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REMOTE SENSING APPLICATIONS IN HYDROLOGY

STATUS REPORT
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PREFACE

Water is the most precious gift of nature. The need for proper planning in development, management and optimal utilisation of this vital resource is paramount for the economic development of the country. India's water resources are finite and greatly diversified in space and time. Agriculture is often at the mercy of weather gods, added to these, remorseless floods and droughts, low efficiency of irrigation systems, waterlogging and salinity in command areas, accelerating land degradation, alarming rate of reservoir sedimentation, deteriorating water quality and environment etc. are some of our problems concerned with management and monitoring of water resources. All these are required to be tackled carefully through systematic approaches involving judicious mix of conventional methods and new efforts like remote sensing for optimum productivity and use.

Various hydrologic data and water resources information in our country, including data on soil and land resources required for various activities in water resources are not being collected and maintained at one place or available with one organisation. For remote and inaccessible areas, the existing system of water resources information generation is tedious, time consuming and difficult. Under the circumstances, remote sensing technology can be gainfully used for surveying and monitoring of water resources.

It is contemplated that there is ample scope for the application of remote sensing in the assessment of various components of hydrologic cycle. In the fields of snow hydrology, watershed conservation, command areas planning, groundwater exploration, flood estimation and forecasting, water quality monitoring etc., through fairly reliable, reasonably accurate, incredibly faster and near-real time data acquisition, remote sensing with conventional data would be able to provide best management practices and facilitate efficient monitoring. However, remote sensing is not an immediate panacea to all problems in water resources. It is complementary to conventional data.

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1.0 INTRODUCTION

Water, the elixir of life is one of the best of all things that have happened to the human being. Throughout the history of mankind, great civilizations have flourished only where water has been loved as a caring mother, respected as a powerful enemy and treated and managed as a store house of treasures. History equally records pathetically that whenever this life liquid was neglected of its proper conservation and management, the humanity heavily paid for it. Buried and vanished civilizations bear ample testimony to this. Consequently, the need for planning, conservation, optimum utilisation and management of this precious resource is paramount for the economic betterment of a country. Therein lies a great challenge in the best use of available water resources vis-a-vis looming shortages to best meet the myriad needs of the thronging population, burgeoning economic ambitions, demanding agriculture, expanding urbanisation, increasing industrialisation and other causes. The demand for water has become more exacting and hence water in all its forms and occurrences should be harnessed properly and husbanded judiciously.

India's water resources are finite and greatly diversified in space and time. India is blessed with an average annual rainfall of about 119.4 cm. This rainfall when considered over the geographical area of 329 M ha amounts to 392 M ha m. This may be rounded off to 400 M ha m including snowfall whose potential is not yet fully recorded. Out of this, about 70 M ha m is lost to atmosphere as evaporation, about 115 M ha m flows as surface runoff and the remaining 215 M ha m infiltrates into the ground. The total surface water resources of India have been assessed at 180 M ha which includes about 20 M ha m brought in by streams and rivers from catchments lying outside the country and about 45 M ha m regenerated from ground water. Direct contribution by precipitation is 115 M ha m of which about 10 M ha m is received as snowfall. Estimated utilisable potential from surface water is 88 M ha m and from ground water is 42.13 M ha m on full development. Present utilisation from surface water resources is 28.5 M ha m and from ground water resources is 13.5 M ha m .

Lack of adequate, accurate, reliable and timely data poses great hindrance in proper water resources planning, conservation, management and effective utilisation. Surveying and inventorying of water resources using conventional ground survey methods are tedious, time consuming and impractical especially for remote, inaccessible and inhospitable areas. These methods are less cost effective because of the high density of control points required by them.

Remote Sensing, defined as sensing of objects without touching, could be a sophisticated tool for surveying through synoptic scenes being opened from aerial and space platforms. It seems to provide a shot in the arm by either substituting or complementing or supplementing the conventional technology with reasonably faster, efficient and accurate methods of survey and inventory in the domain of water resources planning, conservation, development, management and utilisation. Its application culminates in harnessing the information about natural resources with incredible speed and reasonable accuracy, it stands unique in respect of its use in collecting meaningful data from remote and inaccessible areas, it renders information on natural resources from aerial and orbital platforms through its three attributes: spatial (synoptic large area coverage), spectral (data at various wavelengths) and temporal (repeat coverage at various times). Synoptic view facilitates study of objects and their relationships. Spectral signatures permit identification of various features. Temporal aspect allows change detection in environment. An attendant bonus is the real-time measurement that facilitates constant and effective monitoring.

The science of remote sensing has given the hydrologist a capability of measuring very important parts of the hydrologic cycle. The ability to measure the state of the surface over large areas, whether soil moisture or snow or the surface energy balance really distinguishes remote sensing from conventional data collection. In case of natural disasters, remote sensing can offer prior information or forecasting the consequences and savings of lives. Remote sensing with the conventional data would be able to provide best practices and facilitate proper monitoring in the fields of snow hydrology, river morphology, reservoir dynamics and sedimentation, watershed conservation, command area planning, flood estimation and forecasting, water quality and drought monitoring, environmental protection, national water plans and developments of irrigation projects in remote areas through fairly reliable, reasonably accurate and incredibly faster data acquisition.

Remote sensing through speedier data collection and transmission would help improve the exactitude of water resources assessment, thus facilitating quick decisions in management that may result in considerable economic and financial gains. Especially in automation of collection and transmission of some hydrologic data such as river stage, rainfall, snow cover area etc. under adverse circumstances in remote uninhibited areas, remote sensing would greatly minimise the ground work. And above all, compared to the conventional field surveys that differ from one region to another, remote sensing offers some common universal methodology for the study of earth resources on global basis.

Snow in hydrology as a renewable reservoir represents one of the most complicated parameters to measure with. Awareness and knowledge of snow resource is essential for appreciating the various problems of water resources management. We have a total area of about 600,000 sq.km which is snow bound for most of the winter period. The Himalaya, stretching west to east for a length of 2500 km and over a width of about 250 to 400 km is the home for several glaciers . Nineteen major Himalayan rivers flow from these perennial ice masses. During summer months, the major contribution to those rivers are by snow melt runoff. Periodic snow monitoring is essential in assessing the snow melt runoff as this would be useful in the planning of water resources management. Unlike in many other countries, where snow fields stretch for miles and miles along flat terrain and where mountains are easily approachable, the snow bound land in our country is mostly in difficult mountainous terrain. The impregnable heights, the inhospitable conditions and the inaccessibility of the area creates many problems in assessing snow water resources by conventional methods.

With the availability of satellite imageries, it has become possible to obtain information about the snow covered watersheds in Himalayas and attempt snowmelt runoff studies. The aerial extent of snow cover, elevation of the snowline in mountainous areas, ablation of snow cover due to rain-on-snow events or rising temperatures, identification of wet snowfalls and snow depth to an extent are some of the features that have been reported to be recognised in satellite imagery. Satellite data can provide to obtain near real-time snow cover maps for the computation of snow melt runoff. Satellite derived snow cover assessment is being extensively used as an important input in snowmelt runoff prediction models to assist in multipurpose reservoir operations. It has been shown that satellite remote sensing has the capability to give snow cover area (SCA) estimates with an accuracy of 93 % or better, also accurate positioning of snowline is possible.

In the present study, a brief status of applications of remote sensing with regard to various aspects of hydrology has been discussed. Uses of remote sensing in various water resources management practices has been described. One complete chapter has been presented for the applications of remote sensing in snowmelt runoff estimation. A detailed list of publications has been given at the end for reference purposes.

2.0 GLIMPSES OF REMOTE SENSING

2.1 BASIC PRINCIPLES OF REMOTE SENSING

Remote sensing is defined as the science and art of acquiring information about objects from measurements made at a distance without any physical contact with the objects. These measurements could be reflectance/emittance, acoustic soundings or geomagnetic surveys etc. The most commonly measured variation in remote sensing is reflectance/emittance (electromagnetic variations). Three important type of variations which form the basis for deriving information about objects are:

Spectral variation - The changes in the intensity of reflected/emitted radiation with wavelengths i.e. different objects reflect/emit radiation of different intensities at different wavelength.

Spatial variations - The changes in radiation with location i.e. difference in shape and position.

Temporal variations - The changes in radiation with time i.e. differences over time.

In order to derive information from these variations one has to measure variations and relate these measurements to those of known objects.

The electromagnetic spectrum is the basis for all remote sensing which takes advantage of the unique interaction of radiation from the specific regions in the spectrum with the earth. Radiation source most commonly exploited is Sun. Other commonly used radiation source is radar in which energy from a limited region of the EM spectrum is propagated towards the earth and the reflected or back scattered energy is measured.The transmission path of the electromagnetic radiations is atmosphere. Specific gases in the atmosphere selectively affect the amount of energy that is transmitted and this leads to a concept known as atmospheric window. An atmosphere window is a wavelength band in which the atmosphere has little or no effect on the intensity of the sun's radiation or reflected radiation from the earth. Good atmospheric windows are available in the wavelength range from 0.3-0.75µm (UV and Visible region), 0.77-0.95µm (Near Infra Red region); 1.0-1.12µm, 1.19-1.34µm, 1.55-1.75µm, 2.05-2.4µm (Short Wave Infra Red region); 3.5-4.16µm, 4.5-5.0µm, 8.0-9.2µm, 10.2-12.4µm, 17.0-22.0µm (Middle and Thermal Infra Red region); 2.06-2.22mm, 7.5-11.5mm, 20.0mm + ahead (Microwave region). That is why all remote sensing satellites receive data within these spectral ranges. The type of sensor is perhaps the only characteristic over which the user has some control. Careful matching of the sensor to the problem can ensure that the results of the study will be useful and easily quantifiable. Commonly used sensors are:

(a) Gamma radiation: Gamma radiation remote sensing is based on the attenuation of natural terrestrial gamma radiation by soil water or a layer of snow. The general procedure is to determine a background measurement for no snow or dry snow conditions. A subsequent measurement in the presence of snow or increased soil moisture will cause an attenuated flux which can be related to snow water equivalent or change in soil moisture.

(b) Aerial photography - This image oriented system is one of the oldest and very popular. It uses photographic camera and record the data on a film. Advances in photography and films have led to the capability of making images in parts other than the visible range of the EM spectrum also. The aerial cameras are normally used to acquire data which view the area below the aircraft for taking pictures. Data can also be obtained at various resolutions or scales depending on the purpose. The photographs obtained by this technique are interpreted visually. Consequently, the data analysis is slow and laborious.

(c) Multispectral scanners - These instruments measure the spectral reflectance in narrow wavelength bands and record the information numerically. This technique involves measuring simultaneously the spectral response of the landscape in two or more narrow wavelength bands of the EM spectrum. Multispectral classification of the data is then used to discriminate objects based on their characteristic reflectances. The data obtained through scanner are stored on magnetic tapes in digital format. Landsat (MSS) and IRS satellites have four spectral bands while Thematic Mapper of Landsat have seven bands. The advantage of this technique over photographic methods is that data can be analyzed rapidly and sophisticated analysis and classification techniques are possible . Examples of use of multispectral data are to estimate land cover, land use, vegetation biomass, soil type , vegetation type, snow cover , water area, impervious area and various water quality parameters.

(d) **Thermal sensor** - These sensors directly measure the emitted thermal energy from the earth surface. In general, thermal sensors are used to measure variations in temperature across the landscape. Examples of the use of thermal data are to estimate evapotranspiration, soil moisture, groundwater seepage zones, canopy temperatures etc.

(e) **Microwave sensors** - Microwave remote sensing can directly measure the dielectric properties of the earth surface which ir turn is strongly dependent on the moisture content. Similar relationships exist for snow. The physical relationships between moisture, dielectric properties and microwave response together with the ability of microwave sensors to penetrate cloud cover make them a useful all weather sensor. These can be both active and passive type. The active sensors like SAR carry their own illumination source that transmit a radar beam to the ground and detect the reflections from the ground objects . Passive sensors receive EM radiations emitted from the ground objects. Examples of use of microwave data are to estimate soil moisture, vegetation type, snow water equivalent, condition of snow pack, frozen soil and sea ice etc.

2.2 REMOTE SENSING SATELLITES

The satellites in the space are capable of providing stable platform with distortion free images covering a larger area under uniform illumination condition to facilitate easy recognition of major features of the earth surface. Since satellites orbit around the earth, with the rotation of the earth as added advantages, it is possible to obtain repetitive coverage at periodic intervals under different seasonal and illumination conditions. Based on the purpose and objectives, the satellites are classified into:

1. Weather satellites/meteorological satellites (Metsat) - TIROS-N/NIMBUS, NOAA, INSAT-1D
2. Remote sensing satellites - LANDSAT, SPOT, IRS, ERS
3. Marine resources satellites - SEASAT, MOS
4. Specific purpose oriented satellites - RADARSAT, SPY satellites

Another type of classification which is common with the satellites system is based on their oribital characteristics. Example: Polar orbiting satellites and Geostationary satellites, Polar orbiting satellites circles around the earth from north to south and the orbit is near polar. Most of the Remote sensing satellites are of this nature which facilitates easy scanning of the earth surface at periodic intervals. Example: LANDSAT, SPOT, IRS, NOAA, etc. The geostationary satellites are positioned in the space in such a way that the satellite orbit is synchronised with the speed of the earth resulting in continuous observations of the same spot of the earth. Example: GOES, INSAT -1D

The early space photography from Gemini and Apollo missions and the expanded activities of satellite for meteorology and communication has provided great impetus for the planning of first unmanned satellite to observe and monitor the earth resources. Features of some remote sensing satellites are described below:

2.2.1 Landsat satellites

As a result of intensive research and development, the first Earth Resources Technology Satellite (ERTS-1) was launched in 1972 by NASA, USA which was later renamed as LANDSAT-1. The LANDSAT-2 and LANDSAT-3 were launched in 1975 and 1978 respectively and currently these satellites have ceased to be functional. These satellites were near polar orbiting, designed for collection of remote sensing data from an altitude of about 900 km. These satellites were crossing equator every 103 minutes circling the earth 14 times each day as the earth revolves beneath it. These satellites were sun-synchronous and repeated its coverage on any specific point of the earth's surface at a constant local suntime of about 9.30 AM every 18 days. The Landsat-1, 2 and 3 carried three types of data acquisition systems - RETURN BEAM VIDICON (RBV) camera or Television systems, MULTISPECTRAL SCANNERS (MSS) and a data collection system (DCS) to relay environmental data from ground based data collection platforms.

