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SNOW COVER ESTIMATION IN HIMALAYAN BASINS USING REMOTE SENSING

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PREFACE

Snow cover area is one of the very important variables required for snowmelt simulation, forecasting and water balance studies. The availability of satellite data provide useful periodic information about extent of snow cover and can thus form a basis for hydrological studies in snow covered mountains. Snow cover can be detected and monitored with a variety of remote sensing sensors. The widely used sensors are operating in the visible and near infra-red region of the electromagnetic spectrum.

The objective of this study is estimation of snow cover area for four major basins in the Himalayan region viz. Chenab upto Akhnoor, Ganga upto Deoprayag, Satluj up to Bhakra and Beas up to Pandoh using IRS IC/1D WiFS data. For all the four basins viz. Satluj, Ganga, Beas and Chenab, snow cover area estimation for the years 1997,1998 1999 and 2000 has been made using image processing system ERDAS IMAGINE. From the snowcover mapping, area covered under snow has been computed. Both maximum and minimum snow cover extent respectively for the month of Sept-Oct and March-April were delineated. On the basis of this database, the depletion curves for each basin for all the years have been made. The output produced in this way is very useful for carrying out snowmelt runoff modelling in these basins.

This study has been carried out by Mr. Sanjay K. Jain, Sc.'E1', Mr. D.S.Rathore, Sc.'C' and Ms. Anju Chaudhry, SRA of Remote Sensing Applications Division. This study is useful for carrying out water balance studies and snow cover melt runoff modelling in snow covered basins.

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ABSTRACT

The mountains cover a large portion of the Earth surface. As the mean altitude of the land area of the Earth is 875 m above sea level, and therefore over 28% of the land areas are above 1,000 m. In these high mountains, it is estimated that 10 to 20% of the total surface area is covered by glaciers while an additional area ranging from 30 to 40% has seasonal snow cover. There are of course variations in depths of snow and ice from place to place depending on the location. Snow forms a natural reservoir, storing water for weeks or months; if properly harnessed it can be used for water supply, agriculture, and industry and energy production. The majority of rivers originating from the Himalayas have their upper catchment in the snow-covered areas. The solid precipitation results in temporary storage and this storage supply water in the river system during snowmelt season. Snow cover measurements are difficult and estimates are not reliable, cheap or easy because of the hostile climatic conditions and the remoteness of the areas. Conventional methods have limitations in the monitoring of snow covered area in the Himalayan basins because of inaccessibility. Due to the difficulty of making field measurements in snow-covered mountainous regions, remote sensing is attractive tool as a means of estimating snow-cover properties. Snow and glacier melt runoff is very important, particularly, in lean season and it plays a vital role in making nearly all the rivers originating in Himalayas which are perennial. Keeping in view the importance of snow cover area, in this study remote sensing methods have been applied for mapping of snow cover area. Snow starts melting just after winter season is over, i.e., in the month of March and reaches minimum after monsoon season. Snow cover depletion curves have been prepared to show the trend of melting of snow.

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1.0 INTRODUCTION

1.1 GENERAL

Snow, glaciers, ice in lakes and rivers, and ice in the ground comprise the frozen part of the land portion of the hydrologic cycle. Water in these frozen states accounts for more than 80 % of the total fresh water on Earth and is the largest contributor to runoff in rivers and ground water over major portions of the middle and high latitudes. Over 30 % of the Earth's land surface is seasonally covered by snow, and 10 % is permanently covered by glaciers. Snow can be regarded as a convenient form of precipitation because it is a natural reservoir, storing water for weeks or months; if harnessed it can be used for water supply, agriculture, and industry and energy production. Snow and ice also play important interactive roles in the Earth's radiation balance, because snow has a higher albedo than any other natural surface. Snow cover represents a changing atmospheric output resulting from variability in the Earth's climate, and it is also a changing boundary condition in climate models. Thus understanding of global and regional climates and assessment of water resources require that we monitor the temporal and spatial variability of the snow cover over land areas, from the scale of small drainage basins to continents.

The snow cover in the Himalayas occurs and exists depending on the terrain and climatic conditions of the region. This snow cover can be categorised into temporary snow cover, seasonal snow cover and permanent snowfields and glaciers. Snow cover that stays for a few days and then melts away is termed as "temporary snow cover". This usually occurs at lower altitudes during winter and even sometimes at higher altitudes during summer. Snow cover that is formed over weeks or months by consecutive snowfalls and which melts away gradually during the following summer is termed as "seasonal snow pack/cover". Above a certain altitude and in certain situations, some amount of snow is carried over to the next winter season without melting during summer, and this turns into 'firn' and ultimately ice, adding to the permanent snowfields and glaciers. It is the seasonal snow pack that contributes to the water resources during the lean summer months, and therefore is very important.

1.2 HIMALAYAS AND HIMALAYAN RIVERS

In the northern part of the Indian subcontinent is the 2500 km (approx.) long Himalaya, the abode of many highest snow covered peaks in the world. The crescent shaped Himalayas is flanked on the west by a wing of mountains approximately 1500 km long stretching from Makran coast to Nanga Parbat peak, and on the east by a wing of hills approximatley 1000 km long, raning from Namcha Barwa peak in the bend of Brahmputra river to Mizo hills, The average altitude of Himalaya is about 6000 m. Many of the permanent snow fields in the higher altitudes give rise to immense glaciers as well as some of the mightest rivers in Asia like the Gangam Indus and Brahmaputra. The Himalayas are actually a series of parallel ranges marked by jutting, snow capped peaks, deeply eroded tiver gorges, and valleys, many of which were carved by slowly creeping glaciers. The southernmost range of Himalayas is called the Siwalik Hills with a maximum altitude from about 2000 to 4500 m. The most northern range of the mountains is the Great Himalays. It is a lofty, rugged chain reaching high above the line of continual snow. Sometimes Karakoram range is considered as a fourth range Himalayas. The Himalaya may be further sub-divided laterllly into western, Central and Eastern Himalayas. The western Himalaya extends right from Nanga Parbat to Nanda Devi and is the origin of Indus and Ganga river systems. The central Himalaya stretches from Ghagra and Gandak to Kosi river systems and limited to Nepal Himalaya. Whereas the Eastern Himalaya ranges from east of Kosi to Namcha Barwa in the bend of Brahmputra river. (Ramamoorthi et al.)

The Himalayas are the cradle of a large number of streams and mighty rivers, which ensure all the year round availability of water. Agriculture being the main source of livelihood, water resources generated in the Himalayas are, therefore, their greatest gift to this country. The Himalayas give rise to drainage, which can be broadly grouped in three main river systems; the Indus, the Ganga and the Brahmputra. The rivers that originate and drain through Himalayas are given in table 1. The most important river system of the Himalayan region, which is also the most important system of the country, is the Indus system. It flows from the Tibetan plateau, through India and Pakistan to the Arabian sea (Indian Ocean). Rivers Shyok, Shigar and Gilgit join it in Jammu and Kashmir. The important tributaries, including the Jhelum, Chenab, Ravi, Beas and Satluj join it after entering Pakisatn. The Indus coverd with in the Indian teritory is shown in Figure 1.1. The contributions of the main rivers measured at the foot of the mountains are 13% from the Kabul, 37 % from the Indus, 14 % from the Jhelum, 15 % from the Chenab, 4 % from the Ravi, 7 % from the Beas and 10 % from the Satluj. Less than 10 % of the average runoff is the result of rainfall over the Indus plains. The runoff reflects the seasonal rainfall and snowmelt regimes of the mountain watersheds. The foothills and front ranges are predominantly exposed to seasonal monsoon rains, leading to runoff peaks from June to September, which produce some 70 % of the total annual runoff of the Indus. (Mountains of the world, 1998)

Table 1.1: The Himalayan river systems and catchment areas.

Sr. No.	River	Catchment Area in Himalayas (sq. km)
	A. Indus System	
1.	Indus	265700
2.	Jhelum	33300
3.	Chenab	26900
4.	Ravi	7900
5.	Beas	13800
6.	Sutlej	47400
	B. Ganga System	
7.	Yamuna	11500
8.	Ganga	22800
9.	Ramganga	6700
10.	Kali	14300
11.	Karnali	52700
12.	Rapti	7700
13.	Gandak	35000
14.	Baghmati	3800
15.	Kosi	61200
	C. Brahmaputra System	
16.	Teesta	12300
17.	Raidak	26100
18.	Manas	30700
19.	Subansiri	16100
20.	Luhit	17900
21.	Brahmaputra	250000

The pattern of runoff from the Himalaya, its timing and intensity, is governed by the quantity and distribution of precipitation and its form, whether solid or liquid, and seasonality. The heaviest rainfall of the summer monsoon occurs on the eastern foothills and produces the strongest effects on rivers such as the Brahmputra and Ganges. In contrast, toward the northwest, the predominance of summer monsoon rain decreases and the importance of high altitude winter snowfall increases; thus the flow of the Indus is mainly determined by the snowmelt and by ablation of some of the world's largest glaciers outside of the polar regions.

1.3 SNOW COVERED AREA

Snow cover measurements are difficult and estimates are not reliable, cheap or easy because of the hostile climatic conditions and the remoteness of the areas. The difficulty experienced when measuring snowfall with precipitation gauges has been identified (WMO, 1982a). Once on the ground, snow is frequently deposited in an irregular way and redistributed by the wind. Thus, over a short distance, snow depths, and hence the water equivalents, may show wide variation. Consequently, point measurement of the snow cover provides insufficient information.

Conventional methods have limitations in the monitoring of snow covered area in the Himalayan basins because of inaccessibility. Snow by virtue of the high reflectivity, is one of the objects on the surface of earth which is readily detected or identified on any visible or near IR remotely sensed image. Fresh snow has a very high reflectivity in the visible wavelengths. However, it decreases as the snow ages. The reflectivity of snow is dependent on many snow characteristics like shape and size of snow crystals, liquid water content (especially of the near surface layers), impurities in the snow, depth of snow, surface roughness etc. In addition, the solar elevation also influences the spectral reflectance to a large extent (Hall and Martinec, 1985).

Over the last two decades satellite remote sensing has opened the possibility of data acquisition at regular intervals, and operational as well as research-oriented satellites have provided information on snow cover. Remote sensing of the seasonal snow cover has been used to improve the monitoring of existing conditions and has been incorporated into several runoff forecasting and management systems. Satellite sensors in the visible and near-infrared wavelengths provide information on the spatial distribution of parameters of hydrologic importance. From these reflectance measurements, we can measure snow-covered area, rates of snow-cover depletion, and surface albedo. The IRS and Landsat systems, in particular, are a source of data for hydrological and glaciological research at the scale of drainage basins. Satellite remote sensing in the visible and near-infrared wavelengths has become increasingly important to snow hydrologists because the data provide information on the spatial distribution of parameters of hydrologic importance. In snow and ice studies, remote sensing has been used to improve the monitoring of existing conditions and has been incorporated into several runoff forecasting and management systems. The principal operational use of remote sensing of snow properties has been to map the extent of the snow cover. Throughout the world, in both small and large basins, maps of the snow cover throughout the snow season are used to forecast melt, both in areas with excellent ancillary data and in remote areas with no ancillary data (Rango et al., 1977; Andersen, 1982; Martinec and Rango, 1986).

Since the first mapping of snow cover from satellite, the spectral and spatial resolution of the available sensors has been much improved. The high spatial resolution satellites such as IRS, Landsat and SPOT and the medium resolution sensors such as the NOAA AVHRR are widely used for mapping snow cover. The selection of the appropriate sensor depends on a tradeoff between spatial and temporal resolution (Rott, 1987). The Landsat Multispectral Scanning System (MSS) has a spatial resolution of about 80 m and is suitable for snow mapping in basins larger than about 10km^2 (Rango et al., 1983). Improved spatial resolution has been available since 1982 from the Landsat Thematic Mapper (30m) and since 1984 from the French SPOT satellite (20m in the multispectral mode and 10 m in the panchromatic mode). A series of IRS satellites launched by India since 1988, has resolution from 6 m to 180 m. The resolution of 180 m available from IRS WiFS sensor is especially suitable for snow cover mapping for large basins.

Since very little information on snow is collected regularly in the Himalayas, remote sensing remains the only practical way of obtaining at least some information of the snow cover in the large number of basins in the Himalayas. At present the visible, near IR and thermal IR data from various satellite (LANDSAT, IRS, NOAA) are being used operationally for mapping the areal extent of snow cover in the Himalayan basins.

2.0 REVIEW OF LITERATURE

2.1 GENERAL

Distributed hydrological models, which can account for the spatial variability of basin physiography and meteorological inputs, have the potential to exploit detailed snow cover data, including distributed snow cover area (SCA). Conventional snowcover data, such as snow surveys, provide detailed information on such snow pack properties but their site specific nature and infrequent occurrence limit their potential for use in distributed models. In order to provide distributed information characterizing the snowcover of a watershed, snow survey measurements must be extended to regions where no snow survey data are available. Remote sensing offers a considerable potential for collecting this data in cost effective manner. Because of difficult access and expensive operation of hydrological stations, radar or satellite data are particularly appropriate, but of course ground truth data are indispensable in the calibration and verification of remotely sensed data. Aerial and satellite surveys are useful in mapping snow lines. The wealth of observational material obtained by remote sensing can be integrated into models, such as snowmelt runoff models, considerably improving the forecast accuracy. Snow was first observed by satellite in eastern Canada from the TIROS-1 satellite in April 1960(Barnes and Smallwood, 1975). Since then, the potential for operational satellite based snow cover mapping has been improved by the development of higher temopral frequency satellites such as GOES (Geostationary Operational Environmental Satellite), Landsat, SPOT and IRS series, and NOAA-AVHRR and DMSP SSM/I satellites.

Snow has a high albedo in the visible region of the electro-magnetic spectrum compared to most natural surface cover. For this reason snowcovered area maps were one of the first satellite remote sensing applications (Tarble, 1963; Martinec, 1972). The technology has developed to the point where image processing systems are widely available (Baumgartner and Rango, 1991) and percent SCA estimates on a watershed basis can be obtained in near real-time for most of North America (Carroll, 1990; NOAA, 1992).

The net radiation balance is usually the most important factor in the snow pack energy budget (Wiscombe and Warren, 1980; Dozier, 1987) and snow covered area estimates can provide a means to estimate the net radiation flux over a discontinuous snow pack. However, few hydrological models make use of SCA, partly because data are difficult to obtain. Exceptions are the U.S. National Weather Service River Forecast Simulation (NWSRFS) model (Anderson, 1973) and the Snowmelt Runoff Model (SRM) (Rango and Martinec, 1979).

Satellite snow covered area information from land resource satellites such as Landsat has proved useful in simulating the snowmelt runoff from alpine snowpacks, where the melt occurs over a long period of time and is strongly related to the percent snowcovered area along basin elevation zones (Rango and martinec, 1981; Baumgartner et al., 1986; Rango and Van Katwijk, 1990). However, the repeat cover period for high resolution satellites such as Landsat is 16 days, which is not adequate for mapping shallow snow cover that can completely melt between images. Also, clouds often obscure visible imagery of the earth's surface and thus estimates of watershed state parameters using visible imagery are not a reliable source of data. However, mapping of shallow snow cover would be useful if provided at the daily repeat coverage intervals of meteorological sensors such as GOES or NOAA. GOES and NOAA imagery have an approximate spatial resolution of 1 kilometer in the region of southern Onatario (Hord, 1986).

Another possible source for snowcover information is microwave satellite imagery. The regular and frequent mapping of snow cover is possible using a sensor independent of time and weather. Depending on waveloength, microwave radiation will penetrate clouds and most precipitation, thus providing an all-weather observational capability, which is very significant in snow regions where clouds frequently obscure the surface (Schanda et al. 1983). There are two types of microwave sensors: active and passive. Passive radiometers include NIMBUS-7 Scanning Multichannel Microwave Radiometer (SMMR) and the DMSP SS/I (Hord, 1986) satellites and measure surface brightness temperatures. Active satellite sensors contain synthetic aperture radar (SAR) and emit microwave radiation at a specific frequency and polarizion and measure the return backscatter in the form of the backscatter coefficient.

Microwaves have unique capabilities for snowcover modelling:

i) they can penetrate cloud cover (Chang, 1986), providing reliable data;

ii) they can penetrate through various snow depths depending on wavelength therefore potentially capable of determining internal snowpack properties such as snow depth and water equivalent (Rott, 1986);

Microwave sensors have been studies as potential sources for snowcover information (Rott, 1986; Goodison et al., 1990; Bernier, 1987; Rango, 1986; Leconte et al., 1990, Leconte and Pultz, 1990). Of interest in the studies is measurement of the snowcover areal extent, depth and water equivalent.

