.Snow delineation using MODIS in Indus basin

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Remote sensing data in visible and shortwave infrared (SWIR) are very useful for delineation of snow cover. Data from several sensors, e.g. IRS LISS-I to IV, WiFS, AWiFS, Landsat MSS, TM and ETM+, MODIS, AVHRR etc., of fine to coarse resolution are available in the atmospheric windows. There is a tradeoff between resolution and repeativity of data. Cloud coverage is again a problem in having high repeativity. In view of this, MODIS 8-day composite data are selected for monitoring of snow cover in Indus basin for six dates from March to August in the year 2007. Snow was delineated using Normalized Difference Snow Index (NDSI) and Red band. NDSI was used in delineating snow and red band is used to discriminate snow and water. Thresholds (same as Snowmap algorithm of NSIDC) 0.4 and 0.11 are selected for NDSI and red band respectively. Temperature causes melt of snow, which adds to runoff over extended period of time. Since air temperature decreases with altitude with appropriate lapse rate applicable, it is pertinent to do elevation zone wise lumping in empirical snow melt runoff models. Elevation zones are obtained from topographic maps and digital elevation models (DEM). DEM at resolutions from 30 m to 1 km are now readily available in internet. For large areas it is useful to choose medium resolution DEM. For this study, SRTM 250 m DEM is selected. The DEM was used to delineate Indus basin. The basin boundary was modified to match historical boundary in the upper reaches. Using the DEM, 1000 m zones are delineated. DEM is also used to plot hypsometric curve and determine mean and median elevations for zones. Snow cover statistics is computed for elevation zone and snow depletion curves are plotted. Elevation in the basin ranges from 948 to 8572 m. Most of the area lies between 3000 to 6000 m. Snow cover area varies from 14909 to 112520 sq. km. In Zone 8 (7000- 8000 m), maximum snow cover reaches by Mid April, where as in other zones snow cover peaks before March. In Zone 8, depletion starts by July 1st week. In Zone 7, depletion starts by June 1st week. In these zones, snow cover is above nearly 70%. In Zones 6, 5, 4, 3, the snow cover peaks to 80, 60, 60 and 5% respectively. In Zones 5 and 4, most of the snow cover depletes by July and May 1st week. The snow statistics will be useful input to hydrological models.

INTRODUCTION

Himalaya is ‘Abode of snow’. Due to its high altitude, precipitation is received in solid form and is accumulated in the glaciers and snow fields of the mountains. Distribution of snow and glaciers varies based on location, altitude, slope, aspect etc. There are also yearly and climatic variations in this form of water. Seasonal changes in climate cause accumulation and ablation of snow. In winter, accumulation may be predominant. In summer, both accumulation and ablation may take place. In the most part, maximum snow extent happens in February to March and minimum extent happens in July and August months. Thus, snow depletion mainly occurs from February to August. Snow and glacier melt augments flow in the streams originating from Himalaya. Thus, Himalaya snow and glaciers are important source of water resources in the river basin encompassing the Himalaya.

Various land cover observations are needed for hydrological modeling. For snow and glacier cover basins, such as those in Himalaya, snow extent and depletion curves are important input to hydrological models. Satellite remote sensing provides repetitive coverage of the earth and discriminates various land cover including snow and glaciers. Satellite data are available at various spatial and spectral resolutions and repeat interval. Several medium to coarse resolution data have almost daily availability. Fine to medium resolution data have moderate repeat interval. Thus, medium to coarse resolution data are more useful for study of snow covered basins having transient information such as snow extent. Satellite data are available in various atmospheric windows. In visible and infrared spectral regions, several sensors operate. These regions also enable discrimination of several earth's features including snow and are widely used in study of snow covered basins. Cloud cover obstructs the sensing of earth's features. Data with higher repetitive coverage have more chance of finding data without cloud hindrance. Suitable methodology may be designed for reducing cloud hindrance in the data and improving snow cover information.