The MSS system had four channel multispectral scanner employing an oscillating plane mirror. The scanning length was approximately 185 km right angle to the orbit trajectory. This system carried four selected channel in Green (0.5-0.6µm), Red (0.6-0.7µm), Near IR (0.7-0.8µm) and (0.8-1.1µm) which were known as BAND 1, 2, 3 and 4 respectively. These satellites using the above scanner continuously scanned the earth surface. However, for convenience of handling the data they were processed into a format covering an area of 185 x 185 km. Orbit forward overlap between consecutive Landsat images is approximately 10% and the sidelap between adjacent orbit range from 14% at the equator to 85% at 80 latitude.

Following the Landsat 1, 2 and 3, Landsat 4 and 5 were launched in 1982 and 1984 respectively. The Landsat 4 and 5 are the second generation satellites currently orbiting at an altitude of approximately 700 Km above the earth's surface with a repetitive coverage of every 16 days. A high resolution new sensor THEMATIC MAPPER was also provided in these satellites. The resolution of MSS of Landsat 4 and 5 are same as that of Landsat-1 , 2 and 3. However, the spatial resolution of thematic mapper is of the order of 30 m except for the thermal band which has a resolution of 120 m.

The Multispectral data obtained from these satellites can be interpreted and analysed using both visual and computer aided techniques. For visual interpretation band separated MSS data in black and white format and false colour composite derived from the combination of band 1, 2 and 4 with appropriate colour filters (Blue, Green, Red) are commonly used. In case of thematic mapper false colour composites are generated from band 2,3 and 4. For computer aided analysis data recorded on computer compatible tapes (CCT) are used.

2.2.2 Indian Remote Sensing Satellites

In India, Department of Space is engaged in space research activities during the past decades. One of the off shoot of space activities is the design, development and management of Remote Sensing satellites. The first Indian experimental satellite for remote sensing, designed and developed by Department of Space was BHASKARA-1, launched from Soviet Cosmodrome in 1979. The second satellite, named BHASKARA-II was launched in 1981. These satellites were placed at an altitude of 525 km with circular orbiting characteristics carrying sensors composed of two television cameras and three microwave radio meters. Parallelly, ROHINI series of satellites, designed and fabricated by the

Department of Space were also launched during 1981 and 1983. The experience gained with the launching of experimental satellites such as BHASKARA and ROHINI has given enough confidence to design and develop Indian Remote Sensing satellite (IRS). The IRS-1A which is a representative of the first series of Remote Sensing satellite for resources survey and monitoring was launched on March 17, 1988. This satellite is sun-synchronous, polar orbiting at an altitude of about 900 Km. with a repetitive cycle of 22 days with equatorial crossing time of 10:00 AM. This satellite is expected to carry a payload consisting of one low resolution (72.5 m) and two medium resolution (36.25m) LINEAR IMAGE SELF SCANNING cameras utilizing solid state linear arrays operating with a "PUSH BROOM' scan mode. The multispectral data in the IRS-1A system is collecting data in four different spectral regions ranging from 0.42 m to 0.86 m. The spectral bands chosen in IRS-A are closer to those of the first four bands of thematic mapper in Landsat-5 and also those provided in the French remote sensing satellite, Spot. Second Indian remote sensing satellite IRS-1B was launched in August, 1991. The life of IRS-1A was to expire in 1991. So IRS-1B was launched as a complimentary to IRS-1A. However, IRS-1A is still working. Various spectral and orbital characteristics of IRS-1B are similar to that of IRS-1A. For acquisition, storage, retrieval, evaluation, dissemination and training for utilization of IRS data, NRSA has been identified to play the key role.

2.2.3 Spot satellite

The French Remote Sensing satellite (SPOT) currently in orbit was launched in February, 1986. The SPOT is designed to carry two High Resolution Visible (HRV) cameras which use charge coupled device (CCD) array as sensing element and collect data on continuous basis every 26 days. Each of these cameras can operate either in multispectral or panchromatic mode. The data in multispectral mode are collected in three spectral bands viz., 0.50-0.59 µm, 0.61-0.69µm and 0.79 - 0.90µm with a ground resolution of 20 m. The data on panchromatic mode are collected in black and white in the spectral range of 0.51 - 0.73 µm with a ground resolution of 10 m. The swath width of the camera is 60 Km at nadir viewing and the camera can be tilted to provide stereoscopic coverage.

The relevant characteristics of some of the past, present and future satellites are described in Table following this chapter. The spectral definition and utility of various bands is given in subsequent table.

2.2.4 Metsat

Meteorological satellite which can provide weather data over the globe. Meteorological polar orbiting satellites, comprise series of Tiros-N/Noaa-A to G. Currently , NOAA-10 and 11 from the two meteorological satellite system are providing meteorological data at regular intervals. Noaa-10 scans the global surface for weather data at 03:30 Hrs and 15:30 Hrs with a swath width of 3000 km and noaa-11 scans similarly at 07:00 and 19:30 Hrs. The primary objective of these satellites is for understanding the weather phenomena and the data can also be used in conjunction with other remote sensing data for improving interpretation.

2.2.5 Earth Resources Satellite(ERS-1)

This satellite of European Space Agency is principally meant for ocean observation carrying sensors related to Synthetic Aperture Radar (SAR) with a resolution of 20 m.

2.2.6 Radarsat

A joint venture of UK and Canadian satellite planned mainly to study ocean currents and ice flows. It will carry Synthetic Aperture Radar with complimentary optical sensors.

In view of the fact that all the satellites described above orbit at more than 700 km above the earth, all the data gathered have to be telemetered to the earth. The signals are recorded at ground receiving stations capable of accepting the very rapid data flow generated by the satellite sensors. Once the signals have been recorded on magnetic tape, they can be re-recorded in a computer compatible format for use on conventional or special purpose computer systems.

The tapes can also be played back in a system similar to video tape recorder in which the data are made into pictures on photosensitive materials. In India, National Remote Sensing Agency has built up a ground receiving station to acquire the satellite data at Shadnagar.

2.3 ADVANTAGES OF REMOTE SENSING

Remote sensing data both in image and digital format is utilised in deriving information about resources adopting either visual interpretation techniques or computer aided analysis. Using ground truth, the remote sensing data are analysed, interpreted and maps related to resources are generated. Remote sensing is capable of carrying out fast and repetitive inventory, mapping and monitoring of resources. Some of the advantages of remote sensing over conventional methods are as follows:

(i) Speed of operation - One of the main advantages of remote sensing is that great savings can be made in the length of time which personnel spend in the field. Although it is essential that accurate ground measurements must always be taken during any remote sensing exercise as a reference control to the sensed data, this saving in time is most marked in the distributional mapping of surface features. In addition to speed, remote sensing has opened up new boundaries in the detection of previously unplotted hydrological features. For example, the use of airborne infrared line scanners enables water surface temperatures to be detected.

Coastal fresh water intrusion can be located and groundwater inflows in lakes and river beds can be detected.

ii) Measurement accuracy - The major advantage of many types of remote sensing data, especially when in the form of imagery, is the ability to achieve higher degree of cartographic accuracy. It is possible to enhance the boundaries of features under observation. For example, in the near infrared part, the boundary between water features and land is greatly enhanced as a result of their differential reflectance in this wavelength region. In addition to the accurate location of features using remote sensing, methods are available to enable measurements of their condition. However, the precision of remotely sensed measurements is generally poorer than those of ground based instruments but by using these measurements in conjunction with suitable ground control can increase the overall accuracies.

iii) Sampling frequency - Conventional measuring techniques rely on accurate point readings such as snow depth or rainfall depth and attempt to interpolate between these points when distributional estimates are required. With remote sensing techniques, the precision of measurement may be inferior but the possibility of inaccuracies resulting from unrepresentative sampling is reduced by increasing the number of measurements taken over a given area . Generally, where variable hydrological parameters are being sampled, an overall increase in accuracy results from the use of remotely sensed data.

One area in which remote sensing generally cannot match the performance of ground based instrumentation is in frequency of observation. While ground based instruments can be set to record at almost any desired frequency, the frequency of observation of aerial remote sensors is largely governed by the capabilities of their platform.

iv) Data processing - Considerable efforts are required to process conventional hydrological data as measurements are often recorded on paper charts. Groundsurveys consist of masses of measurements and observations. Remote sensed data is normally produced in a form which is much more conducive to computer handling. Direct computer processing is often possible for interpreting and classifying this type of data.

v) Cost effectiveness - Information or data obtained using remote sensing techniques comes to be highly cost effective in comparison to conventional techniques for variables which are distributed in space. This may not be the case for single point measurements.

vi) Feasibility aspects - Some areas such as vast snow covered mountains, thick forest areas etc. may not be accessible to ground surveys. Information about such areas can easily be obtained using remote sensing techniques.

Details of some current Remote Sensing Satellites

	Multispectral Scanner (LANDSAT 1,2,3)	Thematic Mapper (LANDSAT 4,5)	HRV (SPOT)	Linear Imaging Scanning Sensor (IRS-1A & 1B)
Organisation	NASA(USA)	NASA(USA)	CNES(FRANCE)	DOS(INDIA)
Launch date	1972,75 & 78	1982 & 84	1986	1988, 91
Spectral bands(µm)	0.5 - 0.6 0.6 - 0.7 0.7 - 0.8 0.8 - 1.1 LANDSAT 3 only 10.4 -12.6	0.45 - 0.52 0.53 - 0.61 0.62 - 0.69 0.78 - 0.91 10.42 -11.66 2.08 - 2.35	0.50 - 0.59 0.61 - 0.68 0.79 - 0.89 Panchromatic band 0.51 - 0.73	0.45 - 0.52 0.52 - 0.59 0.62 - 0.68 0.77 - 0.86
Linear resolution (m)	80 Thermal (IR) 240	30 Thermal (IR) 120	Multispectral 20 Panchromatic 10	LISS I 72.50 LISS II 36.25
Orbit repeat period	18 days	16 days	26 days (5 day revisit capability)	22 days
Mean altitude	918 km	705 km	832 km	904 Km
Swath width (Nadir)	185 Km	185 km	2 x 60 Km pointable across track (+/- 400 Km)	148 Km(LISS I) 2x74Km(LISS II
Equatorial crossing time	9:30 Hr	9:30 Hr	10:30 Hr	10:00 Hr

Spectral definition of different bands in the current Remote Sensing satellites

Band	Spectral Region (in micro meters)	Utility
i) LANDSAT (MSS):		
4	0.5 - 0.6	Useful in delineation of areas of shallow water such as shoals, reefs etc. determination of turbidity in water.
5	0.6 - 0.7	Useful for defining cultural and topographic features.
6	0.7 - 0.8	Emphasises vegetation boundary between land and water and landforms
7	0.8 - 1.1	Provides the best penetration of atmosphere haze, effective for land and water delineation
ii) LANDSAT (THEMATIC MAPPER)		
1	0.45 - 0.52	Bathymetry in less turbid waters, soil vegetation differences deciduous/coniferous differentiation soil type discrimination
2	0.52 - 0.61	To measure visible green reflectance peak of vegetation for vigor assessment
3	0.63 - 0.69	Chlorophyll absorption band important for vegetation discrimination
4	0.76 - 0.90	Useful for determining biomass content and for delineation of water bodies.
5	1.55 - 1.75	Indicative of vegetation moisture, useful for differentiation of snow from clouds
6	10.4 - 12.5	Useful in vegetation stress analysis soil moisture, discrimination thermal mapping
7	2.08 - 2.35	Useful for hydrothermal mapping and for discriminating rock
iii) IRS		
1	0.45 - 0.52	Shallow water mapping, soil/vegetation differentiation forest species differentiation, geological applications
2	0.52 - 0.55	Green reflectance of healthy vegetation
3	0.62 - 0.68	Chlorophyll absorption for plant species differentiation
4	0.77 - 0.86	Biomass survey water body delineation

3.0 REMOTE SENSING APPLICATIONS IN HYDROLOGY

3.1 MEASUREMENT OF HYDROLOGICAL VARIABLES USING REMOTE SENSING

The nature of the hydrological cycle is such that changes in hydrological variables occur over a wide range of space and time scales. The commonest example of this occurrence is atmospheric precipitation. Other influential factors such as soil moisture and evaporation etc. tend to be less variable than precipitation Catchment characteristics such as area and mean slope do not change for most purposes.Thus hydrological studies require accurate mapping of the relevant static physical features within an area followed by the statistically acceptable sampling of parameters which are subject to change. Remote sensing can often be useful in fulfilling or aiding both of these measurement requirements. The following section describes how remote sensing techniques can be used to measure the hydrological variables:

3.1.1 Precipitation

As precipitation is the input to the hydrological cycle, it is vitally important to quantify it accurately. Determining the spatial and temporal depths of precipitation input to the earth is necessary for everyday management of water resources such as rivers and reservoirs, irrigation, weather forecasting and predicting snowmelt runoff. Raingauge generally provides a fairly accurate measure of point rates and depths of precipitation but the major shortcoming of this instrument is that the measurement is only at a point though the rainfall varies greatly both in time and space from the shortest and smallest scales upwards. Recognizing the practical limitations of raingauge , hydrologists have increasingly turned to remote sensing as a possible means for quantifying the precipitation input to the globe.