Active microwave sensors was there on the First European Remote Sensing Satellite (ERS-1) and Canadian RADARSAT offer the possibility to observe seasonal snowcover characteristics in detail over the entire snow-cover season (Way et al., 1993). In one simulation of RADARSAT data, snow-cover classification accuracy was 80%, comparable to aircraft Synthetic Aperture Radar (SAR) (Donald et al., 1993). Comparing a classification of snow-covered area based on SAR with that done using TM suggests that a SAR-based classification is sufficiently accurate to substitute for visible-and-near-IR based estimates when such data are not available, for example due to cloudiness (Shi and Dozier, 1993).

Passive microwave signals are also sensitive to the liquid-water content snow, thus offering the potential to develop snow wetness estimates. The sensitivity of passive microwave signals to snow wetness aids in determining the onset of spring melt and the occurrence of multiple melt events during the winter (Goodison and Walker, 1993). In passive mode, microwave emission is strongly dependent on the condition of the snow in terms of humidity, metamorphism and water equivalence. Microwave penetration depth of dry snow is much larger and dry snow cover less than 2.5 cm depth is transparent to the microwaves and ignored even though it is thick enough to reflect incoming shortwave radiation (Carsey 1992). The interaction of microwaves with snow strongly depends on the snow wetness, size and structure of snow grains. The dielectric constants of water and snow are so drastically different that even a little melting will cause a strong microwave response (Rango 1986). Wang et al. (1992) found good agreement between aircraft and microwave depth estimates for an Alaskan snowpack; but they also noted that the radiometric correction for the effect of atmospheric absorption is important at all wavelengths used for a reliable estimation of snow depth. Experimental snow mapping with satellite derived passive microwave radiometer data show the high potential of mapping for dry snow (Kunzi et al. 1982, Tiuri and Hallikainen 1981). However, the poor spatial resolution of the satellite microwave sensors, typically of the order of 25km, has restricted the use of snow cover values estimated from passive remote sensing for snowmelt run-off determination in high mountainous catchments (Chang and Foster 1991). Passive microwave data with a resolsution of about 30m have used to monitor snow extent and to estimate the snow water equivalent with a considerable success (Foster et al. 1987, Hall 1988).

Several researchers have reported on efforts to incorporate remote-sensing data into snowmelt-runoff modeling. Rango(1993) reviewed the progress that has been made incorporating remote-sensing data into regional hydrologic models of snowmelt runoff. The National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) sensor provides daily views over large areas (1000 km swath) and snow-cover maps are produced operationally. Estimates of snow-covered area based on remote sensing data can significantly improve the performance of even simple snowmelt models in alpine terrain [Kite, 1991; Armstrong and Hardman, 1991]. For operational purposes, empirical approaches using combining remote sensing data to estimate snow-covered area, and snow-depth networks to estimate SWE are continuing to improve [Martinec and Rango, 1991; Martinec et al., 1991]. Mcmanamon et al. [1993] have combined airborne and ground based measurements to produce gridded SWE estimates for the upper Colorado River region.

2.2 SNOWMELT STUDIES FOR HIMALAYAN BASINS

The snowmelt studies carried out in the Himalayan region may be broadly categorized as studies related with regression analysis, empirical relationships and application of snow melt simulation models.

2.2.1. Development of regression relationship

In the regression analysis category, regression was carried out to co-relate the snow cover area with the runoff. Efforts were also made to co-relate the winter snowfall and snowmelt runoff. Rango et. al., (1979), used the satellite imageries for finding the snow covered areas during early April over the Indus river and the Kabul river in Pakistan which was regressed with the flows of April to July for the years 1969-73. The early spring snow covered area was significantly related to April through July 31 streamflow, in regression analysis for each watershed. Predictions of the seasonal flows for 1974 using the regressed equations obtained were found to be within 7% of the actual flow. The relationship between snow cover area and runoff of the Beas basin has been studied by Gupta et. al., (1982). Snow cover area was mapped from Landsat imageries and the snow cover area and the subsequent runoff in different sub-basins was found to be well co-related. It has been interpreted that there have been years of uniformly heavier and lighter snowfall all over the basin and snowmelt discharges have systematically varied .

Jeyram and Bagchi, (1982), estimated the snowline altitude and the snow cover using Landsat imageries for Tons river basin in Himalayas. A relationship was observed between the snowline of Beas, Ravi and Tons. Lean season discharge of Sainj river has been studied by Krishnan, (1983), in reference to winter snowfall and discharge, to establish the relationship between two variables. The studies have revealed that both these parameters have a high co-relation coefficient of 0.91. Based on this study a simple linear regression model was evolved to forecast three to four months in advance, the lean season discharge of Sainj river solely on the basis of winter snowfall.

Dey and Goswami, (1983), have presented results of studies involving utilization of satellite snow cover observations for seasonal stream flow estimates in Western Himalayas. A regression model relating seasonal flow from April through July 1974 to early April snow cover, explained 73% and 82% of the variance, respectively, of measured flows in Indus and Kabul rivers.

The importance of permanent snow covered area in the study of the snowmelt was brought out by Ferguson, (1985). A study was carried out for the glacierized mountains (Upper Indus in Pakistan) and a model was developed for annual variation of runoff and its forecasting. The approach is based on identification of a number of glaciological and climatological factors other than snow covered area. Roohani, (1986) related the information about extent of snow cover obtained from the Landsat MSS imageries for the months of March to June with the snowmelt runoff assumed as total flow minus baseflow for different sub-basins of Chenab river. A general linear relationship was obtained. Mohile et. al., (1988), carried out a study to develop a regression relationship between temperature of Kaza and snowmelt runoff collected at a proposed dam across Spiti river, about 4 km upstream of Kaza at an elevation of about 3639 m, in the Satluj basin.

A regression model using percentage of snow covered area of Satluj basin above Bhakra and seasonal snowmelt runoff (April – June) for the years 1975-78 was attempted by Ramamoorthi, (1983). The model was used to forecast the seasonal snowmelt runoff in Satluj for 1980. At the end of June, 1980 it was found that the difference between the forecast quantity and observed flows was about 9%.

2.2.2 Application of empirical relationships

Several snowmelt studies using empirical relationships between temperature and snowmelt runoff have been made. Such empirical relations are generally a function of degree-day factor and snow cover area. Thapa, (1993), estimated snowmelt by considering the melt due to influence of temperature and rainfall in the snow covered area for Beas basin up to Larji. The relationship between snowcover aquired with the help of satellite imageries and the cumulative discharges of the months of March, April and May for the year 1973,1975,1976 and 1977 was studied. Due to availability of limited meteorological and hydrological data, the estimation of snowmelt runoff has been limited to the sub-basin upstream of Manali.

Bagchi, (1981), carried out a study of snowmelt runoff in Beas basin using satellite images. Temperature index method was employed using a lapse rate of 0.65°C/100m. The value of degree-day factor was considered as 2.1 mm $C^{-1}day^{-1}$. The study was carried for the Beas basin up to Manali. An empirical model for prediction of snowmelt runoff in Satluj basin has been used by Upadhyay et. al., (1983). The model for computation of snowmelt runoff has been presented as a function of degree-day factor. Upadhyay et. al., (1983), also analyzed the various components of energy input to a snow cover and monthly budget for net energy available for snowmelt have been worked out for a number of stations in Himalayas.

The snowmelt runoff generation for a sub-catchment of Beas basin was made by Agarwal et. al., (1983), using point energy and mass balance approach. The contribution of various energy sources in different conditions was also worked out. Melt runoff has also been estimated using the degree-day method. Melts thus arrived have been compared with the observed discharge. The study was based on the data for the year 1981-92 collected from the snow courses located in the sub-catchment. Results indicate that although net radiation balance remains the dominant source of melt energy, yet sensible and latent heat contribute in the range of 40% to 60% of the total energy for the altitudes below 3000 m in the open area during clear and partly cloudy days in the active snowmelt period. The influence of radiation on cloudy days ranges from 20% to 34%. Upadhyay et. al., (1985), have shown that for Beas and Satluj basin, the snowmelt caused by the incoming solar radiation is predominant over other physical processes such as long wave energy transfer at the snow-air interface, convective heat exchange and latent heat released by condensation. It was shown that the results obtained by the degree-day approach varied much from the results obtained by energy balance approach.

3.0 THE STUDY AREA AND DATA USED

3.1 THE STUDY AREA

In the present study, snow cover area studies have been carried out for the four catchments located in western Himalayan region. These four catchments are Satluj catchment up to Bhakra, Beas basin up to Pandoh, Ganga basin up to Deoprayag and Chenab basin up to Akhnoor. These basins have been described in brief in the following sections.

3.1.1. Satluj Basin

The Satluj River originates from Rakas-Tal Lake, which is fed by Lake Mansrover in Tibet at an altitude of about 4572-m above mean sea level. Between Raskas-Tal and Ship Ki near the Indian border the Satluj River follows a northwesterly direction for a length of about 322-km in the Tibetan province of Nari-Khorsam. Several tributaries join it in Nari-Khorsam, the bed of, which are lower by about 305 m than the general level of the plateau. Their vertical cliffs, like those of Satluj, have been spared from destruction by rain, and flat portions of the plateau now remain standing between deep and narrow gorges.

The total geographical area of Satluj catchment up to Bhakhra dam is about 56,980 km^2 of which about 37,153 km^2 lies in Tibet. The rest about 19,827 km^2 lies in the Indian terrirtory. The Satluj basin up to Bhakra dam is shown in Figure 3.1. The major portion of the Satluj basin lies in the greater Himalayan range. The bed slope of Satluj from its source to Bhakra dam site is quite uniform. The elevation of the bed is 4572 m near Rakas-Tal, 3048 m near Ship-Ki, 914 m at Rampur, 457 m at Bilaspur and 347m at the Bhakra Dam site. The river bed slope in the reservoir area is about 1.89 to 2.27 m/km. The river leaves the Himalayas near Nangal, where Nagal barrage is located.

In the reservoir area, the catchment starts from Bhakhra dam, where it is flanked on both sides by the foothills of the Shivalik ranges, diverging from a narrow george to a very wide width of about 24 km and again narrowing down up to Kasol forming the tip of the reservoir. The lower catchment largely drains directly into the reservoir and the the higher slopes drain through tributaries. The important tributaries are the Soel khad, Alseed khad, Ali khad, Gamrola khad, Ghambhar khad, Seer khad, Sukhar khad, Sarhali khad and Lunkar khad.

The catchment receives heavy rainfall during the monsoons from July to mid September, sometimes rainy season extends up to late September and very rarely up to early October. The average rainfall in the catchment is 1140 mm. The Satluj runoff basically consists of two parts, one of which is derived from the melting of the snow and the other resulting from the rainfall in the catchmnet. The monsoon is generally marked by high river flows and occasional floods in Satluj. There is significant contribution from snow and glaciers into stream flows of Satluj. The contribution from snow and Ice varies with season to season being maximum in summer months.

3.1.2 Beas Basin

The River Beas is an important river of the Indus river system. The Beas basin up to Pandoh dam was chosen for the present study. It takes off from the eastern slopes of Rohtang pass of Himalayas at an elevation of 3900 m and flows in nearly north-south direction up to Larji, where it nearly takes a right angle and turns towards west and flows in the same direction up to the dam. The length of the river up to Pandoh dam is 116 km. The catchment of the Beas basin up to Pandoh dam is 5278 km^2 out of which only 780 km^2 is under permanent snow. Mostly the catchment area comprises of precipitous slopes and the rocks are mainly bare. The gradient of the river is very steep in upper reaches where it encounters many falls. There are high peaks in the east as well as in the north of the river valley. The altitude varies from 832 m near Pandoh to more than 5000 m near Beo-Toibba. A considerable portion of the river becomes snow covered during winter. There is negligible extent of glacier in this basin. Beas is the principal tributary of river Satluj.

During summer Beas is mainly fed by snowmelt. Some of the major tributaries which join upstream of Pandoh dam are: Parvati river near Bhuntar, Tirthan and Sainj rivers near Larji, Sabari nala near Kulu and Bakhli khad near Pandoh dam. All these rivers have got perennial flow, which varies considerably during different months of the year. A major portion of the catchment lies under degraded forests and cultivated land and therefore the proportion of the silt and sand are of fine, medium and coarse configuration. Steep slopes are very common but are terraced at several places in the lower ranges up to an elevation of 1982 m for agricultural purposes. In certain reaches thick forests exists mostly between elavation of 1830 m to 2744 m. The map showing the Beas basin up to Pandoh dam is given as Fig. 3.2.

3.1.3. The Ganga Basin

The Ganga river rises in the Gangotri glacier in the Himalayaas at an elevation of about 7138 m above the mean sea level in Uttar Kashi District of Uttranchal. At its source the river is called the Bhagirathi. It descends down to the valley up to Devprayag where the Alaknanda, another hill stream rising from the twin glaciers, namely the Bhagirath Kharak and the Satopanth, joins it. After its confluence with Alaknanda, the combined stream is called the Ganga . Alaknanda is the main tributary of Bhagirathi. Other important tributaries of Alaknanda are the Dhauli Ganga, Vishnu Ganga, Mandakini and the Pindar.

The river continues to flow down in torrents and cascades along the vallaey for distance of approximately 160 km and after cutting through the Shiwalik range of hills, it emerges into plains at Hardwar in Uttranchal. Thereafter it flows in a series of channels separated from each other by islands. It flows from west to east practically through the whole of North India. The total length of Ganga from its point of origin to the point where it falls into the sea is about 2525 km (Irrigation Commission, 1972).

The total area of the Ganga basin up to Devprayag (Figure 3.3) is about 19700 km and covers a wide elevation range from 457 m to about 7000 m. All the rivers before emerging out from the Himalayas have formed narrow or broad deep valleys in accordance with lithology. All the main rivers make a steep descent in the first 10 to 20 km of their longitudinal profile and afterward their gradient is not so steep. Near the origin Bhagirathi has a gradient of the order of 33.6 m/km whereas it is reduced to about 5.6 m/km near Rishikesh (Singh, 1971).

Soils of this region do not forma compact block. They differ valley to valley and slope to slope according to different ecological conditions. Soils of upper Bhagirathi and Alaknanda are of mixed region, i.e. glacial and fluvio glacial. In the lower hilly region, soils mostly comprise forest soils and hill soils. The problem of soil erosion in the basin is particularly serious in the Himalayan tract. The soil in this region is very thin and all exposed slopes are susceptible to server erosion and to gullying. Land slides are fairly common in the area. Lower down, in the plains the slope is gentle except in the vicinity of natural drainage where steep slopes have been created through erosion spread over centuries. The bed of the river is rocky up to 20 km downstream of Hardwar.

3.1.4. Chenab Basin

The Chenab river is one of the main five constituent of the great Indus system. The Chenab river has it s major part of course through India and the lower reach including its outfall into the main Indus river in Pakistan. In India the Chenab basin is located in western Himalayas between latitudes 30° to 34° North and longitudes 74^0 to 78^0 East. It spreads over the two states of Himachal Pradesh and Jammu & Kashmir, which comprises of the extreme western sector of Himalayas. Upper half of this basin is located between the Zanskar and the Pir-panjal ranges whereas the lower half is located between the Pir-panjal and the Dhauladhar ranges. In this way this basin covers outer, middle and greater Himalayas.

The Chandra and the Bhaga rivers constitute the Chandrabhaga or the Chenab. The Chandra starts from a large snowbed on the south-eastern side of Baralacha Pass at an elevation of 5639 m asl and after flowing (south-east) through snow clad barren area for about 90 kms, it sweeps round the basin of mid Himalayas and joins the Bhaga at Tandi after a course of about 185 kms. The Bhaga rises in the north-western slopes of Baralacha pass the elevation of 8477 m. The length of the Bhaga up to the confluence with the Chandra is about 105 kms. The combined streams then known as Chandrabhaga or the Chenab, flows in north-west direction through the Pangi valley of Himachal Pradesh and enters Kishtwar area in Jammu & Kashmir. At Benjawar near Kishtwar it turns south and flows through a gorge across Pir-Panjal range and then enters the valley between the Pir-Panjal and the Dhauladhar ranges. It receives its major tributary, the

Marusudar river and then flows in southern direction for about 25 km. Thereafter, it flows almost in westerly direction up to the Salal Dam site and then takes a southerly turn and emerges out into plains near Akhnoor. The total length of the Chenab river up to Akhnoor is about 535 km.

