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AUTOMATED MAPPING OF SNOW COVER USING IRS-1C DATA

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ABSTRACT

Snow is an important phase of the hydrological cycle and is of much importance in India because of the presence of mighty snow clad Himalayas. Some of the great rivers of India, like Indus, Ganga and Brahmaputra originate from Himalayas. Estimation of snowmelt runoff in these rivers, either seasonal or daily, is of immense use in proper management and use of water resources in these basins. Real-time and long-term forecasting of runoff in these basins can result in optimum operation of reservoirs for conservation and flood control, for planning hydropower regulation and hence optimum use of water.

A number of models have been developed for simulation and forecasting of snowmelt runoff. Data requirement of these models is quite high and conventional ground measurement in snow covered areas can not meet these requirements because of various shortcomings like frequency of observation, point measurement not representative of large areas, hostile climate conditions and inaccessibility of areas. Since last two decades, remote sensing techniques have offered excellent synoptic and repetitive overviews in various spectral channels of electromagnetic spectrum which has served as a spatial data base for snow related studies.

The Indian Remote Sensing Satellite, IRS-1C was launched in December, 1995. The LISS-III sensor of this satellite has higher spatial resolution, i.e. 23.5 m. In addition, a spectral channel in the wavelength range 1.55 - 1.7 μm has been added in the sensor while the channel below 0.52 μm has been dropped. The new channel is highly useful for discriminating snow cover areas from clouds. In the present study, the information of the new channel has been utilized for determining the snow cover area in the Spiti sub-basin of the Satluj river basin. A procedure, developed by Dozier, has been utilized for automated mapping of snow cover area in the basin. It has been found that the Dozier's algorithm can be utilised for snowcover estimation using the remote sensing data of LISS-III sensor. However, because of the deficiency of satellite information below 0.52 μm with this sensor, it is not possible to directly identify snow in shadowed areas and under the clouds. An indirect way of predicting snow in shadowed areas and areas under cloud cover has been suggested. This method is based on the combined use of digital image processing techniques (Proximity analysis) and the topographic details. For getting the topographical details, Digital Elevation Model (DEM) for the area was developed using a GIS software, ILWIS. Topographic information such as slope and aspect for each pixel was derived from DEM and used as data for the proximity analysis.

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CHAPTER - 1
INTRODUCTION

1.0 General Description

Hydrology is the scientific study of hydrosphere, its properties, processes and phenomena occurring in it in relation to the atmosphere, lithosphere and biosphere. Hydrology of land deals with the study of water on the Earth surface. Snow is an important phase of the hydrological cycle over a significant part of each year in mountainous and polar areas and also in mid-latitude countries. 23% of the globe, including 50% of the land, is permanently or temporarily snow covered during the year (Gordon and Eagleson, 1982). The frozen part of the land, i.e., snow, glaciers, ice in lakes and rivers and ice on the ground accounts for more than 80% of the total fresh water on the Earth and is the largest contributor to runoff in rivers and ground water over major portions of the middle and high latitudes. Snow and ice also play important interactive roles in the Earth's radiation balance because snow has a higher albedo than other natural objects normally encountered on the Earth's surface.

Snow is hydrologically important in India because of the presence of mighty snow clad Himalayas. With vast coverage of snow bound area, the Himalayan mountains, from where great rivers, namely Indus, Ganga and Brahmaputra originate, exert profound influence on the climate and weather in Indian subcontinent. This vast repository of solid water is a dominant source of streamflow for all major Indian rivers. Influence of snow in estimating runoff forecasting and reservoir operation is of great interest to hydrologists. It is more so because of the reason that snowmelt runoff is available in these rivers during March to May when there is hardly any precipitation in the catchment areas.

Snow data obtained from conventional ground measurements have two shortcomings: they are not collected frequently enough and the snowpacks at the measuring sites are not necessarily typical of the areas that they are supposed to represent. 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. These are exactly the types of limitations that remote sensing approaches are well suited to overcome. Remote sensors make frequent observations of large areas that can be monitored, not just sampled, and satellites view whole regions of the globe.

Space information has substantially influenced the level of hydrologic investigations in the study of the global hydrologic cycle, in the determination of time and space characteristics of water bodies and in the creation of regional and global information systems. Remote sensing techniques, both satellite and aerial, offer an excellent synoptic view in various spectral channels of electromagnetic spectrum which serve as a spatial data base for snow related studies. Since snow and ice occurs mostly in remote and inaccessible areas, the much needed large monitoring capability in such areas is attained with remote sensing because of its synoptic and repetitive overview capability.

Snow can be regarded as a convenient form of precipitation because it is a natural reservoir, storing water for weeks or months. Hydrologists are mainly interested in the amount and time of meltwater. To estimate this, they have to know the areal extent of the snow cover and the water equivalent of the snowpack. Many snow parameters affect the sensor response. Remote sensing methods have long been studied and used for snow mapping purposes in different parts of the world. Some of the methods are in operational use.

A number of models have been developed for simulation and forecasting of snowmelt runoff. Some of these are empirical models, some are based on the energy balance approach and some are based on degree-day approach. The Snowmelt Runoff Model (SRM), is one of the very few models which uses remote sensing input for simulation and forecasting of snowmelt runoff for a basin. The necessary input for the SRM is the regular monitoring of the snow cover area which can only be evaluated using remote sensing techniques.

Under some specific conditions, like, cloud cover, forest area, mountain shadows and shining bare rocks, it is difficult to distinguish snow in the remote sensing imagery for calculating snow cover area. Two techniques, that are used to evaluate snow cover area using remotely sensed data can be classified as digital analysis and visual interpretation. In this report, various remote sensing techniques that are employed to interpret snow under such conditions have been briefly described. Because of the availability of information in different spectral bands and the availability of relevant software and computers, digital analysis techniques have become more popular. The digital techniques are less cumbersome and give more accurate results as compared to visual interpretation.

1.1 Purpose of this Report

In this report, a procedure developed by Dozier (1989) has been utilized for mapping the snow cover area in a basin using the remote sensing data of an Indian satellite. The Indian Remote Sensing Satellite, IRS-1C was launched in December, 1995. The LISS-III sensor of this satellite has higher spatial resolution, i.e. 23.5 m. In addition, a spectral channel in the wavelength range 1.55 - 1.7 μm has been added in the sensor while the channel below 0.52 μm has been dropped. The new channel is highly useful for discriminating snow cover areas from clouds. The information of the new channel has been utilized for determining the snow cover area in the Spiti sub-basin of the Satluj river basin. A Digital Elevation Model (DEM) for the area has been developed. The automation procedure, when calibrated and run on the data of a basin, automatically comes out with the snow cover area presentation in the basin. This avoids the need of image interpretation in terms of discriminating snow for other surface features and from clouds. For identifying the snow in the shadowed areas and areas below the clouds, proximity analysis of the snow covered area was carried out. The topographical information from the digital elevation model and the results of proximity analysis were utilized for determining the snow cover in the shadowed areas and areas below the clouds.

The GIS software used to carry out the present work is the Windows version of ILWIS (Integrated Land and Water Information System). ILWIS has been developed at the International Institute of Aerospace Survey and Earth Sciences (ITC), The Netherlands. The system uses both, the vector and raster graphics data. A conversion program allows to import remote sensing data, tabular data, raster maps, and vector files in several other formats. Analog data can be transformed into digital format by means of digitizing program. Complex modelling of features can be executed by the Map Calculation. It integrates tabular and spatial databases.

A brief review of the procedures pertaining to the mapping of snow cover using remote sensing concepts is presented in Chapter - 2. Details of the automation procedure and its application in a sub-basin have been presented in Chapter - 3. Conclusions of the study have been summarized in Chapter - 4.

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CHAPTER - 2
REMOTE SENSING APPLICATIONS IN MAPPING SNOW COVER AREA

2.1 PROPERTIES OF SNOW USEFUL IN REMOTE SENSING ANALYSIS

The application of remote sensing, with its ability to cover large areas, has been studied intensively for many years. In the following section, some properties of snow and ice which are exploited for interpreting snow using remotely sensed data are discussed briefly.

2.1.1 Optical and Thermal Properties

The spectral reflectivity of snow is dependent on snow parameters like grain size and shape, impurity content, near surface liquid water content, depth and surface roughness and solar elevation. The freshly fallen snow has a very high reflectance in the visible wavelengths. As it ages, the reflectivity of snow decreases in the visible and especially in near-IR (near-infrared) wavelengths. This greater decrease in the near-IR wavelengths is largely due to melting and refreezing within the surface layers and to the natural addition of impurities. Melting of snow increases the mean grain size and density (Hall and Martinec, 1985).

Reflectivity of ice in the visible and near-IR wavelengths varies greatly, depending on the overlying material, impurities within the ice and the presence of surficial meltwater. Reflectance curves of snow, firn, glacier ice and dirty ice vary greatly with wavelength. For example, fresh snow has a reflectance of almost 1.0 at 0.4 μm while its reflectance drops to 0.6 between 1 to 1.05 μm. The change in reflectance with wavelength is even more dramatic with glacier ice, having a reflectance of approximately 0.65 at 0.6 μm, dropping to less than 0.1 at 1.0 μm (Qunzhu et al., 1984). The spectral reflectance curves for fresh snow, firn, glacier ice and dirty glacier ice are shown in Fig. - 1.

Thermal-IR sensors measure the radiation emitted by features in a wavelength region in which the physical temperature of an object can be calculated. For the range of temperatures normally encountered on terrestrial surfaces, the wavelength range of maximum emitted radiance is between 8 and 14 μm. The thermal-IR temperature of snow is affected by the temperature, crystal size and liquid water content of snow.

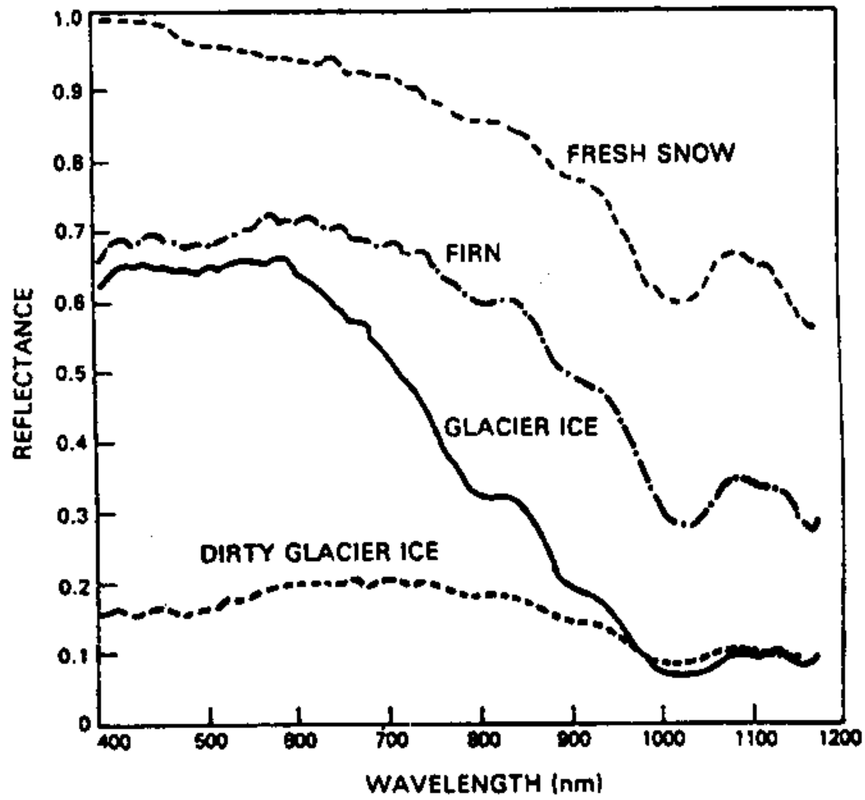

Fig. - 1 Reflectance Curves for Snow, Firn, Glacier and Dirty Ice

2.1.2 Microwave Properties

Microwave remote sensing can be accomplished either by measuring the emitted radiation with a radiometer or by measuring the intensity of the return of a microwave signal which has been sent. The electrical properties which govern the dielectric constant of a material, strongly influence the microwave emission and return. The dielectric constant is a measure of the response of a material to an applied electric field such as electromagnetic wave and is a function of temperature and frequency (Foster et al, 1984). The changes in the dielectric constant between layers within a medium cause reflection of an incident microwave signal or scattering of the natural microwave emission. The presence of liquid water in snow is the most important factor in changing dielectric constant of snow. The amount of penetration of microwaves through a medium is dependent upon the wavelength, crystal size and impurities within the ice or snow medium. For radar, the depth of penetration of the incident radiation depends on its wavelength.