Temperature is an important climatic variable driving the snow hydrometeorological processes e.g. precipitation, ablation etc. Temperature is dependent on altitude with a temperature lapse rate relationship existing for regions. Due to altitude effect in the processes, several hydrological models have elevation zones as hydrological modeling units. Hydrological processes are modeled for these zones and then integrated for the basin. Thus, snow extent information is estimated for the elevation zones. Conventionally, elevation zone are obtained from topographic maps, which depict elevation information as contours. With advent of GIS, elevation information is represented as DEM obtained from topographic data. Remote sensing also provides elevation data observed as gridded data. The satellite remote sensing based DEM, e.g. SRTM are freely available on web. These data are very good source of elevation information in particular in mountainous regions. The DEM may be utilized for deriving elevation zones and obtaining snow extent elevation zone wise.

REVIEW

Snow cover was mapped in Parbati basin and 33 other sub basin in Himalaya for October to June, 2004 to 2008 (Kulkarni and Singh 2010, Space Application Centre 2010). The sub basins are located in Indus, Chenab, Satluj, Ganga and Brahmaputra basins. AWiFS Top of Atmosphere (TOI) reflectance NDSI and NIR bands data were used. Threshold 0.4 for NDSI was based on sensitivity analysis. Pre-winter scene NIR band reflectance was used for delineating and masking water pixels. For Parbati basin nearly one third scenes were identified with cloud cover and excluded from the analysis. In SAC study, 10 day composite snow cover map was derived except for Sikkim (where 5 day composite was prepared). Where three scenes in 10 day window were not available, all scenes in that window were used for the composite. Water body mask from pre- winter scene was used. The accuracy at 134 ground truth points for year 2003 to 2005was nearly 99% for Beas basin. Accumulation and depletion in snow occurs all year round with one processing dominating other at different intermittent periods.

Kulkarni and Singh (2010) has stated snow reflactances in green and SWIR bands to be 78- 97% and 1- 11% respectively. Reflectance of water is 4- 5% and <1% respectively. Thus, high NDSI results for snow and water (0.67- 0.9). NDSI for moist soil and vegetation are respectively 0.33 and negative. For vegetation (<75%) mixed snow pixels the NDSI is greater than 0.64. Vegetation mixed snow has NDSI as low as 0.13. Snow extent determination is less sensitive to NDSI threshold in range 0.35- 0.45. Snow depletion onset and completion is dependent on precipitation, altitude etc. Snowfall in western Himalaya was less in year 2005- 07 compared to 2004- 05. Depletion started from mid February and mid April and lasted up to mid March and beginning of June for Ravi and Bhaga basins respectively.

Negi (2000) mapped snow cover in Beas basin using AWiFS data. NDSI based on reflectance and DN were used and 2-10% higher snow cover was estimated with reflectance. Same thresholds as above were used. Less than 10% additional snow extent was determined for now under vegetation cover using NDSI in range 0.1 to 0.4 and vegetation area mapped from LISS IV. Accuracy with 54 ground truth points was 100%.

NSIDC provides several swath or tile snow cover products at various temporal and spatial resolutions and projections derived from MODIS data (both Terra and Aqua). The products are processed sequentially. Snow is delineated for usable data over land and inland water in the Level 5 swath product (1st in the sequence). Two groups of grouped criteria test are used. First group involved NDSI and reflectance in Band 2 and 4. Thresholds of 0.4, 0.11 and 0.1 were used. For delineating snow over dense vegetation, polygon on NDSI, NDVI plot (NDSI value ranges between 0.1 and 0.4) and MODIS band 1 and 2 are used (thresholds 0.1 and 0.11). For the snow delineation a screen of 283 K was also applied to exclude warm pixels. Only cloud unobstructed snow pixels were retained in the final snow product. Regression relationships developed by Salomonson and Appel (2004) were used to find fractional snow product for NDSI in range 0 and 1. Cloud pixels (not in cloud mask) misclassified as snow may be from 0.001 to 0.1% or maximum up to 3%. Other snow products are derived from the swath snow product without applying snow processing algorithm. From swath product, multiple observations of a day are stacked in gridded product (MOD10_L2G). Single observation of snow cover is selected based on solar elevation, distance from nadir and observation coverage in daily gridded product (MOD10A1). From this, 8- day composite product (MOD10A2) is derived to maximize snow coverage (Riggs et al 2006, Hall et al 2001).

