Application of remote sensing to hydrology including ground water

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Technical Documents in Hydrology

International
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Scientific and Cultural Organization

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APPLICATION OF REMOTE SENSING TO HYDROLOGY INCLUDING GROUND WATER

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PREFACE

Although the total amount of water on Earth is generally assumed to have remained virtually constant during recorded history, periods of flood and drought have challenged the intellect of man to have the capacity to control the water resources available to him. Currently, the rapid growth of population, together with the extension of irrigated agriculture and industrial development, are stressing the quantity and quality aspects of the natural system. Because of the increasing problems, man has begun to realize that he can no longer follow a "use and discard" philosophy -- either with water resources or any other natural resource. As a result, the need for a consistent policy of rational management of water resources has become evident.

Rational water management, however, should be founded upon a thorough understanding of water availability and movement. Thus, as a contribution to the solution of the world's water problems, Unesco, in 1965, began the first worldwide programme of studies of the hydrological cycle -- the International Hydrological Decade (IHD). The research programme was complemented by a major effort in the field of hydrological education and training. The activities undertaken during the Decade proved to be of great interest and value to Member States. By the end of that period a majority of Unesco's Member States had formed IHD National Committees to carry out the relevant national activities and to participate in regional and international cooperation within the IHD programme. The knowledge of the world's water resources as an independent professional option and facilities for the training of hydrologists had been developed.

Conscious of the need to expand upon the efforts initiated during the International Hydrological Decade, and, following the recommendations of Member States, Unesco, in 1975, launched a new long-term intergovernmental programme, the International Hydrological Programme (IHP), to follow the Decade.

Although the IHP is basically a scientific and educational programme, Unesco has been aware from the beginning of a need to direct its activities toward the practical solutions of the world's very real water resources problems. Accordingly, and in line with the recommendations of the 1977 United Nations Water Conference, the objectives of the International Hydrological Programme have been gradually expanded in order to cover not only hydrological processes considered in interrelationship with the environment and human activities, but also the scientific aspects of multi-purpose utilization and conservation of water resources to meet the needs of economic and social development. Thus, while maintaining IHP's scientific concept, the objectives have shifted perceptibly towards a multidisciplinary approach to the assessment, planning, and rational management of water resources.

As part of Unesco's contribution to the objectives of the IHP, two publication series are issued: "Studies and Reports in Hydrology" and "Technical Papers in Hydrology." In addition to these publications, and in order to expedite exchange of information, some works are issued in the form of Technical Documents.

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ACRONYMS AND ABBREVIATIONS USED IN REPORT

AES	Atmospheric Environment Service (Canada)
AID	Agency for International Development (USA)
AISC	Assessment and Information Service Center (NOAA-NESDIS, USA)
ARS	Agricultural Research Service (USDA-USA)
ASP	American Society of Photogrammetry (USA)
AVHRR	Advanced Very High Resolution Radiometer
AWRA	American Water Resources Association (USA)
BIAS	Bristol InterActive Scheme
CCRS	Canadian Center for Remote Sensing
CCT	Computer Compatible Tape
CNR	National Council for Research (Italy)
CPUOS	Committee on the Peaceful Uses of Outer Space
CREAMS	Chemicals Runoff and Erosion from Agricultural Management Systems Model
CRSDTH	Committee on Remote Sensing and Data Transmission for Hydrology (IAHS)
CZCS	Coastal Zone Color Scanner - Nimbus (NASA-USA)
DMA	Defense Mapping Agency (USA)
DNR	Department of Natural Resources (exist in many governments)
EARS	Engineering Consultants for Environmental Analysis and Remote Sensing (Delft, The Netherlands)
EARSel	European Association of Remote Sensing Laboratories
ENEL	???(Italy)
EPA	Environmental Protection Agency (USA)
ERIM	Environmental Research Institute of Michigan (USA)
EROS	Earth Resources Observation System (Data Center in USA)
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer
ESSA	Environmental Science Services Administration (now NOAA)
FAO	Food and Agriculture Organization (United Nations HQ in Rome Italy)
FEMA	Federal Emergency Management Administration (USA)
GOES	Geostationary Operational Environmental Satellite (NOAA-USA)
GSFC	Goddard Space Flight Center (NASA-USA)
HCMM	Heat Capacity Mapping Mission (NASA-USA)
HRAP	Hydrologic Rainfall Analysis Project (National Weather Service,NOAA-USA)
HYDROSAT	Proposed satellite to be dedicated to hydrologic uses
IAHS	Internation Association of Hydrologic Sciences (IUGG)
ICW	Institute for Land and Water Management Research (The Netherlands)
IEEE	Institute of Electronic and Electrical Engineers (USA)
IFC	Instituto per la Geofisica Della Litosfera (Italy)
IHP	International Hydrologic Program (Unesco)
IR	InfraRed
IRIS	Infrared Interferometer Spectrometer
IRLS	Infrared Line Scanner
ISDGM	Instituto per lo Studio Della Dinamica Delle Grandi Massa (Italy)
ISRO	Indian Space Research Organization
ITC	International Training Center (Enschede, The Netherlands)

ACRONYMS AND ABBREVIATIONS USED IN REPORT (continued)

ITOS	Improved TIROS Satellite
IUGG	International Union of Geodesy and Geophysics
JRC	Joint Research Center of the European Economic Communities HQ (Ispra, Italy)
MRSO	Mining Research and Service Organization (Taiwan)
MSS	MultiSpectral Scanner
NAPL	Related to Saskatchewan gov't??
NASA	National Aeronautics and Space Administration (USA)
NCC or NCDC	National Climatic (Data) Center (NESDIS-NOAA-USA)
NESDIS	National Earth Satellite and Data Information Service (NOAA-USA)
NESS	National Earth Satellite Service (now NESDIS)
NLR	National Lucht-en Ruimtevaartlaboratorium (The Netherlands)
NOAA	National Oceanic and Atmospheric Administration (Dept. of Commerce-USA)
NOS	National Ocean Survey (NOAA-USA)
NRSA	National Remote Sensing Agency (India)
NVE	Norges vassdrags-og elektrisitetsvesen (The Norwegian Water Resources and Electricity Board)
NWS	National Weather Service (NOAA-USA)
NWSRFS	National Weather Service River Forecast System (NOAA-USA)
ppm	Parts per million
RBV	Return Beam Vidicon (Camera)
Rn	Range
RSC	Remote Sensing Center (Egypt)
RTSN	Real Time Service availability and cost subject to Negotiation
SAC	Space Application Centre, ISRO (India)
SCS	Soil Conservation Service (USA)
SFISAR	Swiss Federal Institute of Snow & Avalanche Research
SURSAT	Project of the Canadian Government
TELL-US	Computer program to estimate evaporation (EARS)
TERGRA	Simulation model to calculate actual evapotranspiration and soil moisture from crop surface temperatures.
TIROS	Television and InfraRed Observation Satellite
TM	Thematic Mapper sensing system associated with Landsat 4 and 5 (NOAA-USA)
TOVS	TIROS Operational Vertical Sounder
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USACOE	US Army Corps of Engineers (USA)
USDA	United States Dept. of Agriculture
USGS	US Geological Survey (Dept. of Interior, USA)
UV	Ultraviolet
VISSR	Visible and Infrared Spin-Scan Radiometer
VITUKI	Research Centre for Water Resources Development (Hungary)
WDCAGSI	World Data Center A for Glaciology (Snow and Ice)
WRD	Water Resources Division (USGS)
WMO	World Meteorological Organization
WWW	World Weather Watch (WMO)

FOREWORD

Within the framework of the second phase (1981-1983) of the International Hydrological Programme (IHP), the Intergovernmental Council of the IHP established a scientific programme, the aim of which is "to increase the capacity of Member States to apply advanced methodologies and technologies to the assessment, development, protection and management of their water resources."

As a part of this scientific programme, the Council recommended the preparation of the report concerning the application of remote sensing to hydrology, including groundwater (IHP-II Project A.1.5).

For the execution of this project, R. K. Farnsworth (USA) was designated by the Council as Rapporteur and E. C. Barrett (UK) and M. S. Dhanju (India) as Co-Rapporteurs.

A meeting with the Rapporteur and the representatives of international organizations took place during the meeting of the IAHS International Committee on Remote Sensing and Data Transmission for Hydrology (June 1981, Denver, USA).

Two meetings with all Rapporteurs and representatives of international organizations took place in Paris (January 1982 and June 1983).

Unesco is much indebted to the Rapporteurs who have prepared this report, as well as to members of international organizations for their assistance.

I. INTRODUCTION

An adequate and continuous supply of water for drinking, agriculture, and industry is basic for all societies. Significant deviations from normal water supplies generally bring disaster in the form of drought or flood. To avoid the problems resulting from excesses and shortages of water, societies have invested enormous sums of money and employed hydrologists and civil engineers to develop systems to control and distribute water. With nearly three-quarters of the Earth being covered with oceans, it is not a question of a global shortage of total water, but the challenge is to overcome the uneven distribution of water in space and time on land areas and to supply adequate quality to meet local needs. For example, about 20 per cent of the Earth's land area is classified as arid and an additional 15 per cent is classified as semiarid (Petrov,1976). Here, water has been the limiting factor in the development of agriculture and most industries. Yet, even these dry areas are periodically devastated by floods. The requirement placed on technology is to supply, at an affordable cost, a dependable supply and quality of water where and when it is needed.

Systems to control water supplies have consisted of wells, canals, levees, and dams. Because available information is almost always inadequate, wells have been dug that fail to produce adequate quantities or quality of water, dams have leaked or totally failed, and waste waters have contaminated drinking water. These disappointing results could have been avoided if sufficient hydrologic, geologic, and climatologic information for resource planning had been available.

Conventional hydrological data have generally consisted of point measurements and extrapolations of point measurements to areal estimates by means of mathematical models. The relatively young science of remote sensing attempts to estimate attributes of natural processes (generally, by measuring signals of electromagnetic radiation) some distance removed from the process being measured. This measurement commonly results in an estimate that is effectively an areal estimate of the process. Often these new data, by themselves or merged with existing data, can supply the missing key to effective water resource management.

The purpose of this report is to inform hydrologists and water resource planners, primarily in developing countries, of the general capabilities of remote sensing techniques to obtain hydrologic data. Our intention has not been to review all recent research in this field but to examine remote sensing as a possible aid in operational hydrology in the near to mid-term future. We have assumed that a reader has an understanding of hydrology, or at least some basis on which to make water management decisions.

Chapter 2 begins with a brief discussion on remote sensing: how it works, what equipment is required, what data are really measured, and how remote sensings can be processed to provide hydrologic data. In Chapter 3, most of the hydrologic measurements in general use are listed, and a state-of-the-art assessment is made about remote sensing capabilities to provide useful estimates of each measurement. Questions are raised concerning sampling frequency, data value loss due to acquisition-to-application time delays, uniqueness of some forms of remote sensing data, and practical limitations of data.

Chapter 4 is the heart of the report. Having laid some necessary foundations for remote sensing and hydrology, specific applications are discussed in terms of (1) what is being done or can be done, (2) who is currently using the methods that are presented, and (3) how further details of these methods can be obtained. Some effort is made to describe specific applications of the data since this will dictate what sampling frequencies, accuracies, and precision are desired. These applications have been divided into three classes: hydrometeorology, surface hydrology and hydrogeology. A section is also devoted to integrating data from available acquisition systems for application to the entire hydrological cycle on a regional basis.

Chapter 5 presents general information on several vital topics. These topics include costs involved in acquiring, processing, and applying data, evaluation of results, comparisons of equivalent measurements, problems of making efficient use of data, and suggestions for cooperation within and among user groups to enhance use of the data. Sources for additional information are given, such as:

(a) Significant general texts and manuals on remote sensing.

(b) Educational materials offered by national and international groups promoting remote sensing of water resources.

(c) Scientific journals which emphasize remote sensing applications.

(d) Training courses and manuals.

(e) Source lists of directories of companies and individual professionals involved in remote sensing.

The final chapter gives our appraisal of current problems as a result of personal surveys made of national and international agencies working with remote sensing and our consensus of recommendations for future work.

2. THE NATURE AND PRACTICE OF ENVIRONMENTAL REMOTE SENSING

2.1 Remote sensing defined

The young science of remote sensing depends on "the observation of a target by a device some distance away from it" (Barrett and Curtis, 1982). Thus, it is contrasted with *in situ* sensing, in which measuring devices either touch, or are immersed in, the objects or media under scrutiny. It is important to distinguish between remote sensing and *remote data collection*. The essence of remote sensing lies in the separation between the sensor and what is sensed, *not* in the separation between an *in situ* sensor and a data reception facility. Therefore, neither automatic weather stations nor even stream gauges interrogated by satellites are remote sensing devices, even though the installations may be very "remote" in terms of location from a central data collection point. On the other hand, in true remote sensing, the distance between observing device and target may, but need not be, very great. Astronomy depends exclusively on remote sensing to investigate the deeper recesses of space; medicine employs X-ray cameras to examine inner features of the human body, at most, centimeters distant.

Another distinction of basic importance is that which separates "active" from "passive" remote sensing. In passive operation (which requires simpler equipment), devices merely detect and record the natural energy or force which arrives from the target. In active operation, signals are artificially generated by the remote sensing system under carefully controlled conditions, and then transmitted towards the target. Detection and recording then proceed as before, but with the characteristics of the differences between the transmitted and the return signal as the objects of attention.

Remote sensing devices have been developed to exploit a variety of physical phenomena, including acoustical energy (sound waves), electromagnetic energy (e.g., light waves), and the "force fields" of gravity and magnetism. For hydrological applications, those designed to exploit electromagnetic energy are overwhelmingly the most common and important. Therefore, it is upon electromagnetic remote sensing that we will focus primarily hereafter.

2.2 The physical basis of remote sensing

Electromagnetic radiation is of great significance for remote sensing because it is an energy form which can travel either through a medium (e.g., water bodies, the atmosphere) or a vacuum (e.g., space). Although the true nature of radiation energy is still unclear, enough is known of its behavior for us to be able to exploit it widely for practical purposes. Radiation is *emitted* from all bodies with temperatures above absolute zero. Each radiator emits a signal whose configuration is determined by the physical characteristics of its source. This signal can be described in terms of *wavelength*, *frequency*, or *photon energy*. The accepted classification of *all* radiation types (the "electromagnetic spectrum") is based on these criteria. (See Figure 1.) Radiation is *transmitted* through all bodies and media which are not opaque to it. Commonly, some radiation in transit is *scattered* or back-scattered (reflected) by particulate matter (e.g., dust in the atmosphere), and some is *absorbed* before the ultimate target is reached.

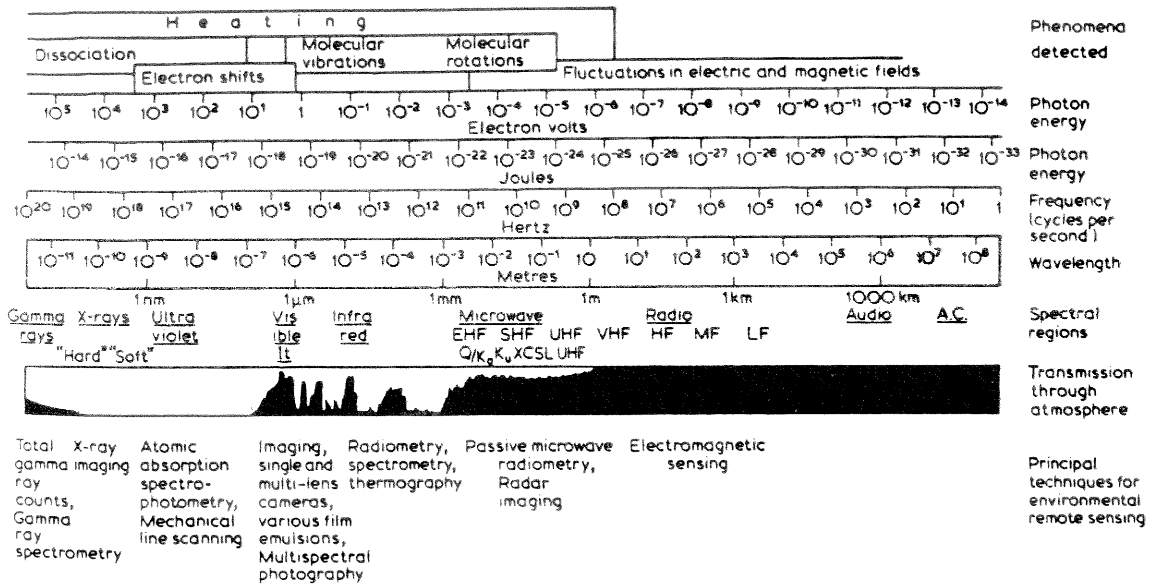


Fig. 1. The electromagnetic spectrum. The scales give the energy of the photons corresponding to radiation of different frequencies and wavelengths. The product of any wavelength and frequency is the speed of light. Phenomena detected at different wavelengths are shown with some of the principal associated techniques for environmental remote sensing. (From Barrett and Curtis, 1982.)