In passive microwave remote sensing, Chang et al. (1976) showed that the depth of penetration of upwelling microwave radiation through ice and snow is also wavelength dependent and that, depending upon the properties of the ice or snow, the emission can emanate from a depth that is 10 to 100 times the length of the wavelength. Thus, for a wavelength of 21 cm, depth of upwelling emission can range from 2.1 to 21 m. As liquid water content in snow increases, the depth of penetration decreases.

2.2 IDENTIFICATION OF SNOW USING REMOTE SENSING

For the optimum management of water resources in areas dependent on snowmelt runoff, it is important that we monitor the temporal and spatial variability of the snow cover over land areas. Over the last 10 - 20 years, 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. The multi-spectral satellite systems have provided visible and near-IR data at the scale of drainage basins. Through careful analysis of satellite images, snow can be identified and the boundaries of snow covered areas can be accurately located.

The electromagnetic properties of snow vary as its structure and liquid content change. Water equivalent is the key property for gamma wavelengths, albedo is most important at visible and near-IR wavelengths, emissivity is most meaningful in thermal-IR and the dielectric constant is most significant at microwave wavelengths.

Snow cover can be detected and monitored with a variety of remote sensing devices. Identification of snow during daylight hours is straight forward during clear weather, because of the high albedo of snow in the visible wavelengths. The reflectance of snow in the visible and near-IR parts of the electromagnetic spectrum is much greater than that of any other natural material on the ground and thus, snow can easily be detected and the extent of the snow cover determined. In the visible (0.4 - 0.7 μm) bands, snow reflectance is not sensitive to grain size, so measurements in these wavelengths will show the extent to which snow albedo is degraded by contamination by atmospheric aerosols, dust etc. In the red and near-IR (0.7 - 1.0 μm), snow reflectance is sensitive to grain size but not to contaminants, so grain size estimates in these wavelengths can be used to extend albedo measurements spectrally. However, in densely forested areas, snow on the ground is difficult to be detected by this technique. Clouds are the main problem in this region of the EMS, because cloud cover prevents imaging.

The emittance of thermal radiation can also be used to determine the snow cover area. Because ice has strong absorption in the IR wavelengths, snow is infinitely thick at small depths as far as emission and absorption of IR radiation is concerned. The underlying surface does not contribute to thermal emission, even for snow only a few mm thick. This can be especially useful in mapping the snowline in forested areas, because, being colder, the snow can be detected between trees. The best result in snowline mapping, however, can be achieved by combining the information of the thermal emission and the reflectance in the visible part of the EMS.

Detection of natural gamma radiation emissions from the Earth using low altitude aircraft (about 150 m) has been used not only to detect snow but to measure the water equivalent of snow. Background gamma radiation of the soil is obtained before the snowfalls and subsequent flights are flown to measure the gamma radiation through the attenuating snow cover. The degree of attenuation is related to the snow water equivalent through various calibration curves. However, this procedure has two drawbacks: a) flying at low altitude in mountains is difficult, b) interpretation of data is difficult if the soil moisture level changes.

Since the first mapping of snow cover from satellite, the spectral and spatial resolution of the satellites has improved a lot. 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 identifying and mapping snow cover. The selection of the appropriate sensor depends on a trade-off between spatial and temporal resolution.

2.2.1 Factors Influencing Accuracy in Mapping Snow Cover

Snow cover is the brightest formation on the Earth surface. Therefore, in the absence of any interference, it is easily identified in satellite imageries. In non-forested terrain, all areas with a continuous brightness distinctly greater than the normal dark background, that are identified as being essentially cloud free, are mapped as being snowcovered. The snowline enclosing all such areas represents the limit of a snow accumulation of approximately 2.5 cm (1 inch) or more. Areas that appear "mottled" (alternating dark and grey) usually are indicative of less than 2.5 cm of snow.

However, under natural conditions, the boundary of snow cover is not always distinct in a region. Some objects on the Earth surface like bare rocks, have reflectance similar to that of snow cover in visible and near-IR portion of the EMS. The albedo and brightness coefficients of snow are comparable to that of cloud cover. With the passage of snow cover boundary into a forest zone, the reliability of distribution of snow boundary decreases. During the winter, sun angles are generally low and the resulting northern hemisphere terrain shadows on north facing slopes may be difficult to distinguish from bare south facing slopes. Thus, reflectance from cloud covers, obscuration of snow by thick forest vegetation, reflectance from bare rocks and shadowed snow covered area hinder accurate discrimination of the boundary of snow cover while interpreting satellite imageries. With experience, techniques have been developed to overcome some of the possibilities of misinterpretation. Various confusion factors and the techniques that are employed to identify and correct them are presented in the following section:

a) Clouds

In the visible bands, snow cover and clouds both have high reflectance. Differentiating between the two was one of the problems in the use of satellite observations for snow cover analysis. Snow cover was distinguished from the clouds using some interpretation keys. Clouds and snow have nearly the same reflectance, but the snow areas are usually smooth textured while clouds are often rough or lumpy in appearance. The sun angle at the time of satellite pass produces cloud shadows which can be used to identify a cloud.

However, with the improvement in the spectral resolution of the satellites, it has now become possible to distinguish the cloud cover from the snow. A spectral channel (1.55 - 1.80 μm) currently available on the Landsat TM instrument and the IRS-1C LISS-III sensor, can be used to assist in mapping snow cover when clouds partially cover a drainage basin. In this band, clouds are usually more reflective than snow (Dozier, 1989). As a result, automatic discrimination between snow and clouds is possible. Although useful, this capability does not overcome the problem of a complete cloud cover or an inadequate frequency of observation.

When a basin is partially snow covered, a method has been developed to estimate the snow cover in the cloud obscured parts of the basin (Lichtenegger et al, 1981; Baumgartner et al,1986). The method uses digital topographic data and assumes that pixels with equal elevation, aspect and slope have the same relative snow coverage over the basin.

b) Forest cover

Forest areas can consist of everything from dense conifers to less dense deciduous forests, to sparse range type vegetation. Generally, snow tends to filter through the forest canopy. Even with substantial depths of snow, the reflectance from the forested areas remain considerably darker than non-forested areas. Therefore, analysis of satellite imagery with regard to detecting snow in forested areas require a considerable amount of subjective interpretation. The analyst must be thoroughly familiar with the area being analyzed. Information on the distribution of forest can be obtained through reference to land use charts, topographic maps and satellite imageries at the time of no snow cover. All areas, except those with dense conifer forests do exhibit some change in tone with snow cover. After becoming familiar with the area under study, the analyst can make judgment on the snow extent by examining the overall tone, checking the tone of open areas within overall forested terrain and identifying snow cover in non-forested land at lower elevations.

c) Bare rocks

In the late spring and early summer, partial snow cover may be difficult to distinguish from highly reflecting bare rock. Data from the late summer, when no snow is present, is studied to become thoroughly familiar with the terrain and vegetation patterns. Analysis have found that aerial surveys of suspect areas are very helpful for becoming familiar with the terrain.

d) Mountain shadows

During the midwinter period, low sun angles produce mountain shadows which cause ambiguity in locating the snow. In some cases, the reflectance of a north facing ridge, that is totally snow covered, may appear the same as the reflectance of terrain that is completely snow free. Mountain shadows can be a problem in areas of numerous ridges and canyons. The problem of mountain shadow can be tackled to some extent using NOAA-AVHRR data since the equatorial passing time of this satellite is in the afternoon. However, the poor resolution of the satellite is the major limitation.

2.3 MAPPING OF SNOW COVER AREA USING REMOTE SENSING

Several techniques are available for the mapping of snow cover area using remotely sensed data. The simplest of all is the photo-interpretation method. The sophisticated method involves use of digital interpretation analysis of remote sensing data. The interactive analysis combines both photo-interpretation and digital processing methods. These are briefly described below:

2.3.1 Photo Interpretation Techniques

Photo-interpretation procedures are straight forward and generally do not require any sophisticated equipment. Snowline delineation and measurement of snow cover area from a 1:1 million satellite imagery requires the demarcation of watershed boundary on it at the first instance and tracing of the snowline on an overlay. The snow cover area is then planimetered and stated as a percentage of total watershed area. This simple technique is fast and does not require much expertise. This direct approach is recommended if the area is small.

Use of Zoom Transfer Scope is often resorted to increase the accuracy of delineation of watershed. Further improvement is possible by using an automatic Planimeter which prints out the snow cover area. The complexity of these photo interpretative procedures depends on the specific method and instruments used. The chance of human error in making subjective measurements can be quite high and depends on his interpretation skill.

2.3.2 Digital Analysis

The use of optical enhancement devices for density slicing of satellite image is quite rewarding. This separates snow from other features on the basis of a selected reflectance level. Automatic snow cover area could be obtained using this technique if a particular reflectance level, corresponding to snow/no snow boundary, can be fixed. There are chances of committing error as proper slicing level for the entire scene or watershed is difficult to specify. However, such method may be acceptable for some watersheds for quick snow cover area determinations.

In the past 10 years, techniques have been developed to interpret snow properties using information from the multispectral bands and different resolution sensors. The selection of suitable sensor data and the appropriate spectral bands for various snow related studies is an important task before the interpretation of an image. The following section gives brief details about the selection criteria for bands and sensors.

2.3.3 Selection of Appropriate Bands and Sensors

Although all objects emit radiation over all wavelengths, for most studies, it is advantageous to use data from sensors operating in discrete portions of the electromagnetic spectrum. One must judiciously select the proper sensor and band to use for a particular analysis taking into consideration factors such as: wavelength, resolution, frequency and timing of ground coverage.

The choice of sensor is often determined by the size of the drainage basin or subarea to be studied and the temporal resolution. Rango et al. (1985) conducted a study to identify appropriate methods for visible band remote sensing based on basin size. For basins < 10 sq. km, visual ground based observations and snow course data can be used to map the snow cover. For basins from 1 to 100 sq. km , aircraft orthophotos can be used to effectively acquire the snow cover data. The advantage of using planes is that the flights can be scheduled to coincide with favourable weather conditions.

