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Importance of snowmelt study for managing mountain basins (Case study; Hamedan province west of Iran)

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ABSTRACT

According to the studies, about 60 percent of surface waters and 57 percent of ground waters in our country originate in snowy peaks. In the most of the northern hemisphere and specifically in Alpine areas, snow melt runoff both causes the instantaneous flow peaks and constitutes the better part of the annual debit. Considering the problems posed by field monitoring and measurement of snow coverage surfaces in mountainous areas, satellite imagery is now considered a viable alternative. In the present study, we set out to investigate a section of Gharachai Basin as a representative case. Data collected via Terra satellite was used in tandem with MODIS for calculation of daily variations of snow coverage surface area. For the days for which no satellite data were available, we substituted the use of daily measured temperature and snow density data. Daily variation of snow coverage surface area was compared against variation in debit, both recorded for a period of two years. Results show that snowmelt runoff has a drastic effect on the debit and this effect is more pronounced in the month of April. Hydrographs representing the basin show that the snowmelt period corresponds to the highest monthly water table. It can be seen that snowmelt causes the increase in and maximization of the groundwater and surface water volume in the area; the issue is hence important for water resource planning.

Keywords: Snowmelt, MODIS, Hydrograph, Gharehchai Basin

INTRODUCTION

Snow is an important form of precipitation in the hydrological cycle of mountainous regions. It has a big role in refilling agricultural and residential water supplies through “delayed flows” during wet seasons and “minimal flows” during dry seasons, as well as in the production of energy. Due to its delayed nature, snowmelt runoff is a major source of resupplying ground water aquifers, and due to its simultaneity with spring precipitations it can be a cause of riverbed overflowing and devastating floods [11]. Upland snow reservoirs greatly affect seasonal runoff patterns of lower low lying regions and this is more conspicuous in regions which have a very dry season, where the snowmelt runoff is a major source for the supplying of water [8, 44]. runoff and natural glaciers’ runoff are the main source of supplying water to more than one sixth of the world population and, a source which may be endangered by global warming. Monitoring the existing snow and ice coverings and their melt-down rates is also very important for understanding regional hydrological cycles [3, 4 AND 15]. Snow is a major factor in determining the Earth surface energy inventory [10]. The researcher used 58 pieces of satellite photography to investigate the variation in the snow covering and snowline of Baspa basin. Their studies showed that due to the rapid industrial growth of the 20th century and the ensuing global warming, temperature in the region has been on the rise and the snowline has been retreating to higher altitudes at a rate of 150 meters per degree Celsius of added temperature. It can be seen that investigating snowmelt runoff is important for understanding river overflows and water supply variations [36]. Predictions of flow debit for the next fifty years show that, due to global rise in temperature, snowmelt would be faster immediately after the snowfall [27]. Obtaining accurate measurements of the time of the beginning of snowmelt and its seasonal extent is of prime importance for predicting flow debits and water supply [34, 38]. Also because of the role of snowfall in creating surface waters and feeding aquifers, its measurement is very important in estimating surface water flows and ground water volumes [30]. The study of snowfall runoff is a basic duty of hydrologists in many places, as it is vital for sustaining water supplies and monitoring floods. In some regions (such as the western United States) snowmelt runoff is almost the sole source for providing water to industrial, residential and agricultural users [9]. In Norway, where 99 percent of the electricity produced comes from watermill power stations, snowfall measurements are very important for energy production planning [2]. In Hirmand river basin in Afghanistan (which is the country's largest river basin) snowmelt runoff feeds downhill meanders. Water supplied to Sistan Plain is from snowmelt runoff [1]. Snowfall is an important component of the hydrological cycle in many places of the world, and snowmelt runoff constitutes the main part of the total flow in mountainous regions [33]. In consideration of the importance of snowmelt runoff measurement, we set out to conduct a study of snowmelt runoff of a section of Gharachi Basin.