Snow cover is under estimated in MODIS snow cover product due to cloud cover. The cloud obstructed pixels may be reduced through post processing of terra and aqua products. It is assumed that due to cloud movement, the location of cloud obscured pixel will change in Terra and Aqua MODIS data acquired over nearly 3 hour lag and thus composite snow cover map will have reduced cloud obscured pixel (close to 40%). Further snow cover was maximized in three consecutive 8-day composite snow maps (close to 50% cloud reduction). 7 X 7 majority spatial filter was applied to cloud and missing data (cloud cover reduced close to 5%). Altitude filter was applied for 8- zones in Hindu- Kush region. Threshold was based on data from heavy snow periods, information from literature etc. Processing was done using program developed using spatial data processing libraries. Maximum cloud cover was 25% and it reduced to 5%. Change in snow cover area was 2- 10%. Accuracy compared to AWFS 5-day snow cover composite map ranged from 46 to 97% (Kappa 0.10-0.91) for 28 to 95 points. Snow in Indus basin was 1116347 sq km (Gurung et al. 2011).

STUDY AREA

Indus River is a major river in Asia which flows through Pakistan and India. It also has courses through western Tibet. Originating near Lake Mansarovar and Mount Kailash, the river runs through Jammu and Kashmir, Himachal Pradesh and Punjab in India. The River flows westward south of Karakoram range and North of Great Himalayas up to Nanga Parbat, where it sharply turns southwards. It flows for over 3180 km (Space Application Centre 2010). The river has a total drainage area and length nearly 11,65,000 km^2 and 2880 km. Annual flow of the river is estimated to be 207 km^3. Indus basin (Indian part) is covered by 37.2°N, 72.4°E and 30.2°N and 82.6°E. The study area (Indus sub basin) is covered between 37.2°N, 72.4°E and 31°N and 82°E and has area of $1{,}78{,}339\ km^2$.

Data

SRTM

NASA Shuttle Radar Topographic Mission (SRTM) data were acquired by Radar on-board 11- day mission of NASA Shuttle in 2003. The data are available at 90 m resolution for nearly 80% of the earth surface. Data are free and are available in 5° tiles. Data have few gaps in high mountains, deserts and water bodies etc., which are filled through processing in GIS. Data are made available by Consultative Group for International Agricultural Research-Consortium for Spatial Information (CGIAR- CSI). A derived 250 m DEM is also available.

MODIS (MOD09A1)

MODIS MOD 09 products are derived from MODIS Level 1B land bands 1 through 7 (http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=09). The MODIS bands are centered at 648 nm (Red), 858 nm (near infrared), 470 nm (Blue), 555 nm (Green), 1240 nm (Near infrared), 1640 nm (SWIR), and 2130 nm (SWIR), respectively. The product contains spectral reflectance values. The product MOD09A1 provides 8- day composite of the surface reflectance in 1 to 7 bands at 500 m resolution for MODIS sensor (https://lpdaac.usgs.gov/products/modis_products_table/mod09a1). The composite is derived by selecting an observation from MODIS daily L2G products based on several factors e.g. maximum observation coverage, low view angle, absence of cloud or its shadow, aerosol loading etc. The accompanying data have quality assessment, day of observation, solar azimuth, and view and zenith angles information. The version-5 product is validated Stage-2 product. It has been validated spatially and temporally through ground truth etc. The data is recommended for scientific use. Data is available in tiles of size 10° in HDF-EOS format. The file size in pixels and lines is 2400 X 2400. The product is gridded level- 3 product having sinusoidal map projection system.

SOFTWARE

GIS and image processing software

A GIS software namely ArcGIS desktop (Arc View) and a GIS and image processing software, namely ERDAS Imagine were used. ESRI ArcGIS is a geographic information system (GIS) for working with maps and geographic information. It is used for creating and using maps, compiling geographic data, analyzing mapped information, sharing and discovering geographic information, using maps and geographic information in a range of applications, and managing geographic information in a database. ERDAS IMAGINE is easy to learn raster-centric software used to extract information from satellite and aerial images. The vast array of tools allows users to analyse data and present it in formats ranging from printed maps to 3D models.