The use of specific satellites depends on the sensor being used. 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. IRS LISS-II and LISS-III and Landsat TM and SPOT can be used on basins as small as 2.5 sq. km, whereas the IRS LISS-I and Landsat MSS can be used on basins as small as 10 sq km. The use of NOAA AVHRR is appropriate for basins as small as 200 sq. km. These areas are appropriate under optimum snow mapping situations. If problems arise such as those due to clouds, vegetation cover, bare rock, shadow, discontinuous snow cover, image quality and illumination levels (Rango and Martinec, 1986), then the size of the applicable basin or sub-basin will increase.

The greatest application of satellite observations in identifying snow has been found in the visible and near-IR region of the electromagnetic spectrum. The red band (0.6 - 0.7 μm) of the Landsat (MSS), band (0.62 - 0.68 μm) of IRS and visible channel of NOAA AVHRR have been used extensively for snow cover mapping because of its strong contrast with snow free areas. Although snow is readily identified in the MSS4 (0.5 - 0.6 μm) band and Band 1 and Band 2 of IRS, the contrast between snow and ground is somewhat less in these bands. Detector saturation (when radiance from a surface is equal to or greater than the maximum sensor sensitivity) in Band 1 of both these satellites is common, causing loss of some detail in snow patterns, but not so severe in other bands.

In the visible region of the spectrum, snow reflectance is relatively insensitive to grain size but sensitive to contamination by dust and soot, while in the near-IR wavelengths, snow reflectance is sensitive to snow grain size and insensitive to contaminants. Thus, Bands 1 to 3 can be used for identification of snow and for analysis of dust and soot on the snow surface. Considerable information relative to the snow and ice surface characteristics can be obtained from Band 4. A spectral channel (1.55 - 1.80 μm), also known as Band 5 in Landsat TM and Band 4 in IRS-1C LISS-III, can be used to assist in mapping snow cover when clouds partially cover a drainage basin. In this band, clouds are usually more reflective than snow.

Both thermal-IR and gamma radiation have only minor importance for snow mapping. Thermal-IR mapping is hindered by cloud cover. In addition, the surface temperature of snow is not always that much different from the surface temperatures of other surfaces in rugged mountain terrain where elevation and aspect differences can cause major changes in temperature. This makes it extremely difficult to distinguish the snow cover from other features, especially during the snowmelt period. The major drawback for gamma radiation approach involves the low altitude at which flights must be made. It is virtually impossible to get areal coverage except over extremely small drainage basins.

Passive microwave data can be used for determining snow cover areas over continents and larger river basins without obstruction from clouds. The accuracy of microwave snow mapping is similar to visible snow mapping over the same area. However, differences in interpretation arise from microwave resolution problems and from the fact that microwaves penetrate very thin layers of snow with little absorption. As a result, the edge of the snow pack, which can be thin, is missed by the microwave sensing and detected by the visible wavelengths. Relative sensor band responses to various snowpack properties as mentioned by Rango (1993) is presented in Table - 1.

Table - 1
Relative Sensor Band Responses to Various Snowpack Properties

Snow Property	Sensor Band			
	Gamma Ray	Visible/Near-IR	Thermal-IR	Microwaves
Snow cover area	Low	High	Medium	High
Depth	Medium	If v. shallow	Low	Medium
Water equivalent	High	If v. Shallow	Low	High
Stratigraphy	No	No	No	High
Albedo	No	High	No	No
Liquid water content	No	Low	Low	High
Temperature	No	No	Medium	Low
Snowmelt	No	Low	Low	Medium
Snow-soil surface	Low	No	No	High
Additional factors				
All weather capability	No	No	No	Yes
Current spatial resolution	Not possible	5.8 m	100 m	25 km passive 10 m active

One of the problems hindering IRS and Landsat snow mapping has been poor observational frequency. Depending on the satellite being used, each study area or drainage basin is only revisited every 16 - 22 days. The WiFS sensor of IRS-1C satellite has a revisit period of 5 days because of large swath width. However, the resolution of this sensor is 188 m (swath 810 km) which is quite poor as compared to 23.5 m for LISS-III sensor. In areas with minimal cloud cover during the snow melt season, this was a sufficient frequency of observation. But, in most mountain areas, this observational frequency is inadequate because cloud cover often hide the underlying snow from the satellite sensors. High distortion of the seasonal snow cover depletion curve can occur if just one of the potential satellite passes are missed combined with the occurrence of a satellite observation immediately following a new snow event. As a result of this problem of observational frequency, many users have turned to the NOAA AVHRR data, which has a resolution of about 1 km in the 0.58 - 0.68 μm band. The major problem with the NOAA AVHRR data is that the resolution of 1 km may be insufficient for snow mapping on small basins. However, this data can be used only as ancillary data to higher resolution satellites so that misinterpretation on account of miss of information due to cloud cover and new storms in between two subsequent overpasses can be avoided.

With certain satellites, night time passes with visible sensors can be used. As snow cover has a high reflectivity, it can reflect enough moonlight at night to allow snow mapping if satellite sensors are sensitive enough to low light levels. Using such sensors on a Defence Mapping Satellite Program (DMSP) satellite, Foster (1983) estimated that five additional images per month could be obtained that would be suitable for snow mapping.

Despite the various problems mentioned, satellite observations have been found to be the most useful information for monitoring the extent of snow cover and buildup of snow in a drainage basin. A digital analysis technique for interpretation of snow cover areas is presented in the next chapter. This method makes use of the spectral information of the IRS-1C satellite LISS-III sensor. Topographic information has also been used for identifying snow in some specific conditions.

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CHAPTER - 3
AUTOMATED MAPPING OF SNOW COVER

3.1 DOZIER'S ALGORITHM

Mapping of snow and estimation of snow characteristics from satellite remote sensing data require that we distinguish snow from other surface cover and from clouds and compensate for the effects of the atmosphere and rugged terrain. Satellite sensors in visible and near-IR wavelengths provide information on the spatial distribution of snow cover area. The IRS and Landsat systems, in particular, are a source of data for hydrological and glaciological research at the scale of drainage basins. Identification of snow in level areas during daylight hours is straight forward during clear weather, because of high albedo of snow in the visible wavelengths. In rugged terrain, snow in the shadows can be darker than soil or vegetation in the sunlight, so that snow mapping in the mountains is not so easily accomplished.

In visible satellite data, clouds can be distinguished from snow by texture. However, in a computer image processing system, texture is more difficult to analyze than spectral information. Hence wavelength bands where snow and clouds have different spectral signatures are used. Clouds may be either warmer or colder than the snow surface. So thermal wavelengths cannot be reliably used to distinguish clouds from snow. Cloud droplets or ice crystals are smaller than snow grains. At most wavelengths in the optical region, water and ice have similar refractive indices, but ice is slightly more absorptive from 1.55 - 1.75 μm. Snow on the ground is usually optically thicker than clouds. Therefore, in the visible wavelengths, snow is brighter, because some of the light incident on the cloud is transmitted through it. Thick clouds, however, are as bright as snow, so that they cannot be dependably distinguished in this wavelength region by a lower reflectance. Topographic effects also, cause variation in the illumination angle and shadowing from local horizons thereby causing significant variation in remotely sensed images in visible and near-IR wavelengths.

Dozier (1989) has developed a procedure for the automated mapping of snow cover area using digital data of Landsat TM. The method uses TM Band 1, 2 and 5 for distinguishing snow from other surfaces and from clouds. Areas with larger surface grain size are distinguished from those of finer grain size using the information from TM Bands 2, 4 and 5. The method is briefly described in the following:

For each band represented by wavelength λ, the digital radiance numbers, Q_{cal} on the satellite image are converted to radiances, L(λ), and then to planetary reflectance, $R_p(\lambda)$. Apparent planetary reflectance, R_p (λ) is the apparent directional-hemispherical reflectance of the Earth and is assumed to have an isotropic distribution. These planetary reflectance, instead of digital radiance numbers, have been used for automated mapping of snow by Dozier. It is given by:

$$L(\lambda) = L_{min}(\lambda) + [L_{max}(\lambda) - L_{min}(\lambda)] (Q_{cal}/Q_{cal,max}) \qquad \ldots (1)$$

$$R_p(\lambda) = \pi d^2 L(\lambda) / \mu_0 S_0(\lambda) \qquad \ldots (2)$$

where μ_0 is the cosine of the solar illumination angle, d is the Earth - Sun radius vector (mean value = 1.0), and $S_0(\lambda)$ is the exoatmospheric solar irradiance in the same wavelength band. The minimum and maximum radiances corresponding to minimum and maximum digital radiance numbers can be obtained from reference from Markham and Barker (1987). Radiometric Characteristics of Landsat TM and IRS-1C LISS-III as used in this study are presented in Table - 2 below.

Table - 2
Radiometric Characteristics of Landsat and IRS-1C

Band	Wavelength Range (μm) in Landsat TM	Wavelength Range (μm) in IRS-1C LISS-III	Satellite Radiance in (W m^{-2} μm^{-1} sr^{-1})		Exoatmospheric Solar Irradiance (W m^{-2} μm^{-1}) S_0
			L_{min}	L_{max}	
TM1	0.45 - 0.52	-	-1.5	152.1	1957
TM2	0.53 - 0.61	0.52 - 0.59	-2.8	296.8	1829
TM3	0.62 - 0.69	0.62 - 0.68	-1.2	204.3	1557
TM4	0.78 - 0.90	0.77 - 0.86	-1.5	206.2	1047
TM5	1.57 - 1.78	1.55 - 1.70	-0.37	27.19	219.3
TM7	2.10 - 2.35	-	-0.15	14.38	74.52

Dozier's model is an atmosphere/topography radiation model developed to simulate planetary reflectance for a range of snow grain sizes and topographic conditions. The calculations show that there are several ways in which snow can be distinguished from other surfaces and from clouds: Snow is brighter in TM Bands 1 and 2 than virtually all other surfaces. Although TM 1 saturates over most snow surfaces, it can be used to distinguish snow in shadowed areas. Clouds are brighter than snow in TM Band 5.

In addition, a procedure to estimate the grain size and detect absorbing impurities has also been suggested. In the visible wavelengths, it is possible to estimate the extent to which the reflectance of snow has been degraded either by absorbing impurities or by shallow depth. This sensitivity would be best for the blue wavelengths. In near-IR wavelengths, estimation of grain size is better.

3.1.1 Automated Mapping Procedure

Three criteria have been made for identifying whether a pixel represents a snow covered area or not. All three criteria must intersect for a pixel to be labelled as snow covered. The criteria are as follows:

1. R_p (TM1) is greater than a threshold. Its precise value is not critical, but it usually lies between 0.15 and 0.2. This threshold distinguishes snow from other surfaces in shadowed areas. It will also apply to many surfaces that are not snow, but these are then rejected by one of the other criteria.

2. R_p (TM5) is less than a threshold, which is about 0.20 - 0.25. This distinguishes snow from clouds.

3. The ratio [R_p (TM2) - R_p (TM5)] / [R_p (TM2) + R_p (TM5)] is greater than a threshold, which is about 0.4. This criterion, which rejects pixels whose reflectance in Band 5 is too great when compared to their reflectance in Band 2, helps distinguish snow from bright soils and rocks and from clouds.