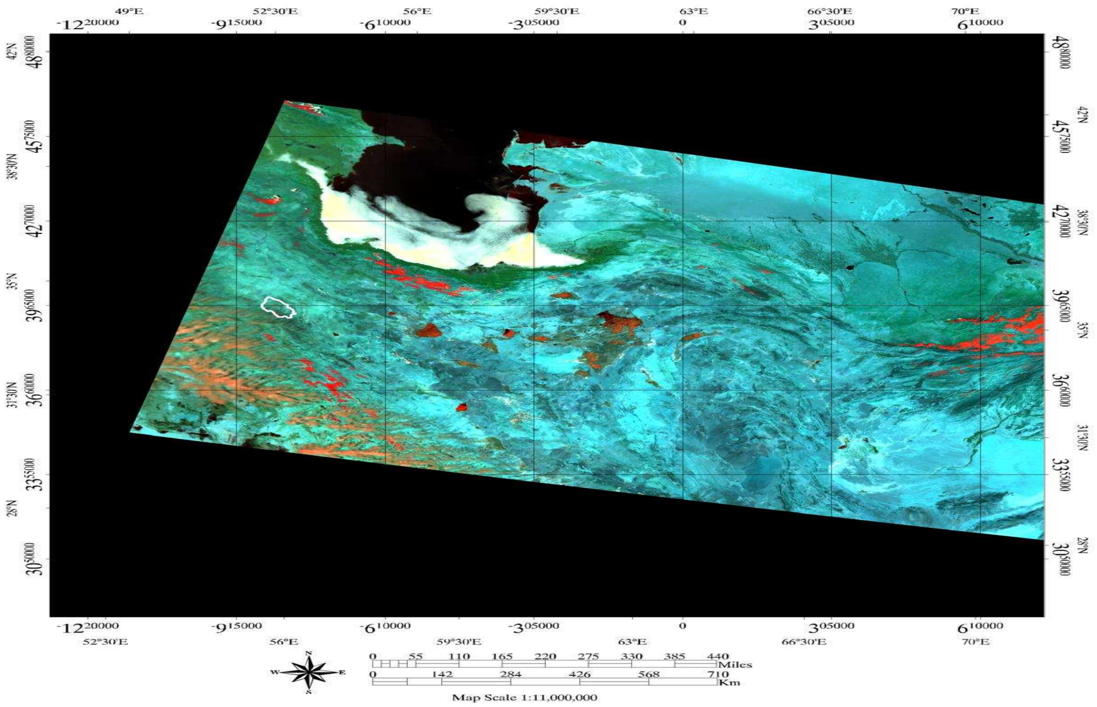


Figure 1: situation of the studied basin

MATERIALS AND METHODS

Region under study

The region under study is a section of Gharachi Basin (located in Hamedan province of Iran) which was selected for its higher snowfall and the presence of 6 snowfall measurement stations within it. It has a surface area of 2420 square kilometers and is located on the northern slope of Alvand Mountain, between 34, 49 and 35, 15 latitudes and 48, 17 and 48, 31 longitudes (Fig-1). Minimum and maximum altitudes within the basin are 1710 and 3372 meters respectively, with the minimum height corresponding to the basin's flow exit and the maximum to a location in the Alvand mountain range. There flows more than 24 kilometers of seasonal and permanent creeks; these join together at the center of the basin and form the main river there, namely Simineh Roud. This river makes its exit in the northwestern side of the basin, where it joins Gharachi River.

Research Method

Here we have used satellite data of snow coverage, field data of snow density during winter months, daily temperature data, and data of hydrometric discharge of the basin during the hydrological years 2005-2006 and 2006-2007. Using MODIS, snow coverage shown in each satellite image is estimated and the results are then used to investigate the effect of snowmelt on the sub-basin under study.

