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SNOWLINE AND SNOWCOVER MAPPING BY REMOTE SENSING TECHNIQUES

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SUMMARY

Snow and ice is a major component of Water Resources and it is hydrologically important in India because of the presence of mighty snow clad Himalayas. Major north Indian rivers originate from the Himalayas and the 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. The density and thickness of snow varies within a short distance to a great extent. So, the field measurements about snow which are point data may be misleading. Besides, the snow bound areas are remote and hazardous to access. Remote Sensing techniques, both satellite and aerial flight offer an excellent synoptic view in various spectral channels of electromagnetic spectrum which serve as a spatial data base for snow related studies. Repetitive coverage of satellite also provides scope to monitor snow-line movement and other characteristics of snow. Delineation of snow in a imagery is relatively simple because of its high reflectance. Problems like location, recognition and measurement in targetting snow and ice in remote sensing are minimum and as such monitoring of snow cover areas by remote sensing could be made automatic and operational.

Amongst various sensors in different available satellites Landsat MSS band 5 (0.6 - 0.7 μm), NOAA visible channel data are most suitable. However, other properties of snow like density, thickness,

water equivalent etc. are becoming viable to be measured by remote sensing as technology progresses and improved sensor systems are put on-board the satellites.

Gamma ray, thermal infrared and microwave portion of electro-magnetic spectrum have great potential for snow studies. The data of band 5 of thematic mapper of Landsat - 4 and 5 satellites which are now available are suitable to separate snow and cloud. The use of remotely sensed data in hydrologic modelling has also been examined and the initial findings are promising.

Considering all the available means to decipher or measure snow and ice, the remote sensing methods has definite advantages and could be judiciously used to make hydrologic studies.

1.0 INTRODUCTION

Snow and ice constitute to be major component of world's water resources and is a very intricate and important phase of hydrologic cycle over space and time. It is estimated that out of the eight million cubic miles of fresh water in the world, some seven million cubic miles are frozen in polar ice caps and in glaciers in various parts of the world.

According to Lvovitch (1970 vide Rodda, 1976), the total volume of water present in the hydrosphere is approximately 1.45 x 10^9 km^3. Ice and snow represetn about 28 x 10^6 km^3 of water (Hoinkes, 1967 vide Rodda, 1976), which is about 2% of water in all its form. If the saline sea and ocean water are disregarded (which is about 97.4% of world's water), ice and snow become the major component (Table 1).

Table - 1: World's Water Distribution

Forms of water presence	Water volume in 10^6 km^3	As percentage
Polar ice and glaciers	24.8	77.0
Soil Moisture in upper zone	0.09	0.3
Ground water within reach	3.6	11.1
Deeper groundwater	3.6	11.1
Lakes and rivers	0.132	0.44
Atmosphere	0.014	0.043
	32.2	100.0

Disregarding the practically unrecoverable groundwater at great depths, ice and snow are normally considered to represent more than three-quarters of the terrestrial fresh water reserves. From the viewpoint of practical utilization of water resources, the renewal rates of different modes of occurrence of water are more important than static volumes of these modes. Of course, on this basis, snow and ice plays a far less active role in the hydrologic cycle than water flowing in rivers.

Reasonable estimate puts about 5% of all precipitation, reaching earth's surface as snow (Hoinkes, 1967 vide Rodda, 1976). In addition to permanent ice and snow, the important contribution of the seasonal snow cover needed to be considered. The major portion of permanent snow and ice cover is formed as ice sheets in Antarctica and Greenland.

The seasonal snow cover spreads over large areas of Asia, Europe and North America and is also available to a lesser degree on the remaining continents. The pattern of runoff and water balance of many highly developed areas around the world is significantly affected by seasonal snow cover. A hydrologist who has to forecast for improved water management will be interested to estimate or know snow extent, distribution, water equivalent, water content, age, thickness and density of snow. All of these properties of snow are important to assess the snow pack's contribution to runoff.

With 6 lakh sq.km. of snow bound area, it is well known that 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 of solid water is a dominant source of streamflow for all major north Indian rivers. The snowline may experience considerable fluctuations in altitudes, day to day and season to season. But, mean seasonal snowline generally lies between 2000 to 2500 meters in western Himalayas. During November upper reaches of the north Indian rivers start building up snow due to prevailing temperature and first snow fall occurs in India usually in December for altitudes below 3000 meters.