The correct threshold values can be derived theoretically if the atmospheric properties at the time of the satellite overpass are known. More simply, one can select them by inspection of images, as the human eye can estimate the correct values, by using textural features. Pixels that meet each of the criteria are assigned separate primary colors. Thus, those pixels that are classified as snow meet all the three criteria.

3.1.2 Grain Size Estimation and Detection of Absorbing Impurities

Four indices, which are useful to estimate grain size and contamination amount are as follows:

1. The ratio $[R_p (TM1) - R_p (TM2)] / [R_p (TM1) + R_p (TM2)]$ would serve as a contamination index if TM1 is not saturated. Higher values represent clear snow.

2. The ratio $[R_p (TM2) - R_p (TM4)] / [R_p (TM2) + R_p (TM4)]$ is a grain size index for all sizes. Higher values represent larger grain sizes. It is also sensitive to contamination, but not enough to reliably estimate absorption by impurities.

3. The ratio $[R_p (TM2) - R_p (TM5)] / [R_p (TM2) + R_p (TM5)]$ is also a grain size index and helps to identify larger grains.

4. The ratio $[R_p (TM4) - R_p (TM5)] / [R_p (TM4) + R_p (TM5)]$ is a grain size index for finer grains. Higher values represent larger grain sizes.

The largest sensitivity of snow reflectance to grain size occurs in the wavelengths from 1.0 to 1.3 μm which is beyond the range of TM4 and below that of TM5. Future sensors with continuous spectral coverage should allow much more precise interpretation of physical properties. Grain size estimation can help us estimate the spectral albedo throughout the solar wavelengths and to interpret spectral signature of snow at microwave frequencies.

Prior to December 1995, this method was applicable for Landsat TM data alone as this method uses Band 5 (1.55 - 1.80 μm) range information which was available only on Landsat TM only. However, with the launch of the Indian Remote Sensing Satellite, IRS - 1C, it has now become possible to use this technique using our own satellite. The purpose of this report is to apply this model over some Himalayan catchment and use the data of the IRS-1C satellite. This application is discussed in detail in the following section.

3.2 APPLICATION OF DOZIER'S ALGORITHM

Dozier's method of automated mapping of snow cover area was applied on a part of the Satluj river basin in India. Bhakhra dam has been built on this river. Hence, the estimation of snow cover area is an important aspect for snowmelt modelling in this basin. In this study, the Dozier's algorithm was applied on the Spiti sub-basin of the Satluj river basin. The remote sensing data of IRS-1C satellite and LISS-III sensor was utilized. The GIS software used to carry out the analysis was ILWIS 2.0. This is a recently developed version of the software for Windows 95. This is installed on 166 MHz Pentium machine. It was only because of the large storage space available and the high speed of the machine that this analysis could be completed. Various steps which were involved in the application are detailed in the following:

3.2.1 Description of the Study Area

The river Satluj is one of the main tributaries of river Indus and has its origin also very near to Indus. It rises in the lakes of Mansarovar and Rakastal in the Tibetan plateau. The river covers a distance of about 650 km before entering the Bhakhra gorge, where the 225.55 m high straight gravity dam has been constructed. Coming out of Tibet, at Namagia, it is joined by a principal Himalayan tributary, the Spiti.

The Spiti river basin is a dry region of the Himalayas. The catchment area of this basin is roughly 10,070 sq. km. The elevation in the area varies in the range from 3600 m above m.s.l. to 5400 m above m.s.l. Very few vegetation was observed in this area in the satellite imagery. A major part of this area mostly remains under the snow cover. The catchment boundary of the Spiti basin and the drainage network in the basin is presented in Fig. - 2. A map of the Satluj catchment up to Bhakhra dam site is shown in Fig. - 3. Various steps of digitization and analysis of topographical information is explained in the following.

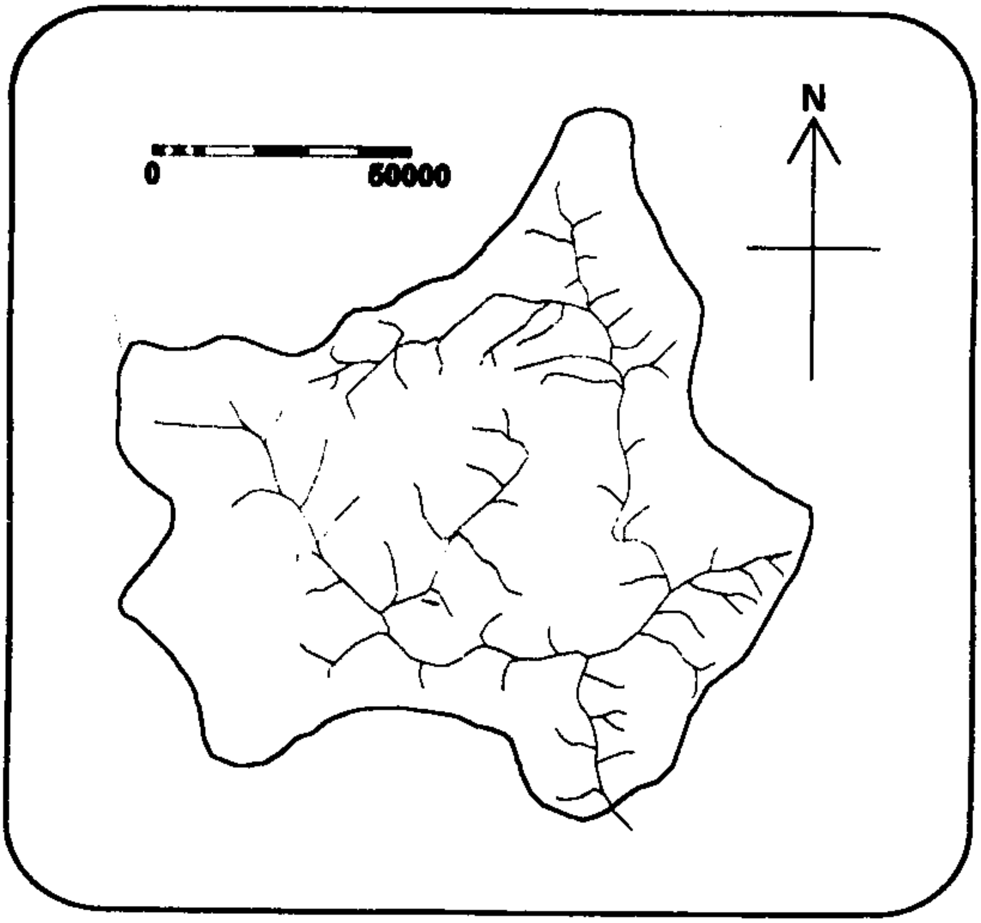

Fig. - 2 Catchment Boundary & Drainage Network in Spiti Basin

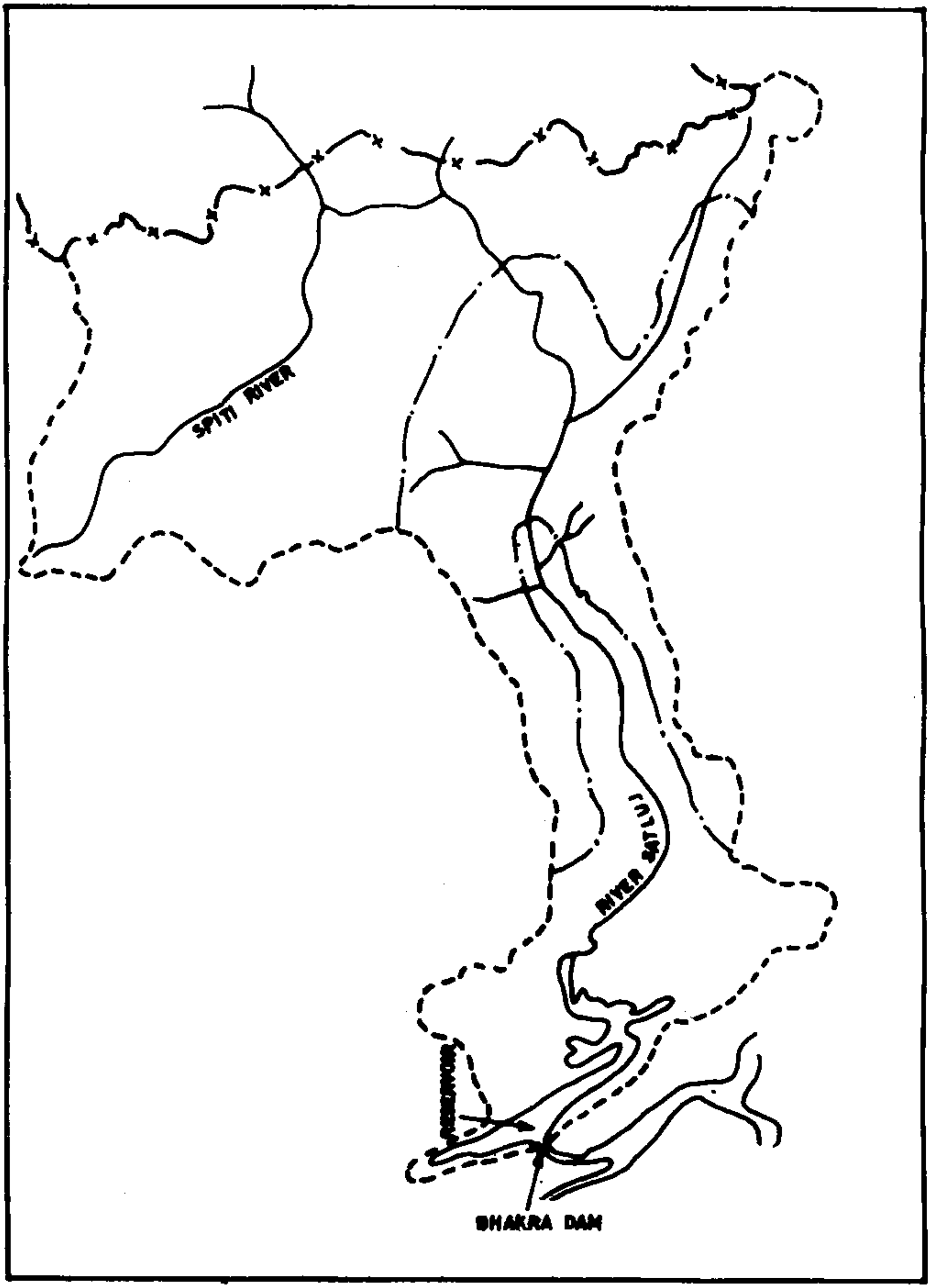

Fig. 3 : Location of Spiti sub basin in the Satluj Basin

a) Digitization

The catchment boundary, the drainage network and the contours in the basin were digitized in separate files. The boundary map was utilized to cut the basin area from the remote sensing imagery. Drainage network was utilized for georeferencing the remote sensing data with the basin map. Contour information was utilized to prepare the digital elevation model (DEM) of the basin. Using DEM information, it was possible to derive various other topographical information like slope, aspect, generation of 3-dimensional view of the study area etc. The map of the basin was available in 1 : 1,000,000 seale and the same was digitized. For mountainous basins in the Himalayas, maps on higher scale are generally, not available. Contours of only a few elevations (3600 m, 4200 m, 4800 m, 5100 m and 5400 m) were available and the same were digitized. The area of the digitized basin came out to be 10,560.7 sq. km while its perimeter was 473.1 km.

b) Digital Elevation Model

Digital elevation model of the study area was prepared using the ILWIS system. The digitized contours of the study area were rasterized. Generally, contours are extended and digitized beyond the basin boundary. This is done to eliminate the side effect, which otherwise can cause wrong interpolation along the boundary of the basin. Next, the interpolation function was used to interpolate the elevation values for the intermediate pixels. A pixel size of 23.5 m was selected to match with the remote sensing data so that pixel information of different layers can be overlaid and analyzed. It took more than three hours to construct the DEM on 166 MHz Pentium machine.