Knowledge of the combined effects of scattering and absorption (expressed in "extinction coefficients") aids in the selection of the most appropriate wave bands for specified remote sensing objectives. For example, for surface observations from aircraft under hazy conditions, infrared is more suitable than color photography, and, for surface investigations from satellites, the preferred choice is through one of the several "atmospheric window" wave bands, in which the atmosphere is relatively transparent. Target absorption is modeled in terms of the comparison between "black bodies" (fully efficient absorbers and emitters at given temperatures) and real objects (always more or less inefficient, and therefore "grey bodies"). If all the radiation incident on the surface of a target is reflected and none is absorbed, this is said to be a "white body."

Sufficient knowledge exists about the behavior of black bodies to enable them to be used as models with which real world objects may be compared, and through reference to which sensor selection and/or design may be geared. Radiation physics tells us that less radiation is emitted from cool than from relatively warmer sources; warmer radiators provide peaks of emitted radiation at shorter wavelengths (higher frequencies, and more photon energy involved) than cooler sources; and emission curves are characteristically negatively skewed, their peaks falling in the lower quartiles of the spectral bands across which their successions spread. (See Figure 2.) However, real radiation sources differ to greater or lesser degree from the simple model behavior at different wavelengths. This complication is both important and useful in the science of remote sensing. Sometimes (e.g., in

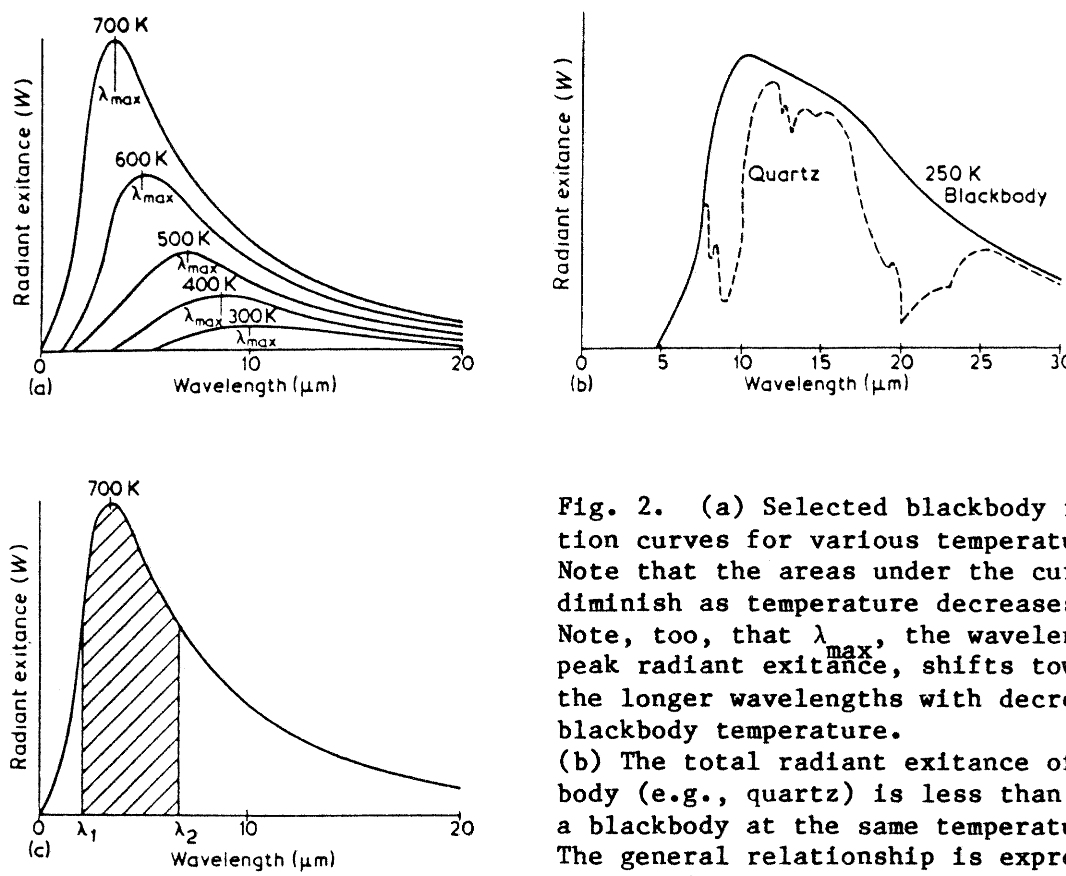


Fig. 2. (a) Selected blackbody radiation curves for various temperatures. Note that the areas under the curves diminish as temperature decreases. Note, too, that λ_{max}, the wavelength of peak radiant exitance, shifts towards the longer wavelengths with decreasing blackbody temperature.
(b) The total radiant exitance of a real body (e.g., quartz) is less than that of a blackbody at the same temperature. The general relationship is expressed by Kirchoff's Law.
(c) One form of Planck's Law of radiation permits the assessment of that portion of the total radiant exitance falling between selected wavelengths, e.g., λ_1 and λ_2. (From Barrett and Curtis, 1982.)

panchromatic air photography), it is enough to record total reflected radiation from a target across a rather wide radiation wave band; other times, comparisons are required between two different wavelength responses (e.g., in the bispectral Surface Composition Mapping Radiometer of Nimbus 5); but often more detailed multispectral information is required so that spectral signatures can be constructed and used to discriminate between different landscape components (e.g., via the Multispectral Scanner on Landsat satellites). The characteristic responses of different rocks, soils, vegetation, etc., can be exploited for terrain classification through the analysis of spectral signature curves. When repeated through time (in "multitemporal monitoring") change detection and evaluation also becomes possible.

2.3 Remote sensing sensors and platforms

Remote sensors in most common use in hydrology can be grouped under five headings. For a more extended discussion, see American Society of Photogrammetry, 1983. These are as follows.

(a) Photographic cameras. These record scenes, usually in the visible and near infrared, through photo-chemical changes in emulsions (carried by flexible film bases) when images are focused on them. Numerous types of cameras are in use, especially in remote sensing using aerial surveys. These include framing, panoramic, strip, and multispectral cameras.

(b) Vidicon cameras. Here, optical images are focused and retained temporarily on photo-conductive surfaces which are then scanned electronically for recording and/or transmission as a continuously variable (analog) electrical signal. Such systems were popular on early Environmental Satellites, e.g., TIROS and ESSA, and the Earth Resource satellites, Landsats 1, 2, and 3.

(c) Scanners. Here, a single detector is used to provide an analog signal of radiation which is incident onto it, while a revolving or oscillating mirror scans the target being sensed. The airborne infrared linescanner (IRLS) is of this type; so, too, are many satellite-borne radiometers including the Landsat MSS, the Scanning Radiometer (SR) and Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) weather satellite series, and the Visible and Infrared Spin-Scan Radiometer (VISSR) of geostationary satellites.

A distinctive scanning instrument consists of an array of detectors which are electrically scanned by adjusting the phases of the returned signal to cause a scanning of the ground. An example is the Electrically Scanning Microwave Radiometer (ESMR) flown on the Nimbus V and VI (NASA, USA).

(d) Spectrometers. In these, incoming radiation is selected and dispersed by means of prisms, gratings, mirrors, or filters to provide multispectral data for detailed spectral signature analysis, (e.g., by the Infrared Interferometer Spectrometer (IRIS) on Nimbus 2), or for vertical profiling of the atmosphere (e.g., by the TIROS Operational Vertical Sounder (TOVS) on operational NOAA weather satellites).

(e) Microwave radars. These, unlike the previous four groups, are active, not passive, radiation sensor systems. Although plans exist for a rainfall radar to be flown on scientific satellites, radars for hydrological applications today are either airborne (for terrain evaluation), or ground-based (for rainfall and severe storm monitoring) systems. The radars are specially useful in cloudy areas because some wavelengths of microwave radiation (unlike visible and infrared radiation) are not significantly attenuated by water droplets in the atmosphere. Various types of radar are available for different types of applications.

Remote sensing platforms include the following wide range:

(a) Ground observation platforms, for very detailed local work (low-level mounts), vehicles (using booms and cherry-pickers), masts and towers. Remote sensing at close range is important for establishing spectral signatures of various objects because individual objects can fill the field of view and atmospheric effects can be essentially eliminated.

(b) Balloons, either tethered or free-flying (up to altitudes of about 30 km). Unfortunately, balloon flight paths cannot be controlled.

(c) Aircraft and remotely piloted vehicles ("drones"). These are in widespread use for topographic survey, hazard monitoring, and disaster assessment (e.g., flooding and associated effects). Piloted aircraft operate up to altitudes of about 15 km; cheap, lightweight drones are used at low altitudes over short distances, e.g., for pipeline surveys.

(d) Rockets. Remote sensing rockets have been flown to altitudes of about 400 km, but their value for surface remote sensing has been limited by the awkward geometrical properties of their images.

(e) Satellites. The use of satellites for remote sensing has grown steadily since 1960; first, through the operation of low altitude polar-orbiting satellites (800-1500 km) (see Figure 3), then through high-altitude equatorial-orbiting satellites at geostationary altitudes (35,400 km). Practical constraints result in tradeoffs between area of imaging, frequency of imaging of individual areas, and the detail (spatial and/or spectral resolution) of the data provided. "Environmental" satellites (observing relatively frequently, e.g., twice daily, but at relatively low spatial resolutions, e.g., 1 km) have contributed to hydrology through depictions of both weather and large-scale surface phenomena; "Earth Resource" satellites (especially Landsat, observing relatively infrequently, i.e., every 16-18 days, but at relatively high spatial resolutions, e.g., from 80 m on the multispectral scanner (MSS) to 30 m on the thematic mapper (TM), have contributed much to the mapping and general monitoring of surface features and conditions. Unfortunately, no dedicated satellite has been designed yet to optimally meet the special needs of the hydrological community.

2.4 Remote sensing data forms and analysis

Remote sensing data may be provided to the would-be user in one or more of the following forms:

(a) Image data, in the form of "hard-copy" films or paper prints. See Figures 4-7.

(b) Analog data, continuously variable electrical signals recorded on magnetic tape, and representing radiation variations along scan lines or selected traverses.

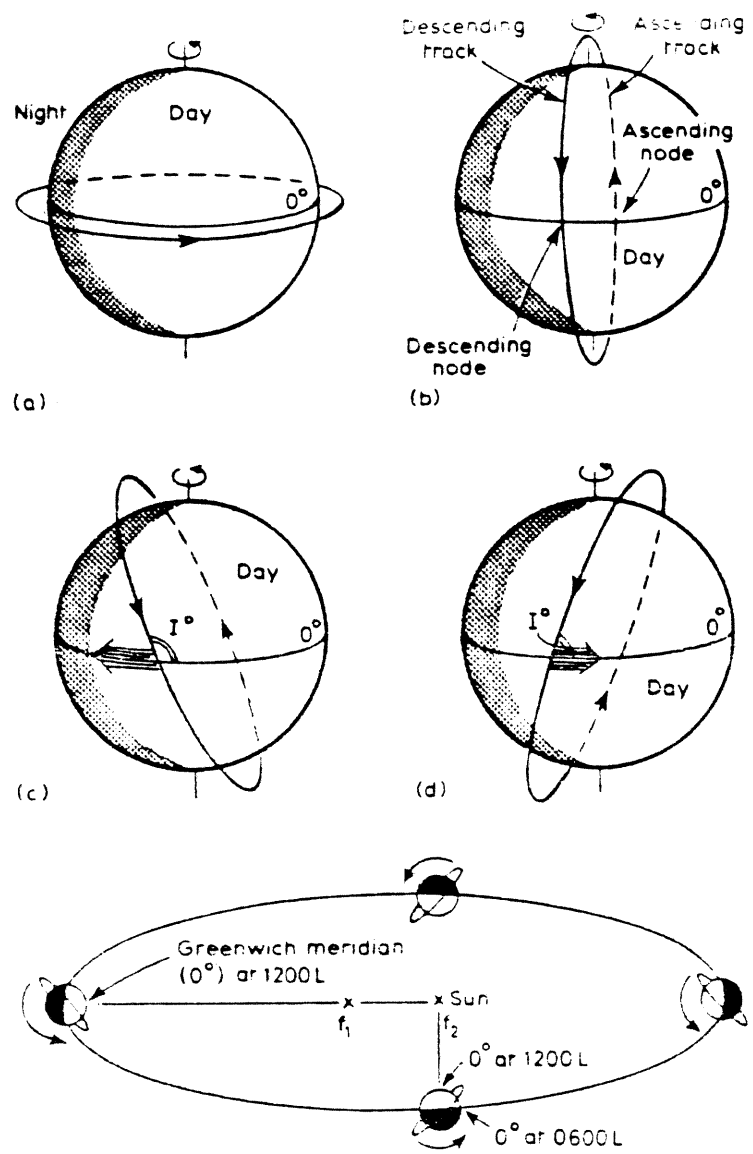
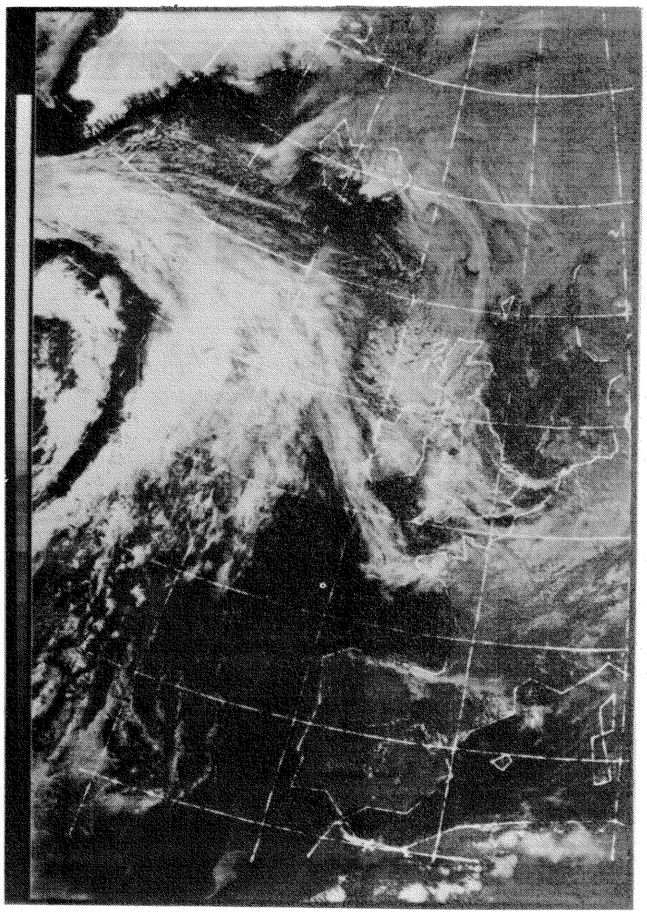
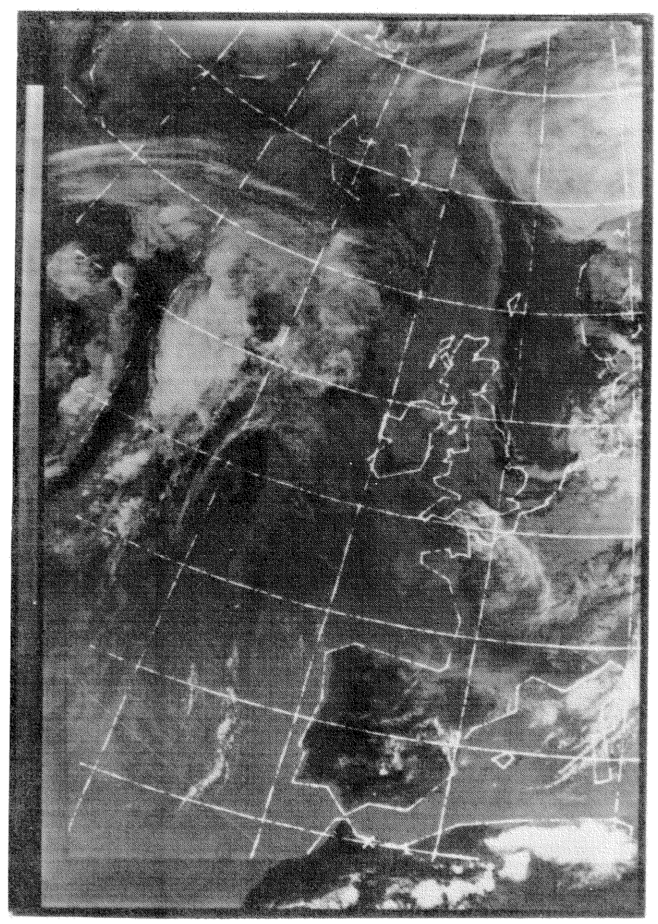


Fig. 3. Orbital characteristics of satellites, and the Earth as a satellite of the Sun. (a) Equatorial orbit; (b) true polar orbit; (c) prograde oblique (launched eastward, regresses westward); (d) retrograde oblique orbit (launched westward, precesses eastward); (e) perpendicular from Sun to Earth, precesses eastward throughout the year.