Radar is an active microwave remote sensing system operating in the 1mm - 1m wavelength region of EM spectrum. A pulse of electromagnetic energy is transmitted as a beam which is partially reflected by cloud or rainfall back to the radar. The area of measurement of ground based radar is limited to a circle with a radius up to about 100 km (Schultz, 1989). A recording raingauge is desirable for calibration. Rain rate can be estimated as

$$Z = a R^b$$

Where Z is the measured radar reflectivity and a and b are calibration parameters. The important applications of radar remote sensing in rainfall monitoring (Barret and Curtis, 1982) are:

i) radar systems are capable of providing real time estimates of rainfall intensities over selected areas.

(ii) radar has a unique capability to observe the areal distributions and estimates of rainfall amounts.

Generally wavelengths of 5-10 cm with beam width less than 2x are recommended for precipitation measurements. Wavelengths less than 5 cm are considered unsuitable for ·rainfall but useful for delineating very light rainfall, drizzle and cloud forms (Linsley et al.,1982) . Conjunctive use of radar and raingauges can yield more accurate aerial averages.

The operational use of radar for rainfall monitoring is extremely limited due to smaller range and is costly and requires sophisticated technical expertise. With the advent of satellites, it has become possible to obtain spatially continuous and homogeneous data over large areas including oceans in near real time. Also satellite monitoring of rainfall greatly simplifies data management and processing requirements compared to radar and raingauge networks. For all these reasons, the mapping of rainfall using satellite data, though they relate only indirectly to rainfall estimation and monitoring, is gaining much attention in recent years.

The use of satellite data for estimating rainfall is mainly based on relating brightness of clouds observed on imagery to rainfall intensities. Several satellite based methods are capable of producing mean cloud maps or other forms of time averaged cloud displays. Identification of rainbearing clouds from satellite imagery makes it possible to forecast rainfall. All portions of the spectrum can be used to attempt observations of precipitation. The results obtained from visible observations have been shown to resemble very closely to concurrent ground based radar observations (Sikdar, 1972). A relationship exists between measurement of the areal extent of storms derived from satellite imagery and the stream runoff measured on the ground (TF-W, 1985). As runoff is proportional to rainfall which in turn is proportional to the areal extent of the storm system covering the basin, it is reasonable to expect a relationship between cloud areas and storm runoff. Rainfall rates may be derived as a function of cloud height from infrared imagery (cloud tops at different levels have different brightness temperatures).

The wavelengths most commonly used for rainfall studies are (Barret and Martin, 1981):

Visible (VIS) : 0.5 - 0.7 µm
infrared (IR) : 3.5 - 4.2 µm and 10.5 - 12.5 µm and
microwave (MW) : 0.81 - 1.55 cm

The physical basis of estimating rainfall from visible and IR images is explained as : high brightness implies large cloud thickness, that implies greater probability of rain. Low temperature implies high cloud tops that means large thickness and greater probability of rain. Therefore rain bearing clouds can be distinguished on the basis of brightness characteristics in VIS images or temperature characteristics in IR images and brightness of a precipitating cloud is a measure of rainfall intensity. The rain is most certain in clouds that are both bright and cold. Visible and IR together resolve ambiguities in cloud type recognition based on either type of data alone. Microwave data have been shown to reveal rain areas embedded in the clouds most obvious over oceans. The experience shows that varying degree of success has been obtained in the studies on the above. Perhaps the best approach involves combinations of multispectral data. Passive microwave data are already proved better than visible and infrared over oceans while the latter two give better results over land.

Presently for operational use, the best suited satellite rainfall monitoring methods integrate satellite data with evidences of rainfall from surface stations to give estimates superior to those from either type of information alone. Satellite data are often used to fill gaps in the conventional data network.

Three dominant approaches have been developed namely: cloud indexing approach, threshold approach and life history approach. Cloud indexing, which is time independent, identifies different types of rain clouds and estimates the daily rainfall over an area through statistical averaging of cloud-rainfall relationships. Daily rainfall is given by

$$R = \frac{K_1A_1 + K_2A_2 + K_3A_3}{A}$$

Where K_1, K_2 and K_3 are empirical coefficients obtained by multiplying relative probability of rainfall assigned to a particular cloud type and relative intensity of rainfall, A is area of study and A_1, A_2 and A_3 are areas of basin under three types of clouds. This method is widely used in support of broad scale hydrology like catchment monitoring, river and flood control etc. This technique has yielded most results in support of continuous operational rainfall monitoring programmes.

Thresholding techniques consider that all clouds with low upper surface temperatures are likely to be rain clouds. PERMIT (polar orbiter effective rainfall integrative technique) (Barrett et al., 1981) is based on temperature thresholding of thermal infrared imagery analysed by computer to identify potential rain clouds. Life history methods are time dependent and consider the rates of change in individual convective clouds or in clusters of convective clouds. This approach implicitly recognizes that convective clouds exhibit different rainfall intensities during their growth and dissipation cycle. A time history relationship between the radar echo area and the cloud area is developed during the lifetime of the cloud. Based on this technique the NOAA flash flood programme in the United States uses half hourly GOES data to develop real time estimates of heavy precipitation on an interactive computer system (Clark and Morris, 1986). This fully operational system has the capability to assimilate data from the GOES satellite together with ground based and atmospheric data to develop precipitation estimates for input to a river forecast model.

Microwave techniques offer a great potential for measuring precipitation because at some of microwave frequencies clouds are essentially transparent and the measured microwave radiation is directly related to the raindrops themselves. Measurements near the peaks of atmospheric attenuation curve are used for monitoring the atmospheric conditions, i.e. water vapour and temperature. Passive microwave techniques react to the rain in two fundamental ways: by emission/absorption and by scattering. With emission/absorption approach, rainfall is observed through the emission of energy by the raindrops themselves. This technique perform best over a uniformly cold background, such as a ocean. With the scattering approach, the rain attenuates upwelling radiation from the earth surface and scatters or reflects cold, cosmic background radiation to the radiometer antenna.

Considerable effort is being made on the development of passive microwave rainfall algorithm using dual-frequency or multifrequency principles. The results are promising (Spencer etal., 1988) although for operational applications in the near to mid-term future it appears as if the most successful operational methods for general rainfall measurement will likely use passive microwave data in conjunction with visible and infrared (Barrett et al., 1988).

Because the fundamental approach to measuring rainfall and snow are different with respect to remote sensing, snow has been discussed separately in the next chapter.

3.1.2 Evapotranspiration

Evapotranspiration (ET) is the loss of water from the earth surface in vapour form. It play a vital role in hydrological cycle and influence agriculture greatly. No widely acceptable satellite monitoring method has yet emerged because of the complexities involved in the process.

In recent years, much progress has been made in the remote sensing of a number of parameters which can contribute to the estimation of evaporation and ET. These include surface temperature, surface soil moisture, surface albedo, vegetative cover and incoming solar radiation. There is little progress in the direct remote sensing of atmospheric parameters such as near surface air temperature, near surface water vapour gradients and near surface winds. The incoming solar radiation can be estimated from satellite observations of cloud cover primarily from geosynchronous orbits (Brakke and Kanemasu,1981, Tarplay 1979; Gautier et al,1980). The surface temperature can be estimated from measurements at thermal infrared wavelengths of the emitted radiant flux, that is 10.5 and 12.5 μm wavebands, and from some estimate of the surface emissivity. The microwave emission and reflection or backscatter from soil, primarily for wavelengths between 5 and 21 cm are dependent on the dielectric properties of the soil which are strong functions of the soil moisture content. Thus, measurement of these microwave properties can be used to obtain estimates of the surface soil moisture.The evaporation from the soil surface is directly related to the vapour pressure difference between the surface and lower atmospheric boundary layer and the water supply in the soil. Assuming suitable supply of water in the soil, the most important controlling factor is the water vapour gradient which is largely determined by corresponding temperature difference. The most promising approach to evaporation monitoring via satellites is based on the thermal inertia properties of soils which are functions of diurnal changes in surface temperature (Barret and Curtis, 1982). These changes are governed by i) radiation budget-related to the external environment of the soil; can be modelled and evaluated with or without remote sensing and ii) thermal inertia-related to the internal characteristics of the soil; can be assessed from thermal infrared imagery. Thermal inertia increases greatly by soil porosity and water content and that any soil experiencing a diurnal thermal inertia cycle is closely related to its porosity. The greatest separation between the thermal inertia cycles of different soils is found about the local solar maximum and minimum. Heating capacity Mapping Mission (HCMM) has provided much useful information to the above.

Numerical models have been developed to provide estimates of soil thermal inertia, surface relative humidity and evaporation. These estimates are obtained by solving inverse equation of heat and mass transfer across the surface of the soil based on consideration of energy balance alone or in combination with moisture balance. Surface temperature measurements derived from thermal infrared imagery obtained from twice daily aircraft or satellite data have been the inputs to these models. It is believed that use of the more frequent radiation temperature measurements made by geostationary satellites like METEOSAT should permit significant improvements in the accuracy of the results. However, there are differing opinions on the capability of remote sensing in monitoring evaporation over the ground (Farnsworth et al., 1984).

Witono and Bruckler (1988) have shown how the heat and mass flow equations can be used to estimate evaporation from a bare soil. They used radar measurements to determine the surface soil moisture which was then used as a boundary condition for the modeling. As regards evaporation over water surface, air and space borne imagery in near infrared bands permit delineation of surface water bodies, whose areas can be planimetered. These in conjunction with field observations on evaporation can help compute surface water evaporation.

Usually the effects of evaporation from the ground and transpiration from vegetation are combined and treated as single unit called evapotranspiration (ET) . For ET monitoring many of the traditional models have limitations for use on a regional basis. It is therefore desirable to use remote sensing inputs for the computation of ET. Several approaches have been developed to use remote sensing, primarily reflectance and thermal techniques for estimating ET. These approaches range from single empirical methods to complex energy balance/aero dynamic models. Estimation of ET using remote sensing methods has been excellently discussed by Hatfield (1983).

An approach explored the use of remote sensing data from weather satellite, Landsat and aircraft data to estimate the potential ET on energy conservation basis. The model used mean daily temperature and daily incoming solar radiation. Wherein temperatures were obtained from NOAA-VHRR (Very High Resolution

Radiometer) data, solar radiation was derived utilising temperature, day length, total incoming radiation, cloud cover, albedo, slope and aspect . Land use as estimated from Landsat and aircraft data was used to estimate albedo (Khorram and Smith, 1979). It is found that incoming solar radiation can be estimated from geostationary satellite data.

Most of the models that exploit satellite data for the computation of ET use a form of energy balance equation which incorporates the canopy-air differential in an aerodynamic expression of sensible heat flux. A general form of the equation is

$$ET = R_n - G - f(u)C(T_c - T_a)$$

where

ET - evapotranspiration flux,
R - net radiation,
G - soil heat flux,
f(u)- function of wind speed
C - volumetric heat capacity of air,
T_c - plant canopy temperature C and
T_a - air temperature C (at some height above the canopy)

Key variables which can be monitored by satellites include R_n, T_c and T_a(Barret and Curtis, 1982). The estimates of ET obtained using remotely sensed canopy temperatures represent instantaneous ET values. Daily values of ET are then realised by modeling the latent and sensible heat fluxes in the soil plant atmosphere system(e.g. TERGRA model of Soer, 1980). In estimating ET using energy balance equation, few relations of temperature differences to ET have been proposed. Jackson et al. (1977) related midday surface air temperature differences linearly to 24 hr ET and net radiation values.

Remotely sensed reflected solar and emitted thermal radiation has been used with ground based measurements of wind, vapour pressure and incident solar radiation to estimate ET with a modified form of the Penman equation (Jackson et al., 1987). The model ET rates were compared with rates measured with Bowen ratio instrumentation over wheat, cotton alfalfa and found to agree within about 12% and between less than 8% and 25% for daily values.

The question of how to use the spatial nature of remote sensing data to extrapolate point ET measurements to a more regional scale has been addressed by Jackson (1985) and Gash (1987) . Gash has formalized an analytical framework relating the horizontal changes in evaporation to horizontal changes in surface temperature.

Soares et al (1988) used active microwave measurements of soil moisture and remotely sensed thermal data to estimate evaporation at the soil surface through an energy balance at the air/soil temperature . These studies provide a good indication of the utility of soil moisture sensing for estimating ET.

The major problems with all remote sensing methods of evapotranspiration are: (1) the process of transpiration in still not well understood and parametrized either for structured crops such as cereals or for complex vegetation such as trees, (2) in the presence of vegetation, the surface temperature T, estimated by a thermal infrared sensor is at an unknown level within the vegetation; and (3) the most appropriate use of microwave observations of surface soil moisture in the presence of vegetation needs to be determined. For the future, we expect that the most practical method will probably use a multispectral approach including repetitive observations at the visible, near and thermal infrared and microwave wavelengths. This will afford the possibility of estimating solar insolation, surface vegetation cover and/or albedo, surface temperature and surface soil moisture from remotely sensed data.