The Chenab basin consists of separate valleys which act as sub-basins, contributing considerable amount of runoff as the tributaries of the Chenab river. The main tributaries in its passage up to Kishtwar are, Thirot, Shedi, Sohal, Lidder and Marusudar. Marusudar is the biggest tributary of the Chenab and meets Chenab at Bandalkot. Between Kishatwar and Akhnoor, it receives the water of Neeru, Pugal, Bagi, Bachleri and Ans tributaries

The catchment of Chenab is elongated in shape and covers an area of about 22200 km up to Akhnoor (Figure 3.4). The elevation of the catchment varies widely from about 305 m to 7500 m. Mean elevation of the basin is about 3600 m asl. The hydropower potential of Chenab river is very high. The gradient is very steep at its source and gradually reduces down stream. The Chenab river has the general character of torrent with a gradient of 10m/km in the higher reaches and 3-4 m/km in the

3.2 DATA USED

For mapping of snow covered area, IRS WiFS data have been used. The four study basins are covered in Path/Row: 96/50 and 96/51. For these two path/rows, the data of 1997, 1998, 1999 and 2000 have been procured from NRSA, Hyderabad. The dates for the years 1996 to 1999 are as follows: 1.12.96, 07.03.97, 24.4.97, 18.5.97, 11.6.97, 5.7.97, 24.10.97, 2.11.97 and 20.12.97. For the year the date are as follows: 13.1.98, 26.2.98, 26.3.98, 19.4.98, 13.5.98, 28.10.98, 21.11.98 and 15.12.98. For the year 1999 the date for which the data was procured include 21.3.99, 14.4.99, 25.6.99, 16.11.99 and 13.11.99.

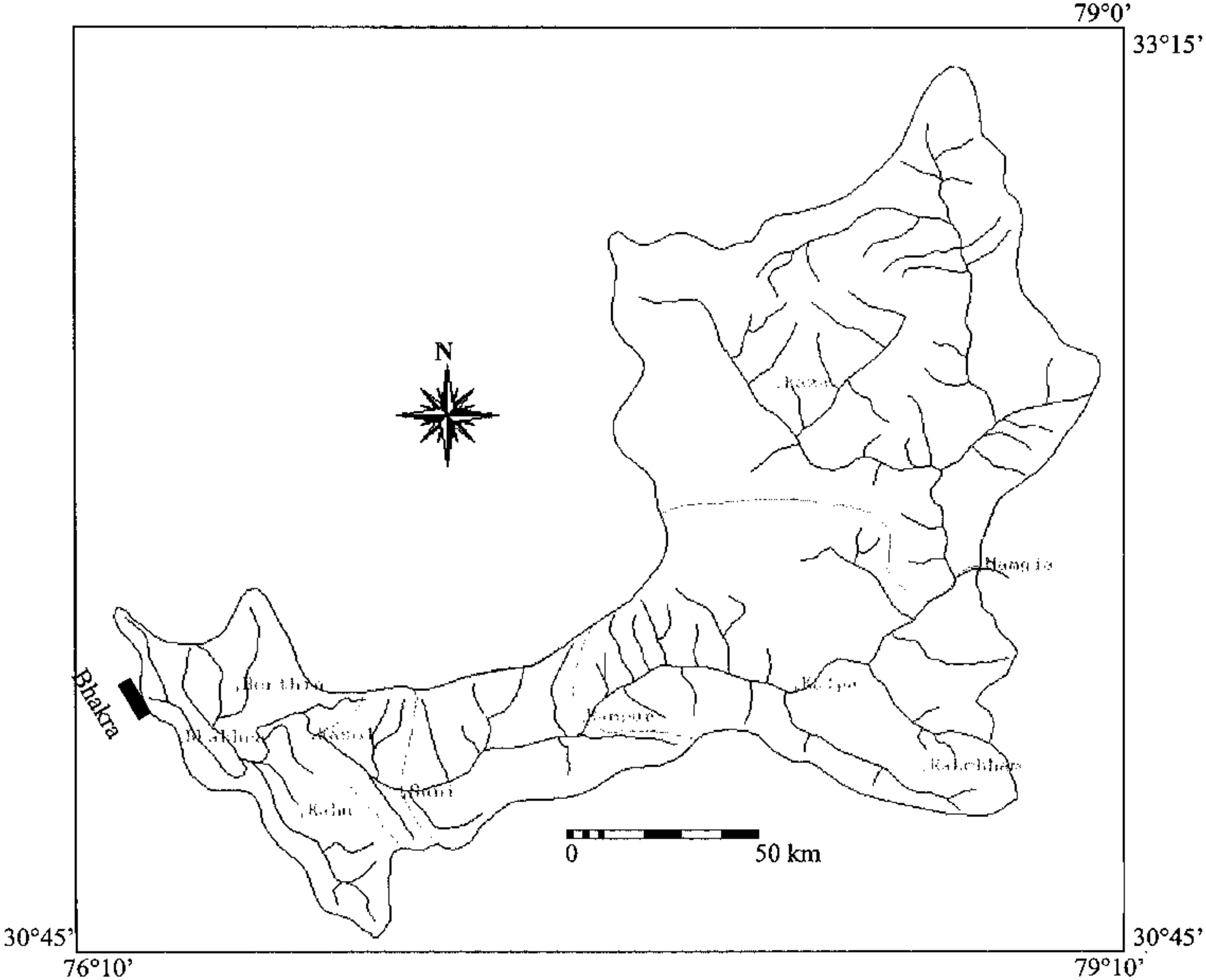

Figure 3.1 : Satluj basin upto Bhakra

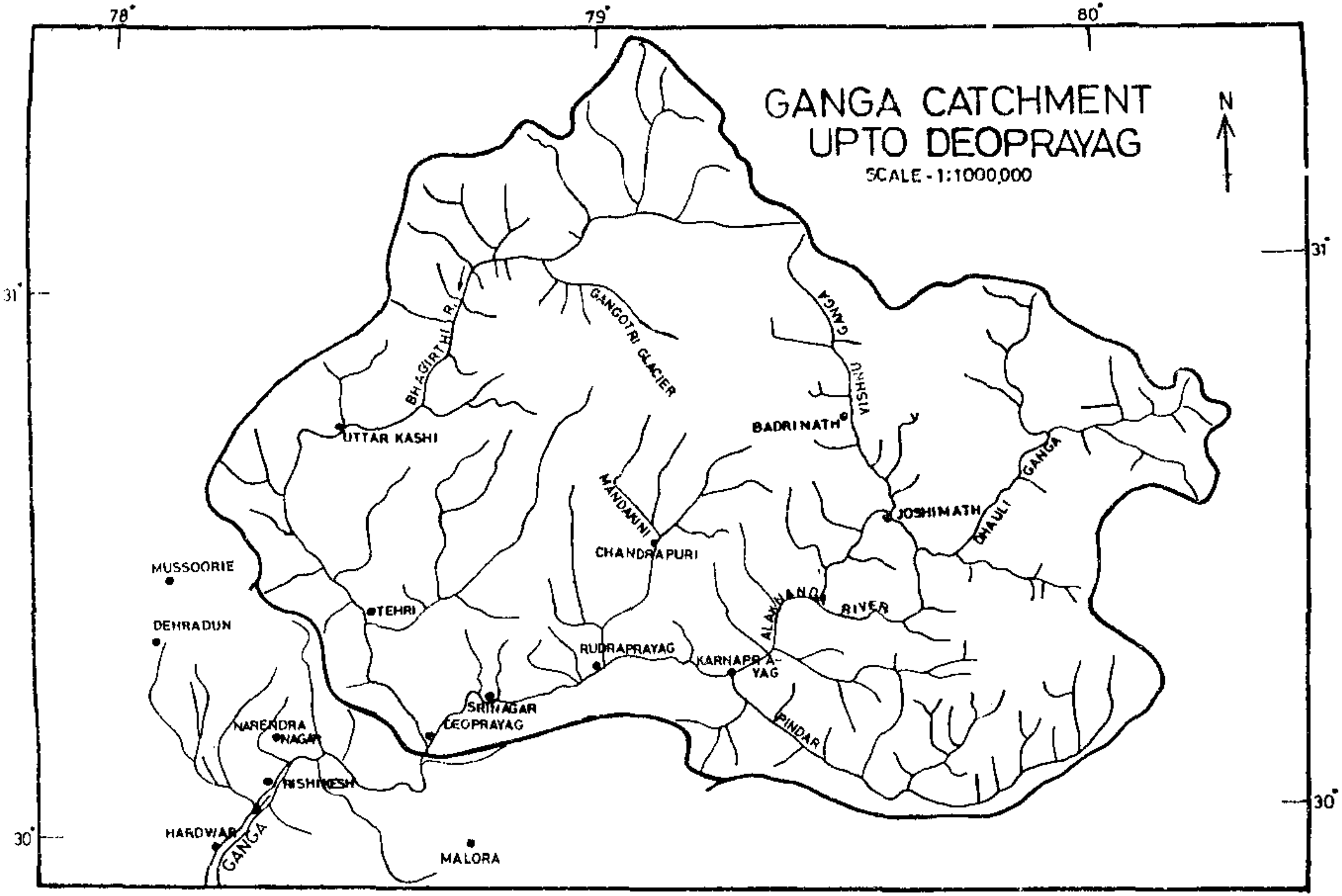

Figure 3.2 : Ganga basin upto Deoprayag

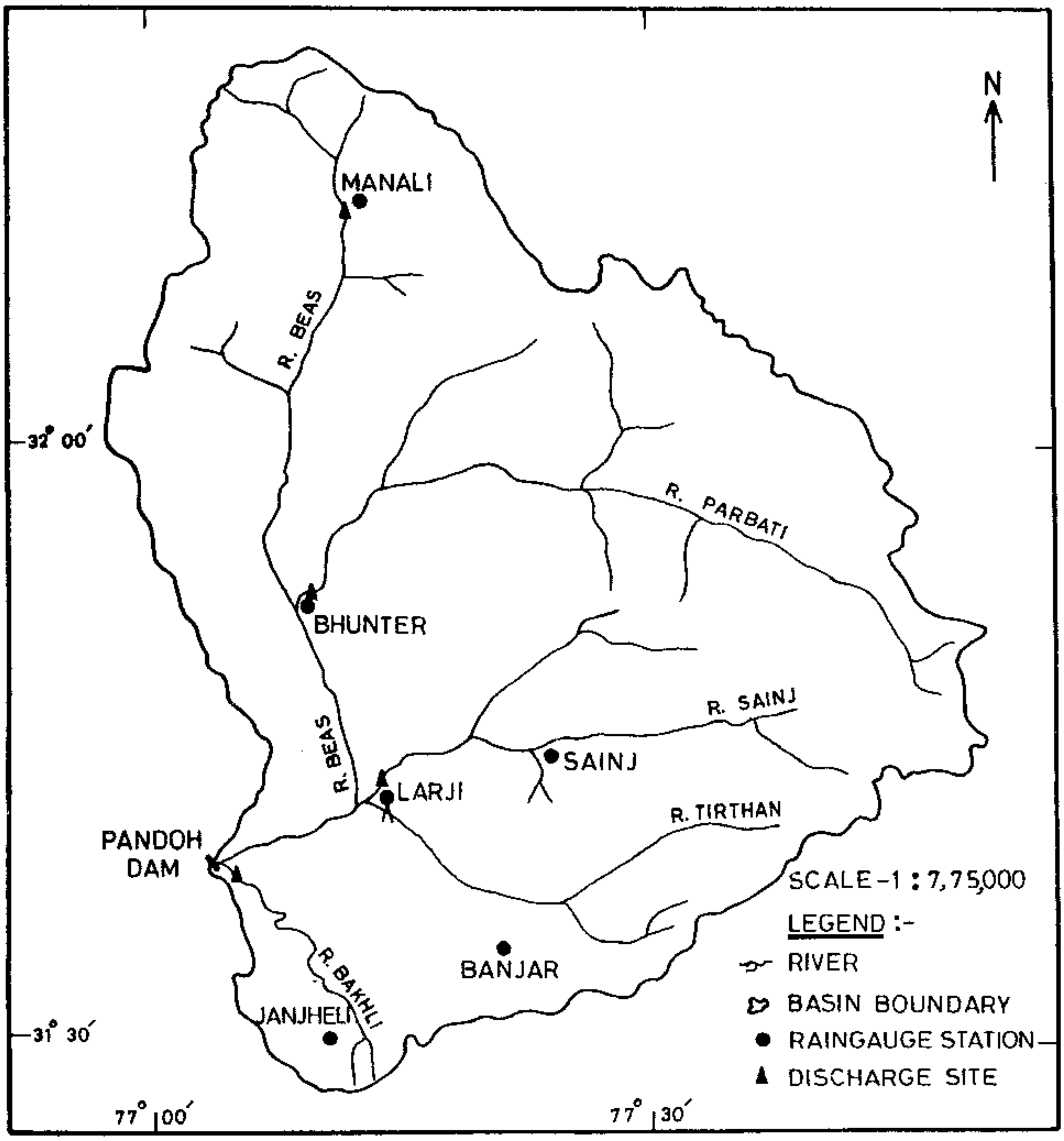

Figure 3.3 : Beas basin upto Pandoh

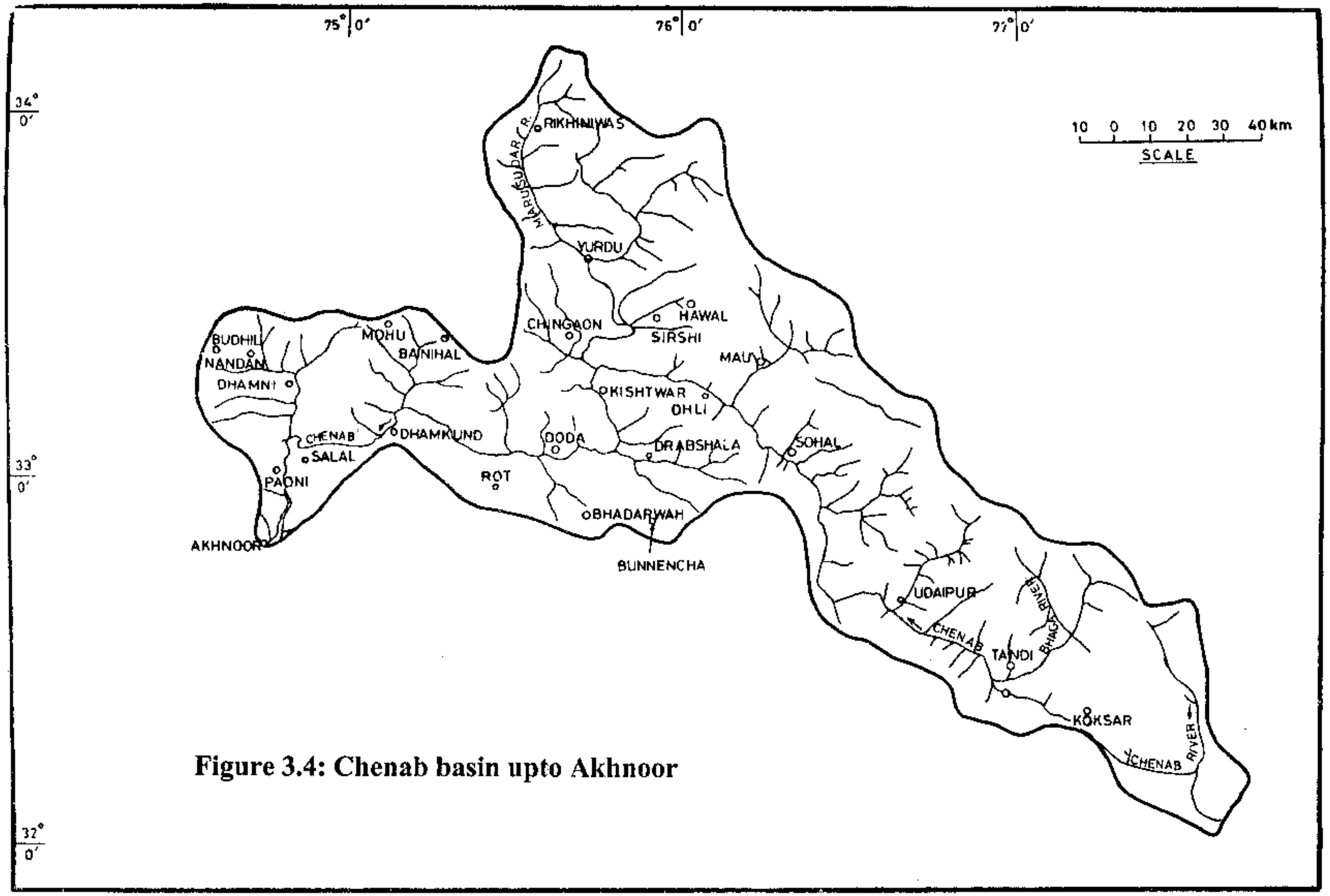

Figure 3.4: Chenab basin upto Akhnoor

4.0 METHDOLOGY

4.1 GENERAL

The duration for which the seasonal snow cover stays in the basin is variable from basin to basin and also from year to year. In the present study, IRS WiFS data in the form digital data was used. WiFS has 188 m ground resolution and two spectral bands in red (620-680 nm) and near-infrared, NIR (770-860 nm) region. One scene for each month was used. The temporal data provide a wider view to find out the qualitative as well as quantitative status of the vegetation. NOAA-AVHRR has been widely used the world over for mapping at global level snow studies. The introduction of WiFS offered an advantage with its spatial temporal resolutions for vegetation studies. Earlier workers have established the application of WiFS for regional studies. For large basins, WiFS has been found useful with its ability to present a temporal dataset to overcome the cloud and snow cover problem.