(a)



(b)

Fig. 4. Examples of imagery from the NOAA polar-orbiting satellite with the Advanced Very High Resolution Radiometer (AVHRR). (a) Visible waveband image, (b) infrared waveband image (courtesy University of Dundee).

(a)

(b)

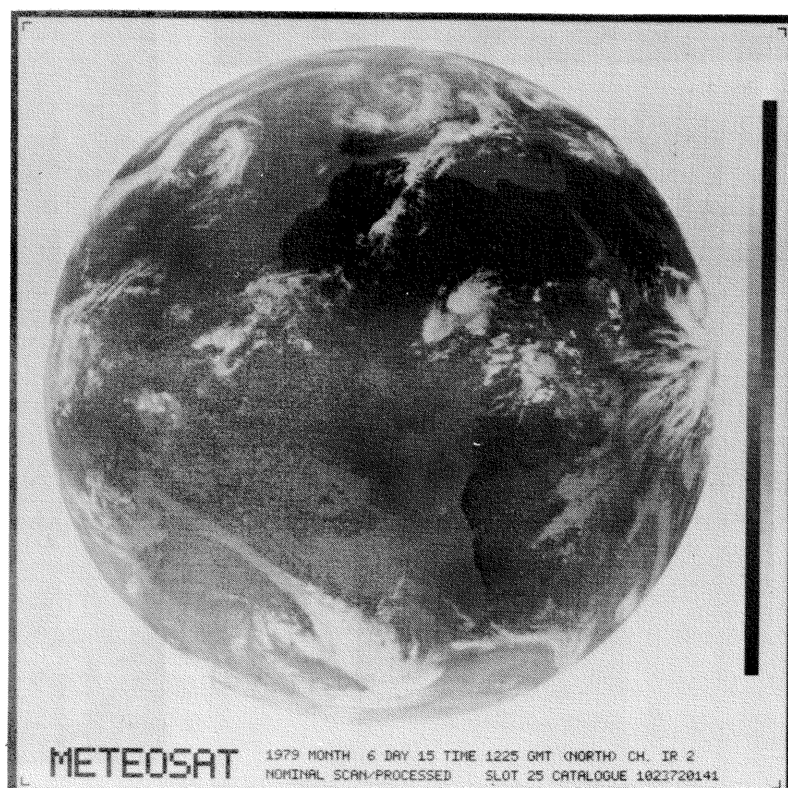


Fig. 5. Examples of METEOSAT geosynchronous satellite imagery. (a) Visible waveband image, (b) infrared waveband image (courtesy ESA)

(a)

(b)

Fig. 6. Examples of Indian geosynchronous satellite (INSAT) imagery. (a) Visible waveband image, (b) infrared waveband image (courtesy Indian Remote Sensing Agency).

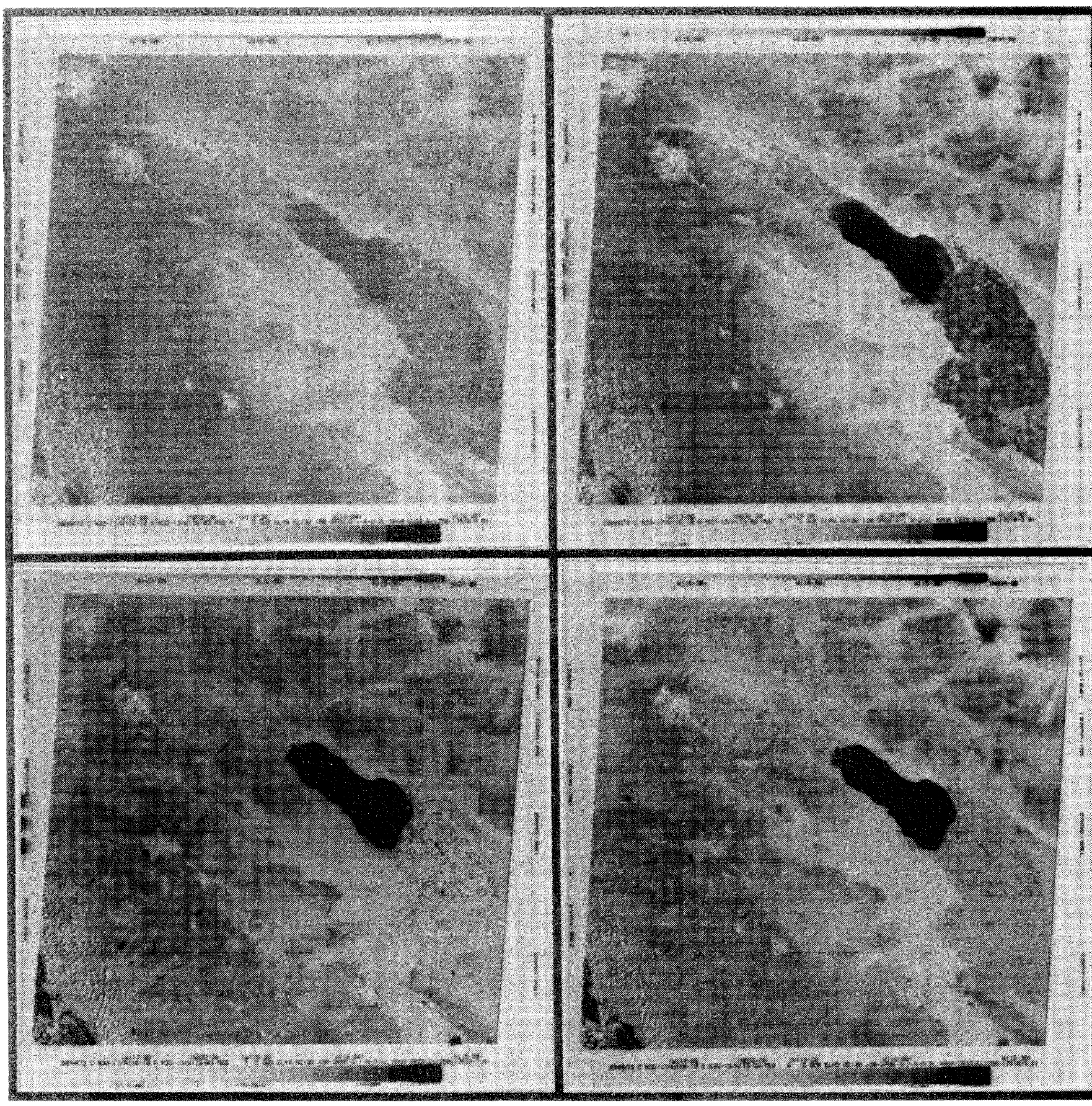


Fig. 7. Examples of Landsat imagery of the Salton Sea in the southern part of the state of California in the USA, acquired 30 March 1973. The bands are in clockwise order, starting in the upper left corner with band 4 and ending with band 7 in the lower left corner.

(c) Digital data, involving radiation values for small individual areas (picture elements or "pixels"), and recorded in map form, or on magnetic or punched paper tape.

Fortunately, all three basic data forms are fully interchangeable; e.g., microdensitometers can be used to produce analog or digital data from images on film, while, in reverse, digital data can be processed to generate one-dimensional analog transect profiles or two-dimensional images. However, any additional processing adds to the cost of data acquisition, and operational programs are generally best served by digital data where analyses can be performed by computers, and by image forms where analyses are manually performed. Although manual analysis (especially air photointerpretation) techniques are well-established, and are in widespread use for hydrological applications, digital (computer-based) methods are required for any reasonably complete exploitation of the very dense information content of even the current satellite systems, not to mention those already planned for the future. In all such work, four stages can be recognized:

(a) Preprocessing. This includes any process which has to take place before the data can be exploited effectively by the user. Ideally, it is performed before the user receives the data, and includes data navigation, registration on the ground, rectification for system deficiencies or peculiarities and atmospheric effects, removal of unwanted characteristics, and primary calibration.

(b) Processing. This entails any data manipulation necessary or useful for later scientific purposes, but which the analyst or interpreter does not want to have to do for himself. Its chief object is to present the data in manageable forms and quantities. Increasingly, processing is being undertaken by central facilities. It often involves some element of selection from and/or compression of preprocessed data, and/or enhancement of selected features of particular significance to the customer.

(c) Analysis. This covers the assessment of remote sensing data contents in terms of specified environmental phenomena or characteristics. Ground truth and/or physical models are often employed to ensure meaningful comparisons between remote sensing and in situ data ("supervised" classifications); sometimes, however, a search is made for natural groupings within the remote sensing data alone ("unsupervised" classifications), e.g., for terrain mapping purposes.

(d) Interpretation and analysis. This involves the identification and recognition of features or characteristics specially selected to satisfy the ultimate objectives of the end user, e.g., flood-plain features and other parameters and phenomena of hydrological significance.

3. HYDROLOGY AND REMOTE SENSING

3.1 Hydrology and hydrological observations

3.1.1 The hydrological cycle. A brief overview of hydrological processes will help to set a framework for describing those areas where remote sensing can assist in observing and in managing water resource systems. Generally speaking, the hydrological cycle traces water through different physical processes, from liquid water (most of which is in the oceans), through evaporation into the atmosphere, back into the liquid (or sometimes the frozen) state as precipitation or condensation. Precipitation falling on land areas may either run off into rivers and streams, or percolate into the soil, or evaporate. Moisture reaching the water table becomes ground water. As a general rule, both surface and ground water flow under the force of gravity toward streams and lakes, and ultimately oceans. The return of water to the oceans can be thought of as completing the cycle. Water on the surface of the Earth, or in the surface layer of the soil is often evaporated from the land or transpired by vegetation thus reentering the vapor phase. A small but important part of the available freshwater is temporarily stored in snow packs, river channels, reservoirs, and vegetation.

A complete study of the hydrological cycle would require monitoring of evaporation, precipitation, changes in storage in major impoundment areas, and runoff into large water bodies. In addition, horizontal transfer of water vapor and energy would also need to be monitored. Studies are in fact underway in these areas. Descriptions of some of these studies are given in a Unesco report on World Water Balance (Unesco, 1971). However, consideration of the world as a single hydrological unit falls more in the fields of climatology and meteorology and is beyond the scope of this report.

3.1.2 Hydrological units. From a practical point of view, hydrology attempts to supply the information required to ensure an adequate supply of water, or at least effective use of fresh water when it is in limited supply, and to minimize damage when there is an excess of water. In this document, areas for which hydrological information will be discussed will be designated as hydrologic units, which will vary from small urban basins on the order of a few square kilometers, up to major river basins such as the Amazon.

3.1.3 Hydrological measurements. The primary hydrological processes which are operationally measured are precipitation, runoff (stage and discharge), water storage, soil moisture, and evaporation. A total list of measurements would be very large and is limited only by the need to know water information and the imagination of users to develop new methods of measurement. Based on a survey of basic texts (Linsley et al., 1949; Wisler and Brater, 1969; and Viessman et al., 1977), and on a survey article in a Symposium (Brown, 1975), the most common hydrologic data that are measured, or derived, are those given in the following list. Some aspect of all of these data have been found inferable by remote sensing. An asterisk will be placed by those applications where no aspects have been found to be independently derivable in an operational mode by remote sensing. Some types of data which are most commonly measured, such as precipitation, are conventionally tabulated in daily, monthly, and annual amounts; other types of observations have not yet achieved the same standardizations, and specific accumulation periods will not be listed with them. More detail on the way the data are estimated and presented will be given in subsequent sections of this Chapter and in Chapter 4.

(a) Consumptive use (annual depth of water loss).

(b) Evaporation (monthly, seasonal, and annual depth).

(c) Flooding (areal extent, crests, return period).

(d) Ground water (occurrence, depth to ground water surface, yield of wells and springs).

(e) Atmospheric humidity (dew point temperature, relative humidity, and air temperature, and wet and dry bulb temperatures).

(f) Precipitation (daily, monthly, seasonal and annual amounts, intensities, return periods, variations about means, per cent falling as solid precipitation, etc.).

(g) Water quality (safety for drinking, adequacy for industrial or agricultural use, deviations from naturally occurring temperatures, sediment, and chemical concentrations).

(h)* Direct observation of river and lake stages.

(i) Sedimentation or sediment load.

(j) Snow (areal extent, depth, water equivalent, density, etc.).

(k) Soil moisture.

(l) Solar radiation.

(m)* Direct observation of discharge.

(n) Air temperature.

(o) Wind.

(p) Basin Characteristics:

(1) Land use (urban, agricultural, industrial)

(2) Soil type

(3) Area

(4) Shape

(5) Elevation

(6) Slope

(7) Aspect or orientation

(8) Type of drainage net (drainage density, channel lengths, indirect drainage areas)

(9) Improvements to drainage by man (dredging, channel straightening, additional drains)

The spectrum of human activities connected with water is so broad that these different portions of the hydrological cycle are frequently measured independently; that is, precipitation, evaporation, runoff, and storage are generally measured by separate networks, each network having different observation locations, density of gages, and frequency of reports. The reporting frequency and densities of gages are generally governed by the requirements of the application for which the data are gathered. Global energy balances, for example, can be calculated with data from a relatively sparse network, while the prediction of urban runoff requires a very dense network of precipitation gages.

Not all of these processes can be measured directly by remote sensing. Evaporation, for example, is computed indirectly and requires measurement of either energy fluxes, or of air temperature, humidity, wind travel, and solar radiation. Prediction models for flows and storages are based upon past observations. They generally require measurement of environmental parameters such as drainage areas and the slope and aspect of river basins.

The primary system of dimensional units used in hydrology today has developed from practical use. The number of types of units, and the amount of data required for hydrologic use are relatively extensive. There is, however, a limited set of units required for most practical problems. Most of the measurements dealing with the storage and flow of liquid water are made in units of volume, or volume per unit time. The accepted dimensions are in cubic meters or cubic feet; however, dimensions such as acre feet are in common use in some areas. Only the units of cubic feet or cubic meters will be used for reporting volumes in this document. The dimensions used in measuring precipitation and evaporation are in depth per unit area. The depth is generally given in millimeters or in inches. When storm or water surface areas are known, and can be multiplied by the depth, the total storm or storage volume can be obtained.

3.1.4 Hydrological regimes. When hydrological data are examined for a given area, it quickly becomes apparent that the availability of water for most useful applications depends on the existence of an excess of precipitation over evaporation. There are many areas of the world where this condition exists for only parts of the year. The relationships between precipitation, evaporation, runoff, and the types of vegetation and soil that exist in basins can often be stratified into different classes. The different classes into which basin source and sink relationships fall are often called regimes. Where water is abundant, rivers are generally fed by ground water even when no rain has fallen for several days. Where evaporation significantly exceeds precipitation, and there is no significant inflow of ground water from a different hydrologic regime, rivers flowing through such basins lose water to the soils.

3.1.5 Hydrological models. A description of the hydrological cycle in a basin is called a model. One of the most useful means of describing the relationships between precipitation, evapotranspiration, and runoff for estimating available water or for forecasting future amounts of water, is the use of mathematical models. There are two general approaches to mathematical modeling. Perhaps the simpler of the two is the generation of equations based, in effect, on the plotting on graph paper of such variables as the discharge in rivers, the amount of rainfall, time since the previous rainfall, etc. When points appear to fall in a pattern, curves can be fitted to the points and equations written describing the curves in terms of the plotted variables. This class of techniques can be carried from this simple beginning to very sophisticated methods employing many observed variables, in rather complicated analyses. Equations developed in this way are called statistical models. In other words, these are models where numerical relationships are sought somewhat independently of physical principals.

A different approach is to use physical laws, which can be written mathematically. Many of these formulations begin with the laws of conservation of mass and energy. Conservation of mass requires that any change in the amount of water existing in a volume of space be balanced by the net inflow of water to (or outflow from) the volume. Energy conservation requires that the velocity of water movement be related to the loss of head or potential energy of the water and the loss of energy through friction to the soil or channel bed.

Many working models are combinations of physical or deterministic models, and statistical models. Physical laws are used to approximate observed data, and constants are then determined by calibration to best fit the data. In most applications, there is a fair amount of uncertainty in the hydrological data that are gathered and this uncertainty must be treated by making further adjustments with appropriate statistical formulations. Data collected from different types of observations carry different types of uncertainties and biases; therefore, it is very important that data sources be considered in model application and that independent methods of data corroboration be used when economically feasible.

3.1.6 Hydrologic applications.

3.1.6.1 Water resources development. The amount of water available to an area is usually estimated by computing an annual water budget for a sequence of years. The data that are required are the time series of the quantities of water that are available from existing sources (rivers or wells). If these sources are to be continually available, then the supply, i.e., rainfall in the contributing areas of the basin, must exceed the natural losses, i.e., evapotranspiration, and runoff. These processes can be related in an equation:

$$U = P - E - R \tag{1}$$

where U is the water available for use, P is the mean precipitation in the contributing area, E is the evapotranspiration over the same area, and R is the runoff from the basin below the point where the water would be used. To some extent, the runoff and evapotranspiration can be controlled by man. To a much lesser extent, even the precipitation can be influenced by man.