Data Used- Climatology Data

Daily temperature data were collected from meteorology stations in and around the area under study. Using the estimated gradients and digital map of the area and an the Spatial Analyst model, daily isotherm maps were compiled and superposed to the area's center of gravity; these data were later used for investigating snowmelt patters in the studied area.

MODIS and the Algorithm of Mapping of the Snow Coverage

Dueto its higher number of bands and higher temporal resolution, MODIS (Moderate Resolution Imaging Spectroradiometer) installed on Terra satellite works better than other similar systems for compiling snow coverage maps [8, 24]. Here we have compiled snow coverage surfaces for the period 2005-2007(Fig2). Snow coverage results are derived by dividing the difference of reflection of the visible band (0.0545-0.565 micrometer) and mid-infrared (1.628-1.652 micrometer) to the sum of reflections of these two. The resulting index, called NDSI, is thus calculated as:

(Formula-*1)* $$NDSI = \frac{band_4 - band_6}{band_4 + band_6}$$

In areas devoid of forest coverage, pixels with NDSI≥0.4 are considered to be indicative of snow, provided that b2 reflection (0.841-0.876 micrometer) is greater than 11% and b4 reflection is greater than10%. In forest areas, due to the fact that most pixels corresponding to snow covered points demonstrate NDSI≤0.4, another index called NDVI is jointly used with NDSI (Zhang 2003, Klein et al 1998).

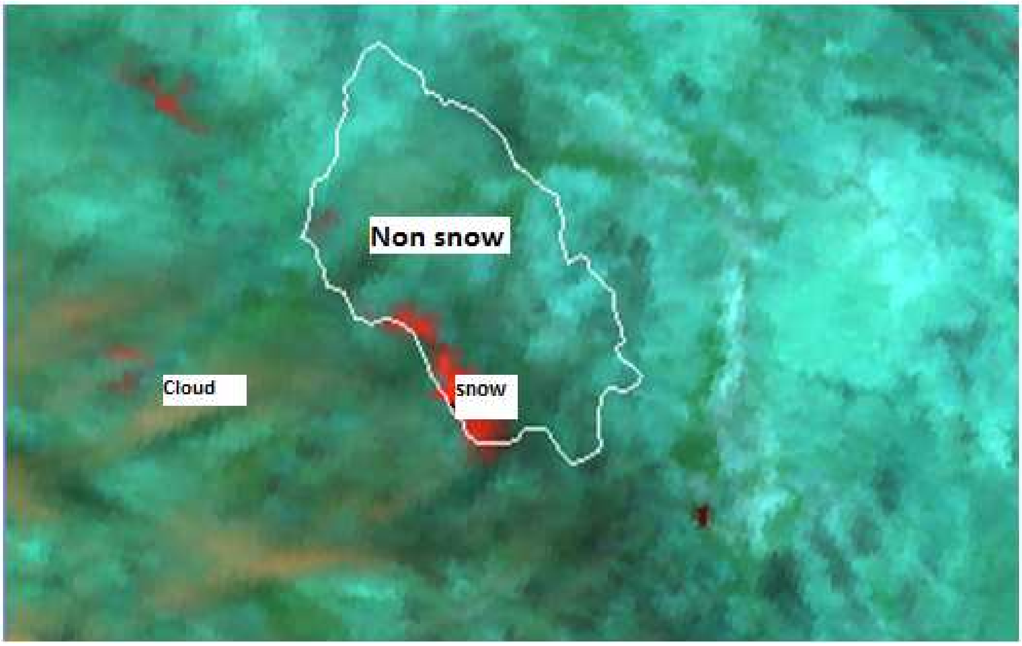


Figure 2: Separation phenomena on TERRA MODIS images

Snow Coverage Trends

The first snow falls in early December in Hamedan province. Snowmelt begins in late March there. Snow accumulation requires that temperature stays below zero for three consecutive days at least (Zhang et al 2010). Winter temperatures have been recorded at four stations in the area during the period 2005-2007. Access to precipitation data for the days on which no satellite pictures are available is necessary for compiling snow coverage maps. Melcher algorithm was used to compile the daily snow coverage for the periods during which there has been snowmelt, with Δm(t1-t2) being the cumulative snowmelt depth in the time interval (t1-t2), itself a function of the day's temperature (α) and the number of subzero temperatures of days with temperatures higher than the critical snowmelt temp (T+).

