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Snow Cover Mapping and Snowmelt Runoff Estimation From Remotely Sensed Data

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Abstract : *Remotely sensed observations of snow cover extent provide useful input for reliable estimates of snowmelt runoff. Snow covered area and snow water equivalent are the properties sensed by remote sensing techniques. Satellite imagery is one of the source for computinq the snow covered area. Airborne gamma ray spectrometry is used for measuring snow water equivalent. Improved estimates of spatial and temporal variation of precipitation for model applications may be obtained by integrating conventional point measurements with remote sensing techniques.*

Several workers have used the remotely sensed data af snow cover area and snow water equivalent for snowmelt estimation. In India also seasonal snowmelt is being forecasted using data of snow cover area and snow water equivalent obtained from satellite imagery and airborne gamma radiation measurements.

Introduction

All the rivers originating from Himalayas are either fed by glacial melt or snowmelt. Snowmelt runoff is an important source of water for hydropower generation and water supply for various uses. It is, therefore, important to estimate the water potential from seasonal snow cover as its contribution to the inflows of all the rivers originating from the Himalayas is highly significant during the months of April to July every year.

The total water equivalent of snow cover depends on (i) surface area of snow cover, (ii) its depth and (iii) average density. Satellite imageries and other remote sensing techniques provide areal extent of snow cover over a catchment periodically.

Remote sensing techniques 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 snowline movement and other characteristics of snow. Problems like location, recognition and measurement in targetting snow and ice are minimum in remote sensing and as such monitoring of snow covered areas by remote sensing could be made automatic and operational.

Amongst the sensors available in the different satellites, Landsat MSS 5 (0 6—0.7 μ m) and NOAA visible data are most suitable. Gamma ray, thermal infrared and microwave portion of electromagnetic spectrum have great potential for snow studies. The data of band 5 of thematic mapper of landsat 4 and landsat 5 satellites which are now available are suitable to separate snow and cloud. The use of remotely sensed data in hydrologic modeling has shown encouraging results. Considering all the available means to decipher or measure snow and ice, the remote sensing methods have definite advantages and could be judiciously used to make snow and snowmelt studies.

Snow and Snowcover

Precipitation in the form of snow occurs in Himalayas during winter months under the influence of east moving extra tropical low pressure systems popularly called western disturbances. Precipitation in the form of snow occurs from October to May in the higher reaches of Himalayas. More than 50% of the annual precipitation is received during winter.

Sesonal snow cover generally builds up by middle of December and persists till the end of June. The snow cover generally reaches its maximum extent cf accumulation by March. The loss of snow cover is caused by settlement, ablation, evaporation and metamorphic changes. The gain of snow cover is due to addition of snow through fresh precipitation or large scale drifting of snow from neigbouring catchments.

Discharge in the mountainous streams during winter is generally low. The stream flows show a maximum during the months of March to May indicating that the snow which has accumulated in preceding months has started melting.

Properties of Snow helpful in Remote Sensing

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 objects. But snow albedo is reduced substantially in the near infrared (0.8—1.1 μ m) 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 μ m (near infrared) in comparison to other substances. This unique property offers an opportunity for automatically separating snow from highly reflective clouds (Barnes et al 1975). The snow that is potentially ready to melt (273°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. Wavelengths longer than 3 cm can go through a dry snowpack and offers an excellent indication about the snowdepth. Because snow has 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 μ m) are most suitable for snow identification because of the strong contrast between snow covered and snowfree areas.

Snow Cover and Snow Water Equivalent

A variety of remote sensing techniques are being investigated to obtain areal estimates of precipitation amount and spatial distribution. Satellite imagery is one of the source for computing the snow covered area (SCA). Satellite imagery from Landsat has a resolution of 30 m but the pictures are only available at intervals of 16 days. Cloud cover over areas of interest can further extend the period between usable images. The Geosynchronous satellites provide images every 30 minutes during day light hours but their resolution is poor. The lower resolution makes discrimination between snow covered and snow free areas difficult under dense forested cover conditions (Shafer, 1985). Snow cover mapping techniques using GOES imagery are currently being used to provide near real time snow cover maps for 184 basins in the western USA (Allen and Mosher, 1986).

Airborne gamma ray spectrometry is a remote sensing technique for measuring snow water equivalent (SWE). The technique uses the attenuation of natural background gamma radiation by snow cover as a measure of the average SWE along a selected line of flight.