Runoff can be stored in dams for use in urban water supplies or irrigation. However, irrigation and reservoir storage both increase the evaporation so tradeoffs do occur in water development. As just indicated, for effective use, water must generally be either stored or regulated. These require the building of structures such as dams, reservoirs, aqueducts, or canals. The success of such structures to perform their designed purpose is dependent upon adequate design data (Andrejanov, 1975). These design data include the meteorological and hydrological observations related to the structure and the intended effects of the structure. The data required for hydrological problems depend to some extent on the nature of the problem, but certain generalizations can be made. For any project, certain catchment characteristics are required. Data needed for projects dealing primarily with surface water will be different from data needed for projects dealing primarily with ground water. The following are non-exhaustive lists of some of the most important types of data needed:

Surface Water Data:

Streamflow (stage or discharge), snow pack characteristics (water equivalent, depth, free water content, areal uniformity, depletion patterns), soil moisture characteristics (permeabilities, porosities, available moisture, field capacities, and moisture tension curves), lake or reservoir levels, storage capacities, drainage areas, channel cross sections, etc.

Ground Water Data:

Infiltration, porosity, temperature, chemical properties, uniformity.

Measurement requirements for each of the types of data mentioned above can vary in terms of the frequency of observations in time and space, depending on the purpose for which the data are collected. Hydrological models of catchment responses are generally driven by estimates of precipitation and modified by estimates of evapotranspiration, to predict or simulate the basin discharge. Model performance depends upon the correctness of the model formulation, and upon the accuracy of the input data. As mentioned previously, most models require calibration, and therefore depend upon having a representative period of data with which to calibrate (Crawford and Linsley, 1966).

3.1.6.2 Water quality. The primary emphasis of this document is on remote sensing aspects related to water quantities. But, it is important to realize that impurities in the water can influence the way that the water must be controlled as well as the uses to which it can be applied. Potable water supply is one of society's basic requirements. Generally, rural communities suffer most from inadequate drinking water because they lack the economic base and the technology for water treatment facilities. In an extensive survey conducted in India in 1972, only a little more than 4 per cent of the 576,000 villages had an adequate supply of protected water (Sethi, 1980). A resolution passed by the United Nations General Assembly declared 1980-90 as a water decade noting that:

"More than 4 billion people live on our water-rich planet, but over a billion must drink dirty water. Nearly 2 billion have no toilets. The world water and sanitation decade aims to ensure that by 1990 everyone has enough clean water and adequate sanitation" (UNESCO Courier, 1981).

In large areas of the Earth, ground water is one of the major sources of domestic water supply. For management of rural water supplies, a systems approach has been suggested and studies are underway (Schultzberg, 1978; and Widstrand 1978). A review of relevant literature has been written by Middleton and Marcell (1983).

3.1.6.3 Hydrological extremes. Precipitation and runoff almost always show a variation from year to year that can be a significant percentage of the long term mean values. Society has sought to reduce the impact of this variation in available water by building dams and canals and by greater use of ground water during the drier years. Where the normal mean water supply is scarcely adequate to support agriculture, such as in the margins of deserts, any reduction in the rainfall can cause privations. On the other hand, in numerous other areas, development of agriculture and industry close to river channels allows only minor increases in river stage before significant economic damage and, in some cases, loss of life can occur due to flooding.

3.1.6.3.1 Floods. In 1887 hundreds of thousands of inhabitants of the Honan Province of China were killed by flooding from Huang Ho River (Information Please Almanac, 1983). In recent years, two major storm surge floods have killed several hundred thousand people in coastal areas of the Indian sub-continent. One of many areas having serious problems with flooding is the Ganga Basin in this same region (Report of the National Commission on Floods, Government of India, 1980).

On the other hand flooding is sometimes beneficial in replenishing depleted water supplies. Intentional flooding is sometimes useful when irrigation sources cause fields to build up toxic levels of mineral deposits and the fields must be leached periodically, to lower the mineral concentrations to a tolerable level. A slightly different example is given by the annual flooding of the lower Nile, which prior to the construction of the Aswan High Dam is said to have brought nutrients in the sediments that were deposited by the flood waters on the agricultural fields (Fukuda, 1976).

Measurements associated with floods include:

(a) River stages in excess of bank full storages,

(b) Areal extent of flooding,

(c) The extent of industrial, residential, and agricultural development, and potential and observed financial losses, and

(d) Estimates of loss of trafficability and workability of fields or roads due to wet ground or the unuseability of fords (crossing sites).

The last two items in the list (c and d) are not generally performed by hydrologists but are vital for assessing a base against which funds can be justified for improving warning systems or making investments in protective structures such as dams or bypass canals.

3.1.6.3.2 Droughts. Drought can occur anywhere and is a constant problem in semiarid areas especially those bordering on deserts. Drought is often expressed by meteorologists in terms of days without rain or the number of millimeters or inches of rainfall below long-term normals. In arid and semiarid areas, farmers generally lack the water to irrigate all the land that could be cultivated. Farmers in the more marginal lands might claim to be under drought conditions during all but the wettest years. The definition of drought is not universal but is influenced by local or personal economic impacts.

Measurements related to the extent and severity of drought include:

(a) Precipitation in terms of annual, seasonal, and monthly amounts.

(b) Deviations of precipitation from normal, that is, mm below means of quantities described in item a.

(c) Evaporation.

(d) Temperature, humidity, and the dew point depression (difference between the mean air temperature and the mean dew point temperature).

(e) Deficits in the soil moisture such as required amount of rain to reach saturation, or adequate levels of available moisture in the soil. It could also be expressed in terms of the amount of available water in the root zone. Many runoff models have some form of a "deficit" term which is the precipitation (or snowmelt) required before surface runoff is expected by the model. This is also useful information.

(f) Ground water conditions determined from ground water discharge into streams, the drying up of ponds, or the lowering of or drying up of wells.

(g) The number of significant days without rain or, in some areas, the estimated percentage below normal of mountain snowpacks.

Terms such as Drought Intensity Index have been defined to express the degree of severity of drought by trying to quantify some combination of factors relating to the drought (Herbst et al., 1966).

In marginal areas where storage of water is possible, careful monitoring of drought indicators such as storm tracks and precipitation amounts should be done to make efficient use of stored water. A well known indicator of possible climatic change is the El Niño event occurring on the Pacific Coast of South America, which is characterized by anomalous ocean surface temperatures. The most recent El Niño event has been associated with drought in Indonesia and Australia (Water Information Center, 1983). Sea surface temperatures are used for making long range climatic forecasts; for example, Lamb (1978) suggests that Subsaharan droughts may be predictable 3 to 6 months in advance using as indicators: (1) sea surface temperatures from the Atlantic Ocean and (2) the movement of the Northern Atlantic subtropical high pressure center.

3.1.7 Recommended standards and methods for hydrological measurements. Several international committees have drawn up tables and lists of desired hydrological measurements, and the recommended methods for their observation (Unesco, 1970; WMO, 1974 and 1980; Interagency Committee, 1977).

3.1.8 Conclusions. If precipitation falling on land could be spread uniformly over the surface, there would generally be an adequate water supply, but facilities would be needed to control or store water in accessible places. However, uniform distribution is not the case. Even in basins of moderate size, there can be some small areas experiencing drought while in the same basin there are other areas having problems with local flooding. The engineering and technical challenges which continue to arise can be met only when the necessary hydrological data have been obtained.

3.2 Need for remote sensing methods in hydrology

In the previous section, the need for adequate hydrological data was described. Hydrologic planning is usually based on limited and often inadequate data, especially in developing countries. Existing hydrologic data bases may not be oriented to newly arising hydrologic requirements. It is intuitive that when situations arise which were not considered in the planning of water management systems, it is possible that the systems can fail to meet their designed purpose. In very few situations will all the information be available upon which to base plans, so that any additional data sources that become available should be impartially examined and used to the extent that the benefits they bring equal or exceed the costs of data acquisition (Watt, 1973). Remote sensing techniques can often acquire data that are available in no other way, or acquire data more quickly, or with more frequent temporal and more complete spatial sampling than other methods of data acquisition. The details of hydrological remote sensing will be addressed in Chapter 4. The launchings of Earth resource and weather satellites have markedly increased the availability and use of remote sensing. The costs for developing these satellites and placing them in orbit have been very large for the governments involved, but these satellites have allowed data in several different portions of the electromagnetic spectrum to be acquired repetitively for very low costs to research and applied data users. Real time data from weather satellites are generally available to anyone having the appropriate data acquisition antennae. Plans for the required antenna for receiving data from the weather satellites operated by the United States are available by writing to the user affairs unit of NESDIS listed in Section 5.1.1 of this report. Data from Earth resource satellites such as Landsat are generally available for only the cost of processing the photographic prints or computer compatible tapes. Details on the availability of these data are found in Chapter 5. The orbiting of these weather and Earth resource satellites has allowed data to be collected over vast areas such as oceans, jungles, and deserts, where aerial surveys would be prohibitively expensive. Data from these satellites allow managers to investigate the potential of remote sensing as an aid to problem solving, for a very modest starting cost.

3.3 Perceived expectations

Remote sensing has allowed scientists to see patterns which occur under conditions not obvious to the human eye. Because of this ability, the field of remote sensing is sometimes given an aura of mystery which causes some people to expect that desired information will become available to them with very little effort. That, however, is rarely the case and much work is generally still required to make the most of the capabilities available. There are also many constraints upon the remote sensing systems of which a user must be aware. Some of these constraints will be addressed in the next section.

3.4 Practical constraints

3.4.1 Sampling frequencies. Quantities such as base flow on large rivers change rather slowly in a relatively predictable manner. These processes can be sampled on a weekly basis, with little loss of information. On the other hand, precipitation, especially in convective storms, is highly variable. Hudlow et al. (1981) show graphs illustrating differences in estimates based on five-minute samples compared with estimates for the same storms based on less frequent measurements (see Figure 8). The figure also shows a relationship between these differences and the area over which the estimates are to be averaged. Figure 9 shows the type of variability expected in different types of storms. In the same report, Hudlow and his associates (1981) on the staff of the Hydrologic Research Laboratory of the National Weather Service of the United States developed the following schematic, giving estimates of the maximum acceptable errors in estimating precipitation from satellites and the number of samples per time period to achieve the required accuracy for various water resource applications (Figure 10).

Storms, or even floods, occur on an unscheduled basis and have finite durations. If a sampling satellite passes over an area on the ground once in three weeks, a flood of two weeks duration could have come and gone without being viewed by the satellite. In the same manner, a satellite which makes a pass every 12 hours can easily miss storms lasting four or five hours. A satellite mapping the area of flooding could be valuable in noting the failure of levees along river banks when the failure occurs just before the image is acquired, but if failure occurs immediately following the sensing, the information available in a subsequent sensing could be of much less value.

3.4.2 Expiration of data value with time. In a study of flood damages on the Susquehanna River in the USA, Day (1970) found that the damage reduction, that is, economic benefit resulting from a warning system, increases as the warning time is increased up to some reasonable maximum value. It, therefore, follows that any decrease in warning time resulting from delays in generating or disseminating warnings once the risk-causing situation has been observed, decreases the value of the observation. The loss in value depends upon the application to which the data are to be applied. This constraint applies to all kinds of data, no matter how they have been acquired. The purpose for mentioning this constraint in this report is to caution that reason must be used in investing in the initial purchase of data acquisition systems, so that available resources are not exhausted in getting a

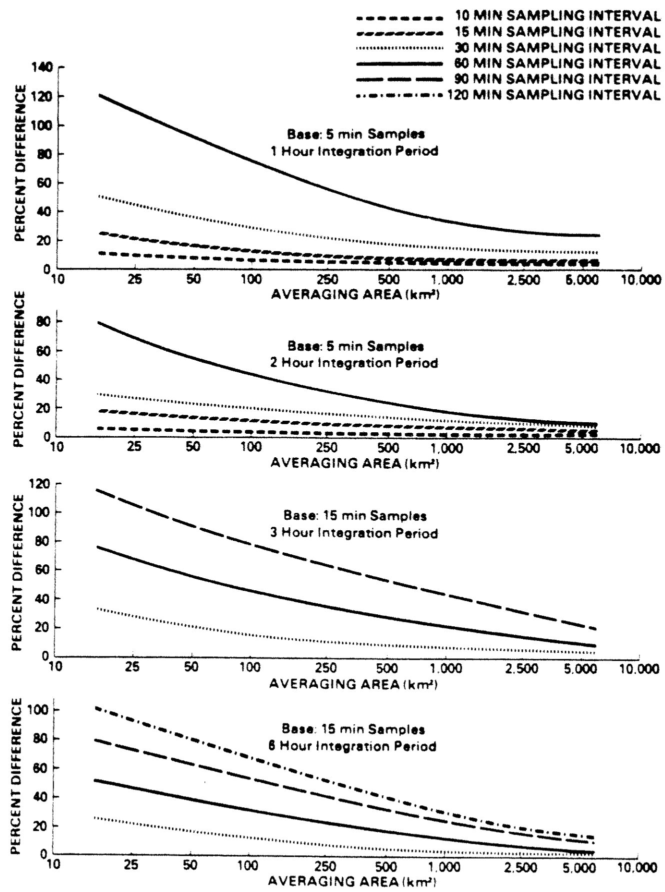


Fig. 8. Upper two panels: Mean absolute percent difference between rainfall estimates using 5-min base sampling intervals and those using coarser sampling intervals for a range of spatial averaging and temporal integration scales. Lower two panels: Same as upper two, except a 15-min base sampling interval was used and longer integration periods were included. Based on analysis by Hudlow and Arkell (1978), who used digital radar data collected over the eastern tropical Atlantic Ocean during the GARP Atlantic Tropical Experiment (GATE).

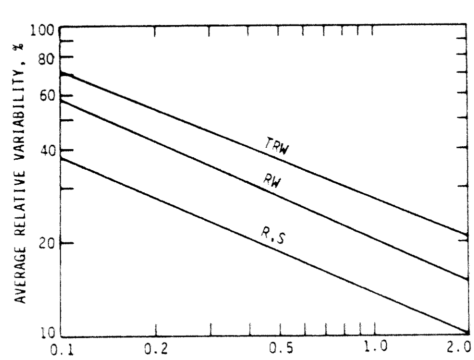


Fig. 9. Relations between relative variability and precipitation type on a 400 mi^2 network in central Illinois (from Changnon and Huff, 1980, p. 40). TRW = thunderstorm cases; RW = rain shower cases; R,S = continuous rain and snow cases.

SPATIAL AVERAGING INTERVAL

Temporal Averaging Interval	1 km² – 10 km²	100 km²	1,000 km²	10,000 km² – 100,000 km²
	Flash Flood Advisories			
0.5 hr-	(100, 144)	(75, 144)	(40, 24)	(15, 24)
1 hr-	(75, 96)	(60, 48)		
2 hr-	(50, 48)	(60, 24)	Flash flood advisories, river forecast, soil moisture condition evaluations ***	
			(20, 24)	(20, 24)
	Soil moisture condition evaluations, reservoir operations		River forecasting, water structures design measurements***	
6 hr-	(50, 24)	(45, 18)	(15, 48)	(15, 18)
				GEOSYNCHRONOUS DATA / POLAR ORBITER DATA
1 day-	(45, 24)	(40, 8)	(15, 24)	(15, 2)*
	Soil moisture condition evaluation, reservoir operations and hydroclimatology		Crop yield, water supply forecasts, hydroclimatology, water structures design measurements***	
1 week-	(30, 4)	(15, 2)*		
	GEOSYNCHRONOUS DATA / POLAR ORBITER DATA			
1 month-	Soil moisture, hydroclimatology and water structures design measurements		(10, 2)*	
	(20, 2)**	(15, 2)**		
1 year-				

*Limited daily sensings (less than 4) can result in significant biases when diurnal effects are introduced either by meteorological or sensor effects.

**If significant diurnal effects do not exist, data from high spatial resolution satellites such as LANDSAT could be useful even with longer intersampling intervals.

***Estimates for these applications and corresponding scales require relatively smaller acceptable errors because they are more highly processed and are of a more quantitative nature.

Fig. 10. Maximum acceptable mean percent error (first value in the parentheses) as a function of temporal and spatial averaging scales. Also, estimates of the minimum temporal sampling frequencies (samples per day) required to achieve the accuracies are given as the second value in the parentheses. Larger errors would be acceptable if the errors in the satellite patterns are primarily due to systematic biases and if other independent data are available for comparison and melding with the satellite data.

sophisticated sensing system which then lacks the means for communicating, processing, and applying the data.