(Formula-2) $$\Delta_m(t_1,t_2)=\sum_{t_1}^{t_2}\left(\alpha T^+\right)$$

This algorithm is based on the assumption that there are two satellite pictures taken at t1 and t2 (start and end of snowfall respectively), and the snow coverage surface has been compiled for the time t1 and t2 as SCAt1 and SCAt2; and that the temperature remains under the critical temperature from t1 till t2, and hence the snowmelt stops. In such circumstances snow coverage at the time TX is calculated from equation-3. Snow coverage surfaces compiled using Malcher algorithm and satellite pictures are shown in Fig-4.

(Formula-3) $$SCA(t_x)=SCA(t_{X-1})-\frac{SCA(t_1)-SCA(t_2)}{\Delta_m(t_1,t_A)+\Delta_m(t_2,t_E)}\Delta_m(t_{X-1},t_X)$$

Accuracy of Snow Coverage Maps Compiled Using MODIS

Because snow coverage mapping is not regularly done in Iran, we did it using a variety of extant resources. In their study of snow coverage maps of Rio Grande Basin compiled using MODIS and satellite data, Barnett and Klein (2003) found that highest errors occur during the earlier and later parts of the snowfall period. According to them, snow coverage maps compiled using MODIS display an accuracy of 88% in cloudless conditions (Fig-3). Salomonsson and Appel (2004) used NDSI to provide a sub-pixel assessment of snow coverage maps compiled through MODIS. These researchers conducted their work in three different regions namely Alaska, Siberia, and Canada. They first took satellite images with a spatial resolution of 500 meters as their basis for work and used NDSI to compile snow coverage maps, then determined the coverage within each 500 meter network cell with Landsat images as the basis. These Landsat images are ETM+ images with a spatial resolution of 30 meters and are taken as mirroring the real situation on the ground. They compiled a regression relation between NDSI values observed through MODIS and percentage snow coverage values. Results showed that the total error of this method is smaller than 0.1. They arrived at the conclusion that the method can be expanded to become applicable at a global scale. In his M.sc thesis, Poon (2004) investigated hydrological simulation using MODIS data as applied to snow covered forest regions of Manitoba. He reiterated that the main limitation of using satellite imagery for compiling snow coverage maps is the limited use of such imagery for forest areas. The ideal situation would be one in which we have access to the vegetation map of the area and can use separate and distinct classification criteria for forest and non-forest regions; and thus Poon used vegetation data in tandem with the algorithm of compiling snow coverage maps to compile the maps for the snowmelt seasons of 2001 to 2002. Using Normalized Difference of Snow Index (NDSI) and Normalized Difference of Vegetation Index (NDVI) has proved very fruitful. Results indicate that the two algorithms "MODIS" and that based on vegetation render similar snow coverage values for a specific year. Also the snow coverage values showed good regression relation with accumulative temperature/day values. Investigation of debit data corroborates to the postulate that using snow coverage data compiled through MODIS gives more accurate estimates of the flow runoff compared to when such data are not used. Sorman et al (2006[42]) compared snow coverage maps of mountainous regions of Turkey compiled using MODIS images for the periods 2002-2003 and 2003-2004 with field observation results. To determine the snowmelt water equivalent of snow, they measured depth and density of snow at 19 points inside and outside the area under study. Comparison of compiled snow coverage maps with field observations shows 62% to 82% conformity between the results. These studies showed that snow coverage maps could be used for predicting hydrographs of floods caused by snowmelt in mountainous regions. Hall et al (2011[16]) conducted a study of snow coverage data obtained through MODIS during ten years and meteorological and debit data for a 30 year period. These data was collected from Rio Grande in the Midwestern United States, Wyoming, where 70% of the water supplied comes from snowmelt runoff. Their studies showed that the runoff has been starting faster during recent years compared to previous decades. Besides, the strong correlation between snow coverage percentage and maximum monthly flow shows that MODIS snow coverage maps can be useful for predicting and simulating flows, and hence of use for management of water resources in drought-prone regions including those located in the western United States.