MODIS Reprojection Tool

The product is developed for use with higher level MODIS raster (gridded) data products e.g. MOD09A1 available in HDF- EOS data format with Sinusoidal projection. In the software mosaicking, sub setting (spatial and spectral), reprojection and format change functionalities are made available. Both command line and GUI interfaces are available. The product is available on multiple platforms. Output formats supported are raw binary, HDF-EOS and GeoTIFF. Input data of 8, 16 and 32 bit signed/ unsigned integer and 32 bit float are supported. Output data type is same as input. Several projections are supported including LCC, UTM, Albers equal area, geographic etc. Resampling available are nearest neighbour, bilinear and cubic convolution. When multiple input files are selected, these are mosaiced. Using band selector, any number of bands may be moved to output list. In GeoTIFF output format, separate output files are created for individual band (Anonymous 2011).

METHODOLOGY

Stream and basin delineation

Stream delineation was done in ArcGIS 9.2 software using SRTM 250 data. To delineate steam network, the DEM was hydrological processed. In hydrological processing, pits in the DEM were filled. Pits are often the artifacts created in DEM due to DEM generation process, random error in data acquisition etc. If cells with higher elevation surround a cell, geospatial processing of flow direction determination is not achieved and thus pit removal is required. Using the filled DEM, flow direction and flow accumulation maps were computed. The value in flow direction grid indicates the direction of the steepest descent from that cell to one of its neighboring cells using eight direction pour point (D8) method. The eight flow directions are assigned values among 1, 2, 4, 8, 16, 32, 64 and 128. In flow accumulation processing, the flow direction grid is used to compute the number of cells that are draining to any particular cell. Generally, higher values in this map visually depict a stream network and thus the map was used to create a stream network by applying a threshold value. Further, Indus sub basin map was delineated in GIS by using an outlet point. The map delineated larger area in Western Tibet. The basin boundary in this region was manually edited and was based in Indus basin map available from ICIMOD web site.

Elevation Zones

DEM was clipped for the Indus sub basin. Typically, elevation zones of 500 to 1000 m are used in hydrological studies. Classification of the DEM was carried out in GIS to obtain elevation zones of 1000 m (Table 1). Thus area has total nine elevation zones. Hypsometric curve (Fig. 1) prepared from the DEM statistics.

Mosaicing, subsetting and reprojection

Tiles of MOD09A1 products available in HDF- EOS data format were mosaiced, subset and reprojected using MODIS Reprojection Tool (MRT). The bands 2, 4 and 6 were selected. Subset was created for Indus basin. Projected coordinate system selected was Lambert Conformal Conic (LCC). Two standard parallels are 12.472944444°N and 35.172805555556°N. Central meridian and parallel are 80.0 and 24.0 respectively. False Eastings and Northings are both 4000000.0. Datum is WGS84.

Snow Mapping

MODIS bands 2, 4, and 6 were used for snow cover delineation. Bands 4 and 6 were used to compute Normalized Difference Snow Index (NDSI). Band 2 was used to discriminate water bodies from snow. Water bodies, both have high NDSI values. However, reflectance in near infrared band (MODIS band 2) is low for water bodies as compared snow. Thresholds of 0.4 and 1100 were used for NDSI and MODIS band 2 values (same is those in Snowmap algorithm of NSIDC). Pixels with values higher than these thresholds were identified as snow. The processing was done on ERDAS Imagine.

Zonal statistics

Snow map was masked by the sub basin map to obtain snow map for the sub basin. This map was used in computing zonal statistics. The geospatial processing was done in ArcGIS.

RESULTS AND DISCUSSION

Elevation zones

Elevation in the Indus sub basin ranges between 948 and 8572 m. Thus basin altitude is 7624 m. In mountainous areas, due to topographic, large elevation range is found for small areal extent close of basin maximum elevation. Close to basin minimum elevation, similar hypsometric characteristics are seen due to converging of the streams near the outlets of a basin. Appropriate representative elevation of the elevation zone (Table 1) e.g. median or mean elevation along with temperature lapse rate and climatic data of a nearby station may be used for determining the temperature for the elevation zone. Table 1 and Fig. 1 indicates that majority of the area of the basin has elevation range of 3000 to 6000 m.

Snow extent

Table 2 and 3 and Fig. 2 and 3 indicate that most of the snow cover occurs in zones 4 to 6 (elevation range 3000 to 6000 m). This may be due to higher basin areas in these zones. Other zones have smaller snow cover extent. Zones 7 and 8 have large percent snow cover due to higher elevations.