The terrestrial gamma ray radiation is observed in snow in comparison to snow free gamma ray measurement. In a typical soil, 96% gamma radiation is emitted from the top 20 cm. After the background radiation and soil moisture are measured over a spectific flight time, the attenuation of the radiation signal due to the snow pack overground is used to calculate the amount of water in the snow.

The technique has been used successfully in the USA (Carroll and Vadnais, 1980), Canada (Carroll et al., 1983), Sweden (Bergstrom and Brandt, 1985) and the Soviet Union (Vershinina, 1985). It has been applied to large open areas with low relief where the areal distribution of snow can be extremely variable.

When satellite images and gamma ray spectrometry measurements are used together, the snowmelt process can be monitored. Satellite images give good information on the location of snow while gamma ray techniques offer good possibilities for determining snow water equivalent values. Kuittinen (1986) determined the springtime areal snow water equivalent values over northern Finland using enhanced digital NOAA images and aircraft gamma ray spectrometry.

Measurement of Snow Covered area by Remote Sensing Methods

To start with, the visual methods are resorted to demarcate snow covered area from remotely sensed data. First attempt was made to qualitatively demarcate the areas of snow cover and classify these areas relatively by using visible band TIROSN and GOES satellite for northern hemisphere. Snow and ice boundaries are marked for areas that are most reflective (moderate snow cover) and least reflective (least snow cover) on 1 : 62.5 million scale charts (Metson and Wiesnet. 1981).

When Landsat data became available, the snowline delineation and measurement of snow covered area from Landsat imagery of 1 : 1 million scale were made and this was found very suitable for snow-mapping for small watersheds. This direct measurement of snow covered area was also made from enlarged Landsat imagery at 1 : 100,000 scale. In case of partial obscurity of snow cover due to trees or shadows, diazo over-exposure technique had been successful to enhance the snowline (Foster and Rango 1975).

The relation between mean snowline altitude and the covered area has always been a useful information for the hydrologists. From a number of imagery (say twenty or more), the mean snowline altitude is derived with the help of a transparent overlay with topographic contours. The mean snowline altitude so determined is converted to equivalent snow covered area using the area-altitude curve for the watershed (Mier and Evans, 1975).

Specially after the prolific availability of useful Landsat data, various optical enhancement techniques were developed and used for delineation of snow covered area. Density slicing of Landsat imagery proved to be rewarding. This separates snow from other features on the basis of a selected reflectance level. This approach essentially indicated to the hydrologists about the possibility of automation in delineation of snow cover area from the remotely sensed data. Automatic snow cover demarcation is possible if a particular reflectance level corresponding to snow/no snow boundary can be fixed. There are chances of committing errors in deciding a slicing level for the entire scene of watershed. Further repetitive slicing of the scene often leads to misclassification. Still, hydrologists used the optical methods for quick snow cover determination in a watershed.

Digital analyses of remotely sensed data opened a new vista for the hydrologists for measurement of snow covered area and the automation of the measurement. Digital analysis is definitely a superior technique. This method analyses individual resolution elements instead of average of several pixels as in the case of optical/visual interpretation. The supervised classification of digital analysis of remotely sensed data is very effective in identifying snow and other snow and ground cover mixture. But the approach is heavily dependent on the accuracy of the ground truth used in training process. Various computer programmes are available for digital analyses. The relatively coarse parallelepiped classifier is sufficient to classify snow though result is slightly less accurate compared to other classifiers available. According to Itten (1973) the computer time for parallelepiped classifier is much less than the maximum likelihood approach and requirement of ground truth data is also less. One of the basic requirement of use of digital analysis is the interpretative skills of the analyst inspite of the fact that the digital analysis for demarcation of snow is automatic. Digital analysis is convenient and yields desired results with accuracy for alarge area.

Because of spectral similarity, separation of clouds from snow has always been a formidable problem. But the differentiation of clouds and shadows from the snow is necessary to have an accurate snow covered area for an acceptable snow melt forecasting.

While studying cloud patterns as seen on TIROS satellite data, Conover (1964) stated that clouds were easily confused by the interpreters with snow cover. Meier (1973) and Barnes and Bowley (1973) pointed out the difficulty in separating clouds from snow on the Landsat data. However, other characteristics in the data (e.g., pattern, configuration etc.) can often be used to advantage to separate cloud cover from snow. As such separation of snow and cloud is relatively easy with analog techniques. A separation based on spectral signatures from Landsat (first three of the series) has become possible after the recent development of software technology. It has been observed that the integration of a band 1.55 to 1.75 μ m in the satellites is a minimum must for snow mapping. Considering this fact, two channels in middle infrared of the spectrum, 1.55 to 1.75 and 2.09 to 2.35 μ m have been provided in Landsat 4 and 5 satellites. The band 5 (1.55 to 1.75 μ m) of the Thematic Mapper (TM 5) data from Landsat 4 and 5 with 30 m resolution are very useful for the separation of snow from cloud. Snow mappers are greatly benefitted with these bands.