RESULTS AND DISCUSSION

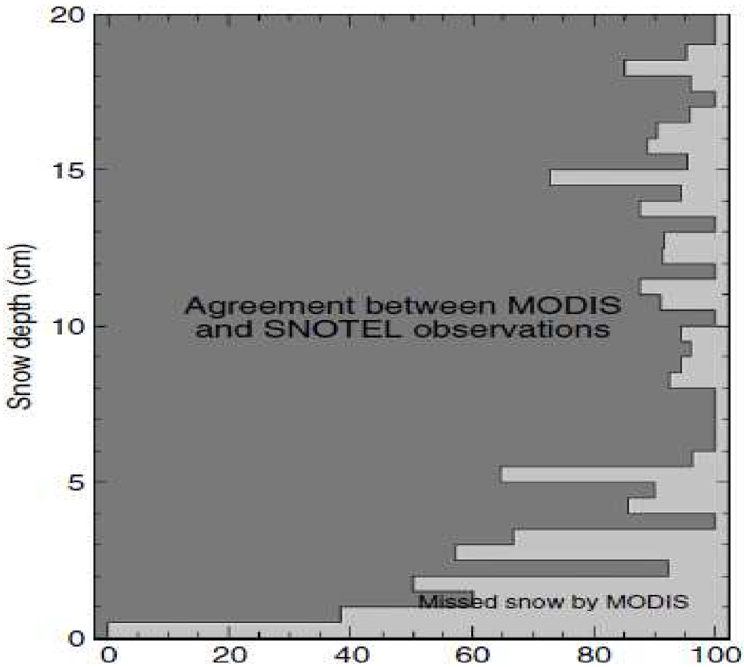
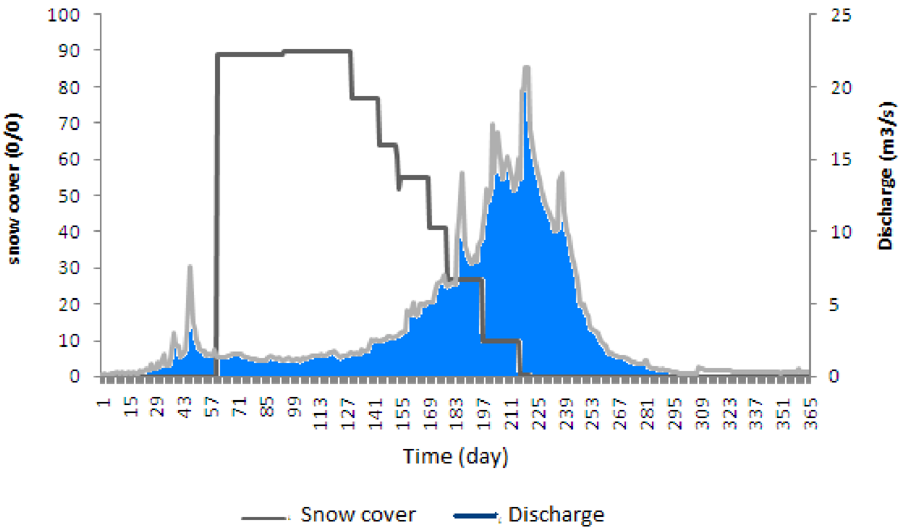


Figure 3: percentage conformity between MODIS data and actual observations made at 15 land stations (Bartlett and Klein 2003)

A Study of the Effect of Snow on Spring Flow

Because March and April are the wettest months in the basin under study, river flow regime there is of the hybrid snow/rain type. To investigate the role of snow within this regime during the periods 2005-2006 and 2006-2007, we first tried to establish the relation between the snow coverage surface and debit of basin (fig-4).