It is observed that snowfall is fairly high during the months of December to February, but daily discharge values in these months are low and reach a minimum during the period. Snow cover reaches its maximum accumulation by March. During March-April-May, there is hardly any precipitation but on the other hand, hydrographs show a steady increase in discharge indicating the snow which had accumulated in the preceeding months is undergoing melting. Snow cover attains its minimum by September/October. The snow depth in the Himalayas may vary from few centimeters to few meters within a short distance, and similarly the density may also vary from as low as 0.01 to as much as 0.15.

Remote sensing has been looked upon as a very promising means of attacking snowpack problem as various important properties or characteristics are amenable admirably to it. It is possible to decipher meaningful information about the snow and ice reserve. Also both snow and ice occurs in great quantities in remote and inaccessible area. Conventional snow pack and ice measurements are difficult to obtain, often hazardous, and give only point measurement which often cannot be extended to entire watershed because of snow properties usually vary within a short distance. The much-needed large monitoring capability is attained with remote sensing because of its synoptic over-view capability. From the initial work done in this regard, it is evident that the extraction of snow and ice information is possible using different spectral regions, namely, the microwave, thermal infrared, visible and near infrared, gamma ray ranges. The use of remote sensing fits quite well for the study of snow and ice because of repetitive and timely coverage. Snow can be monitored effectively by using most of the repreat cycle of existing satellites as it does not have rapid transistory nature like rainfall. Aircraft flight can be resorted to in case of particular critical melt period or break-up situation in absence of satellite pass during the time.

The usual problems like location, recognition and measurement encountered in remote sensing are virtually not found when the target is snow and ice. Snow and ice have the unique physical property of possessing a high albedo in the visible portion of the spectrum. This makes them easily separable from the darker background associated with other natural materials. But, snow albedo is reduced substantically in the near infrared (0.8 - 1.1 μm) especially if liquid water is present though the reflectivity is still much higher than the surrounding substances. Further the reflectivity of snow is reduced drastically in the spectrum range 1.55 - 1.75 and 2.10 - 2.35 μm (near infrared) in comparison to other substances. This unique properity offers an opportunity for automatically separating snow from highly reflective clouds (Barnes et al.,1975).

The snow that is potentially ready to melt (273^{o}K) and eventually will contribute to runoff is very important hydrologically and could be observed with a sensor in thermal infrared region.

Presence of water in snowpack increases the dielectric constant with respect to dry snow and this could be sensed in the microwave range of the spectrum. Wavelength longer than 3 cm can go through a dry snow pack and offers an excellent indication about the snow depth. The terrestrial gamma-ray radiation is strongly observed by snow with comparison to snow free gamma-ray measurement. The absorption offers an excellent means to estimate the snow water equivalent (Barnes & Bowley, 1974). Because snow has a high reflectance, out of the data products available from various sensors of satellites, NOAA-visible channel and Landsat MSS 5 band (0.6 - 0.7 μm) are most suitable for snow identification because of the strong contrast between snow-covered and snow free areas. However, considerable skill is required to delineate snow from cloud as both have high reflectance. Recognition of snow in forested areas and in shadow zone of an imagery are often difficult.

Considering all the available ways to decipher or measure snow and ice in various segments of the spectrum, it is quite likely that applications of remote sensing technique is most promising for snow and ice monitoring.

2.0 REVIEW

2.1 Measurement of Snow Cover Area

For the northern hemisphere, using the data of the visible band sensors abroad TIROS-N and GOES satellites, weekly charts of snow cover boundaries are prepared by NOAA, USA.The charts are in scale 1:62.5 million, and show brightness of the continental snow cover. Snow and ice boundaries are marked for areas that are most reflective (Heaviest snow cover), moderately reflective (Moderate snow cover) and least reflective (Least snow cover) (Matson & Wiesnet, 1981).

Besides, there are several techniques available for mapping snow covered area using remotely sensed data. The simplest of all is the photo-interpretation methods. The sophisticated method involves use of automatic data processing for digital analysis. The interactice analysis combines both photo interpretative and digital processing methods. However, the photo interpretation procedures are straight forward and generally do not require any sophisticated equipment.

Snowline delineation and measurement of snow covered area from a 1:1 million Landsat image require the demarcation of watershed boundary on it at the first instance and tracing of the snowline on an overlay. The snow covered 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 number and area of watersheds is small. Slight variation of this include use of enlarged imagery upto a scale of 1:100,000. Partial obscurity of snow cover due to trees or shadows, a diazo overexposure technique has been successfully employed to enhance the snowline by Foster and Rango (1975).