Using the DEM, it was possible to get the elevation value for any pixel within the basin. Now, the basin boundary was cut from the DEM map to give only the elevation values within the basin boundary. Next, different bands (200 m elevation range) were prepared in the basin. Fig. - 4 shows the distribution of various bands in the basin. The lightest color shows the elevation range from 3601 m to 3800 m. Subsequent darker colors show higher elevation bands: 3801 - 4000 m, 4001 - 4200 m, 4201 - 4400 m, 4401 - 4600 m, 4601 - 4800 m, 4801 - 5000 m, 5001 - 5200 m, > 5201 m.

c) Slope and Aspect Map

Using the information from the digital elevation model, the slope and aspect maps of the area were prepared. The slope maps contained the slope at a point in the vertical and horizontal directions. Gradient filters were used for the purpose. The aspect map was calculated using the slope maps in horizontal and vertical directions. The aspect map of the area is shown in Fig. - 5. If dx is the slope in X-direction and dy is the slope in Y-direction,

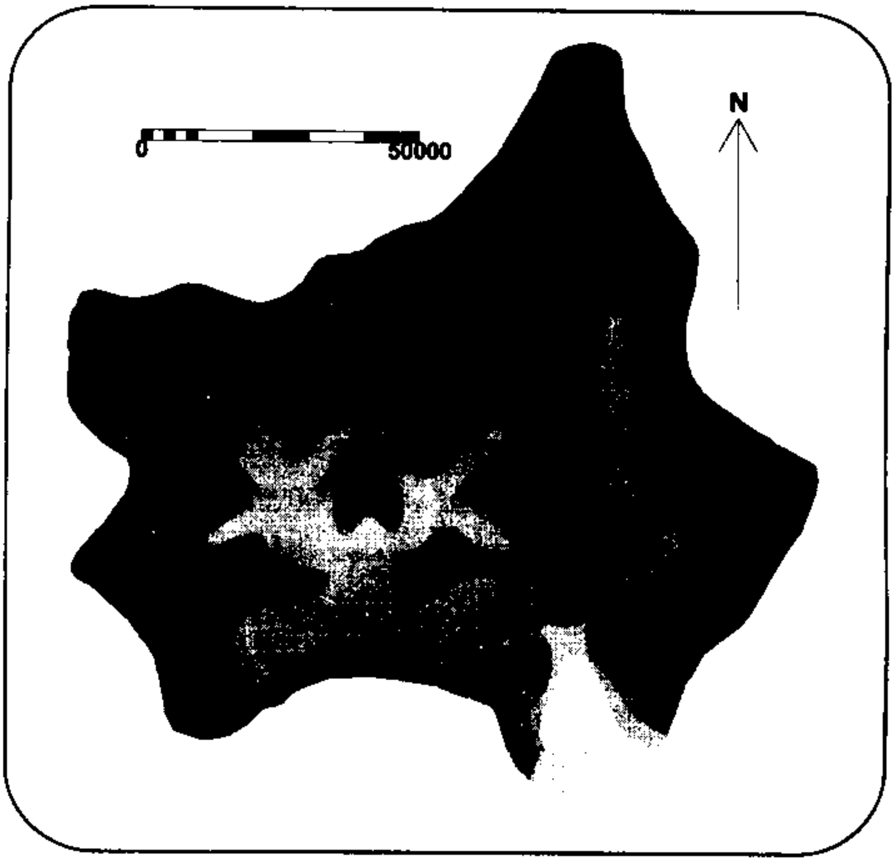

Fig. - 4 Different Elevation Bands in the Spiti Basin

then the following criteria was used to classify the direction of slope of a pixel:

Value of dx	Value of dy	Slope direction	Represented by
= 0	= 0	Flat	5
= 0	< 0	N	2
< 0	= 0	E	6
= 0	> 0	S	8
> 0	= 0	W	4
< 0	< 0	NE	3
< 0	> 0	SE	9
> 0	> 0	SW	7
> 0	< 0	NW	1

d) 3-Dimensional View

Using the information from the digital elevation model, the 3-dimensional view of the area was developed which is presented in Fig. - 6. According to the height information, the ILWIS constructs as output a line grid in X and Y directions. It is also possible to

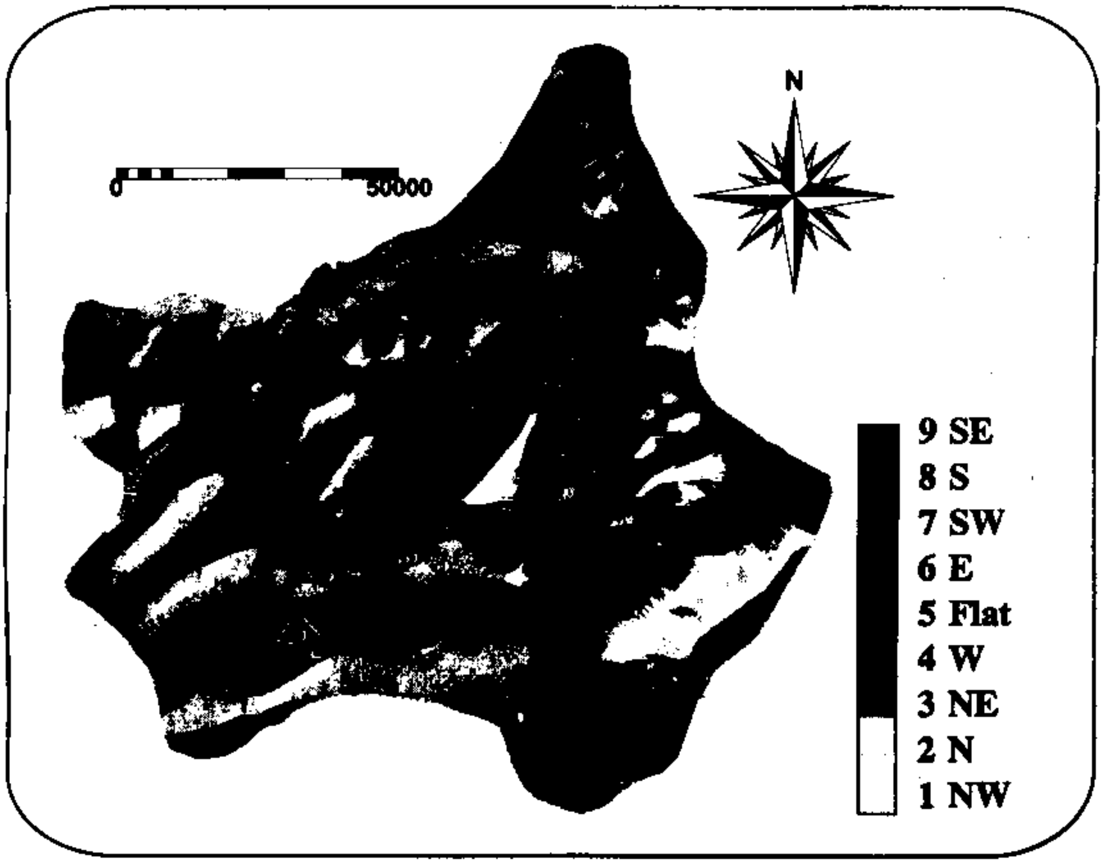

Fig. - 5 Aspect Map of the Study Area

superimpose any raster data over the map. It is also possible to add data layers to the window. In the present case, a drainage layer was added to the 3-Dimensional view to find out from where the various drainage streams are emerging. Various parameters selected for creating the view are presented below:

Grid Distance	:	550
Color	:	Black
Viewing Angle	:	65
Scale Height	:	40
View Point	:	101800.25, 90130.25
Horizontal Rotation	:	10
Vertical Rotation	:	39.965
Distance	:	42121150.02
Location Point	:	4799892.97, 26734338.098
Location Height	:	812098.15

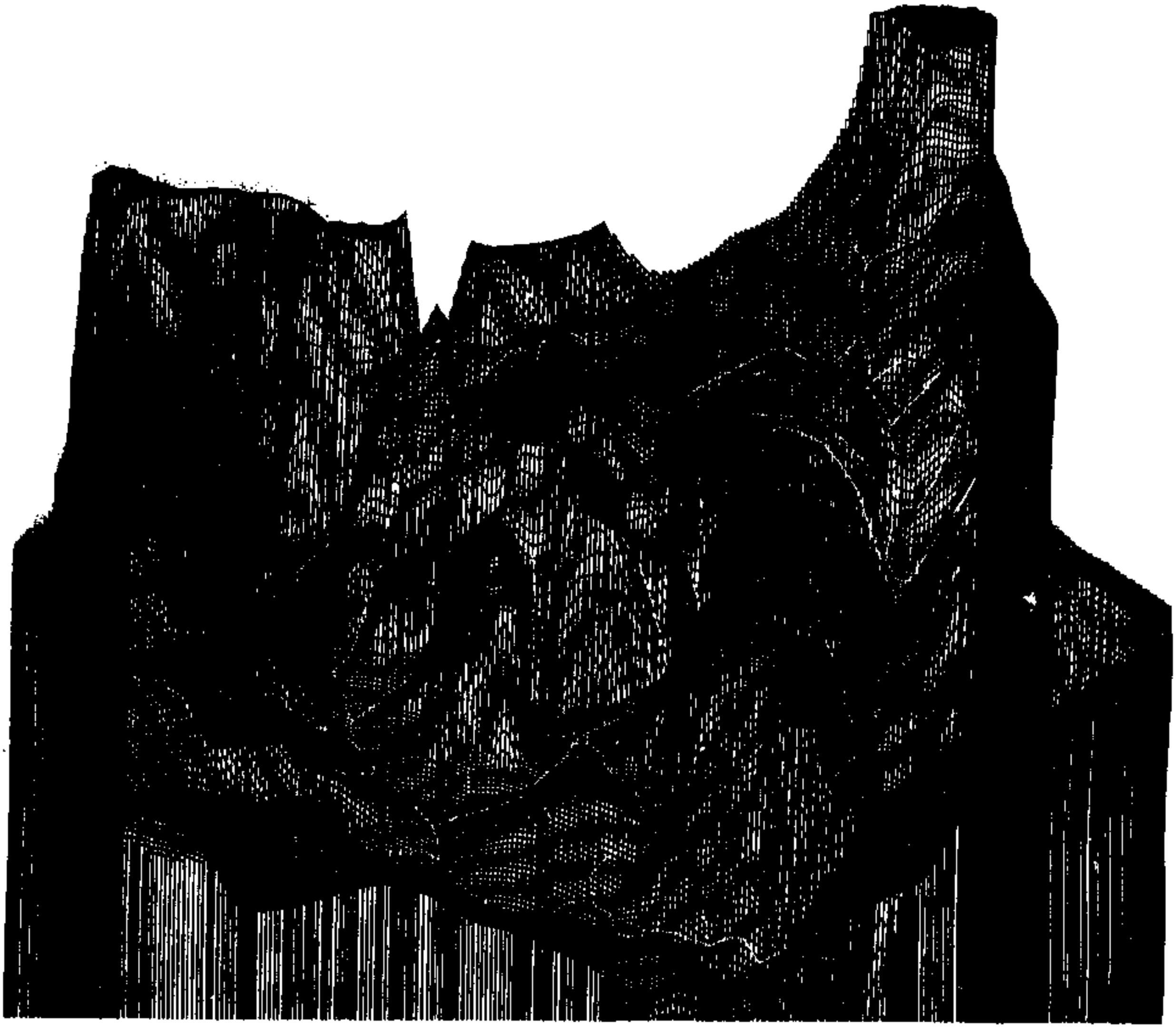

Fig. - 6 3-Dimensional View of the Spiti Basin

3.2.2 Description of the Satellite Data

The Indian Remote Sensing Satellite, IRS-1C was launched in December, 1995. The data of this satellite was used in this study to utilize the information of the 1.55 - 1.70 μm band which was newly added in this satellite. However, one band in the spectral range 0.45 - 0.52 μm has been removed from the satellite. This caused some problems in detecting snow in shadowed regions. An indirect method, based on the topographic details was utilized for this purpose. First, some general features of the IRS-1C satellite are briefly described in the following:

The IRS-1C satellite operates in a circular, sun-synchronous, near-polar orbit with an inclination of 98.69 degree, at an altitude of 817 km in the descending node. The satellite takes 101.35 minutes to complete one revolution around the Earth and completes about 14 orbits per day. The entire Earth is covered by 341 orbits during a 24 day cycle. The mean equatorial crossing time in the descending node is about 10:30 hours.

The IRS-1C satellite carries three imaging sensors which are characterized by enhanced resolution and coverage capabilities. These are briefly described here:

a) Panchromatic (PAN) camera

This camera has a spatial resolution of 5.8 m and it can provide stereo images. The camera operates in the spectral range of 0.5 - 0.75 μm and provide a total coverage of 70 km on the ground.

b) Linear Imaging Self-Scanner-III (LISS-III)

This is a multispectral camera operating in visible and near-IR spectral bands with spatial resolution of 23.5 m and a Short Wave IR (SWIR) band with resolution of 70.5 m. This sensor covers a swath of 141 km for the visible and near-IR band and 148 km for the SWIR band. The number of quantization levels (bit) are 7.

c) Wide Field Sensors (WiFS)

This sensor operates in visible and near-IR region with a spatial resolution of 188.3 m and a wide swath of 810 km. Because of the wide swath, the camera can observe the same region once every 5 days. The WiFS camera operates in two bands: 0.62 - 0.68 μm and 0.77 - 0.86 μm.

3.2.3 Availability of RS Data for Spiti Basin

For the Spiti basin, the path and row of the IRS-1C satellite were found out to be 96 and 48 respectively from the IRS-1C Reference Map. The data was obtained for a 30% shift along track in order to visualize and track the Satluj river in the scene. For detailed snowmelt modelling of the basin for the year 1996, it was required to obtain 6 - 7 imageries during the melt season (March - August). However, it was found that the data of the satellite for this period was not in order and could not be utilized. The earliest scene, which was available in working conditions was available for October 14, 1996. Since it was the lean season from snow melt point of view, imageries for the period ahead of October were not collected and the analysis for automated mapping of snow was carried out for the imagery of only one date. Digital data of the LISS-III sensor of Spiti basin was obtained on the CD-ROM media. Since this sensor has two resolutions (23.5 m for visual and near-IR and 70.5 m for SWIR), the data of SWIR band was resampled to a pixel size of 23.5 m.

The data was loaded on the ERDAS system. One scene of the LISS-III sensor was having 6480 columns and 5998 rows. Header bytes in the data set were 540. It was 7 bit data and the size of one scene was more than 155 Mb. This clearly shows that it needs to have large memory space and fast computers to work with data of very fine resolutions over large areas. However, finer resolutions clearly present various surficial features. Georeferenced image data of Band 4 of the sensor (1.55 - 1.70 μm) is presented in Fig. - 7. This band shows clouds which can be easily distinguished from snow.

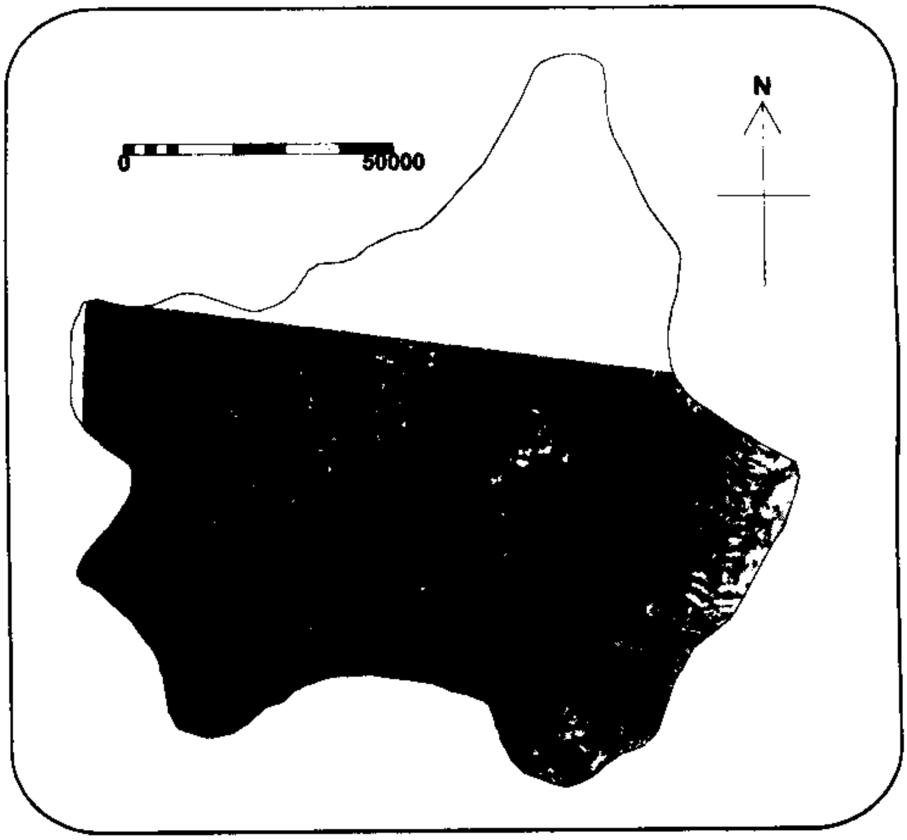

Fig. - 7 Georeferenced Band 4 image of IRS-1C LISS-III

3.2.4 Calculation of R_ps

Dozier's method uses planetary reflectance values in place of radiance numbers. The planetary reflectance R_p values were calculated for each band separately using equations 1 and 2. The radiance data of all the bands was stretched from 0 - 127 (for IRS satellites) to 0 - 255. $Q_{cal,max}$ for all the bands was found out to be 255 as clouds have highest radiance in all the bands. Q_{cal} was the actual radiance number in each band. L_{min} and L_{max} values were taken as those for Landsat TM sensor. The reason was the similar spectral range of the TM 2, TM 3, TM 4 and TM 5 bands with the IRS-1C LISS-III Band 1, Band 2, Band 3 and Band 4 respectively. In the same way, the Exoatmospheric Solar Irradiance values, S_0, were taken for different bands from Landsat TM characteristics. The values of solar illumination angle in the Spiti basin in different time periods was obtained from the Information Management System of NRSA, Hyderabad. The solar elevation and azimuth values in Spiti basin for different time periods are given in Table - 3.

Table - 3
Sun Elevation & Azimuth in Spiti Basin

Date	Sun Elevation (in degree)	Sun Azimuth (in degree)
January 5	32.45	160.00
January 24	35.06	156.88
February 17	41.50	152.89
March 12	51.06	147.82
April 5	59.28	144.04
April 29	67.00	136.22
May 23	71.59	124.87
June 16	72.57	116.09
July 10	71.04	117.21
August 3	67.81	127.26
August 27	62.69	140.64
October 14	47.62	160.27

The value of μ_0 was calculated as the cosine of the solar elevation angle. The value of Earth-Sun radius vector was taken as 1.0, as suggested by Dozier. Using these values, the planetary reflectance equations for the different bands are as follows:

$$R_p\,(L1) = (-\,2.8 + 1.1749 * L1) * 0.0025482 \quad \ldots (3)$$

$$R_p\,(L2) = (-\,1.2 + 0.8059 * L2) * 0.00299 \quad \ldots (4)$$

$$R_p\,(L3) = (-\,1.5 + 0.8145 * L3) * 0.00445 \quad \ldots (5)$$

$$R_p\,(L4) = (-\,0.37 + 0.10808 * L4) * 0.021253 \quad \ldots (6)$$

Since the Band 1 of IRS-1C satellite corresponds to Band 2 of Landsat TM, the first criteria of the Dozier algorithm could not be applied in the present case. This criteria distinguishes snow from other surface features, especially in shadowed areas of mountains or clouds. However, Band 1 of IRS-1C satellite was considered in this criteria. Since Dozier did not define the value for this spectral band, the imagery was inspected and a threshold radiance value of 145 was chosen such that in Band 1, all pixels above this radiance value are snow. Similarly, in Band 4 of the imagery, it was found that clouds have radiance value above 100 while all snow pixels are below 100. Using these values, the three criteria for a pixel to be snow covered were specified as:

$$R_p\,(B1) > 0.427 \qquad \ldots (7)$$

$$R_p\,(B4) < 0.2218 \qquad \ldots (8)$$

$$[R_p\,(B1) - R_p\,(B4)] \,/\, [R_p\,(B1) + R_p\,(B4)] > 0.444 \qquad \ldots (9)$$

These criteria were applied to all the pixels in the image. If a pixel satisfied all the criteria, it was termed as snow, otherwise, no snow. Using this algorithm, the snow cover area was determined in the basin. The snow cover obtained using the Dozier's algorithm is presented in Fig. - 8.

