

Hydrological Response to Snow Cover Changes Using Remote Sensing over the Oum Er Rbia Upstream Basin, Morocco

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Abstract

Water supply for the arid irrigated plains in Morocco depends largely on the upper mountainous basins where significant amounts of precipitation fall as snow. In the Oum Er-Rbia River Basin (OER), snow covers the highest elevations from November to April. Despite the importance of this component in the hydrological cycle, snowmelt contribution to streamflow is still poorly understood and no monitoring stations exist in this zone. Therefore, studying the spatiotemporal change of snow cover through satellite observations to investigate its influence on the hydrological response of this scarce region is thus required to better manage water resources.

This chapter explores basic characteristics of snow cover area (SCA) in the upstream area of the OER River (Tillouguite sub-basin) using MODIS daily snow cover products (MOD10A1). Correspondence between streamflow, accumulated air temperature and SCA changes during the winter and spring periods was examined from 2001 to 2009 at a weekly time step. The result shows an inverse linear relation between the maximum SCA and the mean normalized stream flow values, and a significant relation between the relative streamflow and cumulated temperature, especially during spring melt season depending on the length of the melt period. These primary results could be used to develop simplified predictable models for spring discharge in ungauged watershed using remote sensing and accumulated air temperature.

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1 Introduction

Mountainous regions contain about 70% of the earth's continental fresh water [1] and considered as the world's natural “water tower” [2]. There is thus a strong interaction between mountains and lowlands; about 40% of world's population lives in the catchments influenced by mountainous ranges [3]. Therefore, change in the total amount of water supplied by these areas directly affects human society and has implications for all living species. Vulnerability of Water resources to any change becomes more important, especially in countries with arid conditions, where water is scarce [4]. In this context, seasonal snow cover constitutes an important component of hydrological cycle in several mountainous area around the world [5–10]. However, in Morocco, the Atlas Mountain ranges supply significant amount of water to support irrigation for the large downstream lower plains; (e.g. Tadla, Tensift, Souss, Saiss, Tafilalt, and Draa). These irrigated plains

produce more than one-third of all foodstuffs in Morocco and therefore contribute significantly to food security. In winter, both liquid and solid precipitations fall at high altitudes and snowfall represents between 20 and 80% of total precipitation measured on the southern and the northern slopes of the High Atlas range [11, 12] respectively.

According to the IPCC report, the global average temperature had a rise of 0.3–0.7°C over the past 100 years [13], several studies highlighted a significant increase in temperatures with a general tendency toward drier conditions [14–17]. Whereas, rainfall trends are generally less significant with heterogeneous change depending to the geographical location [18–20]. Similarly to rainfall, snow cover area in the Atlas mountain is characterized by a high inter-annual signal [21] with an increase of snow cover duration in February–March and a decrease in April–May between 2000 and 2013 using MODIS snow product [22]. However, these changes will likely have a strong effect on water availability at the basin scale. In Northern Morocco, future projection using climate change signal under scenarios 4.5 and 8.5 indicates a decrease of respectively 30–57% in surface runoff for the mid-term (2041–2062) [23]. Studies in Morocco have also relived that populations are very vulnerable to extreme hydrological events [24, 25] and the change of the hydrological response will directly affect strategies and policies of water resource management and socio-economic development. Water resources in the high altitude of the Oum Er Rbia (OER) basin, one of the major water resources basin in Morocco, play an important role in crop irrigation, drinking and industrial water supplies and hydropower production. However, OER catchment meets the region needs and demands of drinking water to surrounding urban centres such as Casablanca, Marrakech, Béni Mellal, Settat, and Berrechid. The total annual volume allocated to drinking water is about 386 million cubic meters per year. Agriculture sector, however, consumes more than 85% of available water for agriculture use [26]. In the climatic context of the OER basin, water availability is one of the main limiting factors in achieving good crop yields. The basin supplies water to about 369,600 irrigated hectares, within and surrounding the basin, and requires 3,400 million cubic meters per year and generate about 2/3 of the total hydropower in the country.