Use of a zoom Transfer scope is often resorted to increase the accuracy of delineation of watershed. Further improvement is possible by using an automatically recording planimeter which prints out 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 is quite high.

The approach to mean snow line altitude to snow covered area is relatively precise and simple to nandle. The method produce snow cover area by producing an estimate on mean snow line altitude in a watershed. The mean snowline altitutde is derived by interpolation of the elevation of the snowline at specific location on a transparent overlay with topographic contours (Meier and Evans, 1975). A sizeable number of imagery, say, twenty or more, are then averaged out to produce the mean snowline altitude and converted to equivalent snow covered area by using an area altitude curve for the watershed. This method avoids problem of actual location of snowline in forest or shadow areas.

The use of overlay grid or box system as the interpretation base for snow covered area was first used with 1.98 x 1.98 km. grid overlay boxes by Laves and Draeger (1974). The grid size is often made different than this to suit the convenience. The amount of snow cover in each grid element is noted and summed over the entire watershed for total snow cover. The method is far more time consuming than the simple photo interpretative method. But, it is precise and provides means to store and retrieval of data. This method is ranked as in between visual and digital processing.

The use of optical enhancement devices for denstiy slicing of Landsat images is quite rewarding. This seperates snow from other features on the basis of a selected reflectance level. Automatic snow covered 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 be specified. Repetitive slicing of the same scene often leads to erratic and different results due to machine error. However, such method may be acceptable for some watersheds for quick snow covered area determinations. As the cost of density slicing equipment is high and lacks in measurement precision, the procurement of the equipment is not recommended.

Digital analysis is definitely a superior technique. This method analyses individual resolution elements instead of average of several pixels as is in the case of photo interpretation. In digital analysis, data is attempted to be classified in different thematic ground features. The supervised classification is very effective in identifying snow and other snow and ground covered mixture. It depends heavily on the level of accuracy of ground truth used in training process. Various computer programmes are available to accomplish this classification. The Purdue University LARSYS or Pennsylvania State University ORSER systems which use maximum likelihood classifier produce very detailed snow classification. But it takes a very substantial computer time. It is felt that use of such versatile computer oriented methods may not be necessary as it is relatively easy to identify. Supervised classification which uses relatively coarse parallelepiped classifiers like G.E. Image 100 is suffice to classify snow though the result is slightly less accurate. The results are quite encouraging. According to Itten (1975) the computer time required for image 100 computer processing time is the order of magnitude less than the maximum likelihood approaches and requirement of ground truth data is also less. Requirement of interpretative skills of the analyst is an essentiual part inspite of the fact that the digital processing of snow is automatic. In order to obtain the desired results with accuracy, a large area is needed to be taken.

A comparison of Landsat data analysis with conventional technique of snow identification gives striking information and speaks volume about the suitability of usage of Landsat data for snow. Landsat snow extent data compares very favourly with aerial snow survey results. The comparison shows that more detail in the snow line can be mapped from Landsat data than by aerial observation. The aerial view of the terrain is always at an oblique angle and most often draws a smoothed snowline (Barnes & Bowley,1974). A comparison of Landsat and high altitude U-2 (flown at about 20 km) by Barnes and Bowley(1974) reveals that though more detailed patterns can be identified in U-2 aircraft data, the information content of the Landsat image with respect to mapping snow cover is as good as higher resolution photography. It has been found snowline mapping from Landsat image is consistently easier. Wiesnet and McGinnis (1973) observed that Landsat snow mapping is six times faster than U-2 snow mapping. NOAA-2 VHRR data though of poor resolution offers almost same speed of ease in snow mapping, rather its availablity is more timely and ideally suited for very large watersheds. A cost comparison figure worked out by Wiesnet and McGinnis(1973) between snow measurement by NOAA data and by conventional methods gives a figure of 200:1 in favour of NOAA data. The cost comparison does not include the costs of the satellite or the plane. It is well ascertained out of the various experiments that Landsat and in certain cases NOAA VHRR data is adequate for mapping snow cover in a watershed. The advantages of using satellite derived snow extent over aerial surveys are:

1. Satellite mapping is less expensive and faster.
2. Large areas can be surveyed at one time with reasonable degree of accuracy

The major disadvantage is that the time of coverage and repeat periods of the satellites on small watershed may be inadequate because of cloud cover which require timely aircraft flights.