In the present study, wide field sensor with a capability of covering large areas in single instant field of view (IFOV) has been used, which avoids illumination differences and has better temporal resolution. Such data have found considerable acceptance for land cover studies at regional scale, demonstrated through NOAA-AVHRR data. However many studies have found NOAA data deficient due to their 1.1 km resolution. IRS WiFS data are first of their kind to overcome such deficiencies. This study focuses the potentials of temporal IRS-1C WiFS data for monitoring the extent of snow cover.

First of all a base map of all the study basins was prepared using toposheets from Survey of India. All sets of CDs were analysed using digital image processing techniques. These CDs represent snow accumulation and depletion periods in a hydrological year. The base map has been prepared in ILWIS and imported to ERDAS. The processing of these CDs have been carried in ERDAS software.

When mapping the snow cover there are several possible features on the image, which were considered in order to prevent misidentification of snow and snow free areas. For example, cloud tops exhibit a very bright reflectance in the visible/infrared bands that is often indistinguishable from snow. These aspects have been kept in view when delineating snow covered area.

4.2 DIGITAL IMAGE PROCESSING

4.2.1 Geometric Correction and Registration

A base map of each basin have been prepared and converted to digital form. All the sub scenes were geometrically corrected using the base map and carefully selecting the ground control points (GCPs). Well-distributed GCPs are essential for a successful geometric correction but it is very difficult to select such control points in high mountainous areas, because the roads and other infrastructures used for control points normally follow major valleys and very few run across the uplands. This becomes further complicated in a snow-covered region. A first order polynomial transformation was performed and resampling was done using the nearest neighbour interpolation method. The accuracy of registration was visually verified by overlaying the selected ground features on the geo-referenced images. This procedure was observed to be appropriate because the study area contains features, which can be recognized on images and has boundaries corresponding to rivers, reservoir and roads etc. The final products ensure that all data sets are comparable and areas can be measured. The basin area from each satellite image was extracted using an overlay mask.

After registration work is over the classification was applied to the images. Before classification, the images were studied in detail. Contrast stretching of individual raw bands is one of the initial steps and is effective in improving interpretability of different features through increasing contrast. To have an idea of frequency distribution of the data, image histogram of the bands have been studied. The following ground features were considered for preparing the snow covered area maps.

4.2.2 Mosaicing

The three basins viz. Satluj, Ganga and Bead were covered in one scence and the fourth basin i.e. Chenab basin was partly covered in Path/row 96/50 and partly in Path/row 96/51. Therefore a mosaic was made using these two scenes for this basins. For this first these two scences were registered to each other using image to image registration. After this process, Mosaic was made using the overlap areas in two scences.

4.2.3 Shadows

The Himalayan Mountains are rugged and have high relief. As the Landsat and IRS data have been acquired in the early forenoon, the prevailing low-angle of illumination leads to shadows. In such cases, snow covered shadowed regions appear similar to snow-free areas in tone. Before classification it is necessary to discriminate between snow-free area and the shadows. Small portions in snow covered area, which are under shadow have been considered as snow bound.

4.2.4 Cloud cover

Cloud cover has been seen as the main constraint on the possible operational implementation of the satellite monitoring of snow cover based on satellite data representing visible part of electromagnetic spectrum. Using the estimated snowline altitude and assuming a similar accumulation of snow above the calculated snowline in these obscured regions may approximate the area of snow concealed by cloud. A sequence of satellite images, where different parts of each image are cloud free, can be classified and overlaid to produce fuller areal information for the same snow day or for a snow event. The assumption is that the snow condition for the two images remained the same and only the positions of clouds changed for the successive images. Assuming that the snow conditions did not change significantly between these times, the combined classified image reveals the fuller extent of snow distribution for that day. Extrapolations of snow area beneath clouds for two images have been attempted in this study.

4.2.5 Classification

In the present study unsupervised classification using the Iterative Self-Organizing Data Analysis Techniques (ISODATA) has been applied. The ISODATA uses the minimum spectral distance to assign a cluster for each candidate pixel. It begins with a specified number of arbitrary cluster means which are then processed repetitively, so that these arbitrary means shift to the means of clusters in the data. The required inputs for running the ISODATA process are the number of clusters in the output file, the convergence threshold which is the maximum percentage of unchanged pixels reached between two iterations, and the maximum iteration which is the maximum number of times that ISODATA should recluster the data and prevents ISODATA from running too long or from potentially getting "stuck" in a cycle without reaching the convergence threshold.

The ISODATA utility repeats the clustering of the image until either:

- a maximum number of iterations has been performed, or
- a maximum percentage of unchanged pixels has been reached between two iterations.

The output file will have a gray scale color scheme if the initial cluster means are arbitrary. If the initial cluster means are from an existing signature set, then the output file will use the colors of this signature set. The output classification is recoded into a new classification containing up to five classes. Overlaying the 10 class classifications on the original imagery to aggregate the 10 classes into two does this. Because out aim here is to classify the area into two classes viz snow covered and snow free, therefore only classes have been finally obtained.

5.0 ANALYSIS AND RESULTS

The snow cover area maps have been prepared using the procedure as mentioned above for the dates for which the data was available. In some of the years, the data for the dates of September and October was not available, hence for these years, using interpolation of the data of other dates, snow covered area for September or October was computed. The snow covered area obtained from March/April and September/October for different years for four basins are given in Table 5.1 to Table 5.4.

Table 5.1 : Snow covered area (SCA) and permanent snow covered area (PSCA) in Satluj basin up to Bhakra reservoir.

Year	Month	Snow covered area expressed as % of total basin area	Month	Permanent snow covered area expressed as % of total basin area
1997	March/April	56	Sept./Oct.	7
1998	March/April	68	Sept./Oct.	14
1999	March/April	61	Sept./Oct.	9
2000	March/April	59	Sept./Oct.	9

Table 5.2 : Snow covered area (SCA) and permanent snow covered area (PSCA) in Ganga basin up to Deoprayag

Year	Month	Snow covered area expressed as % of total basin area	Month	Permanent snow covered area expressed as % of total basin area
1997	March/April	47	Sept./Oct.	13
1998	March/April	51	Sept./Oct.	17
1999	March/April	45	Sept./Oct.	12
2000	March/April	52	Sept./Oct.	19

Table 5.3 : Snow covered area (SCA) and permanent snow covered area (PSCA) in Beas basin up to Pandoh.

Year	Month	Snow covered area expressed as % of total basin area	Month	Permanent snow covered area expressed as % of total basin area
1997	March/April	46	Sept./Oct.	21
1998	March/April	44	Sept./Oct.	19
1999	March/April	43	Sept./Oct.	19
2000	March/April	47	Sept./Oct.	21

Table 5.4 : Snow covered area (SCA) and permanent snow covered area (PSCA) in Chenab basin up to Akhnoor.

Year	Month	Snow covered area expressed as % of total basin area	Month	Permanent snow covered area expressed as % of total basin area
1997	March/April	66	Sept./Oct.	23
1998	March/April	71	Sept./Oct.	25
1999	March/April	68	Sept./Oct.	19
2000	March/April	65	Sept./Oct.	15

The results for all the four basins have been depicted in the form of figures for all the years and shown in Figures 5.1 to 5.16.

The results indicate that a major portion of the basin is covered by snow in the month of March/April and it goes on reducing as the snow melt progresses. The snow cover is minimum in the month of September/October. From the above table it can be seen that the maximum snow cover for Satluj basin varies from 55% to 67%. While the minimum snow cover varies from 7% to 14%. It means that approx. 50% of the snow cover melted during melting season for this basin. For Ganga Ganga basin the maximum snow cover varies from 45% to 52% and minimum snow cover varies from 12% to 19%. Therefore the snow cover area reduces approx. 33% during summer season. For Beas basin the maximum snow cover varies from 43% to 47% and minimum snow cover varies from 19% to 21%. It means that the snow cover, which contributes to snow melt, is approx. 26%. The maximum snow cover in the Chenab basin varies from 65% to 71% while the minimum area varies from 15% to 25%. In other words the melting of snow during season is approx. 44%.

On the basis of decrease in snow cover, snow cover depletion curves have been drawn for each basin. The snow cover depletion curves for the four basins have been depicted in Figures 5.17 to Figure 5.20.

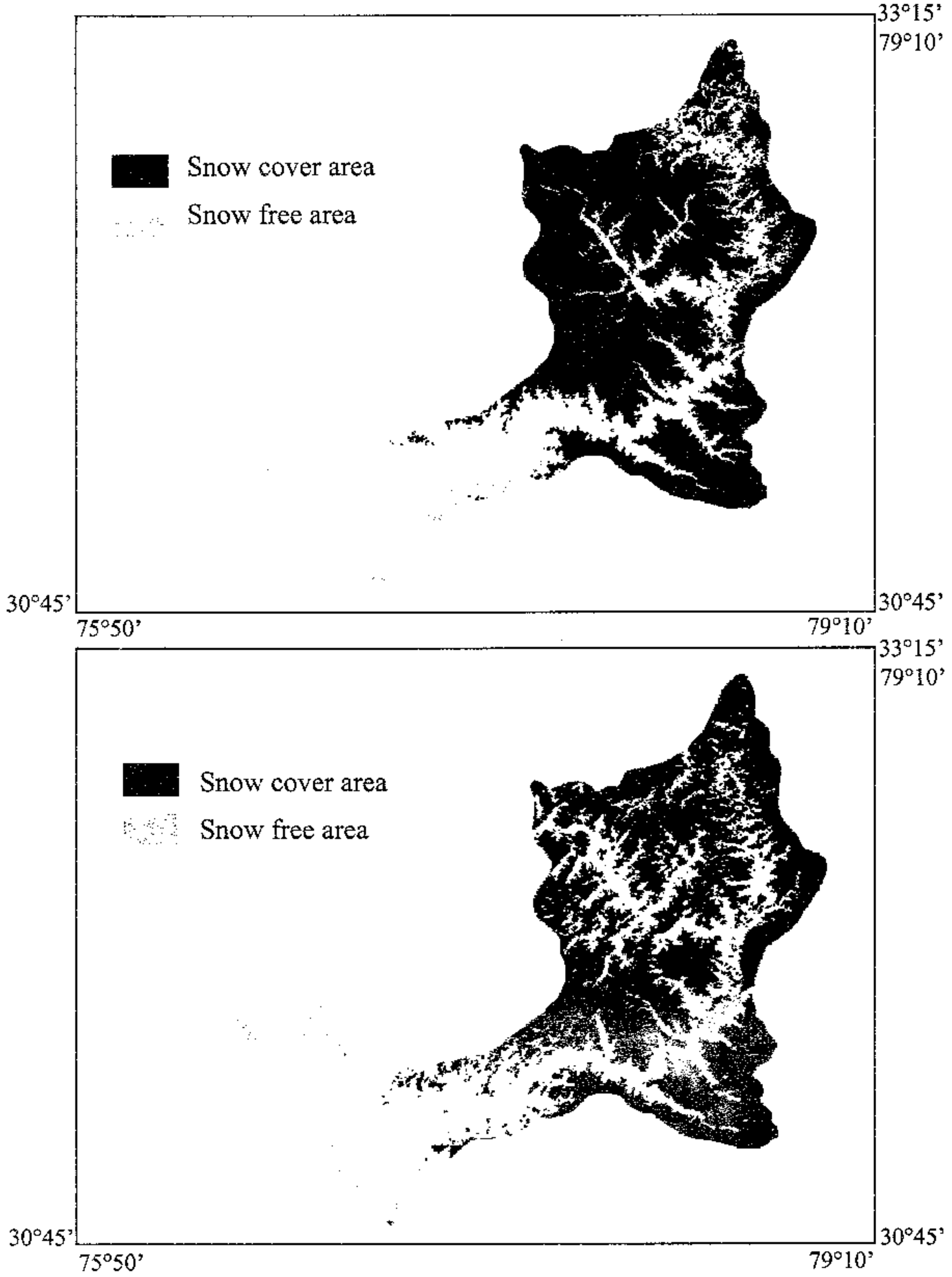

Figure 4.1: Snow covered area in Satluj basin upto Bhakra in March and October 1997

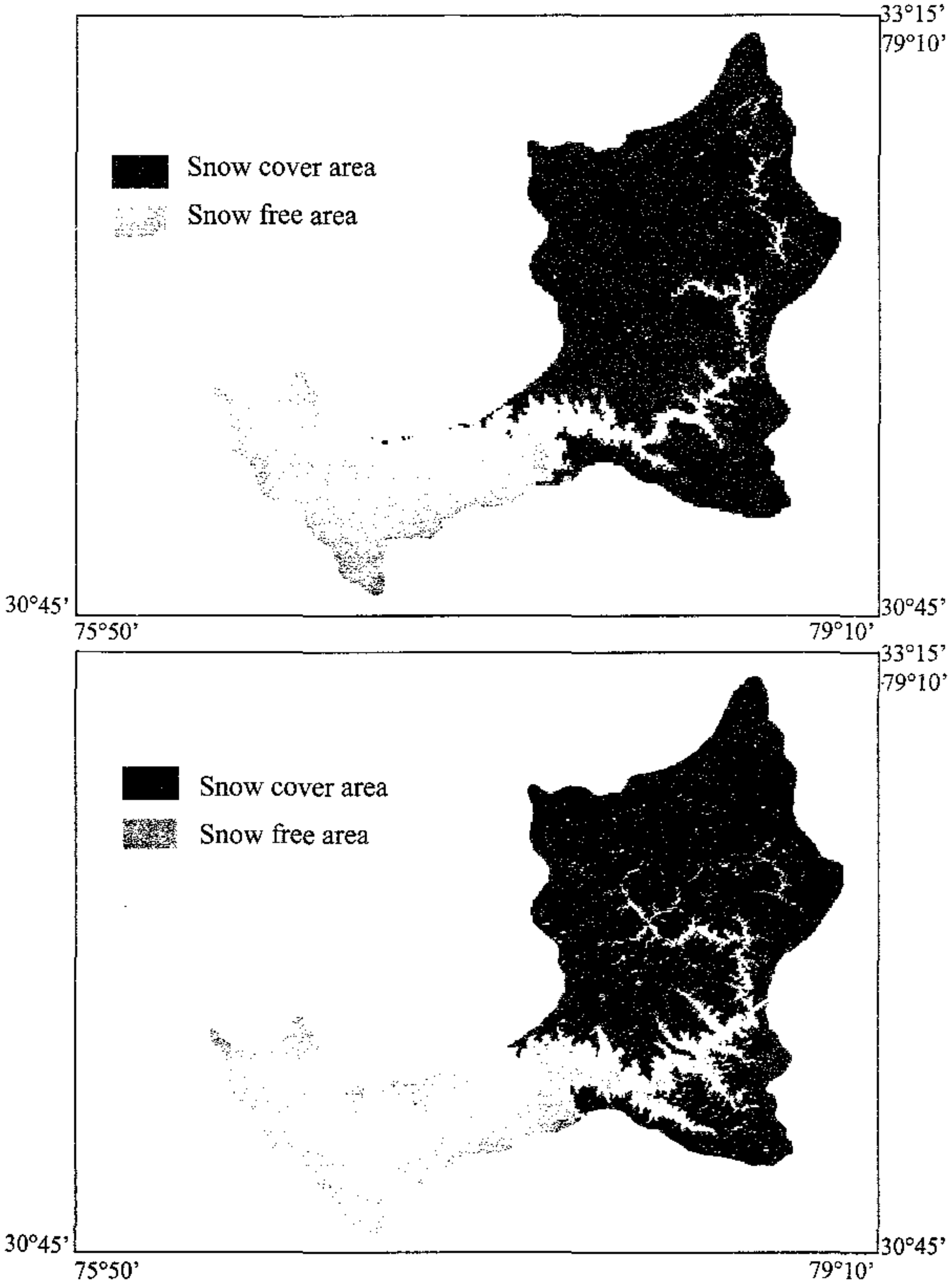

Figure 4.2: Snow covered area in Satluj basin upto Bhakra in March and October 1998