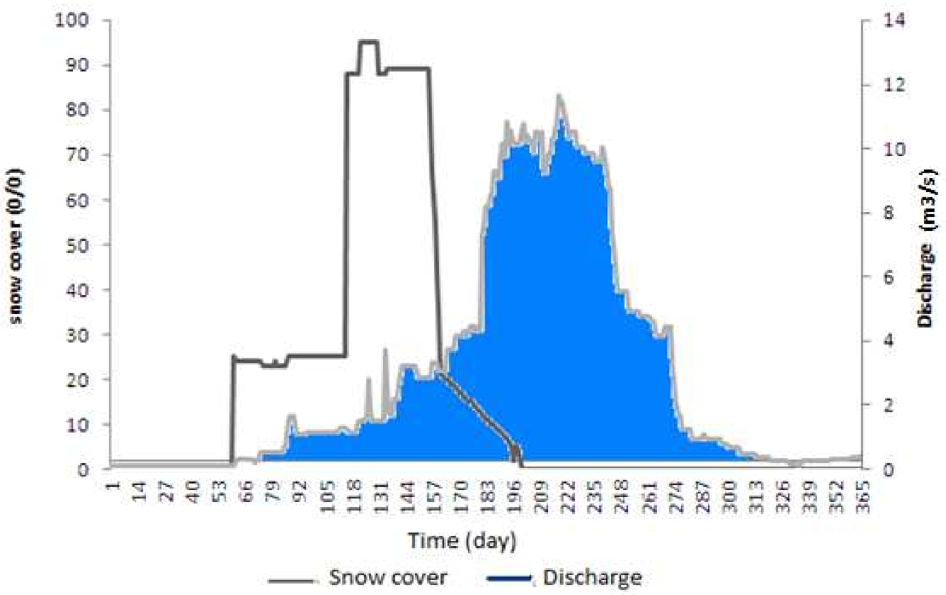


Figure 4: relation between the snow coverage surface and debit of basin for the periods 2005-2006 (above) and 2006-2007 (below)

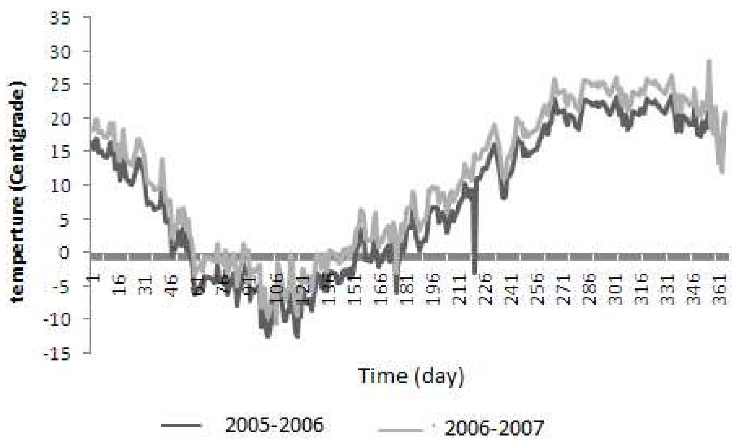


Figure 5: temperature variations of the two periods 2005-2006 and 2006-2007 compared