Detection of areal extent of metamorphosed snow can be done by a comparison of Landsat 0.6 - 0.7 and 0.8 - 1.1 µm bands. The area of snow pack currently and recently melting could be approximately delineated. It is generally found that 0.6 - 0.7 µm band delineates the total snow cover area wheareas 0 .8 - 1.1 µm measures less snow cover. Reason for this is the reduction of reflectance near infrared region of snow associated with melting or refrozening of previously melted snow which is known as refrozen snow.

Slightly melting snow has distinct lower reflectance in the red visible region and major reflectance decrease in near infrared region than the fresh cold snow.(O'Brien & Munis,1975). Refrozen snow has a reflectance curve resembling that of melting snow. This is known, however, from the laboratory experiments. The difference between 0.6 - 0.7 µm and 0.8 - 1.1 µm snow covered area is not entirely due to the melting area. The near infrared banks is less reflective visible band under normal condition and somewhat more so when metamorphic processes have set in. Presently, there is no specific methodology to distinguish between normal and metamorphic lowered reflectance. As such, quantification of metamorphosed area is not possible using these two spectral bands.

2.2 Estimation of Runoff from Snow Covered Area

A good number of investigative results suggest that snow covered area is a meaningful parameter for the forecasting of snowmelt runoff. Analyses of snow covered area data from King's River Basin in California show that a correlation exists between observed melt area, remaining area of snow cover, the conventional 1 April snow water equivalent and remaining volume of snowmelt runoff(Brown & Hannaford,1975). It is indicated that snow covered area could be combined with snow water equivalent to improve runoff forecast.

In Arizona, areal snow cover estimates from Landsat for 1973 were used to derive a statistically significant relationship between snow cover and subsequent runoff during the snowpack depletion period (Aul & Ffolliott,1975). It was inferred that measurement of areal snow cover from Landsat imagery is a very valuable input in forecasting snowmelt runoff in that area. With a slight variation, for Wyoming area, it has been observed that snow covered area on a specified day is related to the ratio of accumulated runoff/total seasonal runoff in a statistical significant expression (Thompson,1975). Such relationship are useful for total flow forecasts and short term forecasts of time distribution of seasonal runoff. It has been further established for Wyoming's Wind River mountains that correlation exists between the extent of snow cover on 15 May and the seasonal runoff from 15 May to 31 July (Rango et al.,1977). Results indicate that snow covered area could be incorporated into empirical runoff prediction methods as an additional parameter after sufficient years of data have been accumulated. Using five to seven years of low resolution meteorological satellite data, a regression relationship is attempted for Indus (162,100 Km^2) and Kabul (88,600 Km^2) river basins in Pakistan with early April snow covered areas to April-July streeamflow (Rango et al.,1977). Significant relationship has been obtained which served as the only way to estimate further runoff for these remote and inaccessible areas. The prediction of 1974 streamflows in these basins using the regression equation were within 7% of the actual streamflow. Though the data from meteorological satellites are available from 1966, but because of poor resolution (4 km) these data can only be used to large watersheds. Day et al.(1983) combined Rango et al.'s (1977) data for 1969-73 with 1974-79 and found April snow cover could explain 60% and 90% of the variance in seasonal runoff prediction for Indus and Kabul rivers respectively. For each year of the study period,1969-79, a multiple regressin equation is developed by dropping the data for the year in question from the data base and using those for the rest of the years. The snow cover area and the concurrent runoff data are used to estimate the snowmelt runoff for the particular year. The difference between the estimated and observed discharge values averaged over the 11-year study period is 10%.

Use of thermal infrared data to delineate snow is very rewarding. The thermal infrared band (10.5 - 12.5 μm) available with NOAA satellite has the same resolution as the visible channel. This data can be acquired during day or night as it is the measurement of radiative temperature of snow rather than its reflectance. In most of the cases, snow cover could be delineated from the VHRR thermal data because of lower temperature of snow, but the thermal gradients associated with snow boundaries are greater during spring than during the winter(Barnes et al.,1974). The data is more relevant during the melt period. Difficulties may arise in the interpretation of the thermal infrared data in mountainous area due to temperature differences arising out of variations in elevations may overshadow the temperature differences associated width snowcover (Barnes & Bowley,1974). A subtle comparison of infrared measurements made with or without snow cover or in combinations with topographic maps and atmospheric lapse rates can resolve most of the problems. External calibration is a must for VHRR thermal data before the determination of absolute temperature.