3.1.3 Runoff

Runoff is the one hydrologic variable that is most often used by hydrologists and water resources planners. The objective most sought by hydrologists is the accurate and timely prediction of runoff at a given point in a drainage basin. Runoff can not be directly measured by remote sensing techniques. The role of remote sensing in runoff calculations is generally to provide a source of input data or as an aid for estimating equation coefficients and model parameters.

Salomonson et al. (1975) studied remote sensing requirements based on a sensitivity analysis of input parameters of the Kentucky watershed model. Of 26 input parameters, six could be determined by remote sensing. The results of a case study demonstrated that more current data from satellite could improve runoff simulation. Peck et al.(1981) conducted a detailed study on the suitability of seven hydrologic forecasting and simulation models to assimilate remotely sensed data. In general, they concluded that remote sensing had limited usefulness for those models in their form at that time. Their study identified model variables in addition to land use and snow cover area that could be provided by remote sensing.

Once the watershed is classified into hydrologically distant classes according to land cover and soils using the remotely sensed data, runoff coefficients for corresponding classes can be ascribed. Aerial photograph based slope aspect can be utilised. Radar and raingauge data permit estimation of rainfall intensities. The runoff factor in conjunction with the watershed area derived from satellite or aerial data is used to predict the water yield from a rainfall event. The watershed runoff potential can be computed using Rational formula:

$$Q = CiA$$

where Q - peak rate of runoff

C - runoff coefficient

i-mean intensity of rainfall for a duration equal to the time of concentration

A - Watershed area

Satellite data can be used to improve empirical equations of various runoff characteristics. Allord and Scarpace (1979) have shown how the addition of satellite data can improve regression equations earlier based on topographic map alone. The addition of land cover determined from satellite reduced the standard error of estimate by 9% for 2 and 10 year 7-day low flow values, and by 14% for the 10, 50 and 100-year flood frequency estimates. Still and Shih (1985) used satellite data to develop a basin wide runoff index which was compared with an earlier index determined from USGS land use maps. They concluded that the runoff index had not changed but in doing so have demonstrated how remotely sensed data can be used to track the changes in runoff that occur in a basin due to landuse changes.

Remote sensing data can be used to obtain almost any information that is typically obtained from maps. In many regions, remote sensing data may be the only source of good cartographic information. There have been a number of studies to extract quantitative geomorphic information from Landsat imagery (Haralick et al.1985). Drainage basin area, drainage network, basin shape, circularity and stream order can be taken from the imagery. Selection of imagery is important factor. In case of Landsat or Spot, the choice of imagery with a low sun angle will enhance topographic and drainage features. Landsat MSS bands 5(0.6-0.7 μm) and 7(0.8 - 1.1 μm) and TM bands 3(0.62-0.69 μm), 4(0.76 - 0.9 μm) and 5(1.55 - 1.75 μm) have proven to be the best choices for discerning physiographic features. The visible red band (MSS band 5, TM band 3), is best for showing stream channel networks when their size is too small to be detected directly. This band is also good for separating vegetation types. MSS band 7 shows the most contrast between water and land areas. France and Hedges (1986) compared MSS and TM data for their application to hydrology and found that the TM data provided much more information.

Land use is an important characteristic of the runoff process that affects infiltration, erosion and evapo-transpiration. Almost any physically based hydrologic model uses some form of the landuse data or parameters based on these data. Distributed models, in particular, need specific data on land use and their location within the basin. Some of the first research for adapting satellite derived landuse data was done by Jackson et al.(1977) with the STORM model . They evaluated the success of this approach by comparing the results of the model using satellite data with those of the model used in the conventional way. The results indicated that for planning studies, satellite approach is highly cost effective. The authors estimated that the cost benefit were of the order of 2.5 to 1 or 6 to 1 in favour of satellite approach depending on the experience of the analysts and the availability of data and background information. However, most of the work on adapting remote sensing to hydrologic modeling has been with the SCS runoff curve number model. There have been attempts to estimate the USDA Soil Conservation Service (SCS) runoff curve number (CN) using satellite data. The SCS models compute direct runoff through an empirical equation that requires the rainfall and a watershed coefficient as inputs. The watershed coefficient is called the curve number, which represents the runoff potential of the land-soil complex. These models involve relationships between land cover, hydrologic soil class and CN. The model for small watersheds is:

$$Q = \frac{(P-0.2S)^2}{P+0.8S}$$

$$\text{where} \quad S = \frac{1000}{CN} - 10$$

$$\text{For India} \quad Q = \frac{(P-0.1S)^2}{P+0.9S} \quad \text{and } CN = \frac{25400}{254+S}$$

where Q - storm runoff in cm

P - weighted storm rainfall in cm

S - storage in the watershed surface in cm

CN - f(soil, land, vegetal cover, ant. moisture etc.)

Runoff curve number (CN) is a coefficient developed from one of four hydrologic soil groups which have been adjusted for land use and management practices. The CN may be further modified by an antecedent precipitation index to account for very wet and dry conditions. Blanchard (1975) showed that runoff estimated from curve numbers based on reflectance measurements obtained from Landsat MSS compared very well with those obtained by conventional methods. Sasso et al.(1979) concluded that using SCS model with satellite data for sites adjacent to lake Isabella, they are able to save $119,504 within the variation of 7% of the result obtained by conventional ground surveys. Mauser (1984) used the SCS TR-20 model for calculating flood hydrographs for the Dreisan Watershed in Germany. The landuse was determined from MSS data with a maximum likelihood classification scheme. There have been several attempts to measure the SCS curve number directly with direct measures of reflectances. It is implicitly assumed that the reflectance is somehow related to the general land use which is an integrated land use of the basin.

Some improvement in forecasting and simulation can be achieved by modifying existing models to use remote sensing data. Even greater gains can be achieved with models designed to use remote sensing as well as conventional data. Such models would resemble contemporary simulation models structurally but would be able to account for the spatial variability found in the natural basins in a more realistic way. A pioneering attempt to develop a model designed to use remote sensing input data has been made by Groves and Ragan (1983). This model is similar to Stanford model but more of its parameters can be determined directly by remote sensing. The US Army Corps of Engineers (1987) developed a microcomputer based system that combines remote sensing image processing and spatial data analysis through a GIS. The system provides options to use the SCS curve number or the Snyder Unit Hydrograph to estimate runoff from single storm events.

Several investigators have proposed the use of remotely sensed rainfall as inputs to real time hydrology and short time forecast models. Rott (1986) studied the potential for using Meteosat data as an indication of rainfall input to a basin. A runoff model that uses a cloud index developed from the thermal data was applied to two large basins in Europe. The concept was demonstrated by predicting runoff for 1 to 3 days ahead, starting with the measured flow. Schultz (1986) proposed using historic NOAA satellite data to generate a long term runoff record for data sparse basins. A cloud cover index developed from cloud top temperatures is transformed into runoff with a linear transformation function. For short term flood forecast problems, Schultz has also proposed developing rainfall inputs from near real time satellite data, and, if available, combining them with ground based radar data. The flood flows are then calculated with a runoff model capable of using this type of precipitation input.

Indian studies on rainfall runoff computation using remotely sensed data are very few. Sharma and Jain (1978) used

1:60,000 scale aerial photographs and topo maps for estimating the runoff factors of several watersheds in the country. These were used in conjunction with watershed area to predict water yield. Nagarkar et. al.(1983) evaluated the use of remote sensing techniques for water potential assessment in Tultuli irrigation project in Maharashtra. They used Landsat imagery, aerial photographs and topomaps to obtain information on drainage pattern, river flow and river widths and land cover/use .These information were used in determining the losses due to infiltration, evaporation and ET. Calculation of runoff from the catchments was done using the water balance equation. Satish Chandra et. al. (1984) through the use of Landsat imagery and aerial photographs first derived land use and vegetal cover information for Upper Yamuna basin and then obtained morphometric and relief characteristics of the basin. These were used to derive runoff coefficients for various land uses for use in simulation of runoff employing rational formula. However, research emphasis needs to be addressed for the use of remote sensing data of above nature in the country.

Improved forecasting depends upon two major factors; more physically realistic models to simulate the hydrologic process and adequate data to drive these models. Remote sensing is beginning to have an important role in determining runoff from rainfall. The remote sensing product can take the place of conventional maps and for many parts of the world these products may be the only source of map types of information. However, the real impact of remote sensing will not be in providing up-to-date maps to hydrologists, but rather in providing new types of data on the state of the hydrologic system. The work to date on determining land use is an example of how remote sensing can be used. In the future, thermal infrared and microwave measurements can prove to be even more valuable.

3.1.4 Soil Moisture

Soil moisture is the temporary storage of precipitation within a shallow layer of the earth that is generally limited to the zone of aeration, which approximately coincides with the root zone. It is highly variable as a result of the inhomogeneity of soil properties, topography, land cover and the non-uniformity of input from rainfall. Remotely sensed data have great potential for providing areal estimates of soil moisture rather than point measurements. Quantitative assessment of soil moisture regime is essential for water balance models, irrigation scheduling, crop management and surface and subsurface flow predictions.

Remote sensing of soil moisture can be accomplished to some degree or other by all regions of the electromagnetic spectrum. The use and application of remotely sensed data for soil moisture assessment is still under research and development. Research studies reveal that in general most remotely sensed measurements of soil moisture either directly respond to soil moisture content in upper few cms (1-10 cm) or use the response of plants as related to their ability to transpire, thereby indirectly providing an indication of the soil moisture status in the root zone (1-100 cm) (Salomonson, 1983). In monitoring soil moisture , the three key parameters needed are (i) soil moisture content in the upper layer of the soil, (ii) surface temperature and (iii) vegetation type and biomass (Rango, 1984). Remote sensing of soil moisture depends upon the measurement of electromagnetic energy that is reflected or emitted from the surface. Reflected solar radiation is not a particularly viable technique for measuring soil moisture because there are too many noise elements that confuse the interpretation of the data. Although wet soil will generally have a lower albedo than dry soil (Christ and Cicone, 1984) and this difference can be measured theoretically, confusion factors such as organic matter, roughness, texture, angle of incidence, colour, plant cover and the fact that it is transient phenomenon all make this approach impractical (Jackson et al., 1978). These along with the other important aspect that the remote sensing observations represent only a very thin surface, limit the utility of solar reflectance measurements for soil moisture estimates. However, one of the most useful applications of reflectance techniques may be to provide estimates of plant cover (leaf area index, biomass percent cover etc.) as inputs into soil moisture budget/water management models (Myers, 1983).

While soil reflectance measurements are sensitive to soil moisture at the very surface of soil, surface soil temperatures are influenced by deeper soil conditions. TIR detection and quantification of near surface soil water content are based on relationships between surface soil temperature and soil moisture. Diurnal variations of surface soil temperature are a function of internal and external factors. The external factors are meteorological factors that represent the driving force for diurnal soil temperature variations. Since water has higher specific heat and therefore a higher thermal capacity than soil, the wetter the soil, the higher will be its thermal capacity and conductivity. The measure of thermal inertia of a soil can easily be obtained by taking daily maximum soil temperature measurements. High diurnal temperature variations result from dry soils and low variations from wet soils. Thus the diurnal range of surface soil temperature can be an indication of soil moisture content (Idso et al., 1975). For TIR measurements, the observations are usually limited to the 8-12 um region of the EMS, where the atmospheric effects are minimized and the emitted energy is near the maximum for terrestrial surface (Salomonson, 1983). Heating capacity Mapping Mission (HCMM) data has been used in remote sensing of soil moisture evaluation (Heilman and Moore, 1981).

The various attributes of microwave remote sensing make it uniquely attractive for soil moisture measurements. In the microwave region between 1-51 cm, water has strong influence on the dielectric properties of soils that make soil moisture measurements possible through both microwave reflection and emission. In addition to dielectric dependence, microwave measurements are also sensitive to polarization and incident angle of emitted or reflected energy, the roughness of the surface and the amount of vegetation present. Moreover, all weather all time capability, little atmospheric attenuation and subsurface penetration make microwave remote sensing highly capable for soil moisture studies. Penetration through soil depth would facilitate integration of subsurface values.

Passive microwave systems measure the natural radiations from the surface which is proportional to the product of the body's emissivity and temperature (referred to as brightness temperature). The natural microwave emission from soil surface is dependent on its surface roughness temperature and dielectric properties. A change in soil moisture causes a change in soils dielectric constant and temperature. The depth at which the energy generated is determined by the sensor wavelength and the water content profile of the soil. This may vary from few centimeters in wet soils to several meters in dry soils when sensed at longer wavelengths. It has been found that by measuring both horizontally and vertically polarized signals from a soil surface, additional information on soil moisture variations could often be inferred. Also, the observed brightness temperature of the surface was highly dependent upon sensor viewing angle (Blyth, 1985).

Most success using passive microwave sensing has been achieved using the band measurements in the neighbourhood of 20 cm. The response to soil moisture at this wavelength is approximately 2 degreeK per one per cent change in soil moisture and observation is only modestly dependent on type (Schmuggee et al. 1974). The results from space supported by more detailed aerial and ground measurements strongly support the possibility of using microwave radiometers for soil moisture sensing (Myers, 1983). However, in one sense passive microwave sensing has less potential from orbital altitudes because ground resolution is limited to few kms.

Active microwave systems provide their own illumination and record the reflected signal. The back scattering coefficient of terrain is dependent on the soil moisture content of an effective surface layer whose thickness is governed by the penetration properties of the terrain at the wavelength used. Also the backscattering coefficient is influenced by surface or volume roughness, soil texture, bulk density, vegetation and snow cover. Research is being continued in the application of active microwave sensing to soil moisture. Results obtained from ground based experiments (Ulaby et al. 1977 and 1978) indicate that C band observations are superior to other wavelengths, that have been corroborated by air borne scatterometer measurements (Jackson et al. 1980). Ulaby et al. (1983) reported that improvement in moisture estimation accuracy of vegetation covered soil could be obtained by combined active and passive microwave remote sensing.