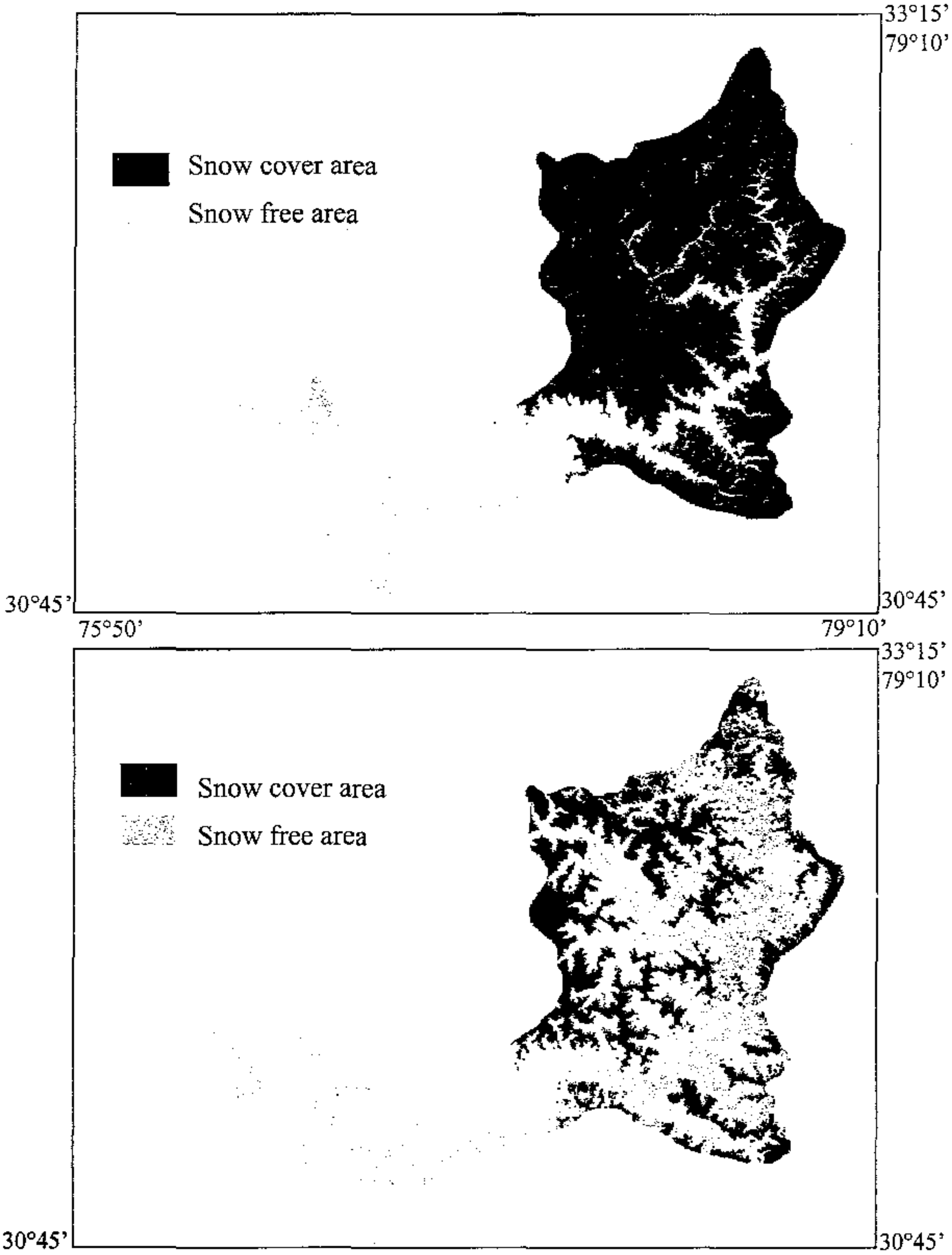

Figure 4.3: Snow covered area in Satluj basin upto Bhakra in March and October 1999

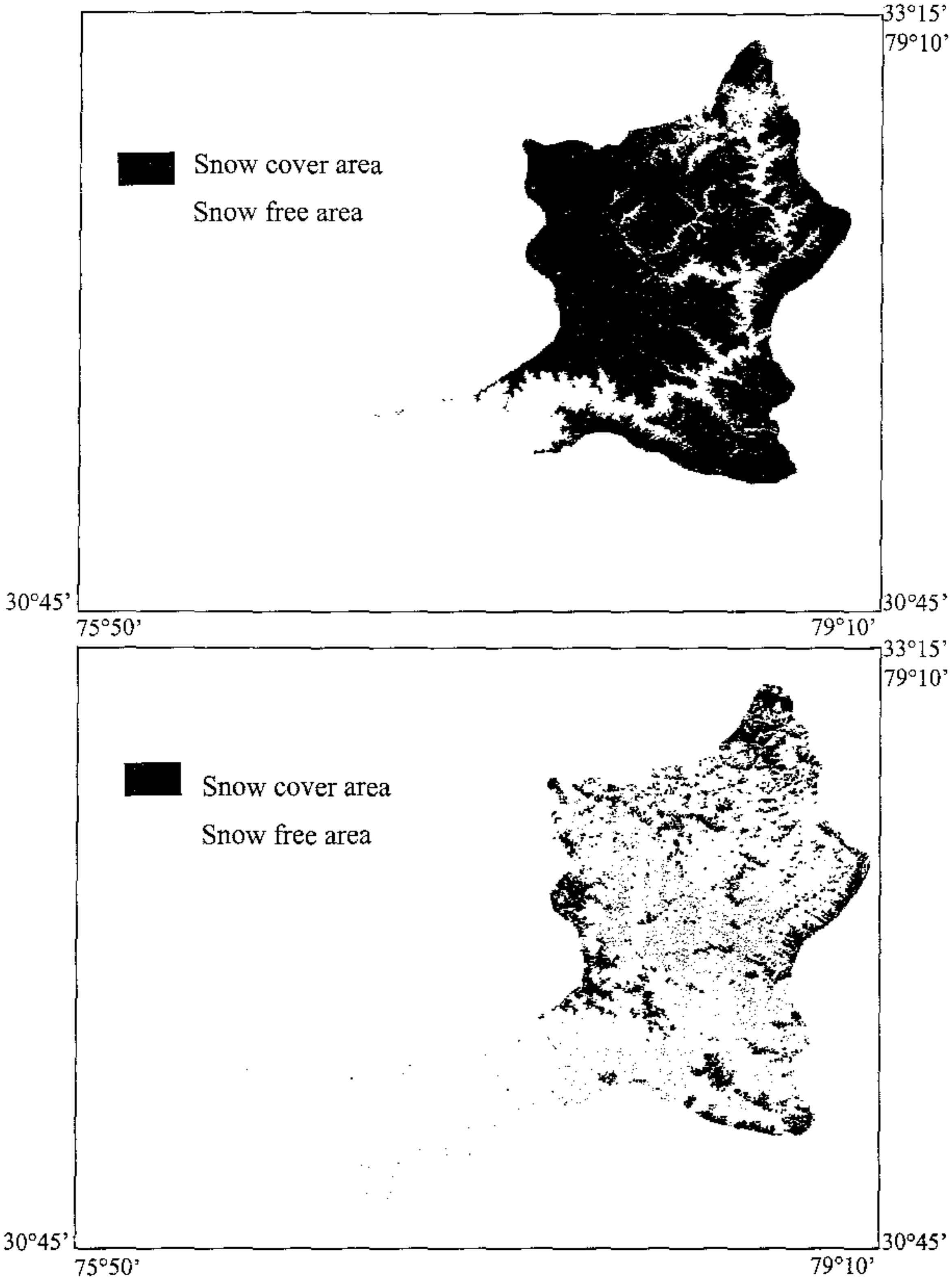

Figure 4.4: Snow covered area in Satluj basin upto Bhakra in March and October 2000

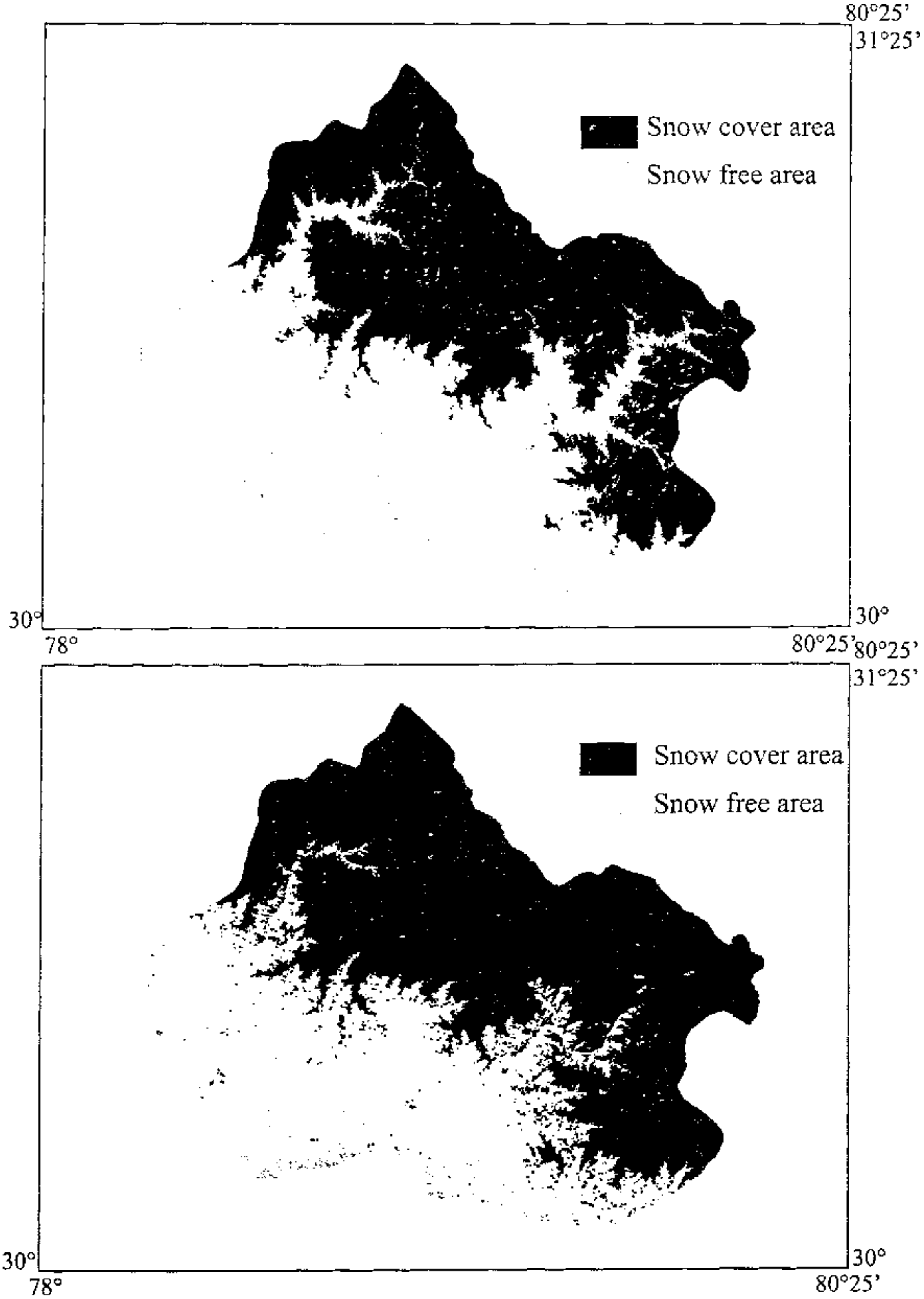

Figure 4.5: Snow covered area in Ganga basin upto Deoprayag in March and December 1997

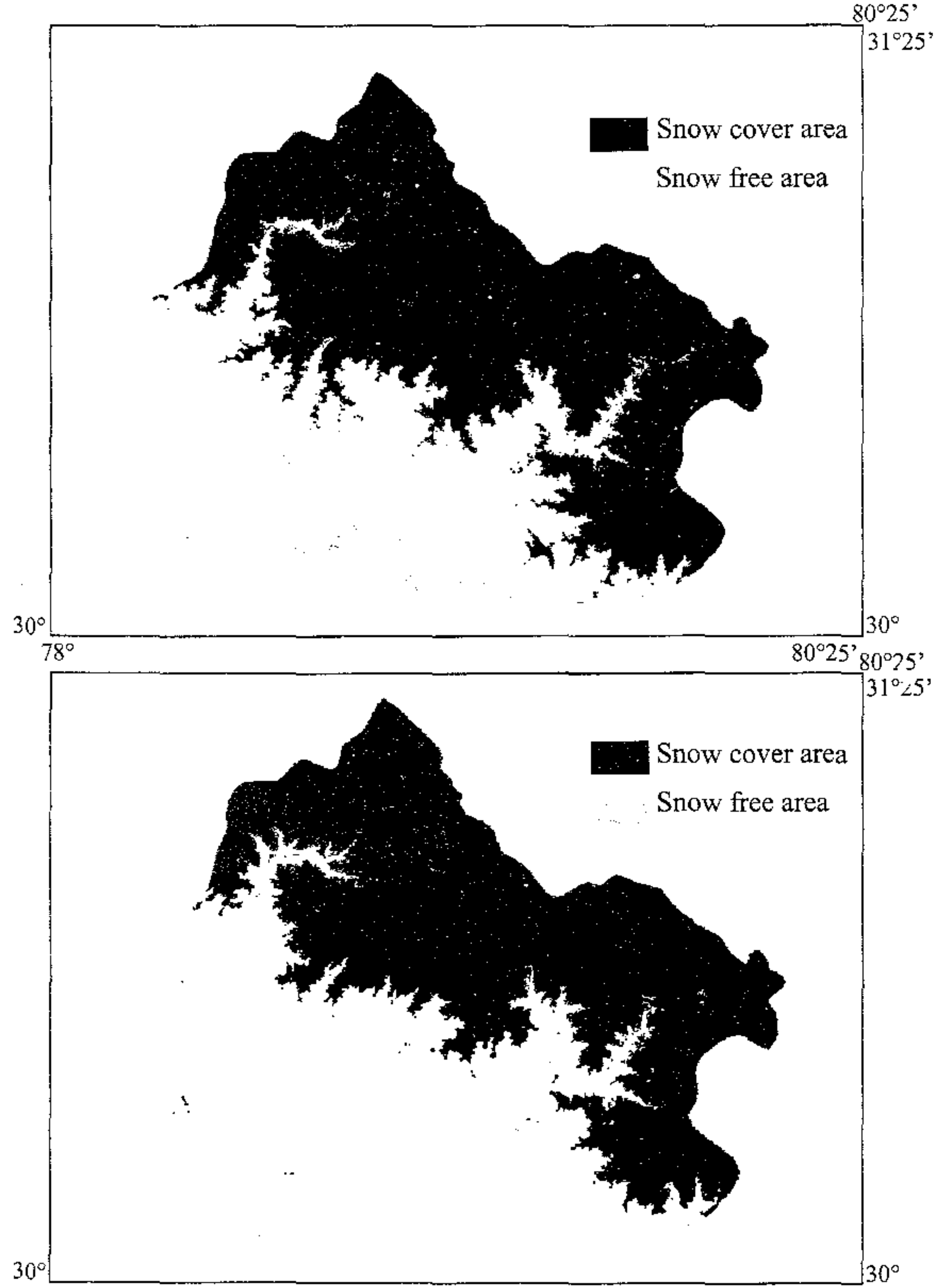

Figure 4.6: Snow covered area in Ganga basin upto Deoprayag in March and October 1998