Notably absent are studies concerning snow hydrology in the headwater part of the OER catchment despite the importance of this component to the water balance. Thus, monitoring snow cover dynamics is a crucial step to anticipate streamflow response. Measuring snow parameters through snow surveys and meteorological stations is the efficient way to quantify and obtain accurate information about seasonal snowpack. Due to difficult topography and inaccessibility conditions, ground measurements are lacking for most of the high terrain mountains. This is the case for the upper part of the OER basin; a spatial distribution of network stations is inadequate and marked by the absence of snow measurements.

Hence, remote sensing data rest a unique way to derive some snow parameters in such rough terrain. In hydrological application, this spatial information of snow cover serve as an input for snowmelt models [27–30].

The purpose of this study is to investigate the potential of using remote sensing data to evaluate the hydrological response to snow covered area (SCA) and temperature change in scarce data basin. The spatial and temporal signal of SCA, obtained from daily snow product MODIS10A1, is analyzed to understand the snow dynamics in the Tillouguite sub-basin located in the upper part of the OER River. To quantify the potential snowmelt contribution to streamflow, the relationship between SCA and hydro-meteorological data is assessed. Defining the link between streamflow and SCA in these areas will provide information regarding the influence of snowmelt rate on discharge over the entire mountainous basins in Morocco.

2 Study Area

The Tillouguite sub-basin is located in the upstream of Bin El Ouidane Dam in Tadla Azilal region between the High Atlas mountainous range and the Tadla plain, at about 60 km in the south of Beni Mellal city in the center of Morocco (Fig. 1). The spatial domain of the sub-basin covers an area of 2400 km² in which the elevation ranges from 1000 to about 3300 m above sea level (a.s.l.). The Tillouguite sub-basin is one of the major contributors of water to downstream area, especially for the Bin El Ouidane dam storage. This reservoir, considered as the largest in the region, is used for domestic water supply, irrigation, industry and hydropower generation.

Topographic characteristics, elevation, slope and aspect, were derived from SRTM digital elevation model (DEM) with a spatial resolution of 3 arc-second. The SRTM (Shuttle Radar Topography Mission) acquired elevation data in February 2000 on a near-global scale to constitute the most complete high-resolution digital topographic database of Earth landmass [31]. In order to overlay MODIS snow cover data, the original DEM was resampled to 500 m using a bilinear resampling method that gives better results for continuous data such as elevation and slope [32].

In the mountainous areas, hydrological and meteorological conditions are related to elevation; therefore, the Tillouguite sub-basin was divided into 6 elevation zones with an elevation difference of 400 m. Figure 2 shows the distribution curve of the elevation zones for the studied sub-basin. The distribution of basin area along with altitudinal variation indicated that the Tillouguite sub-basin lies within the elevation range 1000–3400 m a.s.l. (zones Z1–Z6), and that more than 70% of the basin area lies between zones Z4 and Z5. Further, it also showed that 87% area falls within middle elevation zones (Z3–Z5), whereas only 2 and 10% in the higher and lower elevation zones respectively (Z6 and Z1–Z2).