Both active and microwave systems show many similarities in soil moisture sensing ability to penetrate clouds and moderate vegetation and the limitation to sampling only the surface 1.5 cm of soil. The difference lies in spatial resolution. 25 m resolution was obtained through the use of 18 cm SAR on the SEASAT. The Active Microwave Instrument (AMI) sensor of ERS-1 (European Remote Sensing Satellite) launched in 1990 has (C band 5.3 GHz) with a spatial resolution of 30 m.

Previously discussed approaches mainly deal with surface moisture measurements under the conditions of little or no vegetation. The indirect estimates of soil moisture are based on the remote sensing measurements made on plant response/condition. During recent years much attention has been given to crop canopy temperature and air temperature as they are found to be related to crop stress (Jackson et al., 1978). Jackson (1982) provided an excellent review of the use of crop canopy temperature to detect crop stress. The soil moisture inference is made based on the principle that when the crop canopy temperature is less than the air temperature, the plant is not subject to stress and therefore moisture is readily available in the root zone. Similarly if the crop canopy temperature is equal to or more than the air temperature, the crop is subject to stress which means reduction in soil moisture. Multitemporal remote sensing data permit comparison of temperatures of individual areas with other areas of known water states to correlate the temperature with its soil moisture status in unknown areas. The results of many studies show that plant canopy temperatures relate well to surface soil moisture (Gihlar, 1980; Jackson et al., 1981). The use of surface temperature measurements in soil moisture or crop observations versus soil moisture status was demonstrated by Soer (1980), Heilman and Moor (1981) and Jackson et al. (1981).

3.1.5 Ground Water

Groundwater refers to all water stored beneath the surface of the earth in aquifers. In order to use the water stored in an aquifer, it is necessary first to locate the aquifer, map its size, extent and depth, and then estimate recharge and discharge rates of water. However, the use of remote sensing techniques is a very cost effective approach in prospecting and in preliminary survey because the cost of drilling is such that it is not cost effective to drill randomly. However, remote sensing techniques offer the hydrogeologist a powerful tool to add to his standard geophysical methods. The interpretation of aerial photographs and satellite imagery enables geologists to infer the location of aquifers from surface features. Satellite imagery, in particular, enables image analysts to view very large areas and achieve a perspective not possible from ground surveys or even low level aerial photography.

Groundwater information can be inferred from land forms, drainage patterns, vegetation characteristics, land use patterns, linear and curvilinear features, and image tones and textures. In arid regions, vegetation characteristics may indicate groundwater depth and quality. Structural features such as faults, fracture traces and other linear features can indicate the possible presence of groundwater. Similarly other features, such as sedimentary strata or certain rock outcrops, may indicate potential aquifers. Since the remote sensing approach is limited to surface features, the first step in groundwater exploration is the delineation of surface features and land forms. Differences in temperature measured by remote sensing have been used to infer or identify shallow groundwater and springs. These temperature differences are the result of the high heat capacity of the groundwater that produces a heat sink in the summer and a heat source in the winter. The near surface soil, soil moisture and vegetation temperatures respond rapidly to the local meteorology, whereas the ground water temperature changes are both diurnal and seasonally damped.

It is important to emphasize, however , that remote sensing is nothing more than an additional source of information. It does not replace the more traditional techniques used by groundwater hydrologists such as topographic maps, seismic and resistance surveys, ground penetrating radar, etc., it merely supplements them. Nevertheless, there are some unique features of satellite imagery that make it extremely valuable.

Presently, the remotely sensed data both air and spaceborne cannot be used directly to map aquifers or ground water conditions. However, most applications of remotely sensed data permit us to make indirect inferences regarding the subsurface through surficial expression of the aquifer. The subsurface hydrological conditions are inferred based on identification and correlation of surface phenomena involving geological features and structures, geomorphology, surface hydrology, soils and soil moisture anomalies, vegetative types and distribution, land use, surface temperature, springs, discontinuous ice cover on streams, differential snow melt and many others as indicators. The benefits that accrue in the use of remotely sensed data are usually greatest when they are applied for large scale preliminary investigations of ground water reserves. Most quantitative information concerning a ground water system must come from other types of data.

Generally in ground water studies, aerial and satellite data in conjunction with ground surveys have been applied (Fransworth et al. 1984 and Sharma, 1986) to i) Select likely areas for ground water exploration, ii) progressively narrow down the target areas in pinpointing of well drilling sites , iii) find the indicators of the presence of ground water, iv) identify regions of ground water recharge and discharge, v) indicate the quality of ground water, vi) monitor aquifer changes as ground water development proceeds and vii) to acquire certain remote sensing based parameters of use in hydrologic equations for assessment of ground water resource potential . However, the most contributions of remote sensing are oriented towards improving upon the ground surveys and probability of success in well drilling in the exploration of regional and local ground water supplies (Sharma, 1986).

Remotely sensed data for ground water exploration mostly include photography or imagery obtained in the visible or NIR region with the possible exception being the TIR data (Meyer and Welch, 1975). High altitude aircraft and satellite based observations are generally most applicable to regional exploration while low altitude aerial photography and ground based remote sensing apply to local studies (Salomonson, 1983). However visual analysis especially has a vital role to play in this to achieve best integration of surface phenomena.

The occurrence and movement of ground water in unconsolidated strata are confined within the zones of granular material having primary porosity. Whereas in the consolidated formations, the ground water occurrence is largely controlled by the prevalence and orientation of open spaces namely fractures, joints, fault planes and cracks and also the favourable topographical features. Specific types of rocks inferred from landforms, texture, colour or tone of land surface on imagery would permit broad classification of types of water bearing material near the land surface and hence inference of probable porosity and relative permeability.

High permeable areas permit replenishment of local ground water aquifers through rapid infiltration. These areas can be identified using remotely sensed data because of their geomorphological appearances. In rocky areas linear features and fracture zones can have high ground water potential. It has been shown that fault and fracture zones especially intersections of fractures can indicate high ground water. High permeable areas can be delineated based on drainage density. Lesser the drainage density, higher will be the permeability of the area. In hard rock areas, it is fracture density and fracture frequency that have direct bearing on aquifer base flow. Fracture density is related to permeability of rock materials. The produce of fracture density and fracture frequency results in infiltration number, which would help classify the watersheds into various permeability classes. Fractures and lineament mapping can be done easily on photographs and images (Sharma, 1986). Thus rock fracture patterns and fault zones revealed on images can be related to porosity, permeability and ultimately well yield. For instance, absence of defined drainage over large areas subject to good rainfall may indicate ground water occurrence. In short drainage textures offer clues in the detection of ground water and ground water related features when they are expressed as a function of i) rainfall and vegetation, ii) texture of a weathered rock, iii) infiltration capacity of soil or rock and iv) topography (Sharma, 1986).

Information on sites of gain or loss of streamflow in conjunction with geologic data may permit the inference of confined or unconfined aquifers and of geologic controls on ground water. Large scale aerial photographs and side looking radar imagery have been found highly useful for mapping of gaining and losing streams. Location of ground water discharge points such as springs and seeps can be found directly and indirectly on imagery by identification of vegetation types. Springs and marshy areas indicate relatively shallow depths to ground water. Where seeps, springs or seasonal lakes exist, residue from evaporated water supplies could help infer minerals present in ground water. The synoptic view obtainable in imagery shows relationship of springs, seeps and rivers to other locations on the ground which is useful in understanding the hydrogeologic system of the area and selecting sites capable of successful ground water development (Farnsworth et al. 1984).

Among various remote sensing applications in the country, demarcation of ground water potential zones has got much attention by the researchers. NRSA and SAC have set the trend in utilising remotely sensed data for delineating regional ground water potential zones. Many studies have been successfully carried out by various organisations using visual interpretation of satellite imagery to delineate and classify regional drainage patterns, geologic structures, lithology, landforms, soils and land use patterns and surface water bodies that are favourable for ground water occurrence. NRSA has prepared ground water potential maps of Karnataka, Gujarat, Maharashtra and Rajasthan using visual interpretation of Landsat-TM imagery on 1250,000 scale within 1 - 2 months. All such studies reveal that the technology has reached operational status in the country.

3.2 REMOTE SENSING APPLICATIONS IN WATER RESOURCES MANAGEMENT

Water and changes in the hydrologic cycle have important economic effects for water delivery and drainage to agriculture and urban areas and for flood control. Economic and social aspects as well as hydrologic ones are generally studied as water resources management. There are a number of areas in water resources monitoring and management that can benefit from remotely sensed data. Estimating flood damage, drought prone areas, water quality monitoring, management in command areas etc. are suited to analysis using remotely sensed data. The use of remotely sensed data for water resources management and monitoring is basically for mapping. In the following section, application of remote sensing to some aspects of water management is presented.

3.2.1 Flood and flood plain management

The floods are a regular phenomena in India. Flood damage surveys are essential not only to assess the extent and severity of damage caused by the floods in river valleys but also for economic evaluation of flood control measures. Moreover timeliness of information is crucial for tackling flood events. Conventional methods have serious limitations in this regard. On the other hand, remote sensing admirably facilitates the flood surveys by providing much needed information on flood inundated areas, the river course and its spill channels, the spurs and embankments affected/threatened etc. so that appropriate flood relief and mitigation measures can be planned and executed in time. Through proper selection of platform and sensor, remote sensing can offer a quick and reasonably accurate means of surveying the spatial extent and assessment of flood damage . The effectiveness of existing flood control works in containing the flood can be assessed and vulnerable reaches can be identified for strengthening. New structures can be planned wherever necessary. Remotely sensed data has been successfully employed for flood inundation mapping of many rivers and in different regions using CIR and B&W photography, satellite data and to a limited extent TIR data (Rango and Anderson, 1974, Rango and Salomonson, 1974, Robinove, 1978, Phillipson and Hafker, 1981, Chaturvedi and Mohan, 1983 and Ramamoorthy and Rao, 1983).

In India mapping flooded area using satellite data is quite developed at present. Inundation area of record flood of river Sahibi during August 1977 in Haryana/Delhi was mapped (1:250,000) using visual as well as digital analysis of Landsat MSS data (Ramamoorthy and Rao, 1983). These maps were found to be in conformity with that of SOI prepared using aerial photographs. Similarly flood affected areas consequent upon the devastating flood of September 1982 in rivers - Ganga, Yamuna, Ghagra and Tapti in parts of southern and eastern U.P. were delineated using Landsat - near infrared band (Chaturvedi and Mohan, 1983). Using Landsat MSS and TM FCCs, flood inundation area map of August 1986 flood of Godavari river in Andhra was prepared. These studies indicate that the technology of flood mapping using satellite data has attained near operational status in the country.

Identification and mapping of flood prone areas is a necessity for proper land use planning to keep flood damage to the minimum. Two basic approaches have been proposed by Sollers et al. (1978) for flood plain mapping - dynamic and static. The dynamic or actual or direct approach uses the historical evidence of flooding to map the extent of inundation. An inundated area frequency relationship can be developed by observing the evidence of events. However, a significant drawback of this approach is the lack of information if the flood events of interest have not occurred during the period of study. As a result, the use of static approach is sought for. The various indicators considered in the static approach of flood plain delineation have been given by Burgess (1967). It has been shown that floodprone areas show at times different multispectral signatures than that of surrounding non flood prone areas. This is due to distinctive natural vegetation, soil characteristics and different cultural features acquired over a long period of time in response to increased flooding frequency that enable them to be distinguished from nonflood prone areas. The indicators that could be defined using satellite data (Rango and Anderson, 1974) are:

1) upland physiography
2) watershed characteristics such as shape, drainage density etc.
3) degree of abandonment of natural levees
4) occurrence of stabilized sand dunes on river terraces
5) channel configuration and fluvial geomorphic characteristics
6) backswamp areas
7) soil moisture availability
8) soil differences
9) vegetation differences
10) land use boundaries

useful in most effective relay of such data.

In addition to the above, aerial or satellite estimates of snow cover area permit prediction of snow melt runoff. Meteorological radars have the capability to identify rain bearing clouds and provide estimates of rainfall intensities. These data in combination with watershed information could be used to forecast possible areas of flashflood occurrence and make warning. Satellite estimates of spatial rainfall in conjunction with point observations of automatic telemetering raingauges would give a complete picture of rainfall over a basin for making forecasts of impending floods.

3.2.2 Drought Monitoring

Drought is the frequent factor that continues to haunt Indian agriculture in recent years. Though drought is defined in many ways, generally it is related to water shortage in an area over a long period. Indian agriculture with only about 30% of the cropped area having assured and adequate irrigation support, it is important that droughts be objectively monitored in order to plan and implement effective drought management strategies.

Drought is the major factor of uncertainty that continues to haunt Indian agriculture. It often results in economic and demographic shifts and disturbs natural equilibrium. Measurements/factors related to thee extent and severity of drought are:

a) rainfall - annual, seasonal, monthly and weekly quantums

b) deviations from normal rainfall

c) number of significant days without rain

d) evaporation

e) temperature, humidity and dew point depression

f) soil moisture deficits

g) ground water conditions

11) agricultural development and

12) flood alleviation measures on the flood plain

Satellite data can provide preliminary flood prone area maps for those areas which may not receive a detailed survey for years. They can also be used as another source of data to check already existing surveys and maps. In addition, using satellite data, it is possible to monitor adherence to developmental or land use restrictions in already delineated flood prone areas.