A comparison of Landsat data analysis with conventional technique of snow identifier gives striking information and speaks volumes about the suitability of usage of Landsat data for snow studies. The comparison shows that more detail in the snow line can be mapped from Landsat data than by aerial observation. 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 high resolution photography. It has been found that snowline mapping from Landsat image is easier. NOAA-2 VHRR data though of poor resolution offers almost same speed of ease in snow mapping, rather its availability is more timely and ideally suited for very large watersheds.

A cost comparison worked out by Wiesnet and McGinnis (1973) between snow measnrement 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.

Microwave remote sensing is another potential tool to monitor snow. This can be accomplished either by measuring emitted radiation with a radiometer or by measuring the intensity of the return of a microwave measurements having the capability to penetrate the snow and respond to variation in subsurface properties of hydrologic importance. The large contrast between the dielectric properties of water and those of most solids in the factor that makes the use of microwave radiometric techniques important for problems related to water resources (Schmugge, 1980). The dielectric constants of water (1.0), ice (3.2) and snow (2.0) are different enough so that even a little melting causes a strong microwave response. But, because of the complexities in the microwave interactions significantly, more ground information is needed for microwave snow studies than for comparable visible, near infrared studies (Rango, 1985).

Josberger and Beauvillain (1989) made a comparative study of the passive microwave images from the NIMBUS Scanning Multichannel Microwave Radiometer (SMMR) and visual images from Defence Meteorological Satellite Programme of the Upper Colorado River Basin The study indicated that passive microwave satellite imagery can be used to determine the extent of the snow cover.

Snowmelt Modelling using Snow Covered area.

Remotely sensed observations of snow cover extent provide useful input for reliable estimates of snowmelt runoff. Snow covered area (SCA) and snow water equivalent (SWE) are the properties sensed by remote sensing techniques. Some workers have successfully applied SCA for snowmelt simulation.

Zhidikov et al (1976) described of a snowmelt runoff model in which the computation of snowmelt and melt water yield from relatively small subbasins is carried out separately for open and wooded areas. ψ (z) and ψ' (z) are the coverage of snow in the open and the wooded areas respectively as functions of cumulative melt H_s. $Z = H_s/x$ where x is the initial water equivalent of snow cover before the beginning of snow melt.

Seasonal runoff forecasts using sattellite determined SCA were reported by Rango et al (1977). The Snowmelt Runoff Model (SRM) was developed by Martinec (1975) originally for small mountainous watersheds in Europe. The SRM uses SCA data directly without regard to SWE. With the widespread application of satellite data for monitoring snow accumulation the model has been refined for applications to large basins for simulations ranging from a few days to the entire year (Martinec et al, 1983). Daily temperature and precipitation data along with daily snow cover extent are the three basic input variables required for the operation of the model. Whereas temperature and precipitation are routine meteorological observations within and/or outside drainage basins, the extent of snowpack may be accurately determined from satellite observations. In SRM the discharge for consecutive days is determined from the equation :

$$Q_{n+i} = C_n [Ca_n \, (T + \triangle T_n) \; S_n + P_n] \frac{23223200}{86400} (1 - K_{n+1}) + Q_n \, K_{n+1}$$

where

Q = average daily discharge in cu. ft/sec.

C = runoff coefficient

a = degree day factor

T = number of degree days

$\triangle T$ = temperature lapse rate in °F

S = ratio of snow covered area to the total area of the catchment

P = precipitation in inches

A = area of catchment in square miles

n = sequence of days

Shafer et al (1982) carried out research for development of a real time predictive mode version of the Rango-Martinec model to predict mean daily flows due to snowmelt runoff from mountainous watersheds.

Baumgartner et al (1986) developed a method for determining the change of snow cover during snowmelt period using Landsat MSS digital data. This information was used as input to the SRM for estimating snow melt from a large basin (3249 sq. km) in the Swiss Alps.

Snowmelt Modelling Studies in India

Data from Landsat and NOAA satellites are received at the earth stations of National Remote Sensing Agency (NRSA) and at IMD, New Delhi.