Fig. 1 Geographic situation of the studied basin

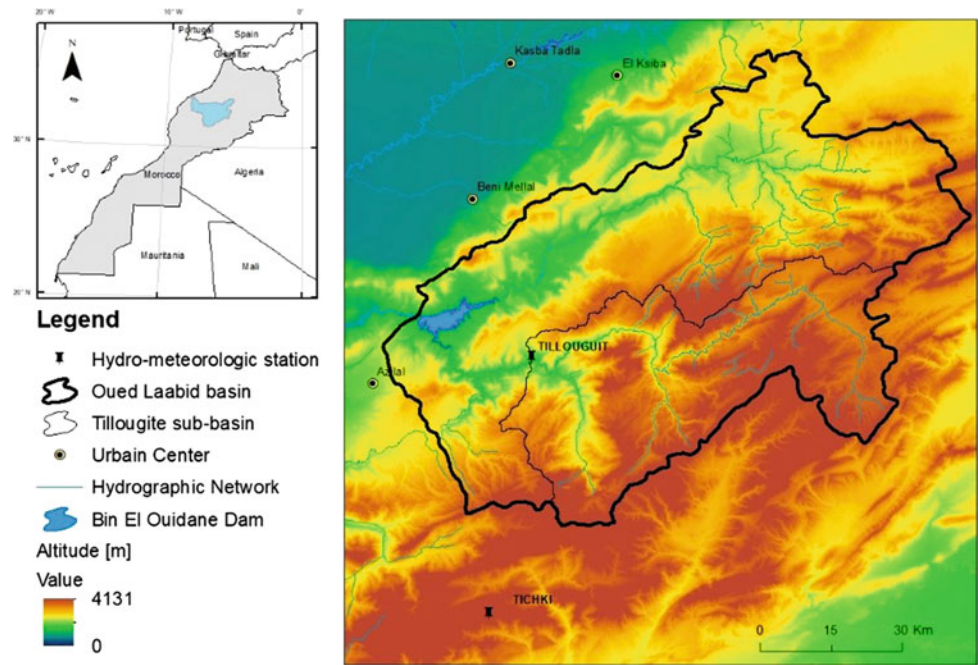
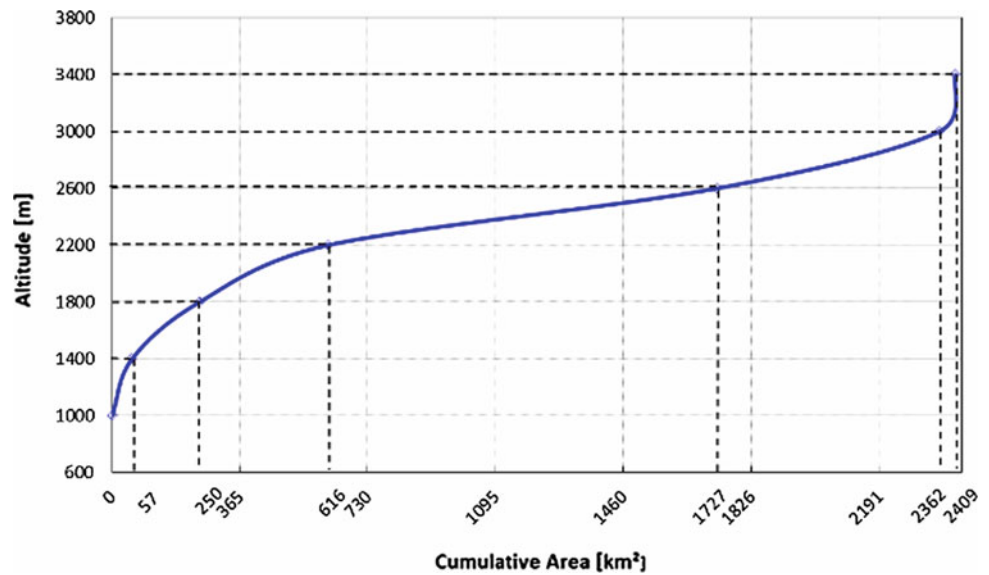


Fig. 2 Hypsometric curve for the Tillougite sub-basin



The situation of the hydro-meteorological stations used in this work and the topographic variation of the basin are shown in Fig. 1. In general, the climate of the study area is semi-arid with a great variability of precipitations in time and space [33]. Due to the topographic effect, the basin receives snow-fall during winter season [22].

Average temperature, in the Tillougite sub-basin outlet, is about 28 °C in summer (July) and 7 °C in winter (January), while in the higher elevation it is below freezing point throughout winter season. The basin receives annual average precipitation of 700 mm in the lower part of the basin, which more than 80% occurs between October and May.

According to the altitudinal effect, this amount decreases with elevation with an important percentage fall as snow. The variation of 10 years (2000–2010) average monthly rainfall and discharge is given in the Fig. 3. Globally, the distribution of rainfall is irregular over the year with two distinct periods; a dry period (summer) from May to October and a rainy period from November to April. Seasonal variability of runoff, illustrated with standard deviation error bar, reflects the heterogeneity form of rainfall. It can be seen also that the maximum runoff is observed in February, April and March, whereas minimum values are measured in Jun to October.