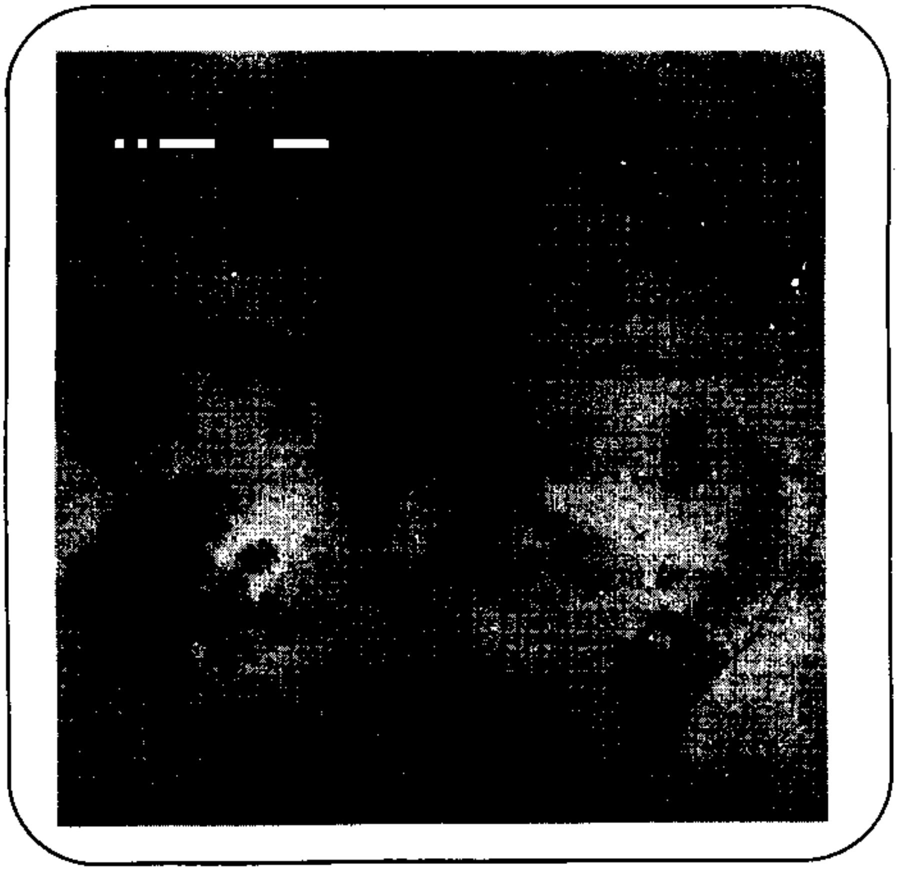

Fig. - 8 Snow Cover Area as Obtained Using Dozier's Algorithm

3.3 ESTIMATION OF SNOW IN SHADOWED AREAS & UNDER CLOUDS

Shadows in an imagery can be either because of high peaked mountains or because of the presence of clouds. Since the time of satellite overpass is roughly 10:00 AM, high shadowed areas are observed in rugged terrains. Around this time, most of the slopes in the SE direction and its surroundings receive direct sunlight and snow on such surfaces can be clearly distinguished. Shadows due to mountains are formed in the north and its surrounding directions. Snow on pixels in these directions are difficult to interpret.

Identification of snow in the shadowed regions using remote sensing data depends on the availability of the spectral channels. Landsat TM sensor contains a spectral channel in the wavelength range of 0.45 - 0.52 μm. In this range, snow, even in shadowed areas, reflects more than other surface features and can be detected easily. However, this spectral range is not available on the IRS-1C satellite. Because of this reason, it was not possible to directly interpret the snow area in shadowed regions using IRS-1C data.

Thick clouds obstruct the flow of information in two ways. A cloud, in addition to obstructing information beneath itself, creates a shadow which further poses problems in snow interpretation in a partially snow covered terrain. If a cloud lies above a terrain which is fully snow covered on all sides, area beneath the cloud can be safely assumed to be snow and vice versa. However, if a snow boundary lies under the cloud, it is difficult to predict the snow extent beneath the cloud. In such situations, it was tried to derive snow cover using the information provided by the digital elevation model.

First, it was tried to carry out the analysis assuming that above some reference elevation (snow line elevation), the area covered by cloud could be assumed as snow. However, when this condition was tried on the imagery, the snow line elevation could not be ascertained. Even in the month of October, snow was observed in the lowest elevation ranges of the basin, say 3601 - 3800 m, while in some higher ranges, snow was not observed. Thus, the snow-line could not be clearly marked. It was also tried to link "Aspect" information with elevation but no definite conclusion could be drawn.

In view of above, to delineate snow in shadowed regions and beneath the clouds, the topographical characteristics near the snow pixels (identified using Dozier's method) were used. A topographical algorithm need not be applied to the whole area. Hence, the proximity analysis was carried out using the snow cover area as delineated with Dozier's algorithm. The application of the proximity criteria requires that clouds must be exclusively extracted from the satellite imagery. This analysis and its results are explained in following.

3.3.1 Extraction of Cloud Cover

Though the second criteria of Dozier's algorithm differentiates snow from clouds, it does not exclude the vegetation pixels from the image as vegetation reflectance in Band 4 of LISS-III is very high. Thus, the first two of the Dozier's criteria were reversed and vegetation index criteria was applied to exclude vegetation. The following three criteria were applied for extracting cloud cover from the image:

a. R_p (B1) is less than a threshold (0.427). This threshold excluded snow from the imagery.

b. R_p (B4) is greater than a threshold (0.2218). This distinguished clouds and vegetation in the imagery.

c. The Vegetation Index (VI=B3/B1) of the cloud-pixels lie between 0.5 and 1. This value is greater than 1 for vegetation and less than 0.5 for snow pixels.

The cloud cover as obtained from the analysis was compared with that observed in the false color composite of the satellite imagery. The cloud map is presented in Fig. - 9.

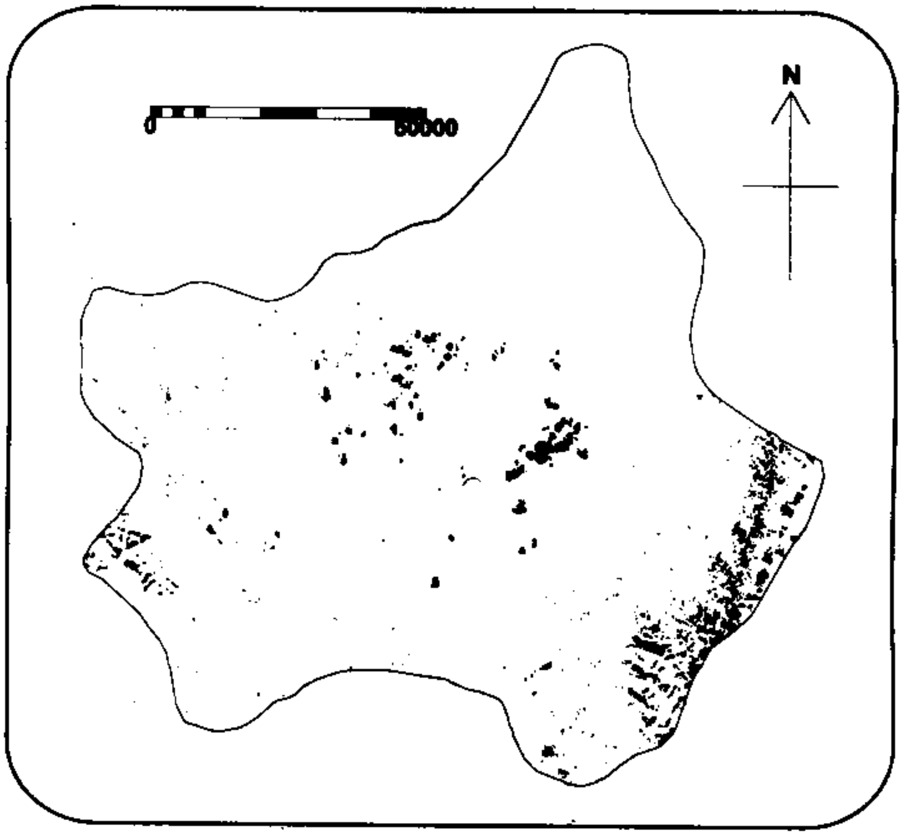

Fig. - 9 Cloud Cover in the Area on October 14, 1996

3.3.2 Proximity Analysis

Proximity analysis for the snow cover area was carried out on the ERDAS system. Twelve pixels around any snow pixel (delineated using the Dozier's algorithm) were considered to constitute the buffer zone around the pixel. This number (twelve) was selected to cover most of the snow-free area within the snow covered area (as identified using Dozier's algorithm). Map of the basin with snow cover surrounded with buffer zone is presented in Fig. - 10. It can be seen that most of the scattered area inside the snow covered area has been covered using the buffer.

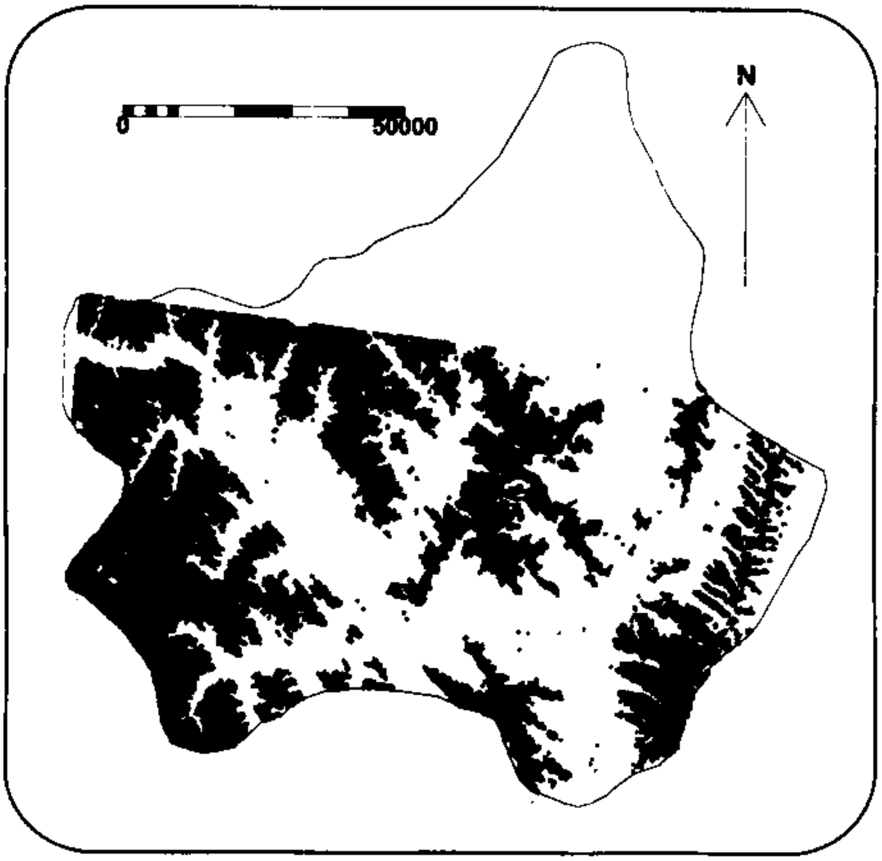

Fig. - 10 Buffered Snow Cover Area in the Basin

After creating the buffer zone around the snow cover area, the following criteria were applied to ascertain snow pixels in the shadowed areas and under the clouds:

a. If the aspect of a pixel in the proximity zone is less than or equal to 5 (either of NW, N, NE, W or Flat directions), the pixel is classified as a snow pixel.

b. If a pixel in the proximity zone lies under the cloud, it is classified as a snow pixel.

Thus, the underlying assumption of concept of proximity is that if the aspect of a pixel in the buffer zone is northward or westward or if there is cloud above this pixel, there are fairly high chances of having snow at that pixel. Some pixels may get wrongly selected by these criteria. However, after trying a number of different criteria, the proximity analysis turned out to be the best. The snow cover as obtained after applying the proximity analysis is presented in Fig. - 11.