Results show that in both periods debit has increased with increase in temperature and reduction of snow coverage surface area. This is, of course, indicative of snowmelt. In the precipitation period 2005-2006, as the snow coverage surface area was reduced by 85% during April as a result of temperature increase, there was a 75% increase in debit. Similarly, in the precipitation period 2006-2007, an 85% reduction in the snow coverage surface area was accompanied by a 75% increase in debit as temperatures increased during April. It can be seen that the maximum measured debit occurred sooner during the 2006-2007 period compared with the previous one; and that it was due to a sharper increase in temperature during the snowmelt season (figure 5). Results also show that snowmelt during spring and especially during April is highly effective on the debit of a basin and supplies a great proportion of the water which produces this debit. The effect of snowmelt varies from one year to the next and is itself determined by the temperature and precipitation within the basin. Due to the considerable increase in temperature accompanied by the halt in snowfall, snow is much less durable in spring compared to winter. As shown in fig-8, the highest level of river swelling occurred during the precipitation period 2006-2007; the said river swelling of 2.95 meters (equivalent of an increase of 64.89 million cubic meters) compensated in part the basin's accumulated water reservoir shortage of the previous years, which amounted to a total of 286.13 million cubic meters. It can also be seen that snowmelt period corresponds to the month of maximum river swelling. In fact snowmelt results in the maximization of ground water and surface water volumes within a basin and this is something which should be taken into consideration in water resource planning. Warming of the region was found to have affected the hydrological situation upland, leading to faster and earlier snowmelt during the 2006-2007 periods. Importance of snowmelt in determining the behavior of mountainous river basins has been discussed in articles by Cayan et al 2001, Stewart et al 2005, Mote 2003, Hayhoe et al 2004, Leung et al 2005, etc; newest scientific findings show that should the current average seasonal temperature rise by three to five degrees as a result of continued accumulation of greenhouse gases, snowmelt will start two month sooner than the time it currently starts. This subprime snowmelt can have a dramatic effect on water resources and hydroelectric power production, and its effect on agriculture and water resource planning can be disastrous.