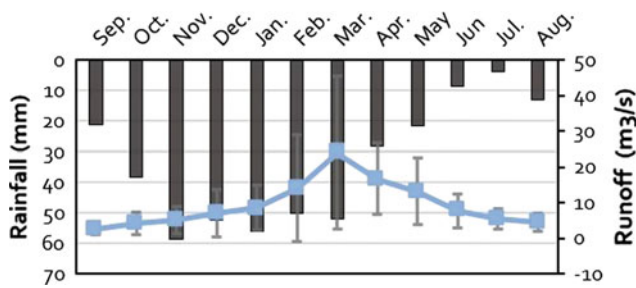


Fig. 3 Mean monthly rainfall (black bars) and runoff (blue line) between 2000 and 2010 over the Tillouguite sub-basin, error bar is a standard deviation of runoff records

3 Data Sets and Methods

3.1 MODIS Snow Product

Given a lack of in situ snow measurements in the high mountainous area in the studied basin, we used remote sensing data to monitor snow cover extent and estimate their spatial and temporal variation. For this, we selected “The Moderate Resolution Imaging Spectroradiometer (MODIS) snow product” that is freely available. We used specifically in this study, the MODIS Terra snow cover daily L3 global gridded products (MOD10A1) version 5 at a spatial resolution of 500 m (http://nsidc.org/data/modis/data_summaries). Under cloudiness conditions, the quality of the snow cover products is strongly affected using optical remote sensing. In order to reduce cloud coverage effect, we adopted a methodology based on a spatio-temporal filtering algorithm [22]. To obtain a continuous SCA at a daily time scale, we applied a linear interpolation method over days without information. The spatial and temporal variation of SCA over the basin was analyzed from 13 hydrological seasons and derived for six elevation zones in the basin.

3.2 Hydro Meteorological Measurements

Hydro meteorological measurements; rainfall, discharge; used in this study were obtained from the Tillouguite station managed by the Hydraulic Basin Agency of OER and located within the basin at the elevation of 1100 m a.s.l (Fig. 1). However, temperature data from the years 2000–2010, which were recorded at the Tichki station installed outside the basin at 3200 m a.s.l, were supplied by IMPETUS program [12]. To understand the interrelationship between SCA obtained from remote sensing and hydroclimatic factors, all datasets at different time step and over the same periods as MOD10A1, from 1 December to 30th April every season between 2000 and 2009 are analyzed. The daily streamflow

data are averaged into weekly values and precipitations are accumulated for the same time step. Due to strong variability of streamflow peak over the year, we used a relative value by dividing the daily discharge by the maximum value observed in the studied period (from December to April) for each season. For temperatures measurements we used the cumulated degree-days (CDD) for each week calculated from the daily mean temperature as a cumulatively summed degree-day over every 7 days when temperature exceeds 0 °C. When daily temperature is below 0 °C, the degree-day is set equal to 0.

4 Results and Discussion

Rainfall and snowfall are the main factors affecting streamflow response in the mountainous arid basins. To investigate this relationship, especially the dependence between surface water availability and snowmelt, we analyze the stream-flow variability with snow cover extent, rainfall and temperature at different time step.

4.1 Spatial and Temporal Variation of Snow Cover

Figure 4 shows the spatial distribution of SCA occurrence over Tillouguite sub basin, calculated from daily SCA MODIS product from 1st December to 30th April during 13 seasons (from 2000 to 2013). Except around the outlet and riverbeds, almost all the area of Tillouguite sub-basin experienced snowfall during the hydrological seasons with an inter-annual heterogeneity. Although, the occurrence of snow events is not consistently even over space and time. Areas close to the banks of the basin’s main rivers rarely register snowfalls with an occurrence below 20% throughout the seasons. However, in the high elevation pixels the snow begins to be more frequent. It ranges from 30% for a drier season as 2009/2010 to reach more than half of the 2012/2013 season.

To describe SCA dynamics at spatial and temporal scales, we calculate the percentage of snow cover extent every 400 m elevation band from 1000 to upper 3400 m. Figure 5 shows the total snow-covered days of the 13 hydrological seasons in six elevation zones. There is an obvious annual pattern for snow cover duration where the topographic control of snowfall is clearly illustrated. Although, a large discrimination between low and high altitudes is shown. Generally, snow is present above 1400 m, except 2006/07 and 2010/11 seasons where SCA appear above 1800 m. The duration of snowpack shows a marked increase with altitude, ranging from an average of 47 days in 2009/2010 to 144 days in 2012/2013. In the high elevation zone (upper 3400 m), snow-pack can rest on ground between 110 and 230 days.