Zone 5 and 6 do not have large difference in the snow cover area. Kinks in the depletion curves for zone 5 and 6 may indicate new snow or climatological variations. In zone 4, most of the snow depletes by May 1^{st} week. In zone 5, depletion occurs by July 1^{st} week. Thus, permanent snow fields will exist in zone 6 onwards. In Zone 8, maximum snow cover reaches by Mid April, where as in other zones snow cover may peak prior to March. In Zone 8, depletion starts by July 1^{st} week. In Zone 7, depletion starts by June 1^{st} week. Late ablation onset at higher elevation happens due to climatological reasons. In general, ablation at high elevations starts later than that at lower elevations. At very high elevations, all year round low temperatures are maintained and thus permanent snow fields will exist at those elevations. In the case of permanent snow field exists mostly above 5000 m. Snow line approximately moves above 4000 m and 5000 m in first fortnight of May and July.

CONCLUSIONS

Hypsometric curve for the basin indicate that majority of the area is in elevation zone between 3000 and 6000 m. Thus, the basin is high altitude mountainous basin. Based on studied data, the seasonal and permanent snow cover are nearly 97611 sq. km (55%) and 14909 sq. km (8%) respectively. Thus, the basin has very high seasonal and permanent snow cover and the contribution to water resources in the basin from snow and glacier will be high. The snow cover maps and depletion curve will form important input to hydrological models for the basin. Visual inspection of the data indicate that cloud cover is less in the basin and thus the employed methodology will provide good estimate of the snow extent. Thus, this data source could be useful for snow delineation in the basin.

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Table 1 Zonal elevation statistics for Indus sub basin

Zone	Area (sq km)	Area (%)	Minimum	Maximum	Mean	St. Dev.	Median
1	17	0.0	948	1000	990	9	993
2	2007	1.1	1001	2000	1616	265	1652
3	7348	4.1	2001	3000	2578	278	2610
4	23407	13.1	3001	4000	3584	280	3619
5	74561	41.8	4001	5000	4565	272	4586
6	67557	37.9	5001	6000	5395	256	5362
7	3334	1.9	6001	7000	6210	212	6137
8	106	0.1	7001	7997	7256	209	7199
9	1	0.0	8022	8572	8263	184	8203