The VHRR resolution has been improved of late from 4 Km. to 1 Km. But, it gives only the general thermal snow pack information. It is resolved to use better resolution thermal infrared sensors on satellites. The envisaged improvement expected will probably help to a great extent in determination of melting areas which hitherto could not be achieved with visible or near infrared data alone. The improved data planned to be used for temperature differences across the snow pack with $0^{o}C$ area being reasonably easy to decipher in the spring. During spring it is reasonable to assume that edge of the snow pack to be at $0^{o}C$, the area that will be subjected to melting in near future can be defined. Abnormally low reflectance of a snow covered area with comparison to nearby snowcovered area (at temperature less than $0^{o}C$) in visible and near infrared bands can be used to locate and quantify the areas of snow currently or recently melting. This however, is not possible at present.

The Applications Systems Verification and Transfer project of NASA on the operational applications of satellite snow cover observations (from 1975-79) demonstrated the areal extent snow cover as derived from satellite imagery have great potential for improving the timeliness and frequency of hydrologic forecasts. Satellite snow cover data were parameter after sufficient years of data have been accumulated. Using five to seven years of low resolution meteorological satellite data, a regression relationship is attempted for Indus (162,100 Km^2) and Kabul (88,600 Km^2) river basins in Pakistan with early April snow covered areas to April-July streeamflow (Rango et al.,1977). Significant relationship has been obtained which served as the only way to estimate further runoff for these remote and inaccessible areas. The prediction of 1974 streamflows in these basins using the regression equation were within 7% of the actual streamflow. Though the data from meteorological satellites are available from 1966, but because of poor resolution (4 km) these data can only be used to large watersheds. Day et al.(1983) combined Rango et al.'s (1977) data for 1969-73 with 1974-79 and found April snow cover could explain 60% and 90% of the variance in seasonal runoff prediction for Indus and Kabul rivers respectively. For each year of the study period,1969-79, a multiple regressin equation is developed by dropping the data for the year in question from the data base and using those for the rest of the years. The snow cover area and the concurrent runoff data are used to estimate the snowmelt runoff for the particular year. The difference between the estimated and observed discharge values averaged over the 11-year study period is 10%.

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In 1979, the Martinec-Rango snowmelt simulation model was developed (Rango & Martinec,1979) and this model with minor modification was adapted by Shafer et al.(Shafer et al.,1981) on the South Fork Rio Grande basin (559 km^2) and Conejos river basin (730 km^2) in Clorado. The model used as primary input snow covered area derived from Landsat imagery for each watershed elevation zone, degree days for each zone with corresponding precipitation which occurred in each zone. Other factors considered are: the areas of each zone, recession coefficients for the hydrograph, daily lag factors, melt rate factors, and runoff coefficients. Daily streamflow simulation during the melting period for 1973-79 showed that the model is capable of explaining on average of 89% and 87% of observed streamflow variation on the South Fork Rio Grande and Conejos rivers respectively.

Rango et al.(1977) used low resolution meteorological satellite data (ESSA and NOAAsatellites) and simple photo interpretation techniques to map snow cover area during early April over the Indus and Kabul river basins in Pakistan. It has been observed that the snow cover area is significantly related to April 1 to July 31 streamflow in regression analyses for each basins.

Snowmelt runoff models can be used for ouperational forecasts provided the snow cover depletion curves obtained from satellite data could be extrapolated by temperature forecasts. Martinec (1985) suggested a set of auxiliary curves relating the snow coverage to accumulated snowmelt depths to be derived for a given basin. The selection of the appropriate curve in the given year is facilitated if the water equivalent of the snow cover at the beginning of the snowmelt season is available.

Quite a number of organisations in India has experience in mapping snow cover areas from satellite imagery and using the same for snowmelt runoff studies. NRSA,ISRO,GSI,IMD, Snow and Avalanche Studies Establishment,Roorkee University etc. are some of these Institutions who have used both Landsat and NOAA satellite data available from Earth Station of National Remote Sensing Agency,Hyderabad.