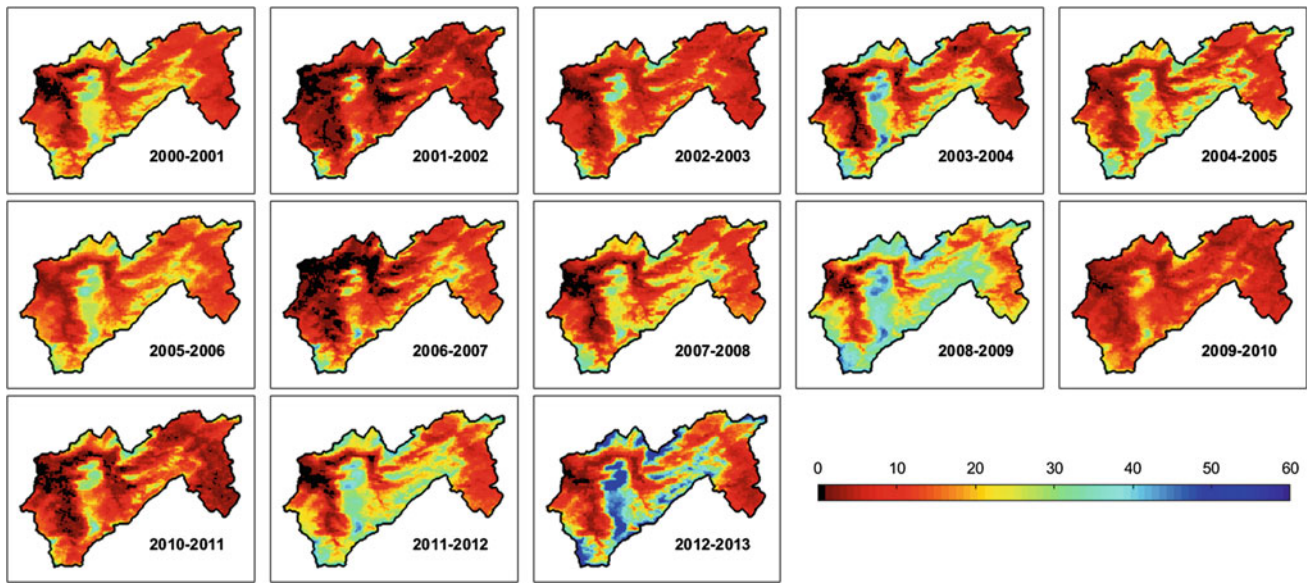


Fig. 4 Annual SCA occurrence frequency over Tillouguite sub basin

Fig. 5 Snow cover duration between 2000 and 2013 period for six elevation zones in the Tillouguite sub basin