Only a few studies on snowmelt modelling have been carried out in India. Mapping of snow covered areas from satellite imagery and using them for snowmelt runotf studies have been attempted by some authors. Indian snowbound watersheds are much larger and at higher altitudes than in countries of northern latitudes.

Thapa (1980) and Bajracharya (1984) used the snow covered area derived from satellite imagery to estimate the snowmelt by degree day approach.

A study 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 area which could form the basis for estimating melt water for long term and short term periods

Gupta et. al., (1982) in their study of Beas catchment concluded that the relationship between snow covered area and snowmelt discharge is affected by morphological characteristics of the catchment. They observed a logarithmic relationship between show covered area and snowmelt runoff.

Ramamoorthi (1984, 1986) carried out studies on snow-melt using a regression model which uses the percentage of snow covered area of Sutlej basin above Bhakra on the basis of NOAA satellite imagerias. Sfnce then the model is being used by the Applications group at the National Remote Sensing Agency (NRSA) for issuing seasonal forecasts of the spring season inflows into Bhakra Reservoir. The flows forecasted by the model are claimed to be within 10% of the actual inflows. The satellite imagery of NOAA covering the snow covered areas over the catchment of Sutlej is shown in figure 1. The results of the snowmelt forecast model developed by NRSA are shown in figure 2.

Concluding Remarks

The areal extent of snow cover is easily measured because of its high reflectance. Automation of snow cover measurement from the remotely sensed data is possible and desirable for operational use. Among the advanced technologies, satellite remote sensing has emerged as a powerful and promising tool for assessment and monitoring of snow cover. However, satellite imagery could not provide any information about either the snow depth or about the water equivalent of snow. Moreover, the spatial resolution of a specific system may not be good enough to detect narrow snow covered ridges or snow free valleys. More valuable and useful information is expected to be available from the thermal infrared and microwave portion of the electro magnetic spectrum. These two bands hold promise for collection of information about snow in the coming years. Passive and active microwave sensors show potential for application to snow-

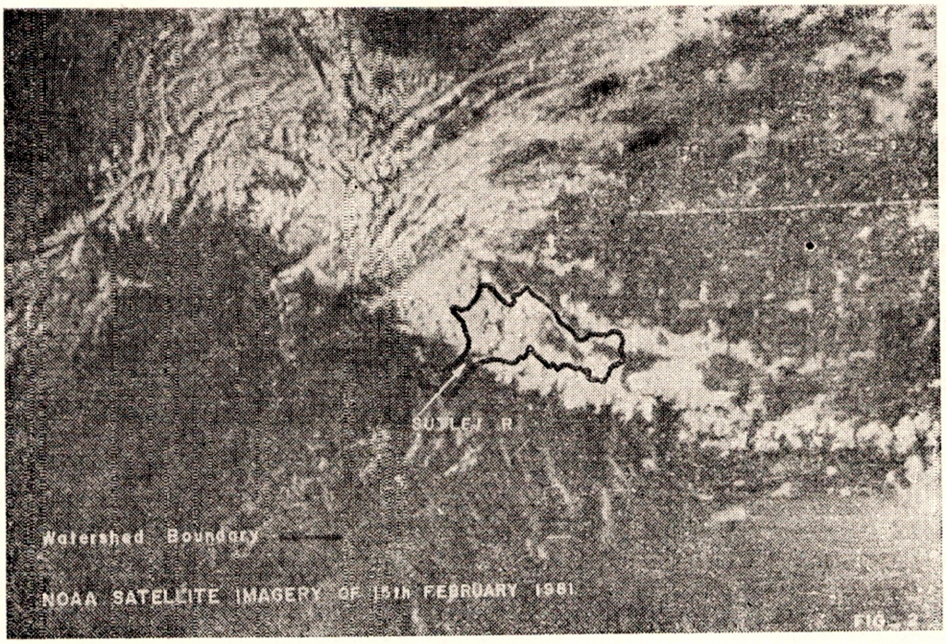

Fig. 1 NOAA satellite imagery of 15th Feb. 1981. (Source : A.S. Ramamoorthi, 1986)