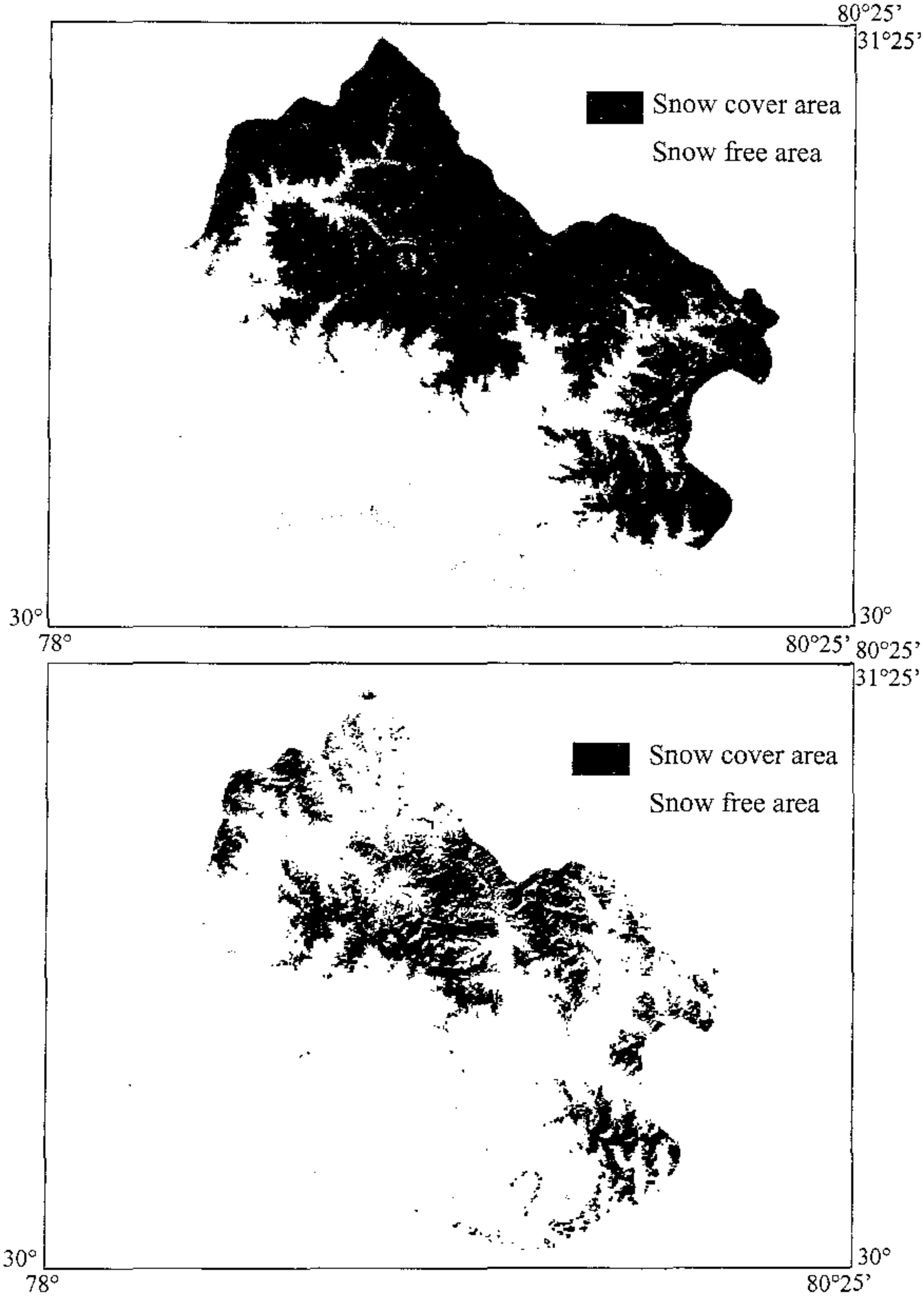

Figure 4.7: Snow covered area in Ganga basin upto Deoprayag in March and November 1999

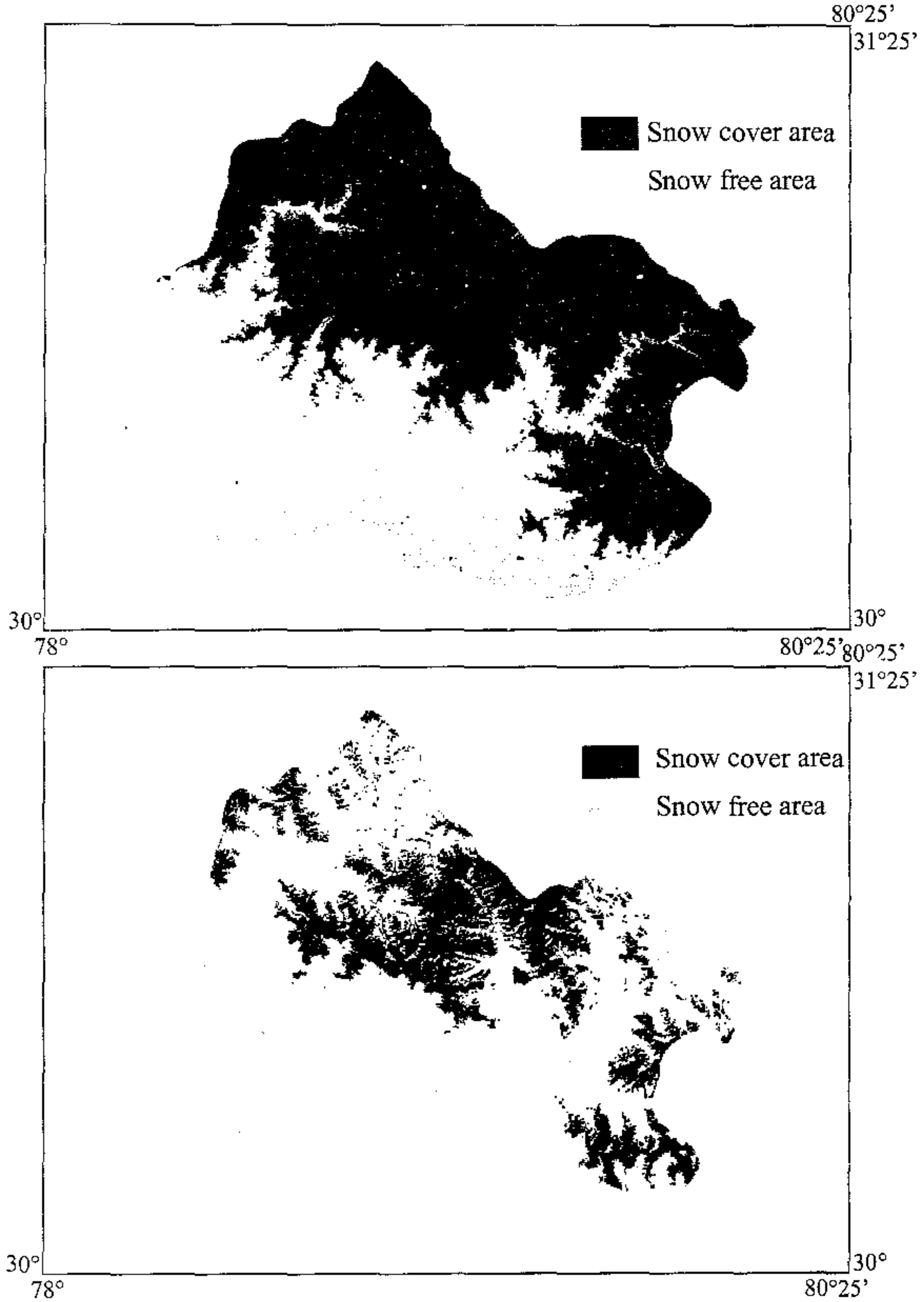

Figure 4.8: Snow covered area in Ganga basin upto Deoprayag
in March and October 2000

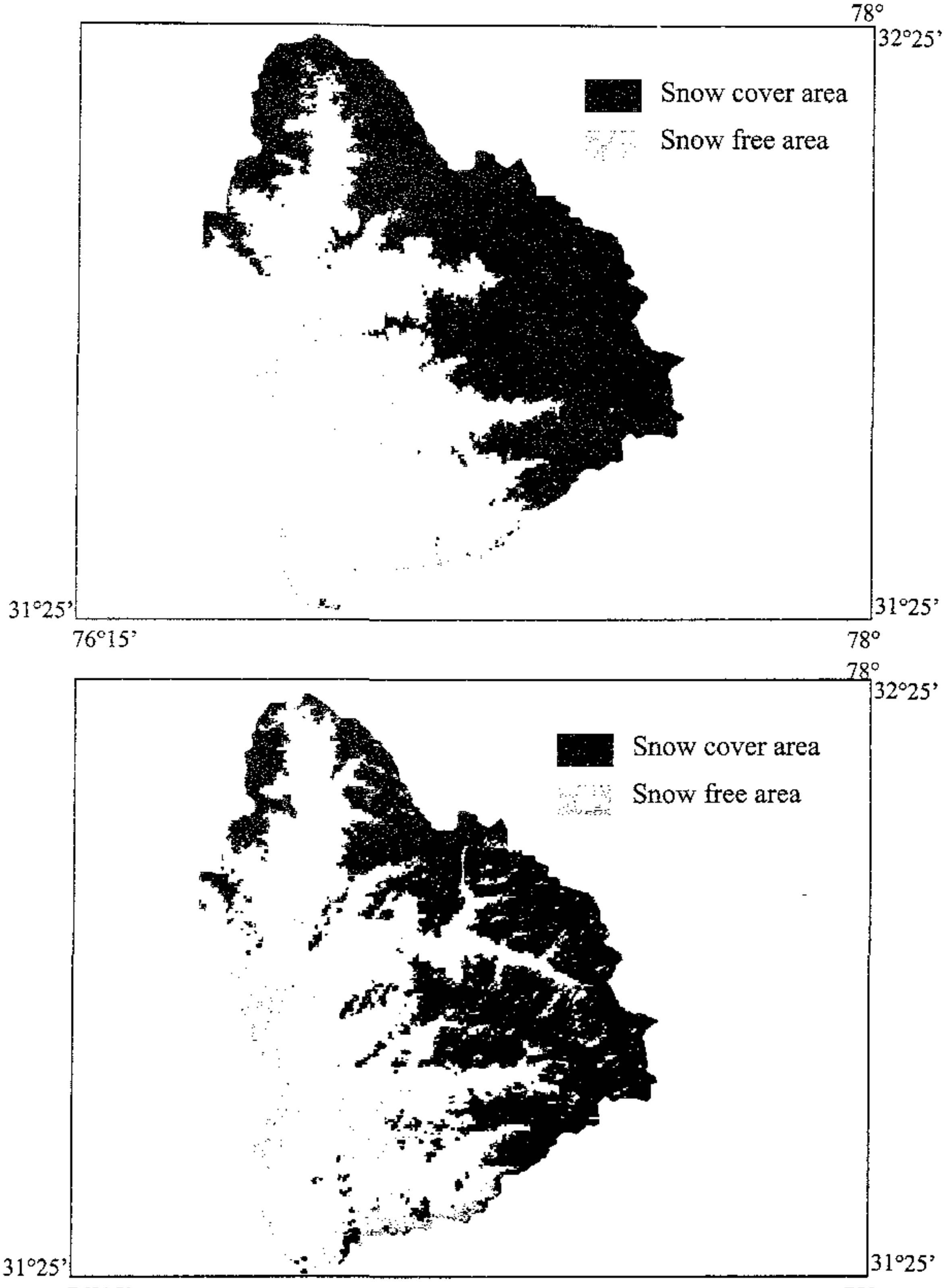

Figure 4.9: Snow covered area in Beas basin upto Pandoh in March and October 1997

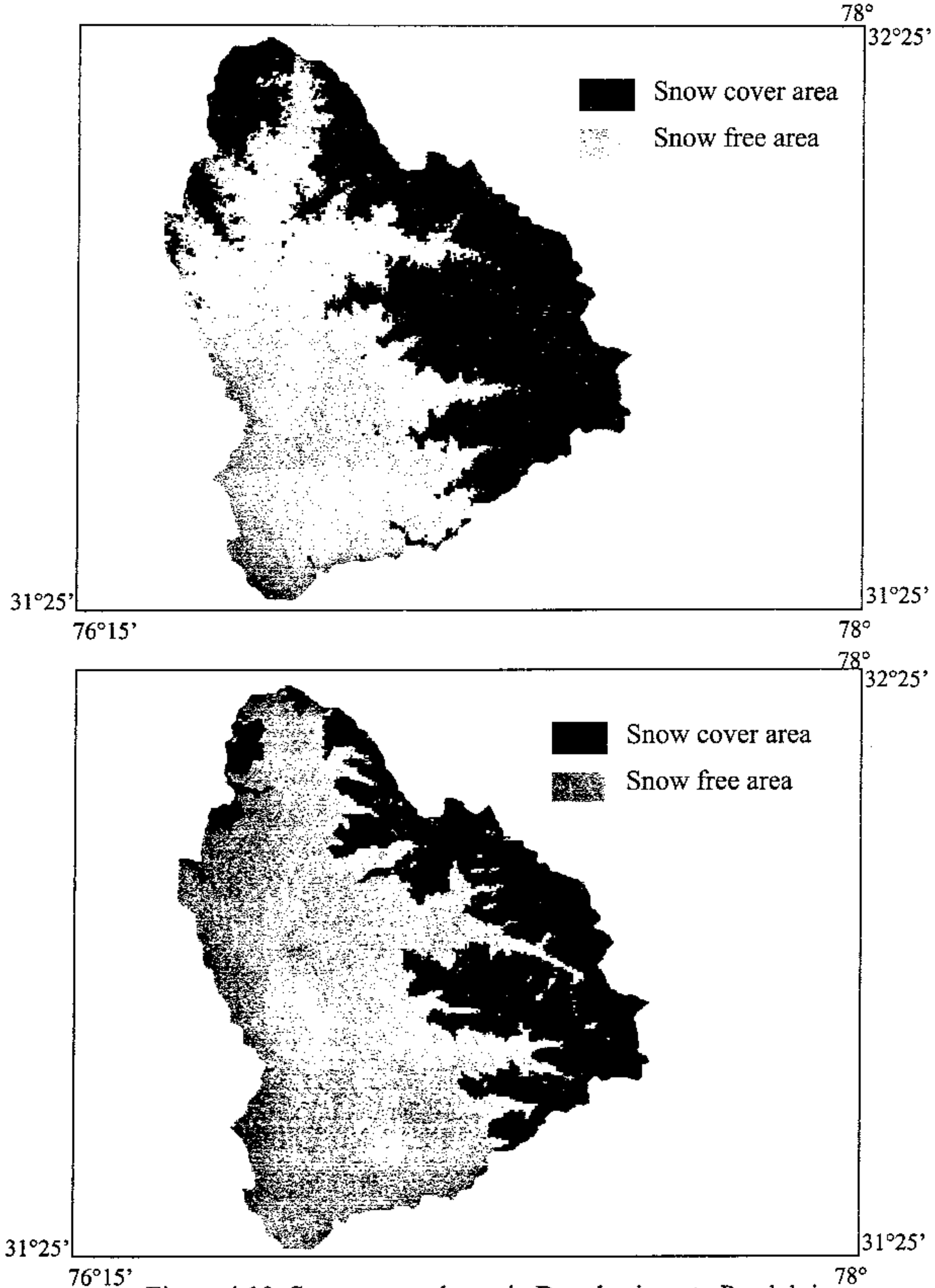

Figure 4.10: Snow covered area in Beas basin upto Pandoh in March and October 1998