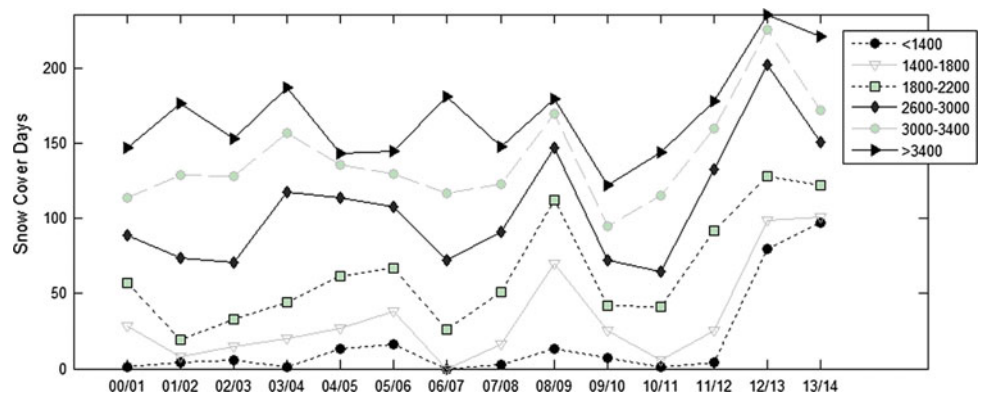
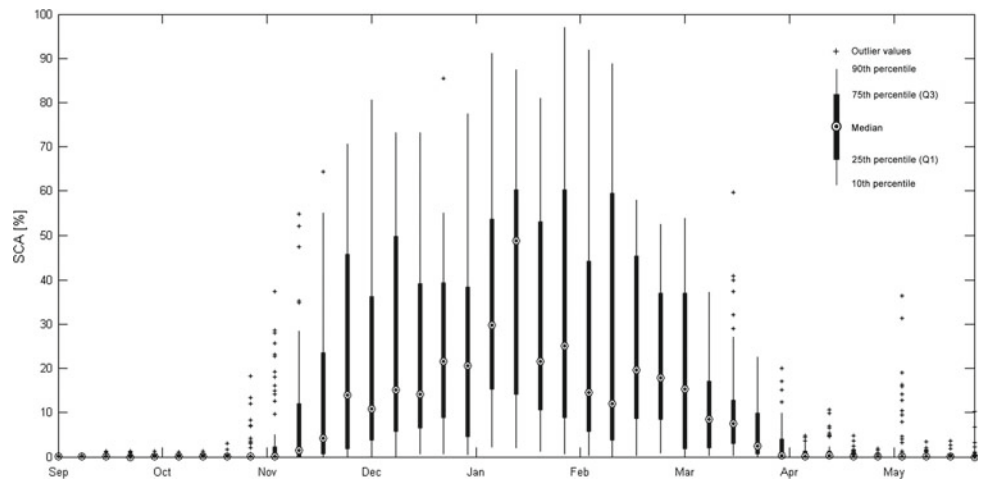


Fig. 6 Behavior of SCA proportion at weekly inter-annual variation between 2000 and 2013 hydrological years