Many studies have been carried out in India using remote sensing techniques for mapping of flood plains in river basins and coastal plains. Dhanju (1976) mapped the Kosi river flood plain using Landsat imagery of 1972 and 1975. He also made study of flood plain of Gangetic basin between Varanasi and Patna (Dhanju, 1980). Srivastava et al. (1983) used Landsat imagery with aerial photographs for geomorphological investigations in the flood plain areas of the Ghaghra river in Azamgar district, U.P. Vaidyanathan (1983) made a comprehensive review of studies on flood plain mapping using remote sensing. Based on a perusal of literature, he suggested the following following bands for use in flood plain mapping in the order of decreasing importance-

colour infrared film (0.5-0.9 µm), infrared band (0.8-1.1 µm) infrared band (0.7-0.9 µm) and infrared film (0.5-0.9 µm).

Speedy and accurate forecasting of floods is critical, if the forecasts are to be useful in the operation of reservoirs and in the evacuation of flood plains. The accuracy of forecasts could be improved greatly if timely data on rainfall in the head reaches of catchments and river stages are available. Limitations of conventional systems under adverse weather conditions lead us to increasing use of remote sensing. Real time data on rainfall, river stages in remote areas, could be obtained through unmanned DCPs which record and transmit via satellite to ground stations for use in flood forecasting. Geostationary satellites would be

h) changes in surface water bodies

i) crop and vegetation conditions etc.

Severity of drought can be quantified through Drought intensity index by combining factors related to the drought (Herbst et al., 1966). Timelines of information is critical for taking drought relief measures. Remote sensing by virtue of its synoptic and temporal attributes has the capability to provide the much needed data for monitoring drought conditions in time. Most of the measurements listed above are amenable to remote sensing, which in conjunction with field based data would help assess the damage caused by drought and also to evolve a drought inventory and monitoring system.

Many studies have been attempted using satellite data for drought mapping and monitoring. The usefulness of a rainfall climatology technology for drought monitoring through the preparation of daily rainfall map using satellite imagery was demonstrated (Follansbee, 1976). Successful application of satellite data for rainfall monitoring in drought study was reported by Howard et al. (1979). Remote sensing techniques were used for detection and monitoring of agricultural drought in LACIE experiment wherein two methods were employed (Thompson and Wehmanen, 1978). One method compared the vegetative vigour (redness) in the IR Landsat images of normal year with that of drought year. The second was based on green index number (GIN) representing the state of the growth of the crop derived from the band 4 of Landsat data. Vegetation indices measured using meteorological satellite data have been shown to be useful indicator of vegetation vigour (Gray and McCray, 1981).

Regarding the use of satellite data for drought monitoring, few studies have been reported in India. Chakraborty and Roy (1979) used Landsat imagery to study the influence of drought on ecosystems in Karnataka state. Satellite data were also used to identify drought conditions through mapping and monitoring of surface water bodies (Chakraborty, 1982; Thiruvengadachari, 1982), Nageswara Rao and Rao (1984) employed NOAA-AVHRR band 3 TIR (3.55-3.93 µm) for delineating drought affected areas. Details of the drought affected areas were studied and severity of the drought was assessed using Landsat MSS imagery. Recently severity of drought was quantified based on reduction in green cover using Landsat MSS digital data (Nageswara Rao and Sugimura, 1987).

Department of Agriculture and Cooperation, Government of India has sponsored the Remote sensing Application Mission on Drought, which is being executed by Department of Space/National Remote Sensing Agency, with participation by India Meteorological Department (IMD), Central Water Commission (CWC) and concerned state government agencies. The project was initiated in the later half of 1986 and has lead to the development of the National Agricultural Drought Assessment and Monitoring System (NADAMS). Drought Assessment with district as the reference unit and monitoring through the kharif season (June-December), is primarily based on normalised difference vegetation index (NDVI) derived from NOAA satellite Advanced Very High Resolution Radiometer (AVHRR) sensor data, acquired daily at the earth station operated by NRSA. NDVI is a function of greenleaf area and biomass and is indicative of the vegetation status of the district. Ancillary data on rainfall, aridity anomaly, cropping pattern and calendar, land utilisation and irrigation support has been collected through state Govt. field agencies to support interpretation of NDVI data.

The processing of NOAA AVHRR CCTs during 1988 and 1989 into biweekly data sets was carried out at the Regional Remote Sensing Service Centers at Bangalore, Nagpur and Dehradun. The drought interpretation was carried out at NRSA, Hyderabad and the biweekly drought bulletins during 1989 kharif season (June-Dec) were sent, within 21 days of each biweekly period, to all District

Collectors, concerned State Government Departments and Central Agencies. During 1990 season, NOAA data was processed on NRSA's METDPS system to provide biweekly drought assessment in less than 2 days turn around time by telex/telegram to concerned district/state/central offices and the printed bulletin was sent within 10 days to all concerned officers including District Agricultural Officers.

3.2.3 Water quality monitoring

Water quality is the general term that describes whether or not water is usable or whether or not the surrounding environment may be endangered by pollutants in the water. Remote sensing has an important role in water quality evaluation and management strategy. The synoptic view provided by remote sensing gives an environmental scientist very different data from that which can be obtained with surface data collection and sampling. What may not be achieved with absolute accuracy is more than made up for by the spatial and temporal nature of the data. Remote sensing is limited to surface measurements of turbidity, suspended sediment, chlorophyll, eutrophication and temperature. These characteristics of water quality can be used as indicators of more specific pollution problems.

Visible and infrared region of EM spectrum is useful for detecting indicators of water quality. Because the intensity and colour of light is modified by the volume of water and its contaminants, an empirical relationship can be established between the reflectance measurement and the water quality sample. Colour is a non specific water quality parameter that describes qualitative information about the biological productivity and the general chemical make up of waterbodies. Observations of colour are made to evaluate the amounts of living and non living substances in the water. Feldman et al. (1984) used Nimbus-7 data to track changes in colour that they associated with phytoplankton concentrations. Turbidity is another non specific water quality indicator that is used to characterise receiving waters. But it is an imprecise water quality indicator because light attenuation is caused by suspended sediments and organic materials. 58

Turbidity estimates from satellite data are useful for tracking the movement of water masses within large lakes. Abiodun (1976) was able to identify five distinct water masses in Lake Kainji on the river Niger. Later work by Abiodun and Adeniji (1978) demonstrated how spectral classification of the lake water with sequential landsat data could be used to chart the movement of different water masses.

A specific remote sensing application of turbidity measurement is in the detection and monitoring of sediment in water bodies. The presence of suspended sediment or organic materials increases the reflectance in the visible regions of the electromagnetic spectrum. However, the reflectance of the sediment and water remains low in the near infrared portion of the spectrum unless there are significant amounts of algae present. The failure of a sensor to detect turbidity deeper than about 1 m, at the most, limits this approach to the detection of shallow suspended sediment.

One of the most advantageous uses of remote sensing for water pollution control is in its application as a surveillance tool to detect and map potential sources of pollution. This is to provide environmental monitor with information on proximity of hazardous materials in water bodies and waterways so that suitable measures can be defined to check water pollution.

Presence of adequate nutrients in the lake or reservoir exposed to sunlight may lead to eutrophication of waters resulting in algae blooms. Determining the trophic state of water body is more complex than determining turbidity (Mintzer, 1983).

Temperature, sunlight, water clarity and nutrients are the principal factors that induce algal growth, thereby making water unfit for use. It has been found that remote sensing can be gainfully used to detect six basic indicators of the trophic state, water transparency, colour, chlorophyll, algal blooms, aquatic vegetation and suspended solids (Thiruvengadachari, 1983). CIR photography is highly useful for monitoring of floating algae. This sensor enhances the differences between surface algae and water thus facilitating detection and mapping of areal extent. Concentration may also be evaluated based on reflectance differences within the algae. Since definite temperature changes are associated with algae growth, TIR would be useful in monitoring algae growth . Particularly TIR sensing can be effectively used for source identification and defining areas of potential algae blooms as thermal discharges into streams are found to stimulate algae growth.

Witzig and Whitehurst (1981) discussed a number of trophic state indices and their estimation from Landsat data. Thermal infrared data have been successfully used to assess lake water quality. A study of Lake Utah (Miller and Rango, 1984) correlated HCMM (Heat Capacity Mapping Mission) data with algal concentrations. They found high positive correlations between emitted thermal energy and algal concentrations. At night the opposite occurred and the thermal (data exhibited a strong negative correlation with algal concentrations.

When the uncontrolled/untreated municipal and industrial effluents are continuously discharged into water bodies of water courses, the natural balance by way of cleaning forces goes off the scale. TIR imagery is frequently used to detect such effluent discharges into water bodies and to monitor the dispersion patterns. The monitoring is done either by virtue of temperature differences between the effluent and the receiving waters or by emissivity differences. 8.0-13.5 um wavelength region is most commonly used for temperature mapping as the emissivity of water surface is about 98% provided the angle of incidence of the sensor is normal to the surface. The great advantage of using TIR is that effluent discharges which are not visible either on the ground or by conventional aerial photos can be discerned. Once the effluent locations have been identified by TIR then ground investigations can be initiated to determine the environmental impact. In India, one NRSA study successfully mapped the paper mill effluent dispersal pattern in the Godavari river near Rajahmundry using airborne 11-channel multispectral scanner (Thiruvengadachari, 1983). Public health water quality aspect requires information on bacterial counting, which is not possible by remote sensing but it may provide information about the dispersion from point of bacterial input (Thiruvengadachari, 1983). Radioactive conditions may develop in water as a result of induced particles that have been contaminated from naturally occurring radioactive sources. This type of pollution can be best monitored by gamma ray spectrometer (Meyer and Welchy, 1975) Development of regression models based on remotely sensed data for mapping chlorophyll and other water quality parameters has also been reported (Johnson, 1980), Khorram, 1981, and 1985). Khorram (1985) developed regression models to represent best relationship between salinity, turbidity, total suspended solids and chlorophyll's concentrations and the corresponding mean radiance values from Landsat MSS data for San Francisco Bay and Delta. Good correlation was found to exist between simulated and observed values. Also it is now possible to couple hydrodynamic models with digitally processed satellite data (Smith, 1985).

Turbidity and algal pigment were successfully modeled for inland lakes in south east Australia (Carpenter and Carpenter 1983). Dwivedi and Narain (1987) used atmospherically corrected TM bands 1 and 2 to develop a relationship for estimating the concentration of phytoplankton pigment. With their regression equation they were able to map the concentration of the pigment for an area of the Arabian Sea off Azhikal on the west coast of India.

3.2.4 Water Management in Command Areas

Water management in command areas requires to be given serious attention in view of the disappointing performance of our irrigation projects despite huge investments. Miserably low operating efficiency and incommensurate yields pose major concern. Remote sensing can play a useful complimentary role in managing the land and water resources of command areas to maximise the production. A comprehensive review of remote sensing applications of water management in command areas can be seen in Mistry and Sahai (1983).

Multispectral satellite imagery in near infrared bands particularly (0.75 - 1.0 μm range) are ideal for inventorying of surface water bodies like ponds, tanks and reservoirs. An inventory of the location, distribution and areal extent of the surface bodies would help assess the availability of water especially for semi arid and arid regions where surface water is the primary source of irrigation. Moreover, assessment can be made for alternative sources, rescheduling demand and supply of reservoir water during drought spells. The assessment of irrigation potential under various irrigation waterbodies in the beginning of the agricultural season would facilitate formulating suitable cropping programmes. Monitoring of these sources over the season would help in achieving the desired and targeted level of irrigation.

Conjunctive use planning of surface and ground waters can be done using the remotely sensed information on surface water assessment in conjunction with ground based data on ground water availability. This would permit development of conjunctive use models for land water allocations.

The waterspread area of a reservoir can be obtained using satellite data to a reasonable level of accuracy. Furthermore, satellite imagery derived rainfall forecasting and estimation would provide data on rainfall in catchment and command areas. This would facilitate prediction of inflow into the reservoirs using rainfall runoff relationships and computation of irrigation water requirements in the command area respectively. Crop types and average information could be obtained using remotely sensed data. All these information would provide data for reservoir optimization models for determining the reservoir operating water release policy for various downstream uses including irrigation. During flood periods, unmanned DCPs would transmit data on rainfall and river stages via satellite which can be used as an input in reservoir regulation models for scheduling water releases in order to minimise damage.

Management of water supplies for irrigation in command areas is a critical problem to tackle with vis-a-vis limited quantities. This requires information on total demand and the distribution of demand for irrigation in command areas. Moreover the vastness of areas involved, time constraints and yearly changes demand fast inventory of the situations. With more area being brought under irrigation, crop monitoring also becomes essential for estimating agricultural production and efficient planning of watermanagement. It is in all these, remote sensing can be looked upon as an aid in planning and decision making. The usefulness of remote sensing techniques in inventory of irrigated lands, identification of crop types, their extent and condition and production estimation has been demonstrated in various investigations.

The identification and acreage of crops is also necessary because of the variations in their water requirements. The idea behind identification of irrigated lands is usually to make some kind of estimates or projection of water use or water demand. Also this type of information can be used as an input for computerised models of ground water aquifers (Williams and Poracsky, 1979). The identification and acreage of crops and their monitoring through their growth stages permit forecast and estimation of crop production. This would help evaluate the performance of irrigation projects.

Salinity and alkalinity are some of the major land degradation processes that restrict the economic and efficient utilisation of soil and land resources in command areas. The soil salinisation is often linked with waterlogging. Reliable and accurate mapping of areas affected by these processes with their location and extent can be extremely useful in chalking out suitable water management strategies and also to undertake remedial measures to prevent their advancement. Remote sensing techniques have shown great scope for providing a quick inventory of waterlogged, saline and alkaline soils and their monitoring. The areas that are not yet waterlogged but have an early potential for waterlogging could also be delineated through the use of remote sensing.