3.4.3 Conversion of raw data to hydrologic data. Early results of remote sensing were often portrayed in thematic maps (maps with colors indicating areas classified as having distinct levels of one variable or distinct types of land characteristics). That is a very useful way to inform people of patterns and relationships, but this method is difficult to use for making quantitative estimates or forecasts. As programs have developed from qualitative information systems to those used for quantitative estimates, digital data rather than images have been used. Digital data immediately requires computers for data processing. The ability of remote sensing methods to gather a large quantity of data very rapidly can quickly saturate the capacity for data processing. The inherent abilities of remote sensing combined with automatic data processing have appeared to present almost limitless possibilities in researchers' hands. However, while these capabilities are limited only by the imagination of the users, the resources with which to implement programs are often very limited. Some of these limitations may be minor inconveniences to those willing to work around them, but major problems for users who are unwilling to accommodate them. The items following in this list are just a partial but important list of some of these.

3.4.4 Data resolution. Data users who are accustomed to seeing aerial photographs or maps often desire greater detail, that is, larger map or image scales and higher spatial resolution. Increases in the resolution increase the amount of data that must be processed. For example if, for a given resolution, there are 80 resolvable picture elements (pixels) per 100 km of distance, and the resolution is then increased so that 100 pixels can be resolved in the same linear distance, then for the same 100 x 100 km square, an additional 3600 data values would have to be processed. In some cases, the user must reorient his ideas of data acquisition and recognize that he may be more interested in average values or general information rather than specific details. An example of this may be in land use. A rural area may have several farm buildings that, while they seem important, would have negligible influence on the infiltration of rainfall into the ground over a 16 hectare farm. Snow may appear patchy over a basin, but the hydrologic worth for runoff forecasting is expected to be in the average value of the water contained in the snowpack and not so much in the relative location of drifts within the basin itself. For some uses, lower, not higher resolution may more adequately satisfy the requirements of the application.

3.4.5 New spectral bands. Many remote sensing images are portrayed in false color. Since the imaging is done in portions of the electro-magnetic spectrum not visible to the eye, there is no logical color to be assigned to these images. Therefore, any of several colors might be assigned to radiation received from a certain wavelength. When a color is chosen to represent non-visual spectra, the objects that naturally reflect that color must be depicted in some other color or else grouped with the non-visual spectra. This effect usually requires some time for familiarization. Some users have found that varying the color combinations often brings out to the analyst new information which was not noticeable in a previous combination.

3.4.6 Cloud cover. Many of the remote sensing techniques depend on reflection of visible or near infrared (IR) radiation, or emission of thermal IR radiation from the surface. None of these techniques can sense conditions on the Earth's surface satisfactorily if there is cloud cover or even significant haze. Microwave sensing, especially radar, can image through clouds, but is generally more costly and sometimes more limited in resolution. Surveys which depend on aircraft scheduling or satellite overpasses may be impeded by clouds.

3.4.7 Contrast. There are many types of surface covers which have significantly different hydrological effects but which may appear the same. For example, clouds can be confused with a surface snow cover when attempts are made to measure either the areal extent of snow cover, or the percent of sky covered with clouds. On a partially cloudy day, special processes may be required to differentiate between snow on the ground and clouds. Only when there is significant contrast can different surfaces be confidently classified. Fortunately, there are many cases where surfaces which appear similar in visible light may appear to be very different in the near infrared or thermal infrared regions.

3.4.8 Optimal conditions for remote sensing related to time of day or season. It is intuitive that lakes can be observed more easily in summer than in winter when snow cover smooths the ground surface and covers both land and ice covered lakes with the same white blanket. Soils, on the other hand, are more observable when the vegetation is dormant. Surfaces having a large heat capacity may not be differentiable from their surroundings in midmorning or late afternoon but stand out in stark contrast at midafternoon or just before dawn.

3.4.9 Ground location. When digital data are used, or when unfamiliar surfaces are imaged, it may be very difficult to determine the location of the surface area to which a particular sensing element belongs. Survey logs for aircraft and ground parties are very important in this respect. Satellite orientation and recognizable ground points are helpful in establishing a mapping of the satellite sensing onto the ground.

3.4.10 Compromises. Remote sensing often necessitates an element of choice in system planning and project design. In ground-based remote sensing, one example is the choice between range and radial movement sensed by Doppler; in airborne remote sensing, the choice between scale and coverage. In satellite operations, tradeoffs occur between spatial, temporal, and spectral resolutions, where the last involves the number of wavebands investigated. Difficulties have been noted where different types of remote sensing and/or in situ observations are to be interrelated, for example, because of differences of interval between aircraft, and polar-orbiting satellite data. In this case, a geostationary satellite may provide at least a partial solution. The orbit for a satellite of this type maintains it at 35,800 km above a fixed location on Earth. From such an altitude, the spatial resolution of the imagery is usually relatively low, and coverage can be obtained only for a fixed sector of the globe, but with much-improved temporal sampling frequency. Many of the considerations involved in making appropriate systems choices have been discussed previously in this chapter, but the problem of making hydrologic observations possible with adequate resolution in the spectral bands desired is so critical to the success of any remote sensing activity that is is re-emphasized here.

4. REMOTE SENSING APPLICATIONS IN HYDROLOGY

4.1 Hydrometeorology

Hydrometeorology is concerned with exchange processes in the hydrological cycle, therefore, particularly with precipitation, evaporation, and evapotranspiration. All three are monitored inadequately by conventional methods for most present applications ranging from the global scale to the meso- and even micro-scales. We will review progress in the remote sensing of these phenomena, concentrating (as elsewhere through Section 4) upon those methods which are both best-developed, and appear to have past, present, and/or future potential for hydrological use.

4.1.1 Rainfall monitoring. In the precipitation arena, remote sensing attention has been paid almost exclusively to rainfall; little or no attention has been paid to snow, except after it has fallen. Consequently, ice and snow will be addressed in Section 4.2.

Remote sensing of rainfall began soon after the end of World War II, when it was realized that areas of large, mobile hydrometeors served to reflect radar signals in some wavebands. Since then, substantial development of weather radar systems has taken place (Battan, 1973) and today, radar is used in numerous meteorological centers for the qualitative, and sometimes also the quantitative assessment of rainfall distributions and intensities. Where calibration with raingages is possible, volumetric estimates of rain falling over selected areas (e.g., river catchments and self-catchments) are possible. Since radar is well-documented as a tool for severe storm meteorology, and is used for rainfall monitoring in some areas, the treatment of it here will be relatively brief.

4.1.2 The use of radar in rainfall monitoring. Radar is a family of active remote sensing systems, most of which operate in the microwave (1mm - 1m) region of the electromagnetic spectrum. Recent additions using radar concepts have exploited acoustic principles (sodar) or other regions of the electromagnetic spectrum (lidar). Some radars have been designed for operation on the ground, and others on aircraft. Recently, proposals have been drawn up for satellite-borne radar systems (Atlas et al., 1978). In rainfall monitoring, ground-based microwave radars have been strongly predominant. It is on these that we will now focus our attention.

A basic distinction within microwave radars separates coherent from non-coherent systems. "Non-coherent" systems do not depend on a stable transmitter frequency, and are used principally to observe the location and pattern of echoes, and to measure the intensity of the back-scattered signals. "Coherent" (Doppler) systems use very stable transmitter frequencies and can measure very precisely the shift in microwave frequency caused by moving targets (Browning, 1978). Unfortunately, these radars are beset by two difficulties which have effectively limited their applications in hydrometeorology to specialized research studies, e.g., in the mapping of 3D fields of motion in severe convective storms (Ray et al., 1975). These difficulties are:

(a) There is a restriction on the range (or distance) over which Doppler radars are effective, a result of ambiguities where a high pulse repetition frequency is used. Many Dopplers operate out to only several tens of kilometers.

(b) Basic Doppler radars measure only the line-of-sight (radial) velocity component of their targets; hence, relatively sophisticated equipment and procedures are required to yield 2D or 3D patterns.

Thus, non-coherent radars have found broader use in rainfall monitoring, including the following applications (Browning, 1978):

(a) Qualitative determination of the dynamical structures of clouds and precipitation structures, e.g., assessment of echo shape and patterns of precipitation associated with different weather systems such as mid-latitude depressions and severe storms.

(b) Short-period forecasting of rainfall, e.g., involving simple extrapolation, or the expected development and/or decay of rain systems, taking account of the particular topography of the forecast area.

(c) Quantitative measurement of precipitation, especially at the mesoscale, operating out to ranges of about 230 km, although the effective range may be less.

Given appropriate knowledge of the technical specification and performance of a radar installation, the radar equation fundamental to most radar studies of rainfall may be represented in its basic form as:

$$\bar{P}_r = \frac{CZ}{r^2}, \tag{3}$$

where $\bar{P}_r$ is the mean received power (the "signal") from the target, C is the "radar constant" (a function of the radar hardware and other factors), Z a reflectivity factor specific to the type of precipitation in the target areas, and r the range (or distance) between the radar and the reflecting shower or rain. In the strict sense when Z is estimated from equation (3) using only radar measurements of power returned and target range, then Z actually is an equivalent reflectivity factor normally referred to as Z_e. The reflectivity factor (Z) or equivalent reflectivity factor (Z_e), is usually related to the rainfall rate (r) through a power law relationship. Although it is possible to derive a theoretical Z-R relationship if the drop-size distribution and vertical wind fields are perfectly known, the normal practice is to relate rainfall rates to the equivalent factor (Z_e) through an empirical relationship. This relationship represents a set of physical conditions prone to considerable variation both from time-to-time and place-to-place. Unfortunately, it is often necessary to evaluate this relationship empirically on a region-by-region basis, over lengthy periods. Inevitably, its use leads to operational errors in the evaluation of rainfall, especially for short time periods and/or small areas. Much better results may be obtained by relating the radar estimated average rainfall in the vicinity of well-exposed rain gages to the rain recorded by the gages, the recorded amounts being telemetered to the radar and the relationship calculated at, say, hourly intervals (e.g., Grinstead, 1974). Unfortunately, such refinements are not always possible. However, the key assumption is that, for different latitudinal zones, and different types of rain, the radar signal is proportional to the rate of rainfall divided by the square of the range.

Radar has a unique capability to observe the areal distribution of precipitation at frequent intervals, and to provide quantitative information from quite large areas to a single center with a minimum of telemetry requirements. However, radar techniques have yet to become the standard method of supplying the user community (meteorologists, hydrologists, agriculturalists, communications engineers, etc.) with the mesoscale rainfall data they desire. A plethora of practical problems explains most, if not all, of the remaining consumer resistance. These problems include and involve the following (Barrett, 1980):

(a) The lack of adequate data processing software for automatic operations.

(b) Signal fluctuations and differences even when rain-rates are constant.

(c) Vertical variations in the reflectivity of the atmosphere.

(d) Effects of occultation of the radar beam (screening), ground clutter, and anomalous propagation.

(e) The need for expert radar operators and analysts.

(f) High system costs.

Although the cost effectiveness of radar is difficult to assess, Figure 11 (Barrett, 1980, after Browning, 1978) is very instructive. It indicates that in temperate mid-latitudes to achieve a mean error of, for example, 25 per cent for hourly rainfall, 10 telemetering gages would be required over 1000 km^2 to yield similar results to those obtainable from a single radar. Estimates by the United Kingdom Water Resources Board have further suggested that, if such an accuracy is required, the cost-effectiveness of a calibrated radar system exceeds that of a telemetering raingage network once measurements are required over areas exceeding 3000 km^2.

4.1.3 <u>The use of satellites in rainfall monitoring</u>. In recent years, following the inauguration of the first fully operational (ESSA) weather satellite system in 1966, much attention has been paid to the possibilities of using meteorological satellite data in rainfall monitoring. A particular advantage of satellites is breadth of view. This is best seen with geostationary satellites, one of which can provide almost instantaneous information for an entire continent of the scale of North America or Africa. This greatly simplifies data management and processing requirements, in marked contrast to those necessitated by ground-based radars, raingage networks, and, especially, multiple monitoring systems in which the corresponding characteristics of the individual system components must all be accommodated. A further advantage for developing countries is that, without having to contribute to the costs of development and implementation of satellite systems, they can share in the acquisition and use of the data therefrom.

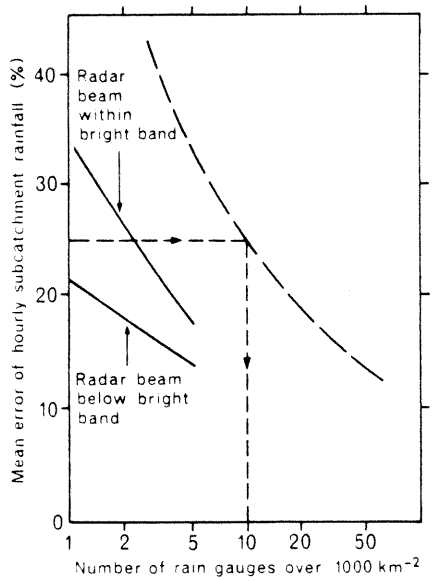


Fig. 11. Radar mean error versus density of calibrating rain gage sites (solid lines), and the mean error of hourly subcatchment totals for mean rainfall events in middle latitudes in the absence of radar (broken line). (From Barrett, 1980 after Browning, 1978.)

Table 1 summarizes the methods which have been developed for rainfall monitoring by satellites, grouping these methods primarily on the basis of general approach. The purpose of some of these methods is to replace surface data; however, most aim to supplement surface data in areas and/or times for which conventional data are inadequate for some purpose(s). The wide range of methods covered by Table 1 has grown up because the physical, interpretational, and methodological problems to be overcome are quite formidable. However, several methods have become quite widely used in both pure and applied climatology and meteorology. A few have been used in support of hydrological operations, but there seems to be considerable unrealized potential in such areas. Given that a suitable technique is available for the region(s) in question, satellite-assisted rainfall monitoring techniques might contribute information on a number of important hydrological variables (Barrett, 1981). These include the following:

(a) Water levels of large inland lakes.

(b) Rainfall amounts and distributions.

(c) Depth-area estimations of precipitated water.

(d) Cumulative (mass) curves of precipitated water.

(e) Basin runoff and stream hydrographs.

(f) The extent and severity of rainfall extremes (both floods and droughts).

Table 1. Summary of main categories of current and proposed satellite rainfall monitoring methods

Method	Chief Applications	Satellite	Sensor(s)	Present Status
Cloud indexing	Meteorology, climatology, hydrology, crop prediction, hazard monitoring, etc.	Polar-orbiting and/or geostationary	Visible and/or infrared	Quasi-operational
Climatological	Crop prediction	Polar-orbiting	Visible and/or infrared	"
Life-history	Severe storm assessment, meteorological research	Geostationary	Infrared and visible	"
Passive microwave	Chiefly oceanic meteorology and climatology	Polar-orbiting	Microwave	Receiving renewed research attention
Bispectral	Meteorological research	Polar-orbiting or geostationary	Visible and infrared	Developmental research
Cloud physics	Cloud research and atmospheric thermodynamics	Geostationary	Visible infrared and microwave	"
Active microwave	Cloud and rainfall research, forecasting	? Polar-orbiting	Satellite radar (active microwave)	Future

Since most of these depend upon rainfall monitoring by satellites, it is worth noting in more detail those aspects of rainfall hydrometeorology which are now amenable to improved analysis using data from satellites (Barrett, 1983a). These include assessments of:

(a) The boundaries of areas likely to have been affected by significant rain.

(b) Basin rainfall totals.

(c) Total rainfall accumulated from particular (especially extreme) events.

(d) The climatology of rainfall distributions.

(e) The (short-term) forecasting of rainfall.

However, even those most active in promoting satellite rainfall monitoring underline that, given the present state-of-the-science, the contribution of satellites to hydrological problem-solving may be expected to be time and cost-effective in limited circumstances only. These are particularly where:

(a) The dimensions of the areas in question are large (say 10^5 sq. km. and upwards).

(b) The spatial distributions of conventional data are uneven and/or relatively sparse.

(c) Recurrent and/or intense rains occur in more localized areas which are deficient in surface rainfall stations.

(d) Rainfall and rainfall-dependent data are required in or near real time.

The best-established satellite methods showing promise in at least some of the above contexts include certain cloud-indexing and life-history techniques. Both groups rely on visible and/or infrared image data as their satellite inputs. Microwave techniques are theoretically more attractive than the visible or infrared because they relate physically to the areas of rain embedded within clouds, not merely to the brightnesses or temperatures of cloud tops. Microwave techniques have been quite successful over sea surfaces (e.g., Rao and Theon, 1977), but, for various reasons, have proved relatively difficult to apply over land (but see Spencer et al., 1983). For the foreseeable future, it is hoped that a combined visible/infrared/ microwave technique might provide better results than any so far achieved. In such a method, the visible/infrared data might be used to delimit the areas of significant cloud cover, within which the microwave data should evidence instantaneous intensities of rainfall. Research along these lines is now in hand. Further in the future, the even more physically direct route of the active microwave (satellite-borne radar) may prove to be even more appropriate. However, since the visible and infrared cloud-indexing and life-history techniques are the only ones available for everyday use today and for at least the short-term future, it is these that it will be worthwhile to examine in greater detail. For more extended treatment of satellite rainfall monitoring, the reader is directed to the book authored by Barrett and Martin (1981) and the conference report edited by Atlas and Thiele (1981).