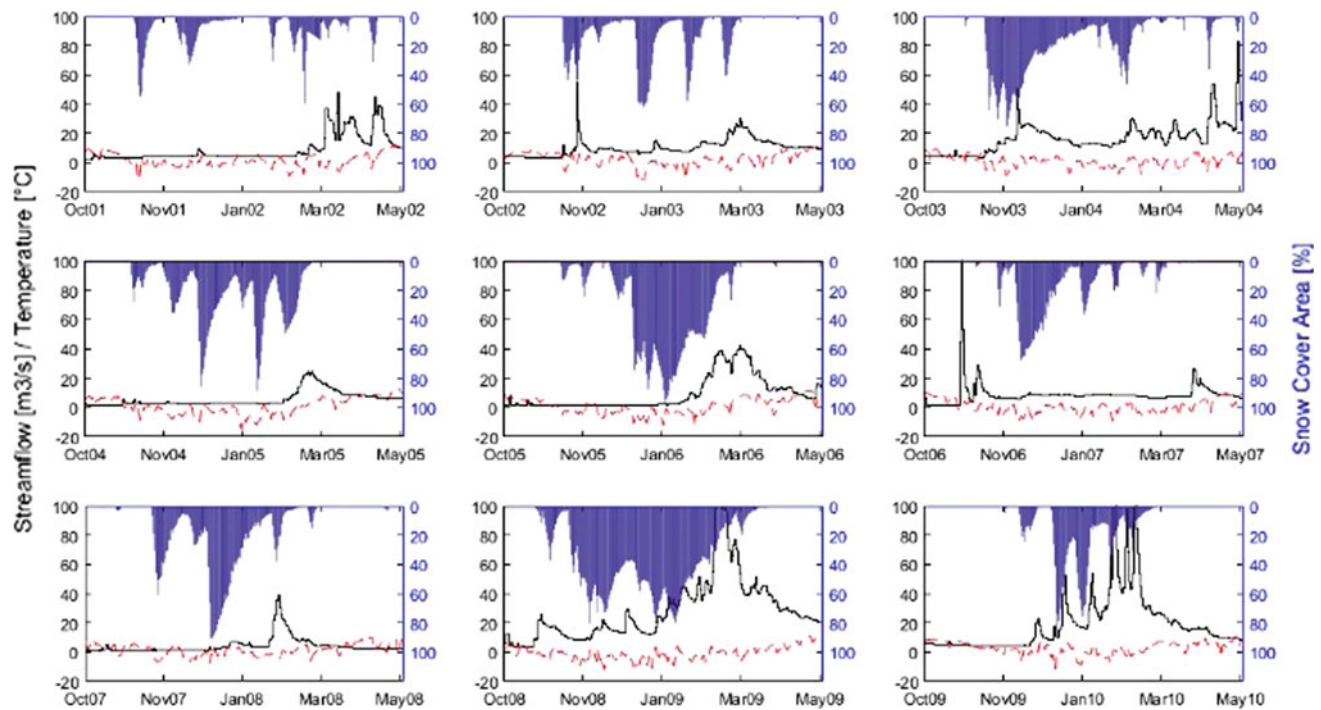


Fig. 7 Daily streamflow variation versus SCA percentage and temperature of nine-season

The box plot graph in Fig. 6 allows us to analysis the behavior of SCA along the studied period in weekly time step. It is relieved that, SCA varies strongly from season to other. Using the median values of SCA proportions, snow season starts effectively in the second week of November and finishes in early April. The 75th percentile indicates that the maximum of snow cover occurs during winter months (December, January and February), when about 36 to 60% of the basin is snow covered.

4.2 Hydrological Responses to Snow Cover Change

Figure 7 compares daily snow cover variation, streamflow and mean temperature from October to April. It is observed that the streamflow variation is strongly linked to temperature and snow cover change. Although, each discharge peak is mostly associated with a snow surface regression period, except 2006/07 season. This relationship, clearly identified for the month from January to March, indicates that snowmelt contributes to runoff for season with a large snow cover duration (e.g. 2008/2009 and 2005/2006).

In order, to understand properly the relationship between temperature, SCA and streamflow, we used a concept of cumulative degree-day (CDD) and normalized streamflow. For each season (from December to April), the linear correlation coefficient between maximum SCA, mean normalized streamflow and CDD was calculated. This analysis was

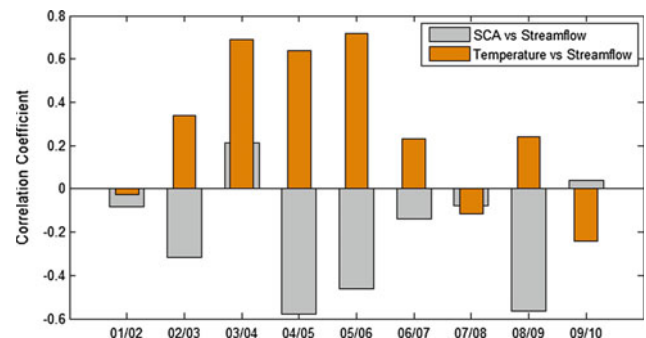


Fig. 8 Annual correlation coefficient between maximum SCA, CDD and normalized streamflow

also assessed for different lag time prior to the observing date of streamflow peak (not presented in this paper). As shown in Fig. 8, normalized streamflow is inversely correlated with maximum SCA, meaning that a regression of SCA in a week derives an increase of streamflow. This results is agrees using CDD variable, where the correlation coefficient reach a value of 0.78 in 2005/2006. We conclude that, if air temperature increased, then SCA decreased accordingly excepting 2001/2002 and 2009/2010 seasons. In addition, it is clearly marked that SCA fluctuations, controlled by air temperature, affect the hydrologic response. This relationship varies with the length of the snowy season and the melt period (Fig. 9). For example, in 2004/2005 season, a regression of the weekly maximum SCA from 50 to 7 % generate a normalized streamflow peak from 0.3 to 0.9 in about two weeks.