NRSA has undertaken snowmelt runoff forecasting studies using NOAA satellite data (Ramamoorthi,1983). A regression model has been developed using percentages of snow cover area of Sutlej basin above Bhakra (43,230 Km^2)from NOAA imageries (April) of the years 1975 to 1978, and the seasonal (April to June) measured snowmelt runoff of Sutlej for the same years. It was found that for 1980 snowmelt season, the seasonal forecast is 6% less than that of the flow actually occurred. The model was improved using 1980 actual flow, and the revised model forecasted 5% more than observed seasonal runoff in 1981. The model has been subsequently updated with data of other years. Now, an operational forecasting model with capability of predicting flow within 10% more or less than actual flow has been made for Sutlej river basin. Similar predictive model are being developed by NRSA for other Himalayan rivers.

Study conducted by Dhanju(1982) on the contribution of snowmelt water to Bhakra reservoir revealed that remote sensing could provide a reasonable estimate of snow cover area which would form the basis for estimating meltwater for long term and short term periods.

Jeyram et al.(1982) estimated snowline altitude and snow cover using Landsat imagery for the Tos basin in Himachal Pradesh. A relationship amongst snowline of Beas,Ravi and Tos was observed and using the Landsat imagery a relationship between the snow covered areas and time from beginning of snowmelt season (1st April) has been established for Tos basin.

Gupta et al.(1982) in their study of Beas Catchment concluded that the relationship between snow cover area and snowmelt discharge is affected by the morphological characteristics of sub catchment such as area, permanment snow cover area, average altitude, topography and relief. All these factors are collectively manifested in terms of stream order which is an important factor. They observed a logarithmic relationship between the snow cover area and snowmelt runoff. This essentially means that initial increments in accummulation of snow cover area lead to smaller increases in snowmelt runoff than later increments in the snow cover area of the same magnitude.

Sharma et al.(1982) used Landsat imagery to study upper Yamuna catchment and marked hydrologically significant land use categories which affect the streamflow. Using these with rainfall data from 20 raingauge stations and streamflow data at Dak pathar and Lakhawar, the streamflows were estimated by using both lumped and distributed system models based on Rational method. The computed 10 day period streamflows of Tons sub basin were compared with observed surface flows with the help of hydrographs, flow comparison graphs and average monsoon period and monthly flow values. It has been observed that distributed system model with sub-area division by Thiessen polygon and considering the slope facet effects is suitable for large mountaineous catchments.

It is suggested that the values of streamflows estimated by distributed approach can be further improved by evaluating substantial yearly changes in vegetal covers and land use areal disribution with the help of time sequence Landsat imagery.

3.0 REMARKS

Being the exorbitant repository of 'Solid' water resources, snow cover survey is essential for development of water resources. For surveying very large area of snowcover and for collecting snow data from inaccessible and hazardous areas as in the Himalayas, satellites are the obvious answer. Of the various snow observations, the areal extent of snow cover is the most easily measured because of high reflectance. It is measured and monitored regularly in many countries. Density and distribution of snow pack are also equally important for snow melt runoff studies. Most of the snow clad basins tend to follow a consistent pattern of melts which eventually leads of have a depletion curve which could be correlated with the snow cover remaining as the snow melt progresses. Automation of snow cover is possible and desirable for operational use. Proper segregation of cloud cover while making automation of snow cover measurement will have to be taken care of. Once this has been ensured, remote sensing methods using satellite and aerial imagery are the only possible methods that can be used for estimating the extent of snow cover and time-spatial distribution of snow. It is difficult to find out snow depth of beyond 10 to 15 cm, there is virtually no change in the snow reflectance. Microwave range of spectrum needs to be used for deciphering information about snow depth. Measurement in thermal infrared band (10-12μm) can give information about the spatial and temporal variations of the snow surface temperatures. This could be helpful for ablation studies of the snowpack and seasonal variations in the snowmelt runoff. Studies carried out with microwave radiometers in the 19.35 GHZ indicate changes in the brightness temperature for the different stages of ice accummulation.

Pack et al. (1981) examined the ' measurability' (i.e., the technique, resolution,time scale and difficulty) of various hydrologic variables. The snow related variables and their possible use in hydrologic variables. The snow related variables and their possible use in hydrologic modelling as given by him is quite encouraging and is given in table-2.