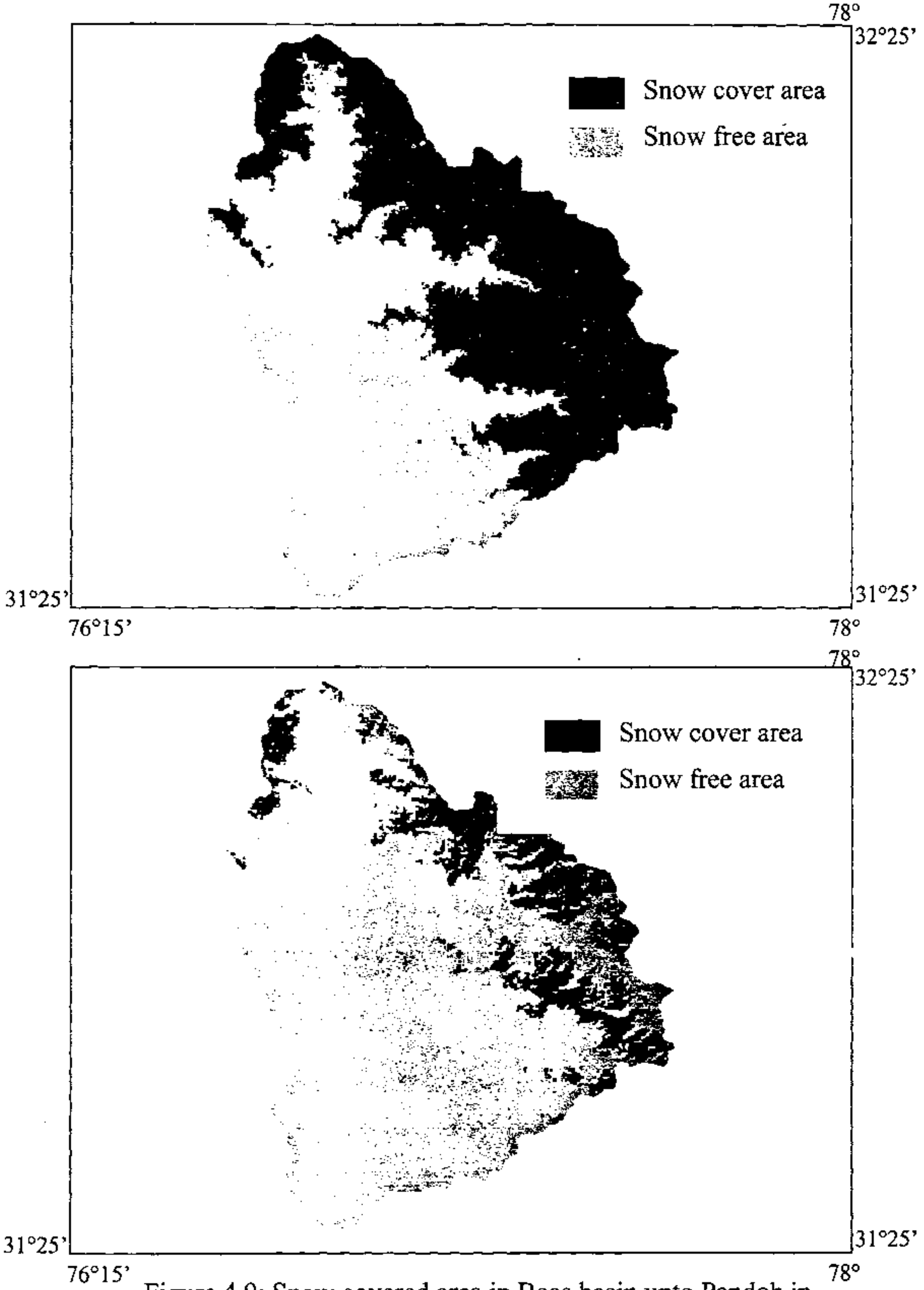

Figure 4.9: Snow covered area in Beas basin upto Pandoh in March and November 1999

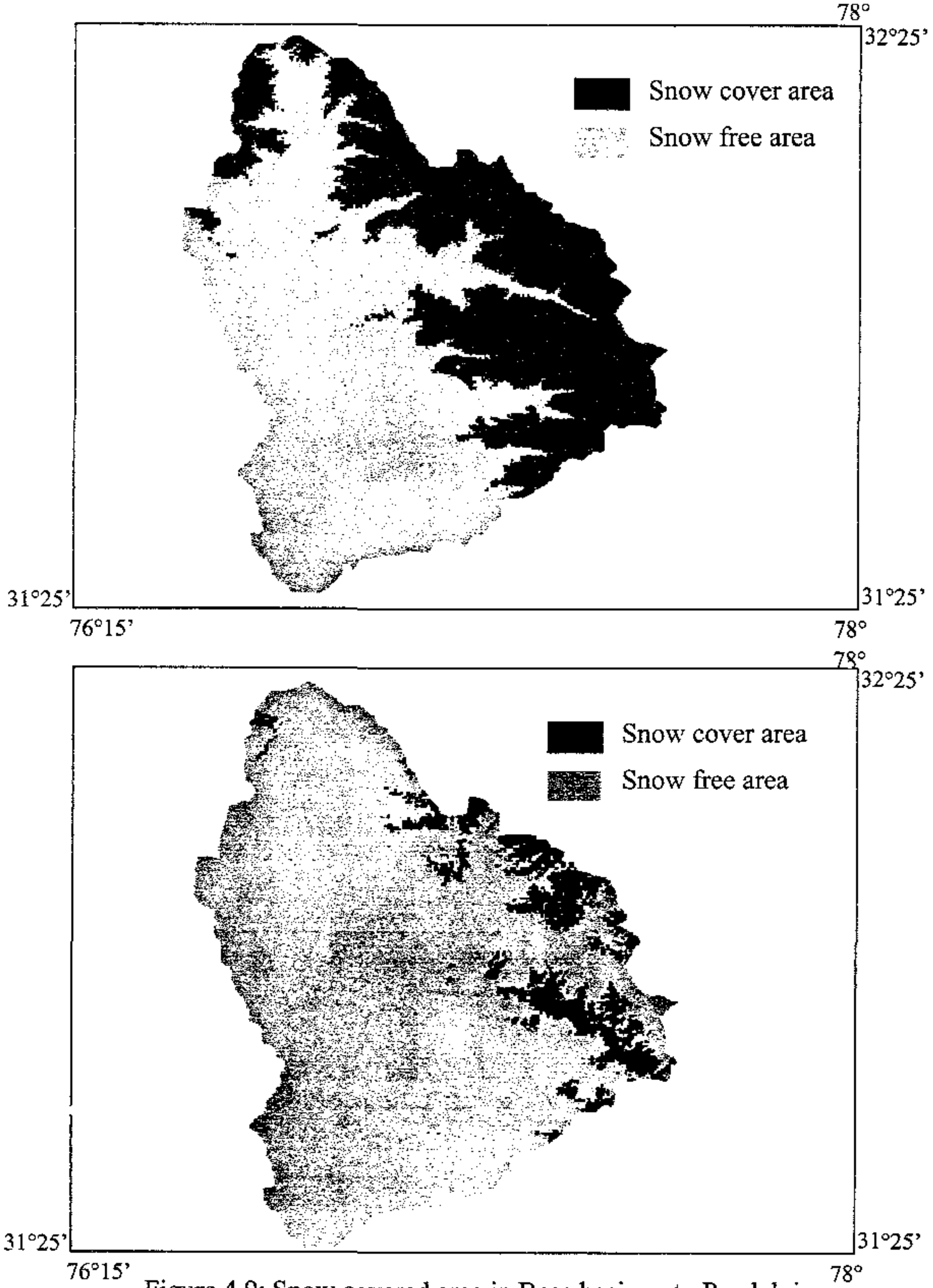

Figure 4.9: Snow covered area in Beas basin upto Pandoh in March and October 2000

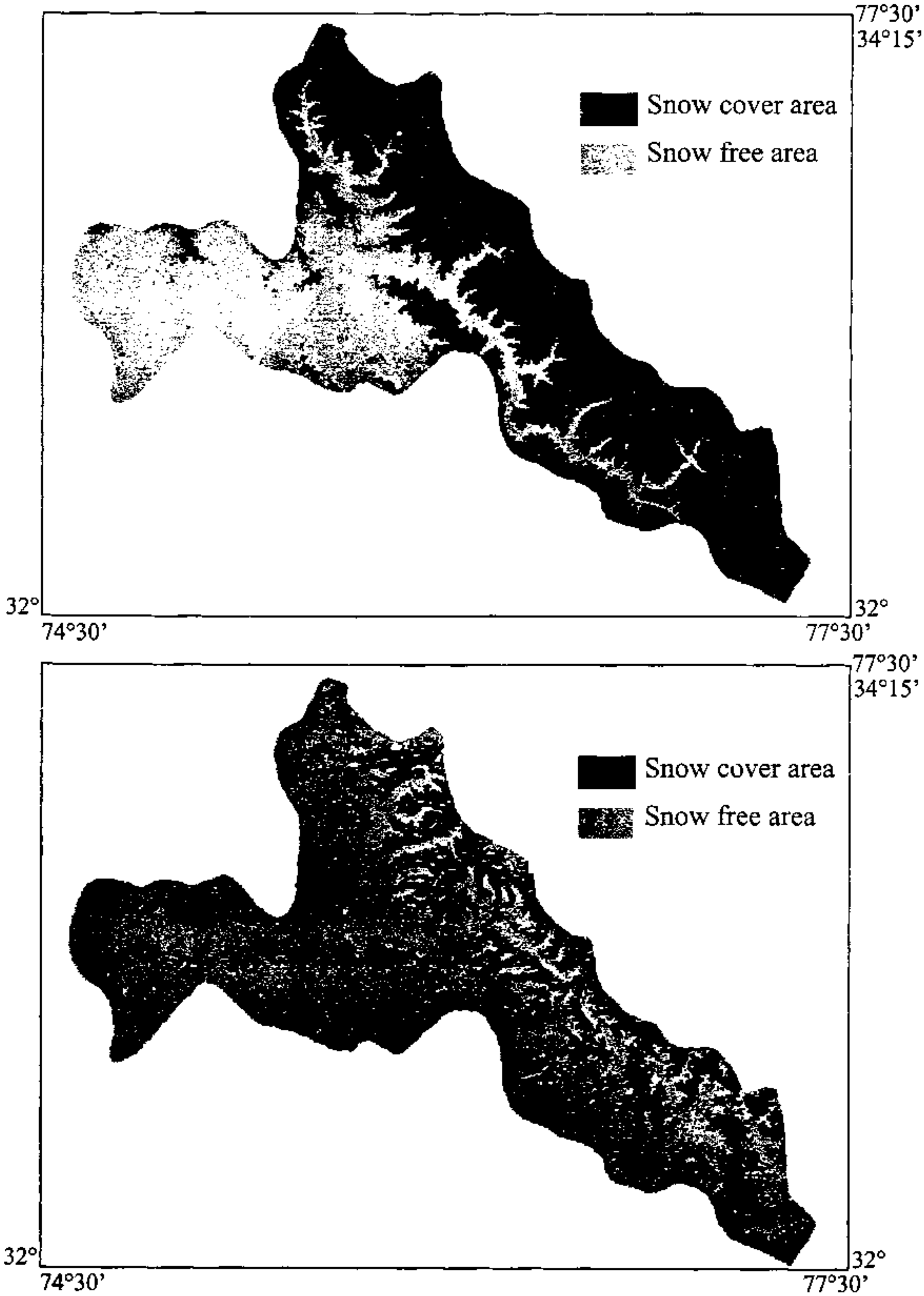

Figure 4.13: Snow covered area in Chenab basin upto Akhnoor in March and October 1997

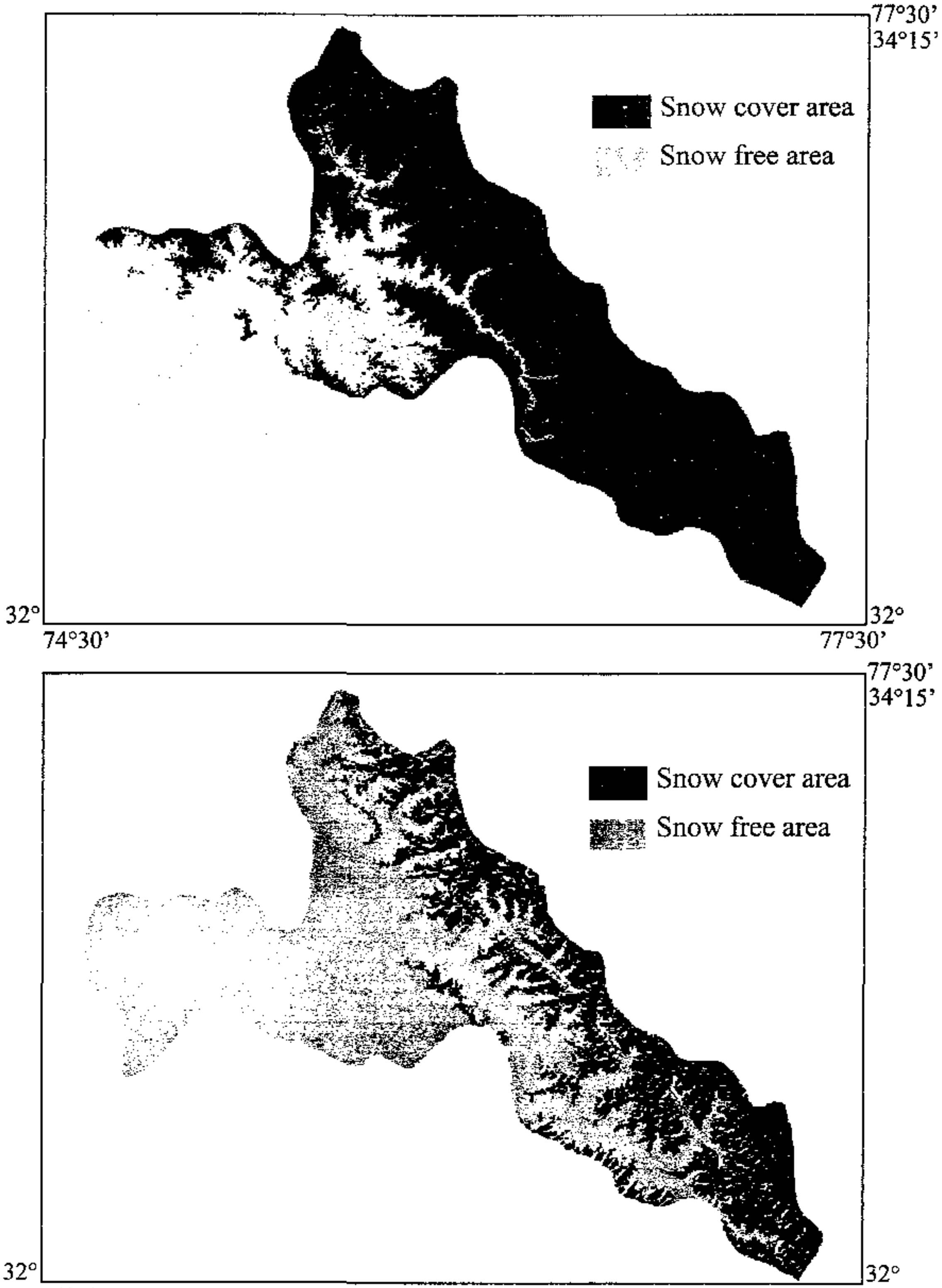

Figure 4.14: Snow covered area in Chenab basin upto Akhnoor in March and November 1998