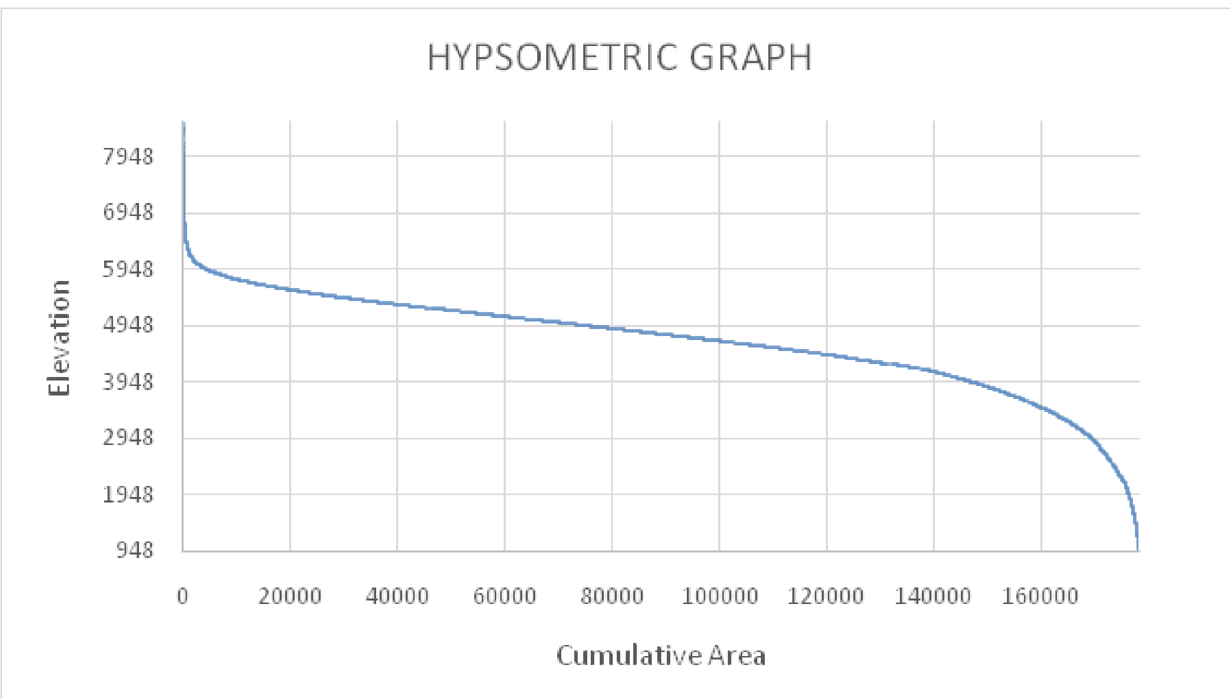

Fig. 1 Hypsometric curve for the Indus sub basin

Table 2 Snow cover statistics for elevation zones in Indus sub basin

Date	zone 3	zone 4	zone 5	zone 6	zone 7	zone 8	zone 9	Basin
09-3-2007	445	13240	45078	50472	3194	89	1	112521
18-4-2007	21	5104	31301	33441	3126	104	1	73097
04-5-2007	1	1750	22515	31549	3078	104	1	58998
05-6-2007	0	304	15173	26207	3086	104	1	44876
07-7-2007	1	124	4630	16248	2650	100	1	23754
08-8-2007	8	88	2029	10481	2223	80	1	14909

Table 3 Snow depletion statistics for elevation zones in Indus sub basin

	zone 3	zone 4	zone 5	zone 6	zone 7	zone 8	zone 9	Basin
09-3-2007	6%	57%	60%	75%	96%	84%	69%	63%
18-4-2007	0%	22%	42%	50%	94%	98%	69%	41%
04-5-2007	0%	7%	30%	47%	92%	98%	100%	33%
05-6-2007	0%	1%	20%	39%	93%	98%	100%	25%
07-7-2007	0%	1%	6%	24%	80%	94%	100%	13%
08-8-2007	0%	0%	3%	16%	67%	76%	75%	8%