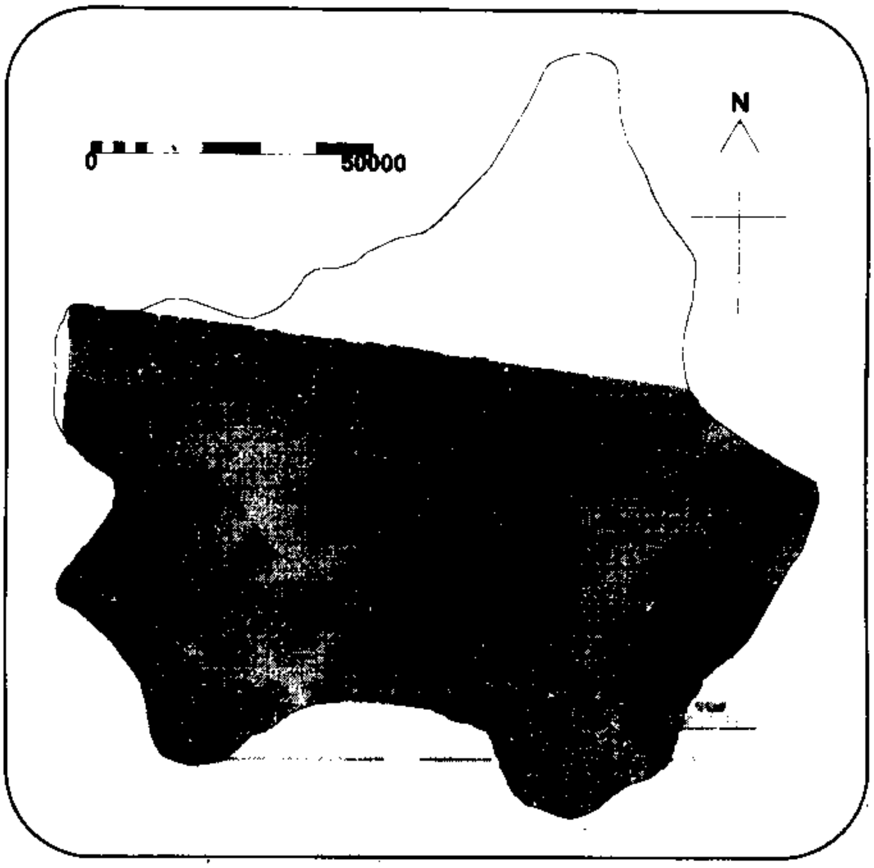

Fig. - 11 Snow Cover in the Basin After Proximity Analysis

3.3.3 Calculation of Snow Cover in Different Elevation Bands

Using the digital elevation model, the Spiti basin was divided in nine elevation bands having elevation range of 200 m each. The elevation bands started from 3601 m elevation and went up to as high as 5400 m. For snowmelt modelling, it is required to find the snow cover area in different elevation ranges. This information was also obtained for the present imagery of the satellite using GIS techniques. The snow cover, as obtained before and after the proximity analysis, were linked with the digital elevation band image using the "Map Calculation" module of ILWIS. Using the "Histogram Calculation" procedure, the number of snow pixels in different zones were calculated and multiplied with the area of each pixel (23.5 x 23.5 m) to get the snow cover area in each zone. The table showing the snow cover area in each zone, before and after the proximity analysis, is presented in Table - 4.

The table gives the total snow cover area in an elevation zone and the percentage snow cover area. It is seen from the table that there is wide variation in the calculation of snow cover area with and without proximity analysis. After the application of proximity analysis, the snow cover area increases drastically. It seems that in a snow covered area, the area in the north and adjacent directions does not give enough reflectance in Band 1 of LISS-III sensor so that it could be classified as snow. Since the cloud cover in this imagery was quite less, most of the increase in the snow area could be attributed to the shadow correction.

Table - 4
Snow Cover Area in Different Elevation Bands

Elevation Range (m)	Area (sq km)	Snow Cover (without Prox. Anal.)	% Snow Cover Area (without Prox. Analysis)	Snow Cover (with Prox. Analysis)	%Snow Cover Area (with Prox. Anal.)
3601 - 3800	304.6	4.08	1.34	10.37	3.41
3801 - 4000	132.9	12.03	9.05	17.38	13.07
4001 - 4200	1774.5	115.81	6.52	217.36	12.25
4201 - 4400	1608.0	278.60	17.33	527.41	32.80
4401 - 4600	766.2	157.44	20.55	262.38	34.24
4601 - 4800	1187.6	354.33	29.83	521.89	43.94
4801 - 5000	1478.6	493.94	33.41	757.51	51.23
5001 - 5200	735.8	155.70	21.16	284.37	38.65
> 5200	293.9	131.55	44.75	185.41	63.08

The snow cover area usually increases with elevation because of higher snow falls and lesser melting in higher elevations. This phenomenon was observed in all the elevation bands except one. It was seen from the table that in elevation band 5001 - 5200 m, the percentage snow cover is less than its previous elevation bands.

The cause of lesser snowcover area in the elevation range of 5001 - 5200 m was investigated in detail. It was thought that aspect of the area may be one of the reasons. For those areas which are predominantly Sun facing (aspect in the direction of East, South-West, West or South-East), snowmelt could be appreciably higher than those facing opposite to the Sun (aspect in the direction of West, North-West, East or North-East) thereby causing lesser snowcover area. Based on this reasoning, the percentage of north facing area in each elevation range was worked out. No appreciable difference could be detected for the elevation band 5001 - 5200 m. % north facing areas for the different elevation bands, as calculated using aspect map, are as: 51.19% (for elevation range 3601 - 3800 m), 19.26% (for elevation range 3801 - 4000 m), 47.75% (for elevation range 4001 - 4200 m), 52.44% (for elevation range 4201 - 4400 m), 42.18% (for elevation range 4401 - 4600 m), 41.87% (for elevation range 4601 - 4800 m), 46.64% (for elevation range 4801 - 5000 m), 48.81% (for elevation range 5001 - 5200 m), and 53.10% (for elevation > 5200 m). Thus, this analysis could not explain less snow cover area for one particular elevation band.

3.4 LIMITATIONS OF THE STUDY

Some of the limitations of this study which can be addressed in similar future studies are given below:

a) The toposheet was available at the scale of 1:1000,000. However, for such studies, topographic information at higher scale must be available for accurate analysis. At least, 1:250,000 maps must be used (which could not be used because they are restricted).

b) Due to (a) above, the available drainage pattern was very approximate and did not match very well with that observed with the satellite. So, accurate georeferencing could not be achieved. This could be the main cause of discrepancy of snowcover distribution in different elevation bands as discussed in section 3.3.3.

c) The Dozier's algorithm was originally developed using the data of TM sensor of Landsat. It was tried to obtain the TM data for the Spiti basin for the month of October, 1996 but two scenes of this sensor for the period were cloudy beyond permissible limits. So, the results of the analysis could not be verified. The ground truth data were also not available. Generally, snowcover terrains are inhospitable and inaccessible and ground truth data for such areas are not easy to gather. Even if the ground truth data are available, they are available for only point observations which can not be assumed to represent a big study area.

d) Generally, the information regarding snowcover area is required by the snowmelt models for simulation and forecasting. For this purpose, it is necessary to have a series of satellite observations during the melt season (April to September). However the basic purpose of this study was to examine the applicability of Dozier's method using the data of IRS-1C satellite.

* * *

CHAPTER - 4
CONCLUSIONS

Apart from its natural beauty, snow is an important component of the Earth's climate, significantly impacting global weather and vital to the water supply in many areas. After being deposited on the surface, snow subsequently serves as a source of water vapour input to the atmosphere through the processes of sublimation and evaporation and as a source of water to the soil and river systems when melting occurs.

Until few years back, the only way to study snow was from ground based observations. While field measurements are still needed, satellites are now providing valuable data that cover large areas. For the optimum management of water resources in areas dependent of snowmelt runoff, it is important that we monitor the temporal and spatial variability of the snow cover over land areas. For the seasonal snow cover, remote sensing has been used to improve the monitoring of existing conditions and has been incorporated into several runoff forecasting and management systems. Operational algorithms are available at present, which can be used to accurately map and evaluate the snow cover area.

In the present study, Dozier's algorithm has been applied to map the snow cover area in a part of the Spiti sub-basin in the Satluj river basin. The remote sensing data of IRS-1C satellite and LISS-III sensor was used. The spatial resolution of this sensor is 23.5 m and the same was used in whole of the analysis. Due to the non-availability of the sensor in 0.45 - 0.52 μm wavelength range, it was not possible to detect snow in shadowed areas. Similarly, it was also not possible to detect snow under the clouds. The digital elevation model of the area was prepared and the aspect map was created. Dozier's method was applied and a preliminary snow cover was identified in the basin. A buffer zone of 12 pixels was created around the snow area. To map the snow pixels in the shadowed areas, it was assumed that if the aspect of a pixel lies in any of N, NW, NE, W or Flat directions and if the pixel lies in the buffer zone, it must be termed as snow. Those pixels which were lying under the clouds and in the buffer zone were also considered as being snow. It was found that there was significant variation in the snow cover area calculations before and after the application of proximity analysis. Some of the conclusions drawn from the study are enumerated below:

I. Dozier's algorithm can be used for automated mapping of snow cover area using the remote sensing data of LISS-III sensor of IRS-1C satellite.

2. Since the LISS-III sensor does not have the 0.45 - 0.52 μm spectral range, an indirect method of identifying snow in shadowed areas and areas under clouds needs to be applied.

3. High spatial resolution data, though improve the accuracy and interpretability of the analysis, cause many operational problems in the analysis. In this study, 23.5 m resolution was used for a basin size of about 10,000 sq. km. Because of this, the file sizes grew very big. This not only required large storage space but also took longer computational time.

4. It is realised that for increasing the accuracy of the analysis, the data of two satellites, IRS-1B and IRS-1C must be used in conjunction. The information of Band-1 (0.45 - 0.52 μm) of IRS-1B can be used for snowcover mapping in shadowed areas. The information of Band-4 (1.55 - 1.75 μm) of IRS-1C satellite can be used to identify and separate cloud cover from the snow cover. The cloud cover on different dates of pass of two satellite would be different and can provide better information about the snow cover in the basin.

5. It was inferred from the analysis that snow cover may be present at any elevation at any time. In the Spiti basin, it was found to be present in the lowest elevation ranges while at some other higher elevations, it was not available. In such circumstances, the role of remote sensing, in identifying snow cover area in a basin, assumes great significance.

Some major limitations of this study included the non-availability of the series of satellite data and the verification of the results of snowcover interpretation. Accurate topographical information was also not available. It would have been ideal to take a series of imageries in the melt season for the interpretation of depleting snowcover area and it was planned to acquire the IRS-1C data from April, 1996 onwards. However, the satellite did not provide the satisfactory data until October, 1996. For confirmation of the results of this analysis, it was tried to acquire Landsat TM data for the month of October, 1996, but the two scenes of TM in the month of October, 1996 were having cloud cover exceeding permissible range.

Ground data was not available for the verification of the results. Though it is very difficult to collect ground truth data for snow cover areas because of difficult terrain, inhospitable conditions and inaccessibility of the area, yet ground truth of even some point observations can be used for the verification of the results obtained using digital image processing of remote sensing data.

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