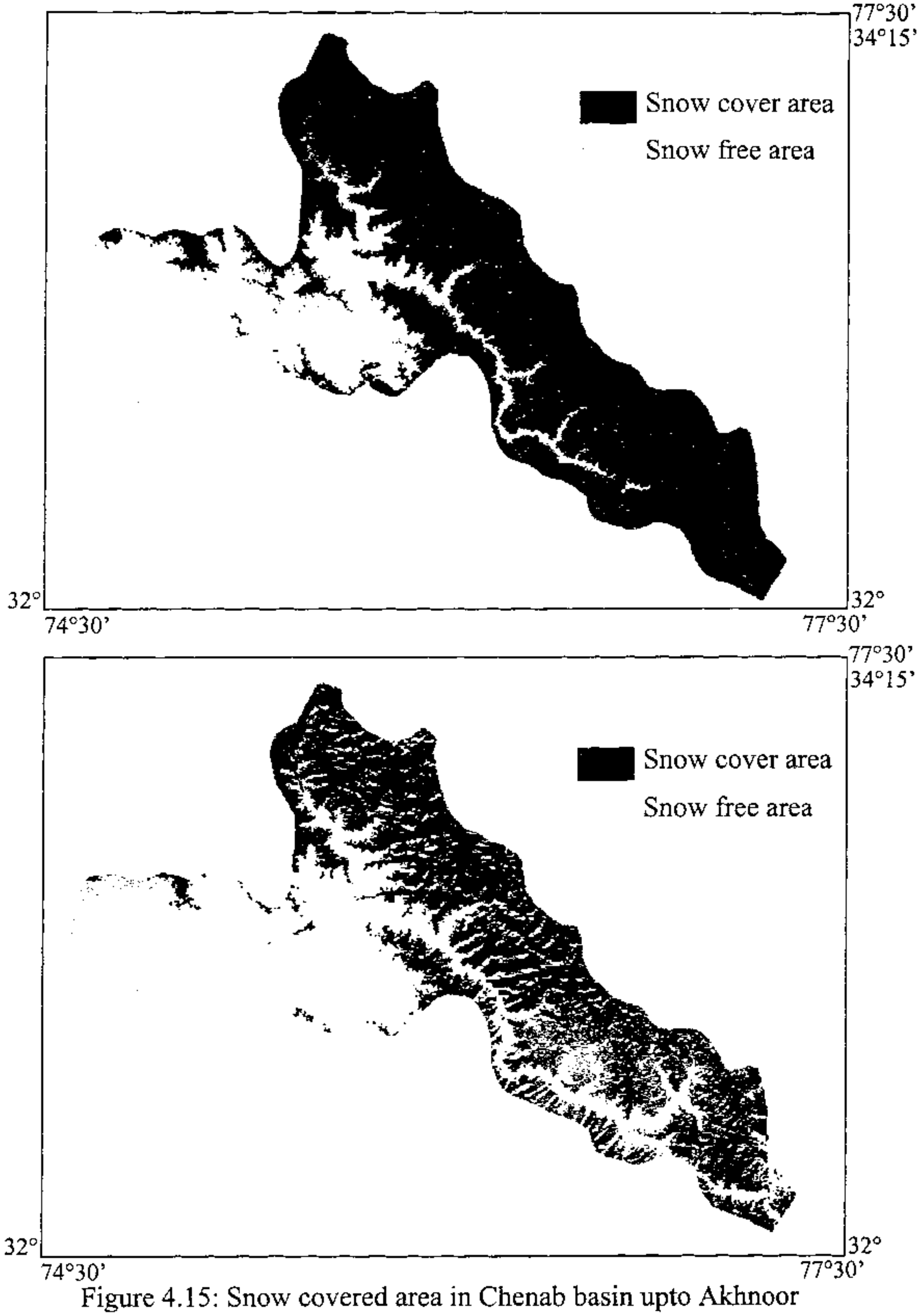

Figure 4.15: Snow covered area in Chenab basin upto Akhnoor in March and November 1999

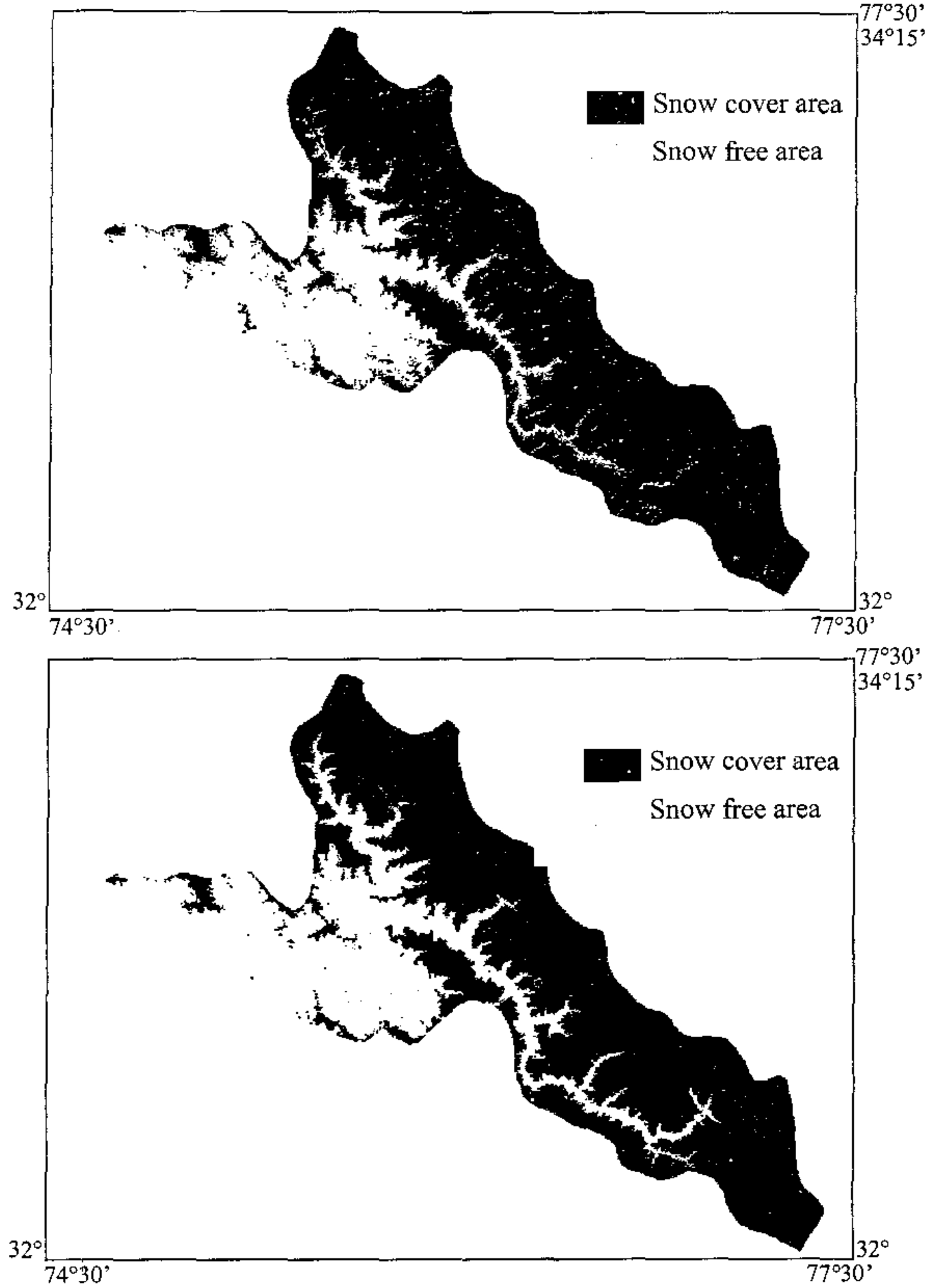

Figure 4.16: Snow covered area in Chenab basin upto Akhnoor in March and April 2000

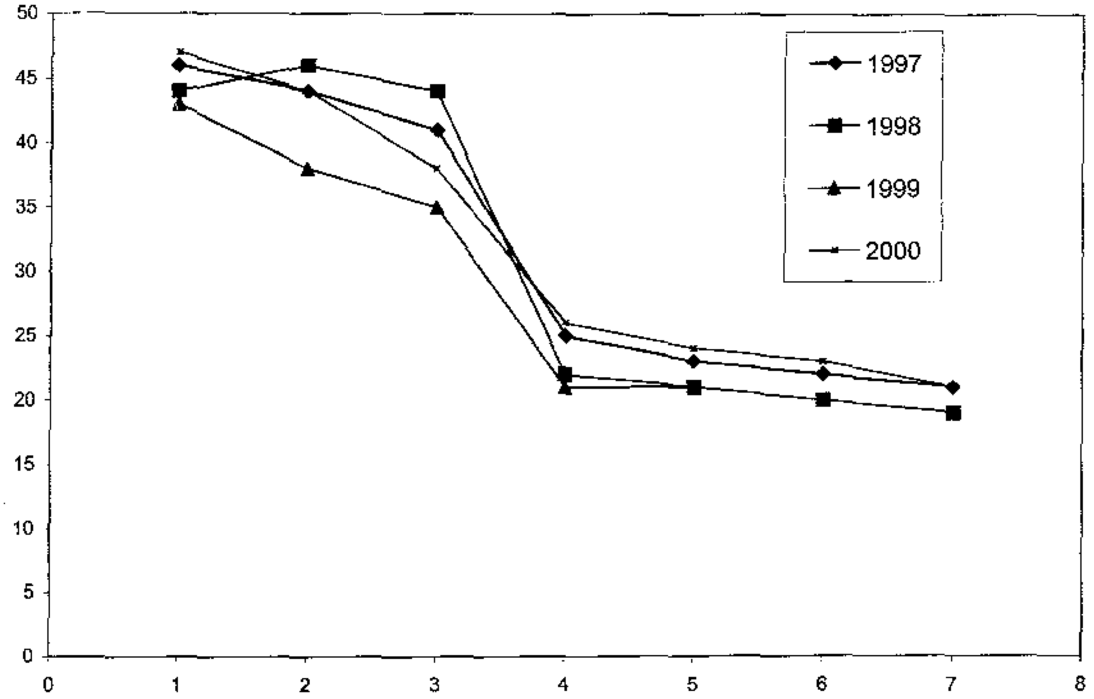

Figure 4.17: Snow cover depletion curves for Satluj

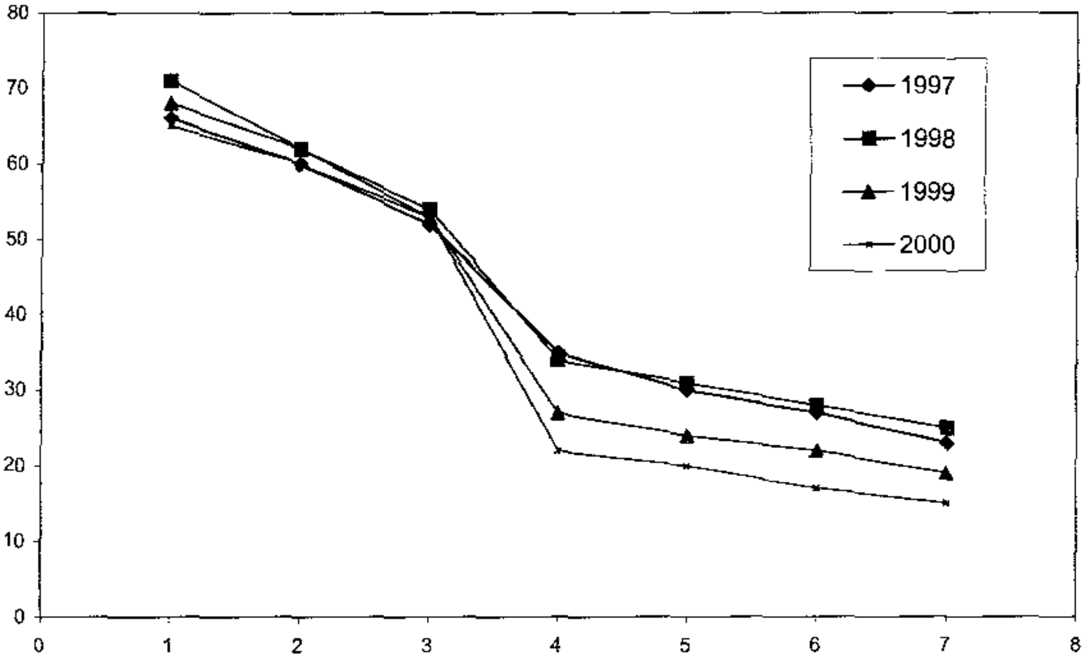

Figure 4.18: Snow cover depletion curves for Ganga basins

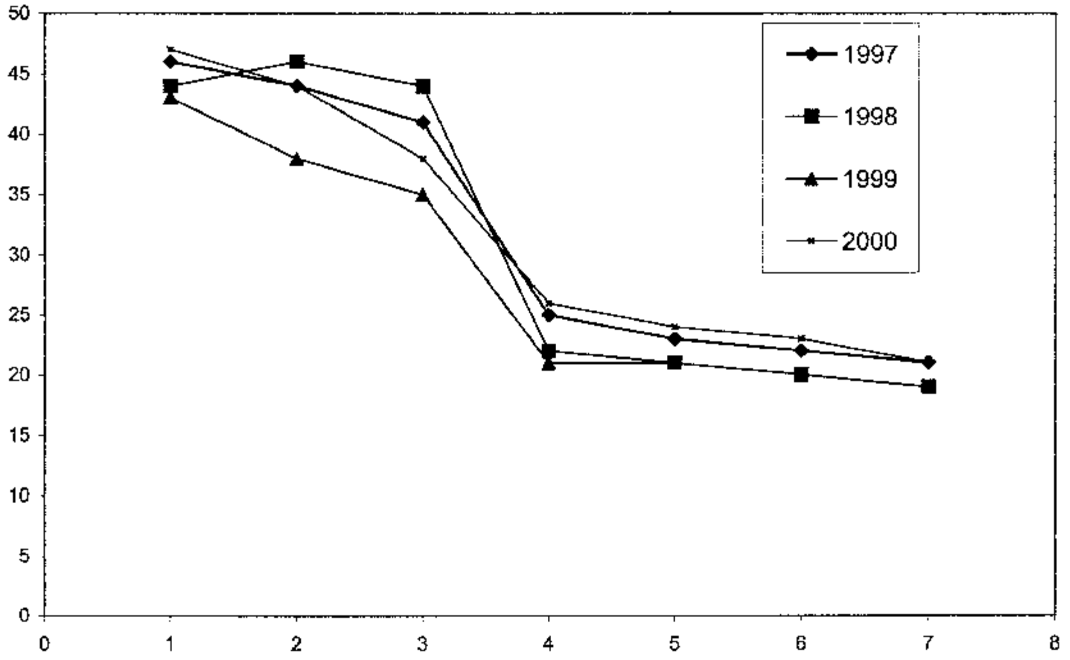

Figure 4.19: Snow cover depletion curves for Beas basin

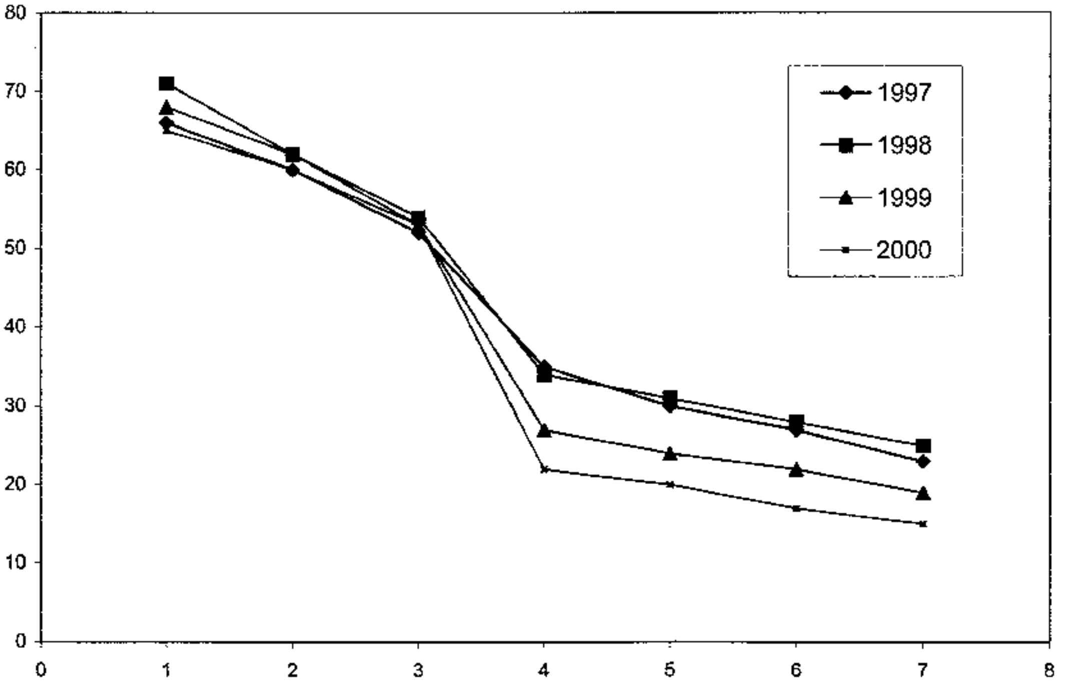

Figure 4.20: Snow cover depletion curves for Chenab basin

6.0 CONCLUSIONS

In this study snow covered area estimation has been made for the four basins located in Western Himalayan region. For this purpose, IRS WiFS data have been used. NOAA-AVHRR a coarse resolution (1.1 km.) data have been used for snow studies by earlier workers. However, many studies have found NOAA data deficient due to their 1.1 km reolution. IRS-WiFS data are the first of their kind to overcome such deficiencies. The present study used the potentials of temporal IRS-1C/1D WiFS data for mapping the snow covered area. For large basins of western Himalaya WiFS has been applied successfully for delineation of snow cover area. This data is very useful for mapping snow covered area for large basins in a economical manner. The snow cover depletion curves prepared for the study areas are very useful in snowmelt runoff and water balance studies.

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