Table - 2 Remotely Sensed Variables Applicable to Hydrologic Modelling

Variable	Possible Phases of Use in Hydrologic Models for Water Resources Management		
	Calibration	Updating	Inputs
Areal Extent Snow Cover	X	X	X
Frozen Ground			
Non Snow Areas	X	X	X
Under Snow Areas	X	X	X

Pack et al.(1981) also studied amenability of various remotely sensed data to available hydrologic models. It has been observed that the areal extent snow cover measured by remote sensing could be used in CREAMS (Chemicals Runoff, and Erosion from Agricultural Management Systems) and NWSRFS (National Weather Service River Forecast System) snow melt models. Based on recommendation of WMO,Task Force on Water Resources listed the observational requirement of various snow related parameters and the present status of availability of data from various existing satellites (1985). These are given in Table-3.

It transpires that remote sensing techniques suits very much for determining the various parameters of snow. Though the measurement of areal extent of snow is fully established at present, other measurements like snow pack, density, thickness etc. are also becoming more viable to be measured by remote sensing as improved and specially designed sensor are designed and put on-board the satellites. The band 5 of the Thematic Mapper (TM-5) data from Landsat-4 and 5 which are now available with a resolution of 30 m are very useful for the separation of snow from cloud. More valuable and useful information are expected especially in the thermal infrared and microwave portion of the electromagnetic spectrum. These two regions of the spectrum hold quite a hopeful trend for collecting more information about Snow in near future. Installation of Data Collection Platforms (DCP) in a suitably designed network in the Himalayas for snow will also be a big stride and convenience for using remote sensing methods for snow studies.

Table - 3: Observational Requirements for Hydrology

Parameter and its definition	Requirements				Available from satellites	
	scale	Resolution	Frequency	Accuracy	Expected 1980s	Remarks
1	2	3	4	5	6	7
SNOW ON THE LAND						
Snowline: Line separating a region of less than 50% snow cover from a region with more than 50% snow cover	A	30 m	Daily	-	Possible (but not daily) over limited areas only.	In the latter part of the 1980s horizontal resolution will be 20-40 m. Frequency about 2 to 4/18 days for cloud free areas & for limited areas only.
	B	100 m	Daily	-	Possible (but not daily)over limited areas only.	
	C	1000 m	Daily	-	Possible for cloud free areas	Meteorological satellites in cloud free areas have 1000 m resolution.
Snow cover: percentage of a basin or other specific area, in horizontal projection, covered by snow.	A	300 m	Daily	± 5% of snow area	Possible for cloud free areas.	
	B	1000 m	Daily	-do-	-do-	
	C	10000m	Daily	-do-	-do-	
Water equivalent: depth of water that would result if a vertical column of the snow pack of unit cross-section were melted Free-water content: equivalent depth of all the water in the liquid phase contained in a vertical column of the snow pack of unit cross-section	A	100 m	Daily	± 2 mm if < 2 cm ±10% if > 2 cm	Not possible	Passive microwave techniquees could be employed. These techniques require still further research and development,but can be possible in the late 1980s for C-size basin requirements. In situ measurements can be made & collected via satellite data collecation systems, either continuously

1	2	3	4	5	6	7
						within the regions covered by geostationary satellites, or upto 4 times per day from any location on the earth.
	C	1000 m	Daily	±2mm if < 2 cm ±10% if > 2 cm	Not possible	
Snow-surface temperature: equivalent radiating temperature of the top surface snow-pack	A	100 m	6 hourly	± $1^{o}C$	Possible(but not daily) over limited & cloud free areas only.	Currently operational. The horizontal resolution for mapping gradients is 10 km or better. The frequency of observation is variable from 2/day(1 km resolution) to 48/day(10 km resolution) on location.
	B	300 m	6 hourly	± $1^{o}C$	Possible(but not daily) over limited & cloud free areas only.	Measurements are limited by the presence of clouds.
	C	1000 m	6 hourly	-do-	Possible over limited and cloud free areas only.	Research has been carried out to determine surface temperature from satellite measurements of microwave emission. However, the resolution will be very low in the 1980s.
Surface albedo:ratio of the energy reflected to the amount of energy incident over a specified range of wavelengths of the electro-magnetic spectrum (e.g. the visible band)	A	100 m	daily	5%*	Possible over limited areas only.	The requirements can be met, if albedo is defined as the ratio of outward bound radiation to inbound radiation in the wave-length regions in which the sensors are sensitive.
	B	300 m	daily	5%*	-do-	
	C	1000 m	daily	5%*	-do-	

A - less than 100 km^2 B - between 100 and 1000 km^2 C - more than 1000 km^2 * - absolute error

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