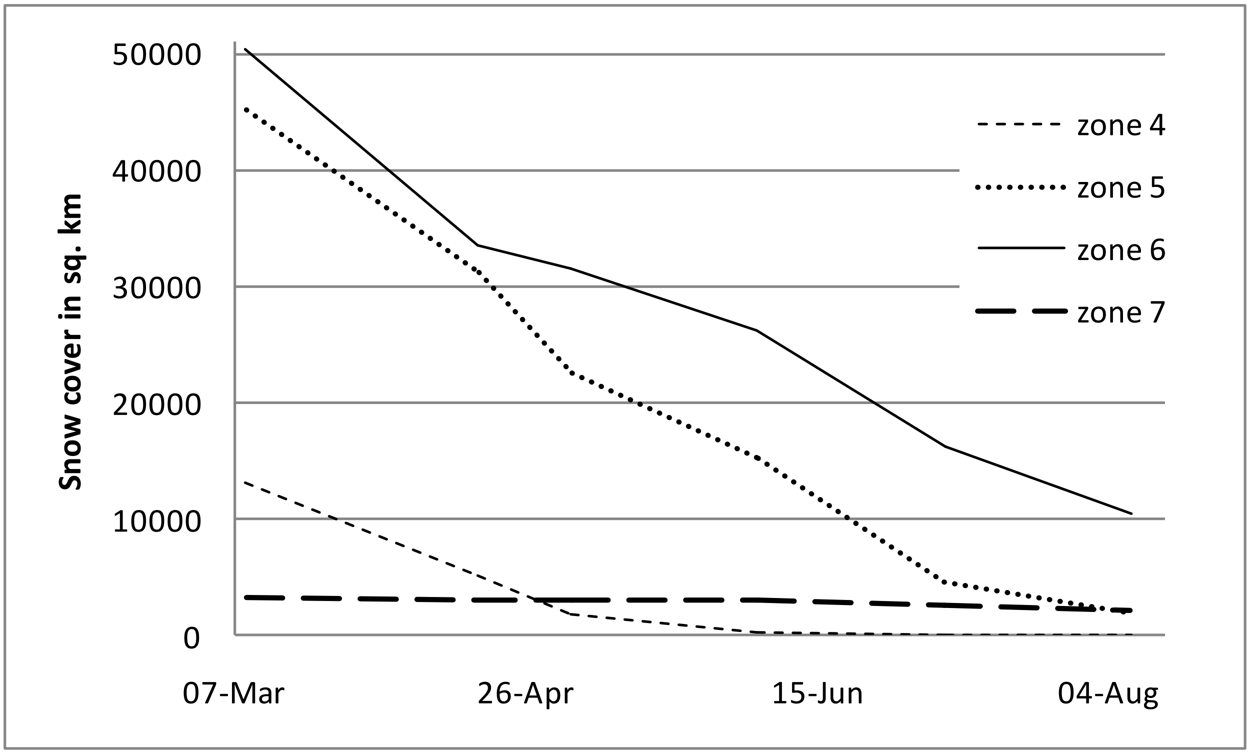

Fig. 2 Snow extent depletion in elevation zones in Indus sub basin

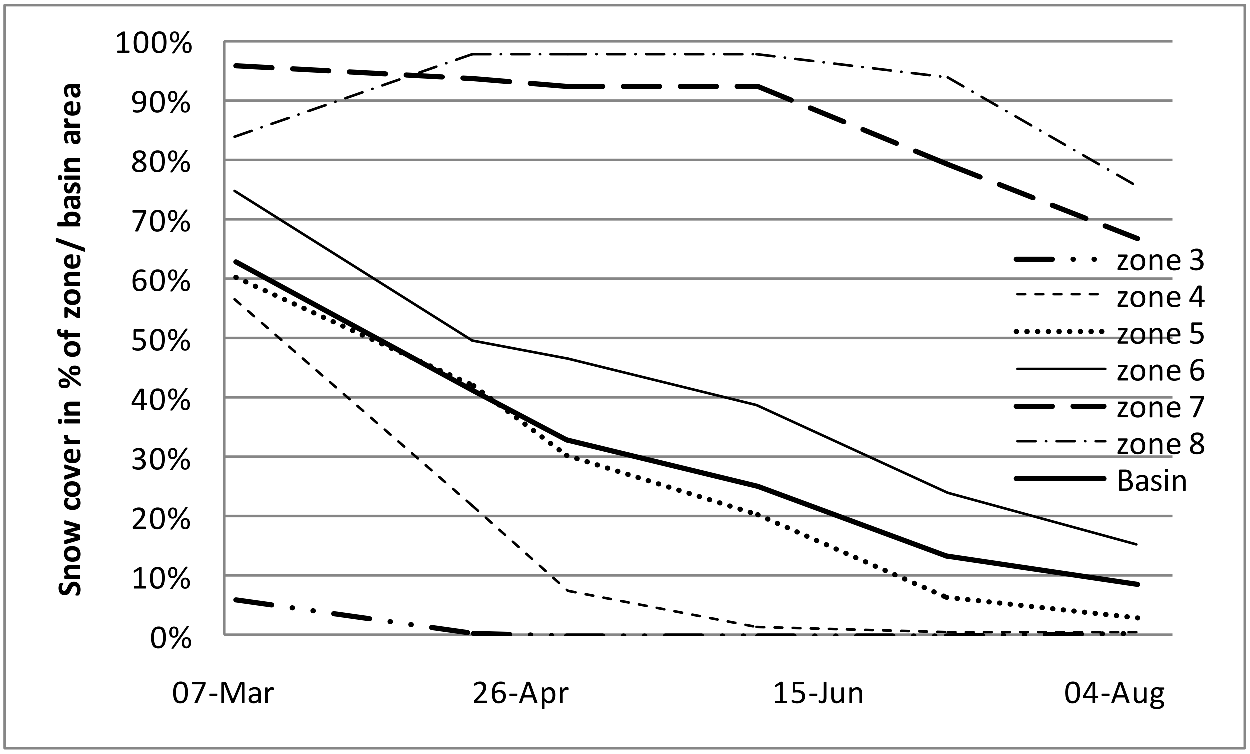

Fig. 3 Snow depletion curves for Indus sub basin