing for snow hydrology applications, Hydrological Sciences Journal*, 41, 477-494.

Rango, A., Martinec, J. and Roberts, R. T. (2008), *Relative importance of glacier contributions to water supply in a changing climate*, World Resources Review, 20(3), 487-503.

Rango, A., Fernald, A., Steele, B. H. and Ochoa, C. (2013), *Acequias and the effects of climate change*, Journal of Contemporary Water Research and Education, 151, 84-94.

Riggs, G. A., Hall, D.K. and Salomonson, V. V. (2006), *MODIS Snow Products User Guide to Collection 5*.

Rott, H., Nagler, T., Glendinning, G., Wright, G., Miller, D., Gauld, J., Caves, R., Ferguson, R., Quegan, S., Turpin, O., Clark, C., Johansson, B., Gyllander, A., Baumgartner, M., Kleindienst, H., Voigt, S. and Pirker, O. (2000), *HYDALP. Hydrology of Alpine and High Latitude Basins, Final Report*, Institut für Meteorologie and Geophysik, Universitat Innsbruch, Mitteilungen, 4.

Seidel, K., Brush, W. and Steinmeier, C. (1994), *Experiences from real time runoff forecasts by snow cover remote sensing*, IEEEIGARSS.

Seidel, K., Ehrler, C., and Martinec, J. (1998), *Effects of climate change on water resources and runoff in an alpine basin*, Hydrological Processes, 12(10-11), 1659-1669.

Sharma, V., Mishra, V. D. and Joshi, P. K. (2013), Implications of climate change on streamflow of a snow-fed river system of the Northwest Himalaya, Journal of Mountain Science, 10(4), 574–587

Sürer, S. and Akyürek, Z. (2012), *Evaluating the utility of the EUMETSAT HSAF snow recognition product over mountainous areas of eastern Turkey*, Hydrological Science Journal, 57, 1684–1694.

Şensoy, A. (2000), *Spatially distributed hydrologic modeling approach using geographic information systems*, Master of Science Thesis, Middle East Technical University, Department of Civil Engineering, Ankara.

Şensoy, A. (2005), *Physically based point snowmelt modeling and its distribution in Upper Euphrates Basin*, Doctor of Philosophy Thesis, Middle East Technical University, Graduate School of Natural and Applied Sciences, Ankara.

Şensoy, A. and Uysal, G. (2012), *The Value of snow depletion forecasting methods towards operational snowmelt runoff estimation using MODIS and numerical weather prediction data*, Water Resources Management, 26, 3415-3440.

Şorman, A. A. (2005), *Use of satellite observed seasonal snow cover in hydrological modeling and snowmelt runoff prediction in Upper Euphrates Basin, Turkey*, Doctor of Philosophy Thesis, Middle East Technical University, Graduate School of Natural and Applied Sciences, Ankara.

Şorman, A. A., Şensoy, A., Tekeli, A. E., Şorman, A. Ü. and Akyürek, Z. (2009), *Modeling and forecasting snowmelt runoff process using the HBV model in the eastern part of Turkey,* Hydrological Processes, 23, 1031–1040.

Tekeli, A. E. (2000), *Integration of remote sensing and geographic information systems on snow hydrology modeling*, Master of Science Thesis, Middle East Technical University, Department of Civil Engineering, Ankara.

Tekeli, A. E. (2005), *Operational hydrological forecasting of snowmelt runoff model by RS-GIS Integration*, Doctor of Philosophy Thesis, Middle East Technical University, Graduate School of Natural and Applied Sciences, Ankara.

Tekeli, A. E., Akyürek, Z., Şorman, A. A., Şensoy, A. and Şorman, A. Ü. (2005) *Using MODIS snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey*, Remote Sensing of Environment, 97 , 216-230.

TÜBİTAK-108Y161 (2008-2011), *Yukarı Fırat Havzasında, arazi ölçümleri, uydu teknolojileri, hava tahmin verileri ve hidrolojik modeller kullanılarak,* *kar potansiyelinin dönemsel ve akımların günlük tahmini*, Anadolu Üniversitesi, Eskişehir

TÜBİTAK-113Y075 (2013-2015), *Dağlık Fırat ve Seyhan Havzalarında EPS ve uydu verileri ile operasyonel hidrolojik tahmin sisteminin geliştirilmesi*, Anadolu Üniversitesi, Eskişehir.

Uzunoğlu, E. (1999), *Application of the SLURP model using remote sensing and geographic information systems*, Master of Science Thesis, Middle East Technical University, Department of Civil Engineering, Ankara.

Westrick, K., Storck, J. P. and Mass, C. F. (2002), *Description and evaluation of a hydrometeorological forecast system for mountainous watersheds*, *Weather and Forecasting,* 17, 250-262.

WMO (1999), *Areal modeling in hydrology using remote sensing data and geographical information system*, Publication No. 885, Operational Hydrology Report No. 44, World Meteorological Organization, Geneva, Switzerland.

Yamankurt, E. (2010), *Harmanlanan uydu görüntülerinin karla kaplı alanlar üzerindeki etkisi ve Türkiye'nin Yukarı Fırat Havzası'nda dönemsel kar potansiyelinin modellenmesi*, Master of Science Thesis, Anadolu University, Department of Civil Engineering, Eskişehir.

Yücel, I., Önen, A., Yılmaz, K. K. and Gochis, D. J. (2015), *Calibration and evaluation of a flood forecasting system: Utility of numerical weather prediction model, data assimilation and satellite based rainfall*, Journal of Hydrology, 523, 49–66.

http://www.enerjiatlasi.com/hidroelektrik/keban-baraji.html (searched in 2015)

http://www.globsnow.info/ (searched in 2015)

http://www.mmm.ucar.edu/mm5 (searched in 2015) http://www.natice.noaa.gov/ (searched in 2015)

https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/numerical-weather-prediction (searched in 2015)

http://hsaf.meteoam.it/ (searched in 2015)

https://lpdaac.usgs.gov/tools/modis_reprojection_tool (searched in 2015)

http://nsidc.org/data/docs/noaa/g02156_ims_snow_ice_analysis/index.html (searched in 2015)

http://oss.deltares.nl/web/delft-fews (searched in 2015)

http://reverb.echo.nasa.gov (searched in 2015)

http://snowpex.enveo.at/ (searched in 2015)

http://srtm.csi.cgiar.org (searched in 2015)