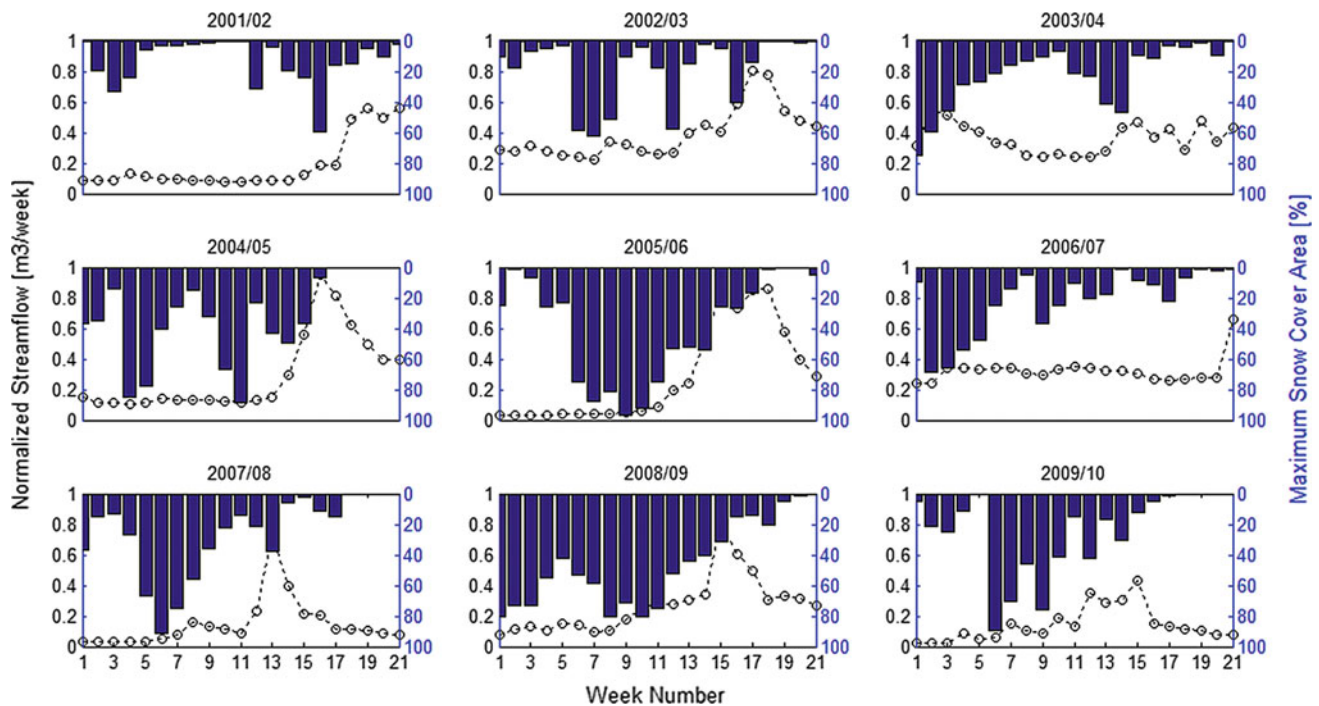


Fig. 9 Relationship between normalized streamflow and maximum SCA at weekly time step

5 Conclusion

Investigating SCA dynamics is the first step to evaluate snowmelt contribution on river streamflow and water cycle in the scarce data basin such as mountainous area in Morocco. In this study, SCA variation at spatial and temporal scales was analyzed over the Tillouguite sub-basin using daily MODIS snow product (MOD10A1) between 2001 and 2009. Generally, there are large differences in snow cover percentage and snow cover duration from year to year, with respect to the topographic effect. The interrelation between streamflow variation together with temperature and SCA change was examined in detail at different time step. It is found that the weekly maximum SCA, for a most of seasons, showed a negative correlation with accumulated degree-days, but the relationship varied with the length of the melt period. SCA is also negatively related to relative streamflow excepting some season (e.g. 2001/2002 and 2007/2008) where rainfall contribution is largely marked.

Despite this importance of snowpack in mountainous basin of Morocco, there are still many gaps in the existing networks of snow measurements at both national and regional scale. Therefore, it may be noted that this is for the first time a snow study has been undertaken for the OER basin. These primary results will be used to develop a simplified model, applicable to individual watersheds, to predict early

spring discharge using remotely sensed snow cover information and accumulated air temperature. This approach may be useful for a practical utility to forecast potential snowmelt in ungauged basin with lack of in situ observations. The approach's simplicity should also make it relatively easy and operational for water resources managers, especially for the Bin El Ouidane reservoir located downstream of the basin and used principally for irrigation and hydropower production. In addition, remotely sensed SCA at the basin scale through long-term period is useful as an indicator of climate change impact to the snow storage and is essential for managing water resources.

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