Irrigation scheduling of crops is not only a very important component of any irrigation programme for efficient use of available water but also necessary for optimal crop productivity. Irrigation water can be optimised by a thorough survey of soil moisture and crop condition over a wide area so that the crop water requirement could be estimated and irrigation scheduling planned accordingly. It has been shown that improvements can be achieved in the existing system by judiciously combining the remotely sensed assessment of crop canopy conditions with the soil and meteorological information (Jackson et al.

1980). The measurement of temperature and spectral reflectance of the crops is possible through remote sensing techniques. The temperature is related to plant stress while the reflectance is correlated with crop cover and density, both of which are in turn related to actual ET.

4.0 REMOTE SENSING APPLICATIONS IN SNOWMELT RUNOFF ESTIMATION

4.1 ROLE OF REMOTE SENSING IN SNOWMELT RUNOFF ESTIMATION

In India during summer months, rivers rising in the Himalayas are substantially fed by snowmelt runoff. Periodic snow monitoring is essential in assessing the snow melt runoff likely to occur. Predicting snowmelt runoff for either water supply or flood warning is a major task for hydrologists in many parts of the world. Accurate and timely prediction of snowmelt runoff is necessary for efficient reservoir management and planning the distribution of water. Certain parts of the world are habitually plagued by flooding from rapidly melting snow. Prediction of peak flow rates and timing are necessary to provide adequate warning and emergency programmes.

Conventional methods have serious limitations in the study of dynamic processes like snow and its monitoring because of inaccessibility. Considering the vastness of snow clad watersheds, aerial surveys are expensive and of little use. Under the circumstances, satellite remote sensing has a vital role to play in snow monitoring. The areal extent of snow cover, elevation of the snowline in mountainous areas, ablation of snow cover due to rain-on-snow events or rising temperatures, identification of wet snowfalls and snow depth to an extent are some of the features that have been reported to be recognised in satellite data. These data can provide near real-time snow cover maps for the computation of snow-melt runoff. Satellite derived snow cover assessment is being extensively used as an important input in snow-melt runoff prediction models to assist in multi-purpose reservoir operation. It has been shown that satellite remote sensing has the capability to give snow cover area (SCA) estimates with an accuracy of 93% or better down to the scale of individual pixels; also highly accurate positioning of snowline is possible(Barret and Curtis, 1982). These estimates can be used to update position on depletion curves.

4.2 SNOW PROPERTIES

Snow is defined as falling or deposited ice particles formed mainly by sublimation (UNESCO/IASH/WMO, 1970). Garstka (1964) describes snow as the solid form of water which grows while floating, rising or falling in the free air of the atmosphere. Snow is a porous, permeable aggregate of ice grains. According to another definition (GHO, 1982), snow is solid precipitation composed of ice crystals, falling in the air or deposited on the ground.

Fresh snow (new snow in many other languages) is freshly deposited snow which has not been subjected to compaction or metamorphism. The depth of fresh snow is defined as referring to snow fallen in the last 24 hours. However, fresh snow can already be partially compacted if there is a strong wind during snowfall. In new snow, the original shape of crystals is still recognizable. After deposition, metamorphism sets in and old snow consists of rounded or angular grains.

Firn is snow which has existed through at least one summer season and is carried over to the next winter. Alpine firn originates in conditions of repeated melting and refreezing while polar firm is created without appreciable melting.

The difference between all types of snow on the one hand and ice on the other hand is that snow has a connected system of air pores. Ice has air enclaves or closed air pores and a density exceeding 0.82 g cm^{-3}.

Snow depth is the vertical distance from the ground to the surface of the snow cover. The thickness of snow cover should not be confused with the snow depth because it is measured perpendicularly to the slope.

Water equivalent of snow is the vertical depth of a water layer which would be obtained by melting the snow cover.

The density of snow is hydrologically a very important property since it enables the depth of snow to be converted into the water equivalent. It can be expressed as the mass per unit volume(g cm^{-3}). The density of snow increases with its age. This process can be accelerated by strong wind, warm temperature (Diamond and Lowry, 1953) and intermittent melting. However, time appears to be a dominant factor so that it is possible to derive a simple approximate relationship as given by Martinec, 1977:

$$\rho_n = \rho_0(n+1)^{0.3}$$

where ρ_0 is 0.1 g cm^{-3}, which corresponds to the average density of new snow and ρ_n is the snow density after n days.

Albedo is a property of snow especially suitable to be remotely sensed. It is the ratio of the reflected to the incoming global radiation. It amounts to 90% or even more for a freshly fallen snow cover and drops below 40% if the snow surface is weathered and dirty. Values as low as 20% have been reported on an avalanche deposit. Consequently, fresh snow is easily recognized on the satellite imagery while old snow cover may at times look darker than certain snow free surfaces. Thus, a remotely sensed albedo can serve as an approximate index of the density of the top snow layer.

The heat of fusion of ice is 79.7 cal per gram which means that a heat gain of about 80 calories per 1 cm^2 melts a depth of 1 cm of water from pure ice at 0°C.

The thermal quality of snow is the ratio of the amount of heat required to produce a given volume of water from snow to the amount of heat required to melt the same volume of water from pure ice at 0 C. The thermal quality has been used to characterize the varying conditions of a snowpack.

Snowmelt by warm rain can be calculated as follows

$$M = P_r \frac{T_r}{80}$$

where M is the depth of water melted by rain in mm , P_r is the rainfall depth in mm, T_r is the temperature of rain in °C (which can be replaced by the wet bulb temperature) and 80 is the ratio of the heat of fusion of ice to the specific heat of water in C (in terms of units, 80 = 80 cal g^{-1}/1 cal g^{-1} °C^{-1}).

4.3 MEASUREMENT OF SNOW PARAMETERS USING REMOTE SENSING

Snow is a form of precipitation, but, in hydrology it is treated somewhat differently because of the lag between when it falls and when it is involved in other hydrologic processes like runoff, groundwater recharge etc. The hydrologic interest in snow is mostly in mid-to higher latitude and in mountainous areas where a seasonal accumulation of a snowpack is followed by an often lengthy melt period that sometimes lasts months. During the accumulation period there is usually little or no snowmelt. Precipitation falling as snow (and sometimes rain) is temporarily stored in the snowpack until the melt season begins. The hydrologist generally wants to know how much water is stored in a basin in the form of snow. Historically, snow data have been obtained manually by means of snow courses, which are extremely labour intensive, expensive and potentially dangerous. Even when available, snow course data represent only a point and, at best, can only be used as an index of available snow water content.

Remote sensing offers a new and valuable tool for obtaining snow data for predicting snowmelt runoff. Snow cover is one of the most readily identifiable measures of water resources from aerial photography or satellite imagery. Present operational satellite systems are limited to determining only the area of snow cover while depth or snow water equivalent cannot be measured directly by these systems. All regions of the electromagnetic spectrum can provide useful information about the snowpack and its condition. Ideally, we would like to know the areal extent of the snow, its water equivalent, the grain size, density and presence of liquid water. Certain regions of the spectrum can be used to measure individual properties.

The water content of some snowpacks can be measured with low-flying aircraft carrying sensitive gamma radiation detectors. This method takes advantage of the natural emission of low-level gamma radiation from the soil. Naturally occurring radioisotopes of potassium, uranium and thallium can be found in a typical soil. Aircraft passes over the same flight line before and during snow cover and measure the attenuation resulting from the snow layer which is empirically related to an average snow water equivalent for that site (Carroll and Vadnais, 1980). This approach is limited to low aircraft altitudes (approximately 150m) because the atmosphere attenuates a significant portion of the radiant energy. This restriction effectively limits the use of gamma detection to relatively flat areas. Because of safety considerations it cannot be used in mountainous areas. Also, this approach has been limited for the most part to non-forested reas because the effect of forest biomass is to attenuate the radiation signal (Glynn et al., 1988).

The albedo of the snow surface is the property most easily measured by remote sensing. Typically, new snow will have an albedo of 90% or more whereas older snow that has been weathered and has accumulated dust and litter can have an albedo as low as 40% (Foster et.al,1987). The reflectivity depends upon snow properties such as the grain size and shape, water content, surface roughness, depth and presence of impurities. Reflectivity of new snow decreases as it ages in both the visible and infrared regions of the spectrum; however, the decrease is more pronounced in the infrared region caused by the increasing grain size of the snow which results from melting and refreezing. For the most part, decreased reflectivity in the visible region can be attributed to contaminants such as dust, pollen and aerosols. Snow can readily be identified and mapped with the visible bands of satellite imagery because of its high reflectance in comparison with no-snow areas.

Determination of density changes of snow and the presence of liquid water in the snow are very important to hydrologists because they are a common signal of incipient melt. The presence of liquid water in the snow does not change the spectral reflectance of snow. However, the process of metamorphosis that occurs during the snow season and is accelerated as the melt season approaches does have an effect on the albedo, primarily through the increase in the crystal size of the snow grains and through the accumulation of litter on the snow surface. Dozier et al.(1981) have reported a study of how satellite data in the near infrared region can be used to estimate snow grain size, at least qualitatively. Using NOAA-6 AVHRR data collected over lake Winnipeg, Canada, the authors attributed the differences in measured albedo to be primarily the result of increased grain size. It was also concluded that a satellite with a spectral response farther out into the infrared region (1.0-1.2 µm) instead of (0.7-1.0 µm) would be more sensitive to grain size.

Thermal data are perhaps the least useful of the common remote sensing products for measuring snow and its properties. In order to determine snowpack temperatures, the spectral emissivity of the snow must be known. Thermal data to some extent can be useful for helping identify snow/no-snow boundaries. Thermal infrared data are also useful for discriminating between clouds and snow with AVHRR data because the 1.57-1.78 µm band is not available on this sensor.

Microwave remote sensing offers great promise for future applications to snow hydrology. This is because the microwave data can provide information on the snowpack properties which are of maximum interest to hydrologists. These can be snow cover area, snow water equivalent (or depth) and the presence of liquid water in the snowpack which signals the onset of melt (Kunzi et al., 1982). The microwave potential for snow is based on the sensitivity to the presence of even minute quantities of liquid water in the snow which results in drastically different dielectric constants of the snowpack. Many of the microwave measurements of snow properties have been conducted with truck and aircraft experiments. Both the scattering coefficient and the emissivity were found to be sensitive to changes in snow water content and liquid water in the snow. The emission and reflection of microwave radiation exhibit the ability to penetrate not only clouds and most precipitation but also the snowpack itself, at least under certain conditions. However, microwave interaction with snow is extremely complex because snow properties such as depth, dryness, crystal size, liquid water content and the underlying soil all affect the response. Active microwave systems offer complexity in the analysis and interpretation of the data. On the other hand, passive systems may result in more simple data interpretation at the expense of relatively poor spatial resolution.

Passive microwave techniques can be used to identify snow cover under certain circumstances. When the snow is dry, the emissivity at microwave frequencies is relatively low and snow -soil boundaries can be identified with measurements at 18 or 37 GHz. Burke et al.(1984) reported that the 37 GHz microwave data displayed a decrease in brightness temperature as depth increased, but at 18 GHz depth was not a significant factor. Passive microwave research based on theoretical concepts (Hallikainen

1984; Chang et al.1987) has led to simple snow depth algorithms. Change et al.(1987) assumed a snow density of 0.30 and a grain size of 0.35 mm to develop the following algorithm

$$SD = 1.59[T_B(18H) - T_B(37H)]$$

Where SD is the snow depth in centimeters, and T_B (18H) and T_B(37H) are the brightness temperatures for the SMMR 18 and 37 GHz horizontal polarization channels respectively.

4.3.1 SUITABILITY OF DIFFERENT SENSORS

The NOAA data have a distinct advantage for mapping snow over the higher-resolution Landsat, IRS and SPOT satellite in the frequency of observation. Cloud cover can negate the usefulness of a Landsat overpass that occurs only once every 16 days. The pointing capability of SPOT increases its flexibility somewhat but the user is still limited to certain day windows of observation. For most hydrologic applications, the compromise made in accepting the coarser spatial resolution as the price to pay for more frequent observations is not serious. With 1 km NOAA data, Odegaard et al. (1979) have reported using digital techniques on basins as small as 20 km. For smaller basins, Landsat, IRS, SPOT or as an alternative, low-level aircraft flights data would have to be used. The Landsat MSS (80m) data can be used on basins as small as 10 km and the IRS, SPOT or Landsat(TM) data can be able to be used in basins as small as 2-5 km (Rango 1983).

4.3.2 MISINTERPRETATION FACTORS

The aerial extent of snow cover can be determined through various remote sensing techniques. However, when mapping snow cover, there are several possible features of the imagery which must be considered in order to prevent misidentification of snow or no-snow areas. Some of these are described below:

a) Cloud tops exhibit a very bright reflectance in the visible bands that is often indistinguishable from snow. Differentiating between clouds and snow is one of the major problems in the use of satellite data for snow mapping. Snow can be distinguished from clouds by using a near infrared channel around 1.6 um because the reflection of the clouds will be brighter in this region but the snow will be dark (Crane and Anderson 1984; Dozier 1984).

b) Forested areas can consist of everything from dense conifers to less dense deciduous forests to sparse range type vegetation. The reflectance from these areas will be considerably darker than non-forested areas even with substantial depths of snow because the snow will tend to filter through the forest canopy. The challenge is to determine the snow covered areas when they may not be directly detectable. This generally requires a great deal of experience and familiarity with the area and the use of all concomitant information available (i.e. land use surveys, topographic maps, non snow imagery etc.).

c) In shadow areas, snow may be distinguished from rocks or soil by selecting a threshold brightness for automated discrimination (Dozier and Marks 1987).

d) During the melt period, highly reflecting bare rock may be difficult to distinguish from late season snow. As above, summer imagery and topographic maps, as well as vegetation patterns, can help in the differentiation.