4.1.3.1 Cloud-indexing techniques. In these, polar-orbiting satellite cloud images are ascribed numerical values or indices, commonly relating to cloud cover within each square in a predetermined grid, and to cloud type (differentiated on the twin bases of the probability and intensity of rain expected from each type of cloud). Additional factors may be invoked to adjust the indices for the synoptic weather situation, and for the effects of local terrain. In some such techniques, indices have been chosen to give rainfall estimates through an intermediary regression diagram or look-up table.

Examples of cloud-indexing techniques include the Follansbee Method (Follansbee, 1973), developed under the auspices of NOAA/NESS in the USA, and the EarthSat Method of the EarthSat Corporation of Bethesda, Maryland (Heitkemper et al. 1982). The Follansbee Method has been used widely in support of broad-scale hydrology, e.g., for catchment monitoring, river and flood control, rainfall estimation over large lakes, and in support of hydroelectric power plant operations. The EarthSat Method, which produces estimates for smaller areas, (~54 km grid squares) is in use currently for crop prediction purposes, but, clearly, has potential for hydrology also. The Bristol Method, now available in both manual (See Barrett, 1980) and interactive forms (see Barrett, 1983b and Figure 12), has been applied to areas as small as 18.5 km grid squares in support of irrigation design, and water resource surveys as well as desert locust monitoring and crop prediction. It invokes regressions to translate cloud indices into rainfall estimates. Mostly, these regressions have been prepared specially for each study area. However, this can be a quite lengthy process. Recently, a "global regression" (see Figure 13) has been compiled on the basis of previous experience in various climatic regions. This has successfully undergone its first tests.

4.1.3.2 <u>Life-history techniques</u>. These geostationary satellite techniques have been designed specifically to evaluate convectional clouds; <u>cloud growth models</u> are invoked to distribute estimated rainfall through both space and time. Such methods are available in manual, interactive, and fully objective forms. The most widely-used objective (computer-based) technique is the Woodley-Griffith Method (See Griffith et al, 1978). However, the uses of this type of approach have been mostly meteorological, and there is recent evidence to suggest that in respect to its ability to distribute rainfall spatially, it may perform no better than polar-orbiting, cloud-indexing techniques, despite its requirement for 24 to 48 images per day as against only two to four in the cloud-indexing cases. Consequently, it is not surprising that it is a manual life-history technique (the Scofield-Oliver Method) which has been the first to achieve operational status in hydrology, in support of extreme event assessment procedures. NOAA uses the Scofield-Oliver Method (see Scofield and Oliver, 1977) to monitor severe convectional storms and forecast associated flash flood potential. Operational requirements in the North American environment have led to the development of four variants, specific to:

(a) Summertime convection.

(b) Wintertime convection.

(c) Tropical storm and hurricane rains.

(d) Warm-top storms.

As Figure 14 reveals, the Scofield-Oliver Method(s) are comprised of three main parts. In the first, the active portion of a convective system is identified; in the second, an initial rainfall estimate is made using knowledge of the typical performance of convective storms in the study region; in the third, images are examined for additional clues indicative of heavier rainfall. Variants of this type of approach have been developed for operation on an interactive computer system (e.g., Moses, 1980) so that, as with the Bristol Method, key analysis tasks may still be done by a "man-in-the-loop," although routine tasks are performed automatically.

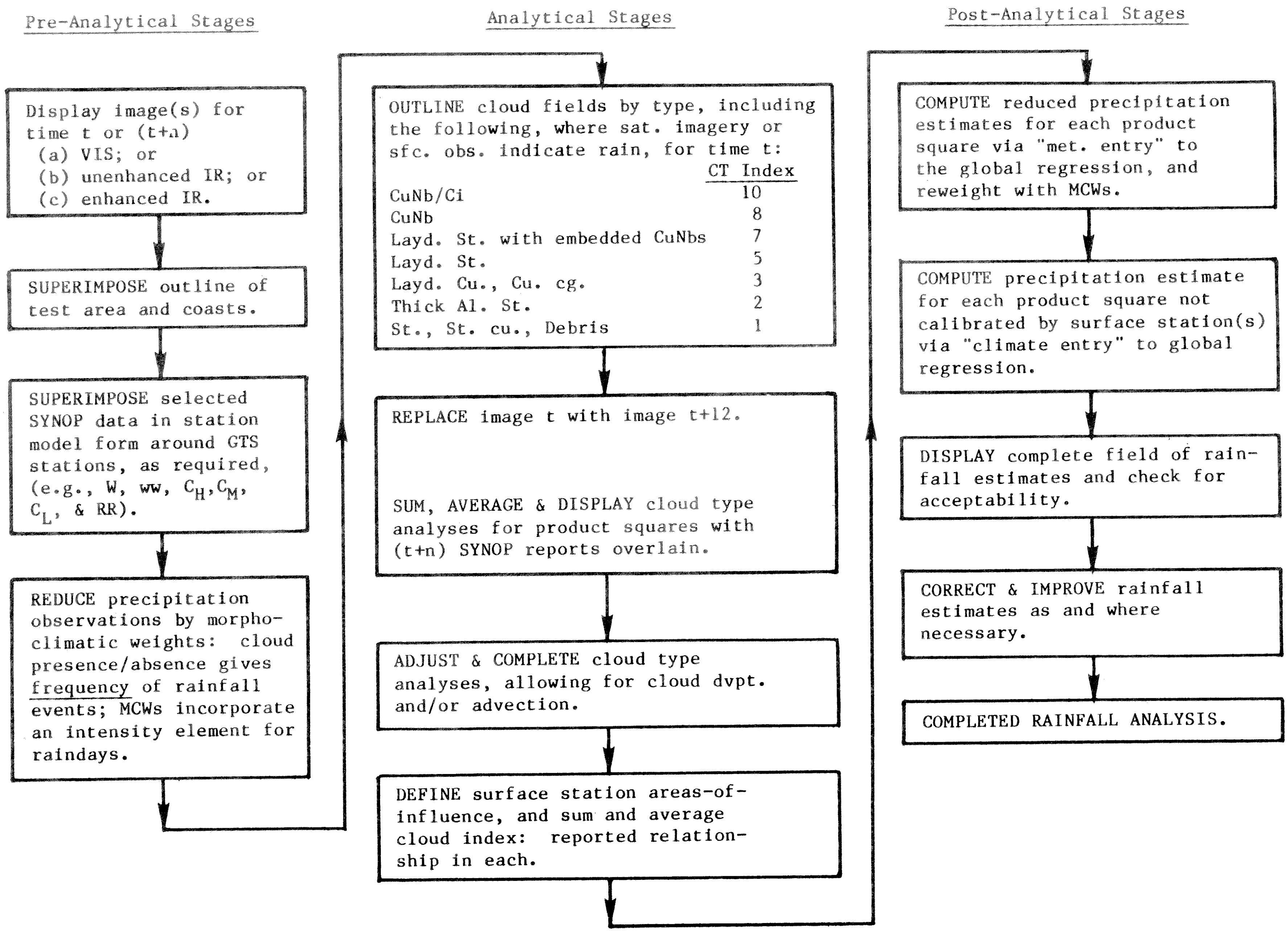


Fig. 12(a). The Bristol interactive scheme (BIAS) in its latest form (Barrett, 1983b).

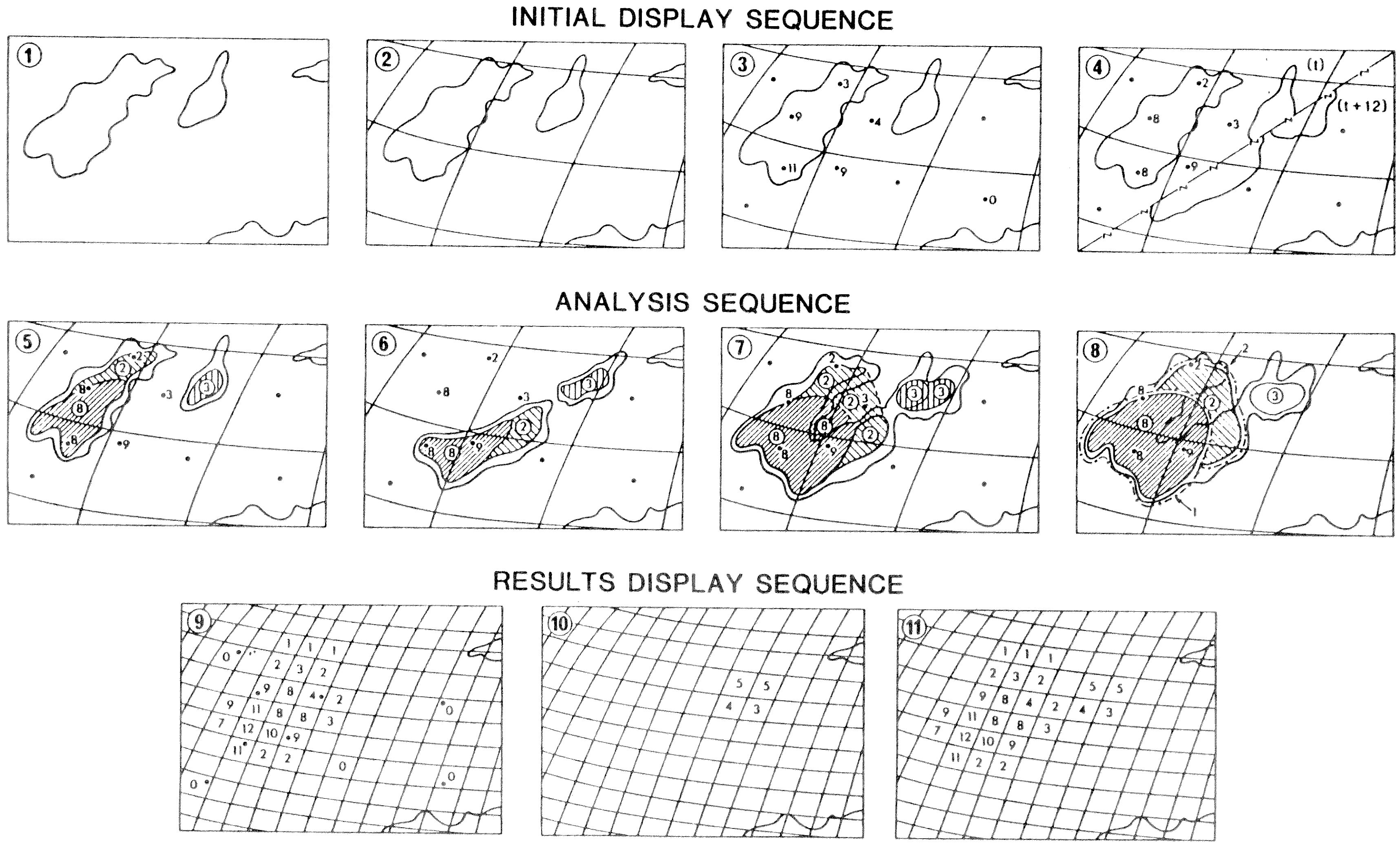


Fig. 12(b). A simulation of BIAS procedures on an interactive image processing screen. In (1) - (3) IR or VIS images are displayed for time (t), and compared with imagery for time (t+12) in (4). In (3) SYNOP reports for time (t+12) are superimposed, and in (4) rainfall totals are reduced by morphoclimatic weights. In (5) and (6), imagery for times (t) and (t+12) are analyzed for cloud type, and in (7) adjustments made for movement and/or development of clouds between those times. In (8) calibration station areas of influence are outlined. In (9), "meteorological entry" estimates of 12-hr rain are made where possible, and increased by the morphoclimatic weights. In (10) "climate entry" estimates are made for remaining rain-bearing product squares. (11) is the final 12-hr analysis.

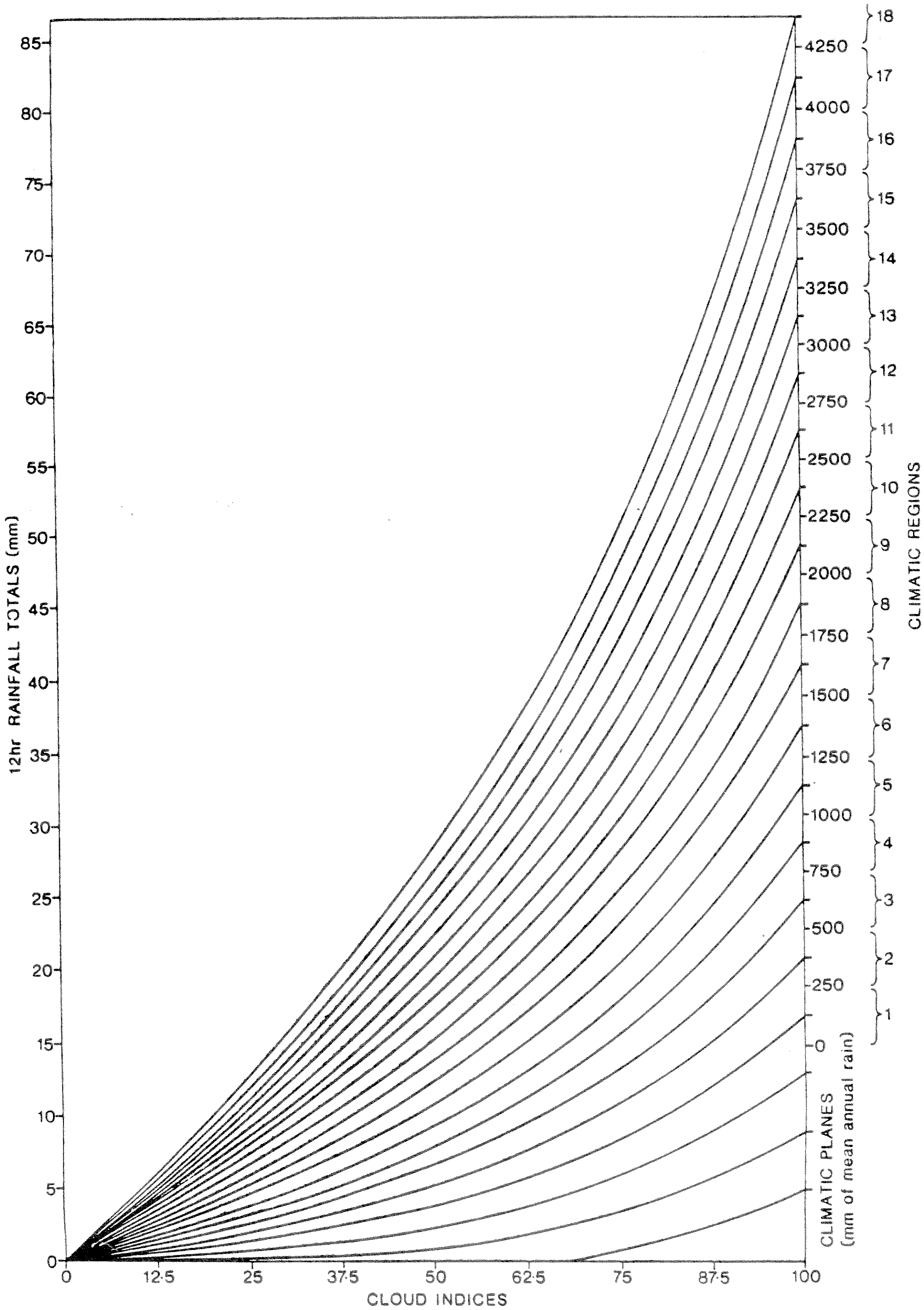


Fig. 13. THE BIAS "Global Regression" (Barrett, 1983b).

CONVECTIVE STORM TECHNIQUE

STEP 1: RAINFALL IS COMPUTED ONLY FOR THE ACTIVE PORTION OF THE THUNDERSTORM SYSTEM:

The following are clues for helping to make this decision.

- IR temperature gradient is tightest around station end of anvil for a thunderstorm system with vertical wind shear (IR).
- Station is located near the center of the anvil with a tight, uniform IR temperature gradient around entire anvil for a thunderstorm system with no vertical wind shear (IR).
- An overshooting top is over the station (VIS and IR).
- Anvil is brighter and/or more textured (VIS).
- From comparing last two pictures: Station is under half of anvil bounded by edge which moves least (IR).
- Station is near 300-mb upwind end of anvil (IR). Skip this clue if no upper air data available.
- Station is near the area of low-level inflow (VIS).
- Station is located under a radar echo.

STEP 2: HALF-HOURLY RAINFALL ESTIMATES IN INCHES ARE COMPUTED FROM THE FOLLOWING FACTORS:

FACTOR 1

CLOUD-TOP TEMPERATURE AND CLOUD GROWTH FACTOR (IR)
Determine amount that the coldest cloud tops increased within half-hour.