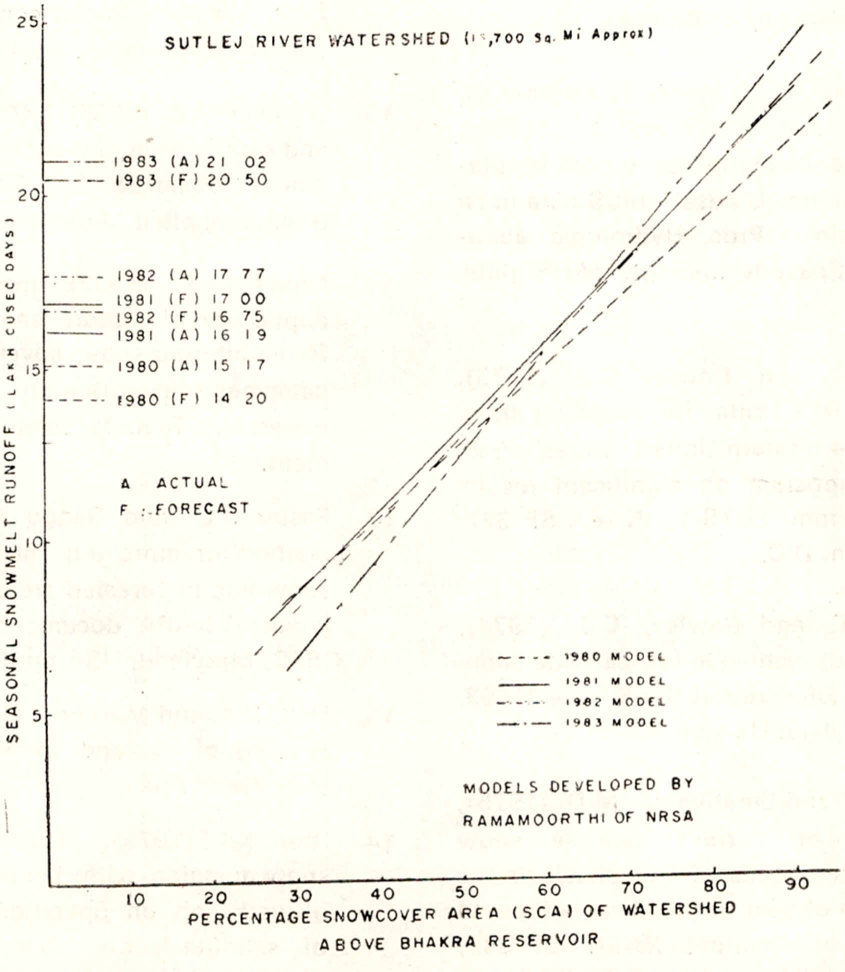

Fig. 2 Seasonal snowmelt runoff forecast model, Sutlej River basin.
(Source : A.S. Ramamoorthi, 1986)

melt modelling. Microwave sensors permit observations during almost all weather conditions. Improved estimates of spatial and temporal variation of precipitation for model appllcations may be obtained by integrating conventional point measurements with remote sensing techniques such as aerial gamma radiation surveys and satellite measurements.

References

1. Allen, M.W. and Mosher R.R. (1986), Monitoring snowpack conditions with an interactive geostationary satellite system Proc. Western Snow Conference Phoenix, Arizona USA pp. 51-60.

2. Bajracharya, A,, (1984), 'A study of snow melt runoff processes M E. dessertation thesis. University of Roorkee.

3. Baumgartner, M.E. Seidel K, Haefner, H. Itten, K.I. and Martinec, J. (1986). 'Snow cover mapping for runoff simulations based on Landsat—MSS data in an Alpine basin'. Proc. Hydrologic applications of Space technology, IAHS publ. No. 160.

4. Barnes, J.C. and Bowley C.J. (1973), 'Use of ERTS data for mapping snow cover in the western United States' Proc. of the symposium on significant results obtained from ERTS-1, NASA-SP-327, Washington, D.C.

5. Barnes, J.C. and Bowley, C.J. (1974). Handbook of technique for satellite snow mapping' Final report NASA 5 – 21803, NASA Maryland USA pp. 95,

6. Barnes J.C. and Smallwood M.D. (1975), 'Symposia of current satellite snow mapping techniques with emphasis on the application of near infrared data Proc. of Workshop observations NASA - SP 341, pp. 199.

7. Bergstorm S. and Brandt M. (1985), 'Snow mapping and hydrological forecasting by airborne gamma ray spectrometry in northern Sweden' Proc. Hydrological applications of Remote sensing sensing and Remote data Transmission' IAHS Publ No. 145 pp 421-428.

8. Carroll, T.R. and Vadnais K,S. (1980), 'Operational airborne measurement of snow water equivalent using natural terrestrial gamma radiation. Proc. Western Snow Conference Laramie, Wyoming USA pp 97 – 106.