4.4 SNOWMELT RUNOFF ESTIMATION

Snowmelt runoff procedures using remote sensing have followed two distinct paths-an empirical approach and one based on modeling. The choice of approach depends somewhat on the available data and to a great extent on the detail in output desired. Each approach is discussed below.

Historically, data from snow courses have been used by hydrologists for their predictions with forecast models that have typically been of the multiple regression form

$$Y = a + bX1 + cX2 + dX3 + \dots$$

where Y is the volume yield or runoff for the forecast period, and X1, X2 etc. are the snow water contents from each snow course. The coefficients a,b etc. are developed from empirical data. Although useful and 'state of the art', these models have serious limitations. They are only valid for the basins for which they were developed and for the range of data used in the regression equations. In addition, snow course data are point measurements which at best serve only as indices of the snow in a basin. Snow course data are time consuming and expensive to obtain and are unavailable in many of the mountainous snow basins in the world.

The most direct approach is to relate the satellite snow cover on a given date to the seasonal runoff. Snow cover area is not an ideal description of a snowpack. However, research has demonstrated that a good relationship exists between runoff and snow cover area. In an early application of satellite data, Rango et al.(1977) used simple photointerpretation techniques to map snow cover areas in the Indus and Kabul river basins in Pakistan. Their approach was to use a simple regression between the percentage of snow cover in the basins from 1 to 20 April and the April-July streamflow. These results demonstrated the usefulness of satellite derived runoff estimates, especially for remote and data sparse regions of the world. This work was extended by Dey et al., 1983 with an additional 6 years of data. The additional data improved the regression for the Kabul River but decreased it for the Indus River. Such results point out the inherent weakness of simple regression models representing complex processes. On the other hand, in data sparse regions there are seldom many alternative approaches.

NASA, in cooperation with several federal and state water resource agencies in the USA, conducted an applications systems verification and transfer (ASVT) study on the effectiveness of satellite derived snow cover data for operational forecasting (Rango 1980). Both empirical and short term models were tested. Three years of testing in three California basins resulted in a reduction in the forecast errors between 10 and 15%. In modeling studies of the Boise River in Idaho, USA, the use of satellite snow cover data reduced the 5-day forecast error by 9.6%. These results were extrapolated to estimate the benefits that would be possible through increased forecast accuracies in the 11 western states in the USA. Based on a 1980 dollar and an assumed 6% improvement in forecast accuracy, the benefits would include more than 10 million dollars from improved hydropower predictions and 28 million dollar in irrigation water forecasting. A benefit/cost ratio was calculated to be an impressive 75:1 (Castruccio et al., 1980).

The use of snow cover area alone can provide a useful runoff parameter, but annual differences in snowpacks limit its universal usefulness. More promising results have been obtained using a concept known as the dimensionless basin snow cover depletion accumulation curves. Use of dimensionless snow cover area (snow cover area on a given date normalized by the total basin area) and dimensionless accumulated runoff (accumulated runoff at the date normalized by the total seasonal runoff) effectively compensates for the season to season variations in snowpack depth and water content and weather.

Snow cover depletion curves are another empirical approach that use satellite derived snow cover area. Depletion curves of snow covered areas continuously indicate the gradual areal diminishment of the seasonal snow cover during the snowmelt season. They are derived by connecting points of a known snow coverage. A long interval between the measurements increases the uncertainty and risk of errors in drawing these curves. The snow cover must be monitored again in each new year because the depletion curves always take a different course depending on the initial snow reserves, meteorological conditions and intermittent precipitation during the snowmelt season. The typical shape of depletion curves can be approximated by the equation:

$$S = \frac{100}{1 + e^{bn}}$$

where S - SCA, % can be obtained from satellite imagery

b - a coefficient and

n - number of days before(-) and after(+) the date at which S = 50%

The rate at which the snow cover becomes depleted provides an index which is inversely related to the snow water equivalent and snow-melt runoff. The shape of the depletion curves tends to be relatively constant, but their location will be displaced from year to year depending on snow, climatic conditions and the snowpack water content. In low snowpack years the melt begins earlier and the runoff is reduced and vice versa. The snow cover data for each day can be estimated from the depletion curves and used as input to the snow-melt model.

A number of models for predicting and simulating snowmelt runoff have been developed or have been modified from existing models to incorporate satellite derived snow cover data. The California Department of Water Resources has taken an existing hydrologic model for the Kings River basin, removed the original snowmelt component and replaced it with a procedure based on the snow cover area (SCA). The model is based on the premise that snowmelt does not occur until the snow has been primed. Experience has shown that this is an elevation dependent phenomenon. Thus, the basin is delineated into specific elevation zones known as the elevation of prime. The basic empirical relationship for computing snowmelt at a given elevation of prime in this basin is

$$E_p = 3.1 \times K \times (1.009)^D + 0.017 \times K \times (T1 - 100/K)$$

where E_p is the elevation of prime (100 ft(30.5 m)) which is the maximum elevation at which snowmelt can occur, D is the number of days since 1 February, T1 is the decayed annual temperature taken as the degree days at 7000 ft. (2135 m) since 1 January and using a decay factor of 0.96 , and K is a variable that affects the elevation of prime that is related to the snow water content.

A fairly complex sub alpine model has been developed by the US Forest Service to simulate daily streamflow (Leaf and Brink 1973). The model accounts for winter snow accumulation, a short wave and long wave radiation balance, snowpack condition and the resulting snowmelt. When applying the model, the basin is divided into as many as 25 subunits of relatively uniform aspect, slope and cover. During the snowmelt season the model is updated by real time snow telemetry data and satellite snow cover area data.

In the Pacific north western United States, satellite snow cover data are being used operationally in the streamflow synthesis and reservoir regulation (SSARR) model. After initializing the model, the model parameters (snow cover area, soil moisture, initial melt rate, base flow and seasonal volume) are adjusted until the forecast and measured hydrographs agree within a predetermined tolerance. The snow cover area data are very important especially during the initial adjustment phases.

The snowmelt runoff model (SRM) for simulating snowmelt is one of the better known and most thoroughly tested empirical models available. SRM has been developed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major component of the annual water balance. SRM is a degree day model that uses the percentage of the basin or elevation zone covered by snow as the primary input. With the advent of satellite snow cover data in the 1970s, the model was shown to be usable in larger basins. Using Landsat data, SRM has been successfully run for various sized basins in Europe and the United States (Rango and Martinec 1979; Rango, 1980; Rango, 1983; Martinec and Rango 1986). Kawata et al.(1988) have shown how Landsat MSS data can be used with the SRM to predict runoff and manage water levels in the Sai River dam near Kanazawa, Japan. The model is a good compromise between the amounts and types of data usually available.

Applications of SRM usually involve simulating snowmelt runoff for basins with some hydrologic data, specifically measured discharge and one or more meteorological stations that measure precipitation and temperature. The minimum required inputs to the model consist of periodic snow cover area and daily temperature and precipitation. Each day during the snowmelt season, the water produced from snowmelt is computed and superimposed on the base flow to yield the total basin discharge according to the equation:

$$Q_{n+1} = c_n[a_n(T_n + \quad T_n)S_n + P_n]\mathrm{x}A(0.01/86400)(1-k_{n+1})+Q_n k_{n+1}$$

where Q_{n+1} is the average daily discharge (m^3s^{-1}), c the runoff coefficient expressing the losses as a ratio (runoff/ precipitation), a the degree day factor (cm $C^{-1}day^{-1}$) indicating the snowmelt, depth resulting from 1 degree day, T the number of degree days (C day), T the adjustment by temperature lapse rate necessary because of the altitude difference between the temperature station and the average hypsometric elevation of the basin or zone, S the ratio of the snow covered area to the total area, P the precipitation contributing to runoff (cm) (a preselected threshold temperature, T_{crit} determines whether this contribution is rainfall and immediate), A the area of the basin or zone(m^2), (0.01/86400) the conversion from cm m^2 day^{-1} tom^3s^{-1},k the recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall, (k =

$(Q_{m+1}/Q_m)(m,m+1)$ are the sequence of days during a true recession flow period), and n the sequence of days during the discharge computation period. The above equation is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 h. As a result, the number of degree days measured on the nth day corresponds to the discharge on the (n + 1) the day. Different lag times will result in the proportioning of day n snowmelt between discharges occurring on days, n , n+1 and possibly n+2.

There are a number of steps a user must take before the model can be run. The user must determine the physical characteristics of the basin and select the model variable and parameters. After the basin boundary has been defined by the stream gauge site, the basin must be subdivided into elevation zone separated by about 500 m. The elevation zones are created in recognition that snowmelt is very elevation dependent and thus the model is applied to each of the zones to distribute the rate of snowmelt spatially. A hypsometric curve is developed for the basin and the mean elevation for each zone is determined graphically. Temperature and precipitation would be measured within the basin and at each mean hypsometric elevation for each zone. Seldom is this the case is real basins. Usually these data must be extrapolated from one or more stations.

The model can be adjusted to any wide elevation range of a basin in the following general form:

$$Q_{n+1} = (I_{AN} + I_{BN} + I_{CN})\ (1 - k_{n+1})\ Q_n k_{n+1}$$

where I - input from snow-melt and precipitation as outlined in earlier equation, computed separately for elevation zones A,B,C or any number of zones which may be necessary. With snow covered areas read off the depletion curves derived using satellite data, the temperature and precipitation are the only other variables required to run the model. Snow cover data are used to construct snow cover depletion curves for each zone of the basin. Usually the snow cover data are plaimetered from remote sensing satellite data. Model parameters include a runoff coefficient, a degree day factor, a recession coefficient and a time lag. Each of these can be chosen and modified by the user to adjust the simulation results.

Typical applications usually require several iterations that involve changes in parameters or the subdivision of the basin into equal elevation zones. Depending on how good the initial simulations were and what type of discrepancies exist between the measured and simulated hydrographs, the user chooses different strategies to improve the simulations. SRM has been tested over a wide range of basin sizes and areas of the world. It has been found that the model has done quite a good job of simulating the measured flows. SRM has been considered in the World Meteorological Organisation project on the intercomparison of models of snowmelt runoff (Rango 1985). The 11 models (including SRM) were testing using six standard data sets compiled by the WMO (1982). The results confirmed previous testing of the model which indicated universal usage. SRM is being modified for forecasting (Rango and Van Katwijk 1990).

Another model that is perhaps more physically based than SRM has been modified to use remote sensing data of the snowpack. The PRMS (precipitation-runoff modeling system) (Leavesley et al.1983) is a modular, distributed parameter watershed model which treats the snowpack as a two layer system. Heat and mass (rain or snow) are transferred across a 3-5 cm surface layer to the main body of the snowpack, which is maintained and modified both as a water reservoir and a heat reservoir.

Snow hydrology is one of the first areas in water resources to make effective use of remote sensing data and it appears to be able to take advantage of future development as they become available. The parallel development of understanding sensor response and modeling is a major factor in the present state of the field.

CONCLUSION

Remote sensing, a recent spin off man's space expedition, has emerged as a powerful tool of inventorying and surveying of water resources. Most of the progress made in the past decade has shown clearly that remote sensing through its spatial, spectral and temporal attributes can provide synoptic and repetitive observations in order to obtain highly useful quantitative measures of the area, shape, length and related attributes of hydrologic features examples of which include determination of snow cover extent, drainage basin geometry and hydrogeological surface features related to groundwater exploration.

Remote sensing techniques are particularly useful in Indian conditions. India is a very large country stretching from Himalayas to the sea and it experiences all the tastes of different seasonal calamities. Floods and droughts come to this country hand in hand and most of the water resources depend on the monsoon. For such a large area, it is very difficult to have a dense network of observatories. So remote sensing can play a crucial role in the proper and judicious monitoring and management of water through its spatial and temporal attributes.

Snow and ice is a major component of water resources and it is hydrologically important in India because of the presence of the mighty snow clad Himalayas in the northern boundary. In India, snow melt runoff occurring mostly during April, May and June months constitutes a substantial part of the water resources of the rivers rising in the Himalayas. Important projects like the Bhakra depend heavily on snow melt runoff for power generation during summer. Therefore correct information about the snow cover conditions in the watersheds and about the volume of snow melt runoff likely to occur is of great importance to managers of water resources, especially to those responsible for operation of multipurpose reservoirs. With the advent of satellite remote sensing mapping and monitoring, it is now becoming possible to rapidly provide synoptic, repetitive and reliable, timely information on extensive snow cover areas for making reasonably accurate snow melt runoff studies.

Due to inadequate frequency of the satellite data, satellite data applications related to direct measurement of hydrological parameters like rainfall, evapotranspiration, snow depth, rainfall, runoff has met with limited success. In most cases, remote sensing does not replace conventional data, instead it complements these data by permitting interpolation between or extrapolation beyond conventional data over larger regions. This capability can increase confidence in the input to water management and hydrologic models or operational procedures.

Continuing development of new remote sensing systems and improvements in the spatial, spectral, radiometric and temporal measurement capabilities would considerably enhance the use of remote sensing for water resources development and management as well as hydrologic studies. It seems safe to predict that as a result of more pressure being placed on our finite water resources, the remote sensing technology would be increasingly sought for with the passage of time and eventually become an integral part of operational procedures.

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