		>2/3° LAT	>1/3° <2/3° LAT	<1/3° LAT OR SAME	AREAL DECREASE OF SHADE OR WARMING FROM WHITE TO RPT GRAY OR WITHIN THE RPT GRAY	COLDEST TOPS 1 OR MORE SHADES WARMER
Med gray	(-32° to -41°)C	0.25	0.15	0.10	0.05	T
Lt gray	(-41° to -52°)	0.50	0.30	0.15	0.10	
Dk gray	(-52° to -58°)	0.75	0.40	0.20	0.15	
Black	(-58° to -62°)	1.00	0.60	0.30	0.20	
Rpt Gray*	(-62° to -80°)	1-2.00	0.60-1.00	0.30-0.60	0.30	
White	(below -80°)	2.00	1.00	0.60	0.40	0.10

*Colder repeat gray shades should be given higher rainfall estimates.

OR

DIVERGENCE ALOFT FACTOR* (IR and 200-mb analysis)

Med gray	Lt gray	Dk gray	Black	Rpt gray	White
0.15	0.30	0.40	0.60	0.60-1.00	1.00

*IR imagery shows edges of thunderstorm anvil along the upwind end forming a large angle of between 50-90 degrees pointing into the wind; 200-mb analysis often shows these storms just downwind from where the polar jet and subtropical jet separate.

FACTOR 2

OVERSHOOTING TOP FACTOR (VIS, IR). Add to the overshooting tops*

Med gray	Lt gray	Dk gray	Black	Rpt gray	White
0.50	0.45	0.40	0.30	0.30	0.30

*High resolution visible imagery is the best data for determining this factor.

FACTOR 3

THUNDERSTORM OR CONVECTIVE CLOUD LINE MERGER FACTOR (IR, VIS).
Add 0.50 to the colder tops in the area of the merger.

FACTOR 4

SATURATED ENVIRONMENT FACTOR (IR, VIS). Add to the colder tops stationary for a given amount of time:

	Med gray	Lt gray	Dk gray	Black	Rpt gray	White
>1 hour but <2 hours	0.20	0.20	0.20	0.20	0.30	0.30
>2 hours	0.40	0.40	0.40	0.40	0.50	0.50

FACTOR 5

MOISTURE CORRECTION FACTOR = PRECIPITABLE WATER (SFC-500 mb) · RELATIVE HUMIDITY (SFC-500 mb)

STEP 3: FACTORS ARE SUMMED AND MULTIPLIED BY MOISTURE CORRECTION FACTOR:

TOTAL HALF-HOURLY CONVECTIVE RAINFALL ESTIMATES (in inches) =

$$\left(\begin{array}{l}\text{(Cloud-top temperature and cloud growth factor or} \\ \text{divergence aloft factor)}^1 + \text{overshooting top factor}^2 \\ + \text{merger factor}^3 + \text{saturated environment factor}^4\end{array}\right) \cdot \left(\text{Moisture correction factor}^5\right)$$

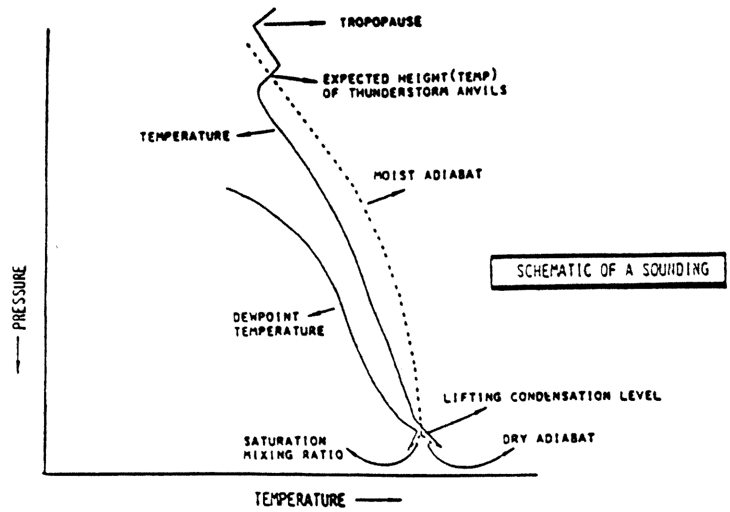
END OF TECHNIQUE

Fig. 14a. Scofield-Oliver convective storm decision tree method--basic form (courtesy, NOAA, 1984).

CONVECTIVE STORM TECHNIQUE

WARM-TOP MODIFICATION

STEP 1. COMPUTE THE EXPECTED TEMPERATURE (EQUILIBRIUM LEVEL) OF CONVECTIVE TOPS FROM THE SOUNDINGS.



↓

STEP 2. USE THIS TEMPERATURE AS THE SPREADING ANVIL LEVEL AND ASSIGN IT THE RAINFALL RATE OF THE WARMEST REPEAT GRAY LEVEL (BETWEEN -62 TO -67°C).

↓

STEP 3. COMPARE THE ANVIL TEMPERATURE WITH THE COMPUTED TEMPERATURE. FOR ANVIL TEMPERATURES COLDER THAN THE COMPUTED EXPECTED TEMPERATURES, USE AN APPROPRIATELY HIGHER ESTIMATED AMOUNT. FOR ANVIL TEMPERATURES WARMER THAN THE COMPUTED, ADJUST THE ESTIMATES UPWARD THE SAME RELATIVE AMOUNT.

↓

STEP 4. USE THE ADJUSTED CLOUD-TOP TEMPERATURE TO CHANGE THE OTHER FACTORS, WHERE APPLICABLE.

↓

USE THE ADJUSTED FACTORS OBTAINED IN THE ABOVE STEPS TO COMPUTE THE RAINFALL IN THE CONVECTIVE STORM TECHNIQUE.

TOTAL HALF-HOURLY CONVECTIVE RAINFALL ESTIMATES (IN INCHES) =

[CLOUD-TOP TEMPERATURE AND CLOUD GROWTH FACTOR OR DIVERGENCE ALOFT FACTOR + OVERSHOOTING TOP FACTOR + MERGER FACTOR + SATURATED ENVIRONMENT FACTOR]

X

[MOISTURE CORRECTION FACTOR]

↓

END OF TECHNIQUE

Fig. 14b. Scofield-Oliver convective storm decision tree with warm-top modification (courtesy, NOAA 1984).

WINTER SEASON TECHNIQUE

STEP 1: ANALYZE PRECIPITATION TYPES & INTENSITIES

Using the schematics of evolution and the mechanisms, signatures, and observations of moderate to heavy precipitation, analyze on the satellite pictures the precipitation types (shower or continuous precipitation) and intensities (light, moderate, or heavy). Dashed lines -- continuous precipitation; dotted lines -- showers. Label each line light, moderate, or heavy.

MECHANISMS, SIGNATURES, AND OBSERVATIONS OF MODERATE TO HEAVY PRECIPITATION

MECHANISMS

- To the north of the jet max at the exit zone
  and
- To the south of the jet max at the entrance zone
- Location of maximum warm air advection
- Location of maximum low level moisture convergence
- Location of maximum positive vorticity advection
- Upslope flow

SIGNATURES

- Convective cloud bands or elements remaining the same or growing and becoming colder
- Bright textured clouds in VIS; cold tops in the IR
- Middle level clouds becoming colder and growing
- A comma or wave head becoming more and more anticyclonic
- A comma or wave with a tail growing and becoming colder

OBSERVATIONS

Observed precipitation type (showers or continuous precipitation) and intensity (moderate or heavy) from surface reports and radar data:

Intensity	Showers	Continuous Precipitation
Light	1	1
Moderate	2	2
Heavy	3	3

Radar Vip levels

STEP 2: COMPUTE PRECIPITATION ESTIMATES FOR THE LINES DRAWN IN STEP 1

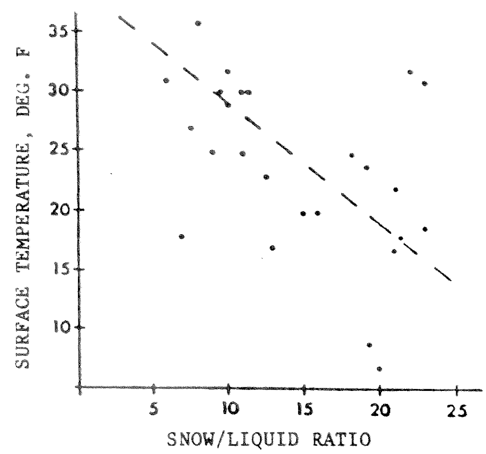
Line	Showers (in/hr)	Continuous Rain (in/hr)
Light	.05 - .20	< .10
Moderate	.20 - 1.0	.10 - .30
Heavy	> 1.0	> 30

STEP 3: IF NECESSARY, MODIFY THE PRECIPITATION ESTIMATE FROM STEP 2 BY THE OBSERVED PRECIPITABLE WATER

$$\text{(ESTIMATE OBTAINED FROM STEP 2)} \times \frac{\text{Observed Surface - 500 mb Precipitable Water}}{\text{Standard Surface - 500 mb Precipitable Water}} \; *$$

*Use this precipitable water (PW) factor only when the observed surface to 500 mb PW is < 0.75 inch and use a value of 1.0 inch as a standard surface to 500 mb PW.

STEP 4: IF NECESSARY, CONVERT PRECIP ESTIMATE INTO SNOW EQUIVALENT BY USING THE GRAPH BELOW



Note: These ratios may have to be adjusted for mountainous regions.

STEP 5: PRODUCE A SHORT RANGE FORECAST OF PRECIP

$$Fec = \frac{Eec\ Dec}{Vec}$$

where:

Fec = Short range forecast of precipitation amount (3 hours)

Eec = One hour precipitation estimate (obtained in step 2, step 3, or step 4)

Dec = Cross sectional length of the isolines (drawn in step 1) in the direction of motion

Vec = Speed of precipitation portion of cloud

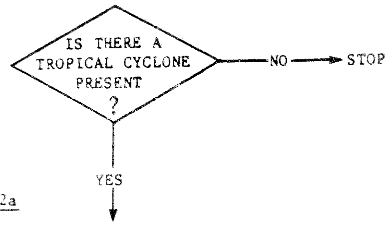
- If the storm is expected to intensify as determined from cloud evolution, other satellite signatures, the LFM model, etc., increase the forecast value (Fec) of precipitation
- If the storm is expected to weaken, decrease the forecast value (Fec) of precipitation

END OF TECHNIQUE

Fig. 14c. Scofield-Oliver winter season decision tree (courtesy, NOAA 1984).

TROPICAL CYCLONE TECHNIQUE

STEP 1



STEP 2a

Identify and locate the following cloud features in the tropical cyclone:

- Eye (or cloud system center)
- Wall cloud (20 n miles either side of the eye or the cloud system center)
- Central Dense Overcast (CDO) area
- Outer Banding Area (OBA)
- Area of embedded cold convective cloud tops (ECT) in the OBA area

STEP 2b

From comparing two consecutive pictures, draw isolines in the second picture around the following:

- Wall cloud (approximately 20 n miles either side of the eye or the cloud system center)
- A 50 n mile radius either side of the cloud system center within the CDO; heavy rain often occurs within this radius. Use IR and VIS to help modify the size and location of the isoline. Within this isoline, coldest and brightest areas should also be analyzed; these areas often locate the heaviest rainfall within the CDO.
- Bands in the OBA that are convective
- Within the OBA, areas of embedded cold convective cloud tops in the convective cloud bands

STEP 3

From comparing two consecutive pictures, compute rainfall estimates for the isolines drawn above; the underlined rainfall accumulation is normally the value used in the estimate.

Estimates for the CDO Area and Wall Cloud	Rainfall Accumulations (inches per hour)
CDO (a 50 n mile radius either side of the storm center; this radius can be modified by the IR and VIS)	0.50 - 1.00 - 2.00
Outer edge of the CDO	0.01 - 0.05 - 0.10
Wall cloud (20 n miles either side of the storm center)	1.00 - 2.00 - 3.00
Estimates for the OBA	
Outer Banding Area	0.10 - 0.30 - 0.50
The first band from the CDO located in the onshore flow	0.50 - 1.00 - 2.00
Area of cold convective cloud tops embedded in the convective cloud bands	
Growing, becoming colder, or remaining the same	0.25 - 1.00 - 4.00
Decreasing in area	0.10 - 0.50 - 1.00
Becoming warmer	0.05 - 0.20 - 0.50

STEP 4

Compute the rainfall potential along the tropical cyclone track before landfall.

$$\text{Rainfall potential} = \frac{R_{CDO}\,D_{CDO} + R_{WC}\,D_{WC}}{V} + \frac{R_{OBA}\,D_{OBA} + R_{ECT}\,D_{ECT}}{V}$$

where:

R_{CDO}, R_{WC}, R_{OBA}, and R_{ECT} are rainfall rates (R) of the CDO, wall cloud (WC) area, significant bands in the OBA, and embedded cold convective tops (ECT), respectively.

D_{CDO}, D_{WC}, D_{OBA}, and D_{ECT} are diameters (D) of the rainfall rates in the direction of motion.

V is the speed of the tropical cyclone.

END OF TECHNIQUE

Fig. 14d. Scofield-Oliver tropical cyclone decision tree (courtesy, NOAA 1984)

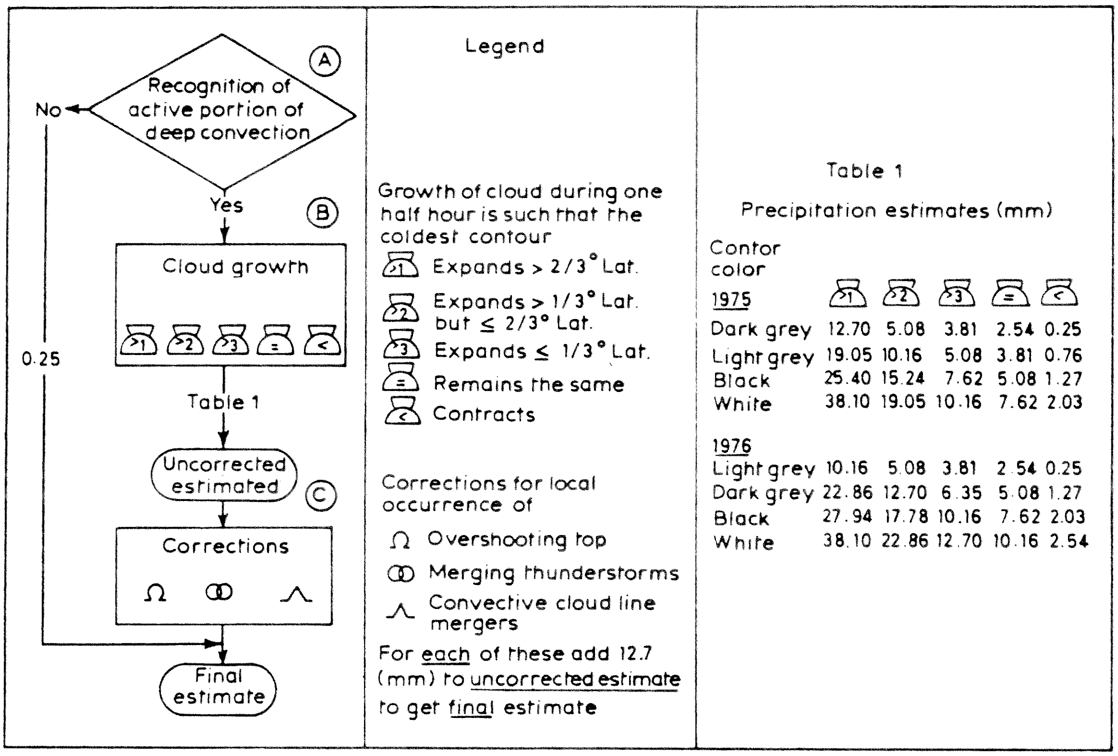


Fig. 15. Flow chart and table for the estimation of point rainfall from geosynchronous satellite imagery for South America (Ingraham and Amarocho, 1977).

Some efforts have been made to apply simplified life-history techniques to basin rainfall monitoring in South America (see Ingraham and Amorocho, 1977, and Figure 15). The use of such methods has also been demonstrated in support of river hydrograph estimation and prediction. The results seem to show considerable potential for such applications.

4.1.3.3 Integrative approaches. In the United Kingdom, intensive research has led to the development of a short-term forecasting ("nowcasting") program for rainfall amounts and distributions up to 6 hours ahead. The "FRONTIERS" plan (Browning, 1979) seeks to integrate raingage and radar data with imagery from METEOSAT (the ESA satellite) to provide small-area rainfall forecasts over a national teletext system (See Figure 16). A similar scheme named "ARAMIS" (Gilet et al., 1983) is now under development in France. In the United States, the Hydrologic Rainfall Analysis Project (HRAP) involves a multivariate objective analysis approach to the estimation of rainfall and other meteorological variables (Greene et al., 1979). Its aim is to achieve optimal integrations of data from varied sources, such as radars, raingages, and satellites.

It seems likely that such approaches will set the trend for further research and operations in the near- to mid-term future.