9. Carroll T.R., Glynn, J.E. and Goodison, B.E. (1983), 'A comparison of US and Canadian air borne gamma radiation snow water equivalent measurements', Proc. Western Snow conference. Vancouver, Washington, USA pp 27 - 37.

10. Conover, J.H. (1964). 'The identification and significance of orographically induced clouds observed by TIROS satellites' Journal applied Meteorology. Vol. 3.

11. Dhanju M.S., (1982) Investigation in the application of remote sensing techniques for monitoring snow cover in Himalayan catchments contributing melt water to Reservoir' Remote sensing of environment.

12. Foster, J.L., and Rango A., (1976). 'A method for improving the location of the snow line in forested areas using satellite imagery' NASA document X-910-75-211, GSFC, Maryland, USA pp 8.

13. Hall, D.K. and Martinec, (1985), 'Remote sensing of ice and snow' Chapman and Hall, New York.

14. Itten, K I., (1975), 'Approaches to digital snow mapping with Landsat data' Proc. of workshop on operational applications of satellite snow cover observations, NASA, SP-391, pp 235-247.

15. Josberger, E.G., and Beauvillian, E., (1989)' Snow cover of the Upper Colorado river basin from satellite passive microwave and visual imagery. Nordic Hydrology, Vol. 20., No. 2., pp 73-84.

16. Kuittinen, R., (1986), 'Determination of areal snow water equivalent values using satellite imagery and aircraft gamma ray spectrometry. Proc. Hydrologic Applications of space technology, IAHS Publication No. 160.

17, Martinec, J., (1975) 'Snowmelt runoff model for stream flow forecasts, Nordic Hydrology, Vol. 6, pp. 145 - 154.

18. Martinec, J., Rango, A., and Major, E. (1983), 'The snow melt runoff model (SRM) User's Manual, NASA Ref. Pub. 1100, pp. 110.

19. Meier, M.J., (1973), 'Evaluation of ETRS imagery for mapping and detection of changes of snow cover on land and on glaciers' Proc. of symposium on significant results obtained from ERTS-1, NASA-SP-327.

20, Meier, M.J. and Evans, W.E., (1975), 'Comparison of different methods for estimating snow cover in forested, mountainous basins using Landsat (FRTS) images Proc. of workshop on operational applications of satellite snow cover observations, NASA pp 215-360.

21. Rango, A.. Salomonson, V.V. and Foster, J.L., (1977), 'Seasonal Stream flow estimation in the Himalayan region employing meteorological satellite snow cover observations. Wat. Res. Vol. 13, No. 1, pp. 109-112.

22. Rango, A., (1985), 'A survey of progress in remote sensing of snow and ice. IAHS Publ. No. 145.

23. Ramamoorthi, A.S., (1984), 'Snow melt runoff stodies using remote sensing data' in Remote Sensing (Ed) B.L. Deekshatalu and Y.S. Rajan. Indian Academy of Sciences, pp 185-192,

24. Ramamoorthi. A.S., (1986), 'Forecasting snowmelt runoff of Himalayan rivers using NOAA AVHRR imageries since 1980' Proc. Hydrologic applications of Space Technology, IAHS Publ. No. 160.

25. Schmugge, T., (1990), 'Techniques and applications of microwave radiometry' Remote sensing in Geology John Wiley, New York.

26. Shafer, B., (1985), 'Integration of SNO-TEL data and remotely sensed snow covered area in water supply forecasting Proc. International Symposium on Remote sensing of Environment. Ann Arbar, Michhigen, USA pp 1045-1056.

27. Thappa, K.B., (1980), 'Analysis for snow melt runoff during pre-monsoon months in Beas basin usingsatellite imageries' M.E. Desertation, University of Roorkee.

28. Vershina, L.K., (1985), 'The use of areal gamma surveys of snowpack for spring snowmelt runoff forecasts' Hydrological applications of Remote sensing and Remote data transmission, IAHS Publ. No. 145.

29. Wiesnet, D.R., and McGinnis, D.F., (1973) 'Snow extent mapping and lake ice studies using ERTS - 1 MSS together with NOAA - 2 VHHR', Proc. of the third Symposium on Earth resources Technology satellite - 1 NASA SP - 351, pp. 295 - 1009,

30. Zhidikov, A.P., Levin. A.G.. Nechaeva, N.S. and Popov, E.G., (1976), 'A snowmelt runoff model and its application to short range forecasting of flood discharges' Hydrological Sciences Bulletin, Vol. 21, No. 3.