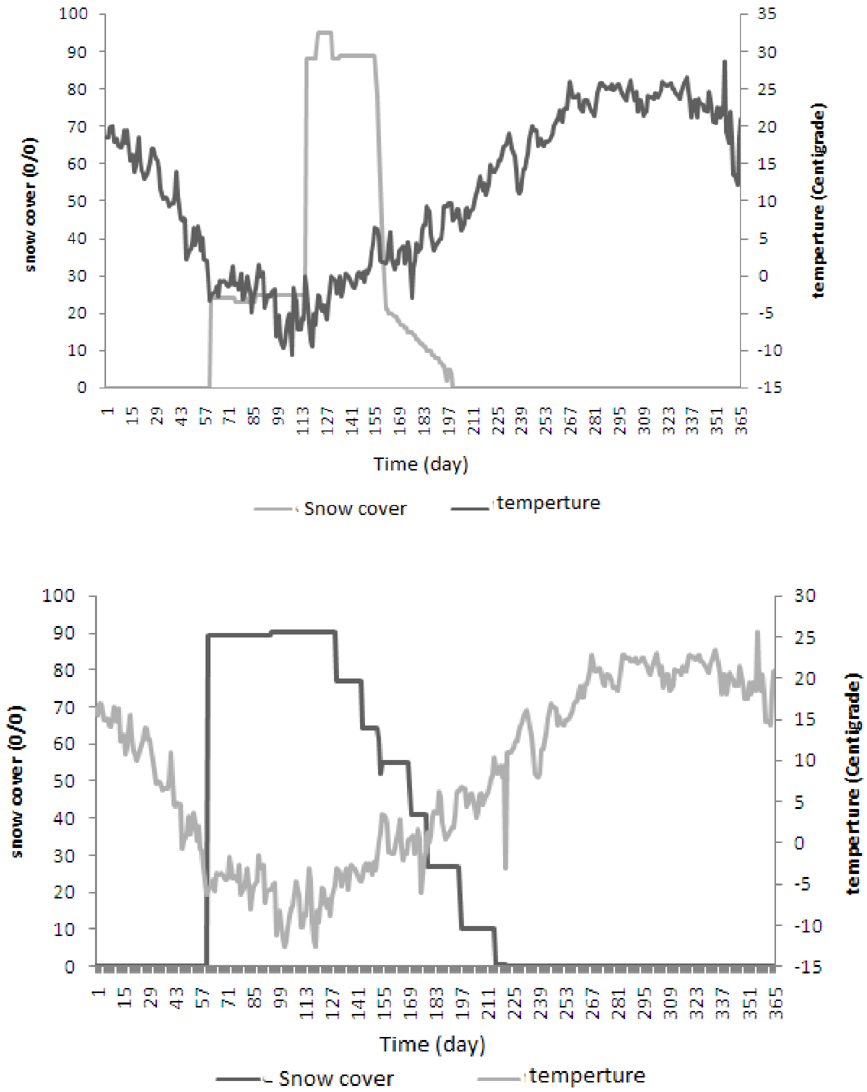


Figure 6: relation between the snow coverage surface and temperature for the periods 2005-2006 (above) and 2006-2007 (below)

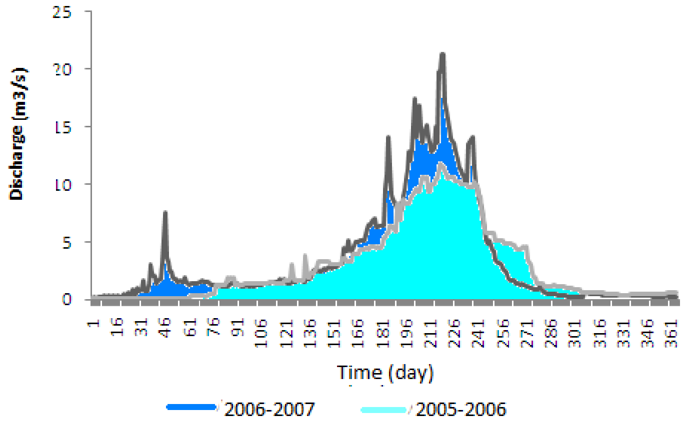


Figure 7: debit variations of the two periods 2005-2006 and 2006-2007 compared

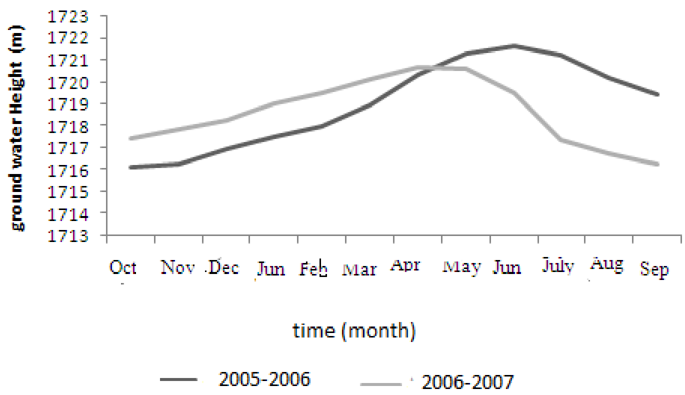


Figure 8: groundwater hydrographs of the two periods 2005-2006 and 2006-2007 compared

CONCLUSION

Snow coverage is regarded as an indirect but important source of supplying water to industry and agriculture. In Australia, for instance, 57000 cubic meters of water is pumped into the agriculture sector from snow covered mountains, and this has made implementation of spring-time flood prevention measures imperative there [36]. Another advantage is production of hydroelectric power by harnessing snowmelt runoff flows. Hydroelectric power is a much cleaner energy compared to power produced through burning of fossil fuels, and it is renewable too. As population increases and the need for drinking water grow, so does the importance of identifying snow reservoirs. Monitoring snow covered surfaces is also important for prediction of floods. Considering the results presented here, prediction of river flow debit during April and May and identification of debit peaks can be of help in planning and management of water resources in the area. Dissemination of floods during these high flow times can help replenish the natural reservoirs.

Acknowledgement
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