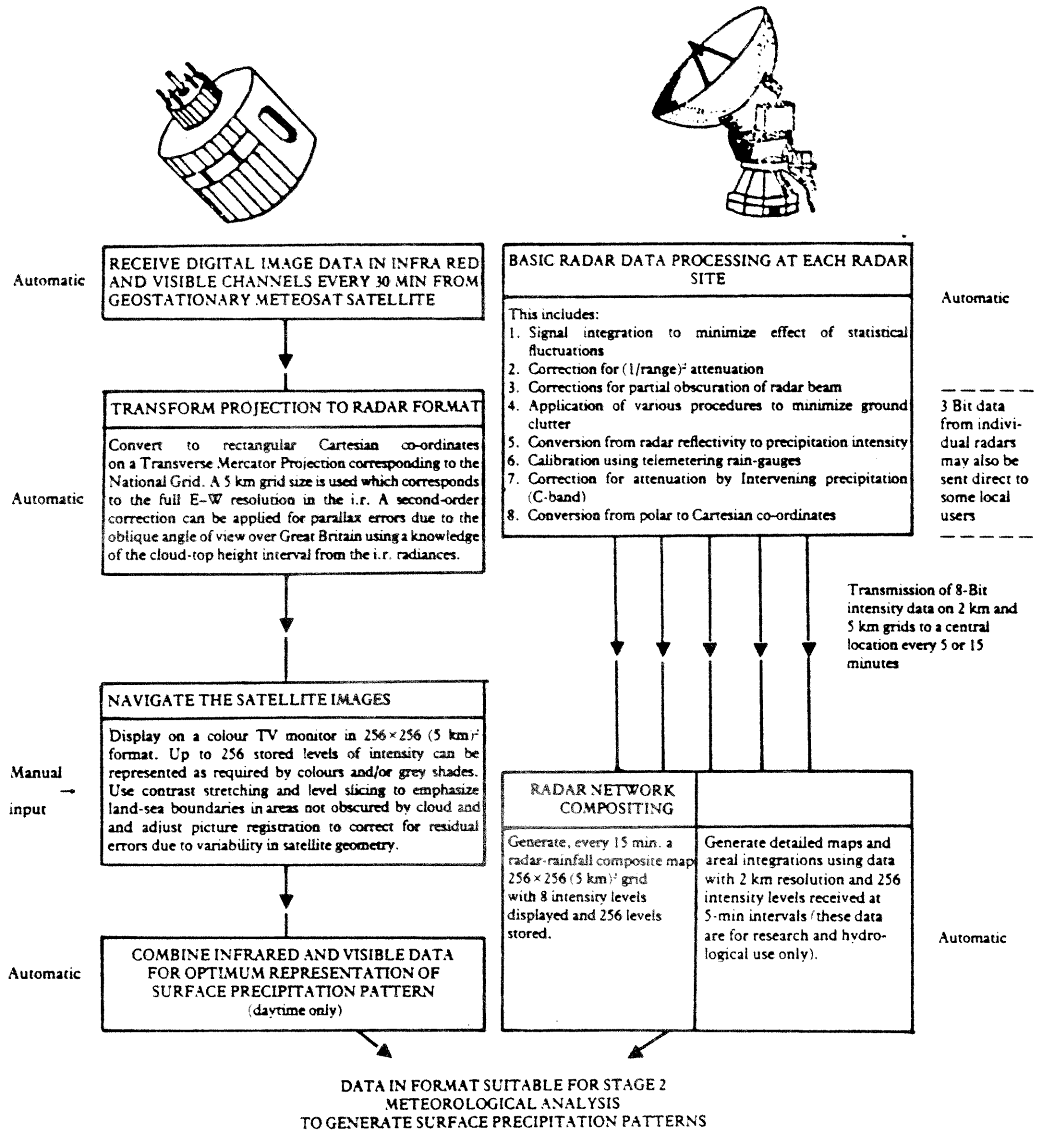


Fig. 16. Preprocessing of satellite and radar data for the "FRONTIERS" plan to use radar and satellite imagery for very short-range precipitation forecasting. (From Browning, 1979.)

4.1.4 Evaporation processes. The estimation of evaporation and evapotranspiration from satellites has been described by Rango (1980) as "the most challenging of all the applications of remote sensing to hydrometeorology." There would appear to be three chief reasons for this, namely:

(a) The inadequacy of in situ monitoring of evaporation and transpiration in the field.

(b) The physical complexities of these problems.

(c) The limited progress which has been made to date in the development of techniques to estimate evaporation or evapotranspiration from remotely sensed data. Because of this point, the notes which follow are brief and general.

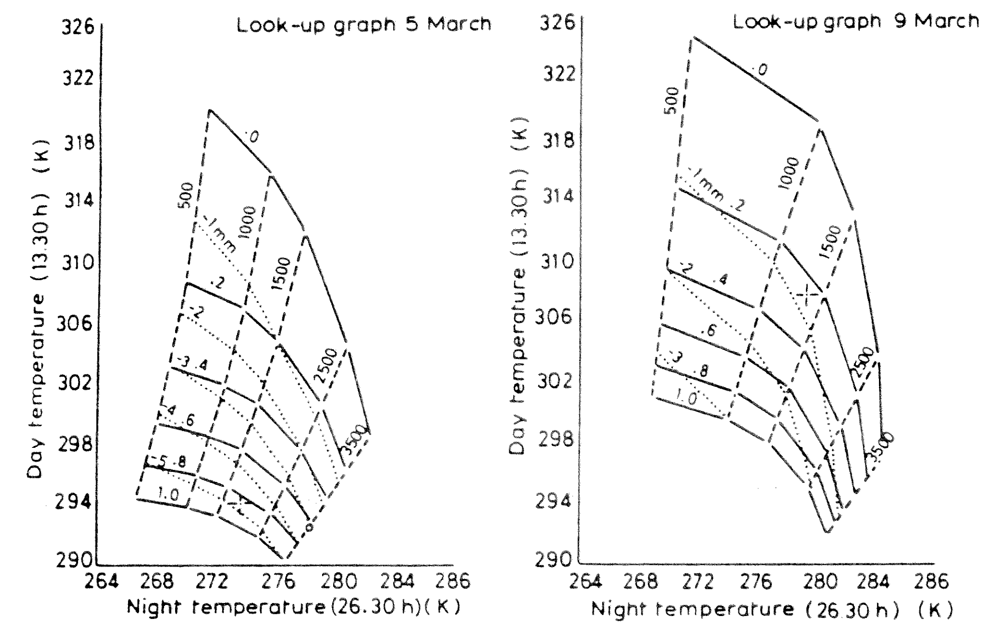
Evaporation and evapotranspiration are complex processes which lead to particularly elusive outputs (parameterized as the latent heat flux into the atmosphere from soil, vegetation, and water surfaces). While free water surfaces perform relatively simply in such a context, soil and vegetation surfaces manifestly do not.

Thermal modeling of bare soil requires knowledge of the nature of the soil itself, with particular reference to its thermal inertia (which is especially dependent on porosity, and affected by water saturation), and to the external environment of the soil (which is dominated by the surface radiation balance, itself affected by a range of soil surface and meteorological parameters). Soil moisture monitoring by remote sensing has been expertly reviewed by Schmugge et al. (1980), and Jackson et al. (1982).

Numerical methods have been developed to provide estimates of soil thermal inertia, surface relative humidity, and evaporation, through solving inverse equations for heat and mass transfer across the surface of a soil [e.g., those of Rosema (1981) which depended essentially upon energy balance equations alone, and Camillo et al. (1983) and Rosema (1975), which included consideration of both energy and moisture balances]. These methods utilize surface temperature measurements derived from thermal infrared imagery obtained by aircraft or weather satellites, and interpreted through the solution of key equations, and in some cases by appropriate graphs or look-up tables. (See Gurney and Hall, 1983). Rosema (1981) used physical evaporation principles to generate a computer program called TELL-US. With this program, he simulated conditions in a bare field that was irrigated, then allowed to dry for 15 days. Surface temperature, surface relative humidity, thermal inertia, and evaporation since the previous observing time were stored for 1330 and 2030 local time. The plots in Figure 17 show the apparent relationships which emerged among evaporation, surface relative humidity, and thermal inertia, and a way of explaining them from diurnal ground surface temperature extremes. Figure 17 also shows how the range of diurnal temperatures increased with decreasing soil moisture, and how evaporation increased with decreasing humidity. In the referenced article, Rosema further discussed the use of thermal surveys in support of in situ measurements for adjusting irrigation schedules. Additional work in this area has been reported by Khorram and Smith (1979), Hielman et al. (1976), and Rosema (1983).

Evapotranspiration monitoring methods are not dissimilar, but are further complicated by the differences known to exist between ground surface and plant canopy surface temperatures, and the changing nature and behavior of vegetation through its seasonal growth cycle. The range of temperatures in the crop canopy in fields of a single crop has been used by Jackson et al. (1977) to determine when irrigation should be repeated for optimum crop yield.

In the present stage of development, remote sensing methods of evaluating these elusive but important parameters still necessitate inputs of other



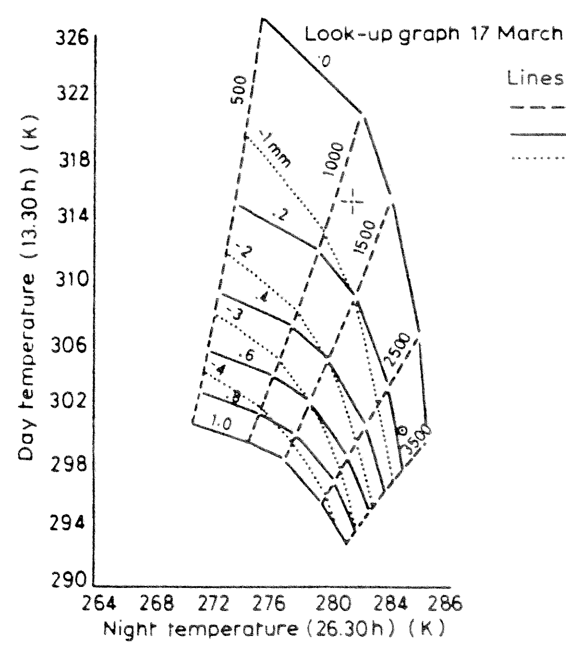


Fig. 17. Look-up graphs determined by the TELL-US Method representing three subsequent stages in drying of a test plot in the USA, March 1971. The crosslets mark observed day and night temperature pairs. From the graphs, values of thermal inertia, surface relative humidity and daily evaporation may be read. (After Rosema, 1979.)

meteorological observations that cannot yet be obtained from satellite sources, e.g., air humidity and the horizontal wind velocity near the ground. There are differing opinions concerning the ability of remote sensing to map evaporation from the ground surface. While acknowledging the difficulties associated with any estimates of evapotranspiration, one group of scientists has suggested that because of the limitations associated with making in situ evaporation measurements using classical methods, any information provided by aerial estimates or satellite data is valuable. This view receives support in the very recent summary by Menenti of evaporation in arid regions (1984). On the other hand, to quote Rango again, "Only preliminary studies have been conducted, with inconclusive results. No widely acceptable or transferable technique has (yet) emerged."

Insofar as vegetation extent and condition may influence other hydrological parameters, it now seems likely that the new "Vegetation Index" products now under development by both NOAA and NASA, based on polar-orbiting weather satellite imagery, will provide direct and, therefore, probably more dependable information for the foreseeable future (see Figure 18). These data will indicate the presence or absence of transpiring vegetation in arid areas and the onset or cessation of seasonal transpiration in agricultural, rangeland, and forest areas. On the synoptic scale, these products complement the more detailed but much more costly vegetation analyses which can be derived from Landsat-type data. As far as soil moisture is concerned, this may be depicted more satisfactorily in the immediate future through monitoring rainfall and processing this through local mass-balance models, and in the mid-term future, by passive and active microwave sensor systems currently under development. However, in this latter case, there is considerable doubt as to whether remote sensing approaches will be able to sense moisture contents below a relatively shallow surface layer, some 5-10 cm thick. Even this should be of some benefit to hydrologic modelers.

4.2 Surface water hydrology

Surface water hydrology is concerned with the amount and quality of water flowing over the surface of the land in rivers and streams or stored in lakes, reservoirs, and ponds. Because the amount of water in any one location constantly changes in response to rainfall, evapotranspiration, infiltration, and flow under the influence of gravity, the primary questions to be answered in order to set up or maintain any water resource management system are: how much water is there, where is it, where has it come from, how much more can be expected, where is it going, what impurities does it carry, where have these impurities come from, and where are they going? The capabilities of remote sensing systems to answer these questions will be discussed below.

4.2.1 General capabilities. The answers to many of the questions just posed might be presented best in the form of various types of maps -- maps that might show locations of water bodies, or of water-contributing areas of watersheds. Mapping is one of the basic and most powerful capabilities of most operational remote sensing systems. Maps originally depended almost entirely on data from surface surveys and observations, but now can be generated, to a very large extent, from aerial photography, satellite vidicon camera pictures, or scanner imagery. Some ground checking is still needed, but that is true of nearly all remote sensing activities. Generation of maps is described in the Manual of Photogrammetry (ASP, 1980). The hydrological variables that require measurement were presented in Chapter 3. Remote sensing can also identify attributes which are not limited to what can be seen by the human eye on the Earth's surface. The following sections will show the application of mapping capabilities of remote sensing from the more straightforward planimetric maps, to multi-attribute thematic

Fig. 18. NOAA Vegetation Index (NVI). This index is calculated from the NOAA AVHRR channels 1 and 2 data through the equation NVI = $(ch_2 - ch_1)/(ch_2 + ch_1)$. High values (dark areas in the image) are associated with greater density and, therefore, greater reflection from the plant canopy in the near infrared wave band.

maps which show (by color, stipple, or cross-hatching), the principal attributes of surface areas related to desired themes, for example, land use.

4.2.2 Assessments of surface water storage capacities and contents. The location of surface water, and the planning of its storage and distribution all require maps. Maps based on aerial photography can show the location and surface area of lakes and reservoirs having significant areas relative to the map scale. Aerial photographs show existing water surface areas (on the day the photograph was taken) and by the presence or lack of vegetation can show the normally existing shorelines, suggesting current storage quantities compared with capacity or possible long-term average values. When necessary maps are not available, satellite imagery or aerial photographs taken perpendicular to the ground surface can be substituted if they are available at the necessary scales. Satellite imagery is available for most areas of the world at the data centers discussed in Section 5.2.

With maps, or remote sensing imagery used as maps, inventories of water surface areas may be done. The work performed by the U.S. Army Corps of Engineers in 1973-74 is an example of an inventory of surface water storage. The Corps of Engineers used Landsat imagery in addition to using existing maps, to ensure that no surface water was missed (Moore 1973).

Remote sensing imagery used as maps also show rivers and streams, indicating the overall flow patterns of an area. Several of the basic values needed for water management models can be taken from imagery or a planimetric map developed from remote sensing; for instance, basin areas, stream channel densities, and as mentioned earlier, the area of surface water (Rango et al., 1975).

For many applications, aerial photographs or satellite imagery of adequate clarity and scale may already exist and be available at relatively low cost from one of the data centers listed in Chapter 5. However, there may be some applications where the resolution (scale), format, sampling frequency, and time of acquisition that are available with existing aerial photographs, or satellite imagery are not adequate for the required application. In that situation, a custom survey must be planned. Basic details for planning aerial surveys are given in many good texts on photointerpretation. Ramey (1970) details the planning of aerial surveys specifically for hydrologic applications. It should be noted that publication of his report preceded the launch of Landsat and GOES type satellites, and for satellite planning more recent reports should be used (Short, 1982).

4.2.3 Detection of aquatic vegetation. An excess of aquatic plants and vegetation can interfere with navigation, impede water flow, cause an increase in sedimentation and shoaling, and clog water management devices such as intakes, screens, etc. Detection of aquatic vegetation infestations has been discussed by Link and Long (1979). They concluded that in regions similar to the southeastern United States, the most effective method involved aerial photography using false color IR film at flight altitudes resulting in photograph scales of from 1:60,000 to 1:20,000.

4.2.4 Mapping of snow and ice. Reliable estimates of snow water equivalent provide the basis for water supply estimates in many areas where water for irrigation comes primarily from mountain snow packs. In parts of the western USA, for example, it is estimated that 70 per cent of the irrigation water comes from snow. Many of the reservoirs where snowmelt water is stored also have a flood control application. The flood control and the irrigation uses have conflicting operational requirements. Irrigation interests want to store the maximum possible water, while the authorities responsible for flood control desire adequate potential storage capacity. The resolution of this conflict requires timely and accurate assessments of snow and snowmelt. Knowledge of the rate of release of water from snow packs is also of vital importance for operators of hydroelectric power plants. For example, all of the commercial electricity produced in Norway is generated at hydroelectric plants, so information about the water contained in snowfields is extremely important (Andersen and Ødegaard, 1980).

Of various desired snow observations, the areal extent of snow cover is the most easily measured. The areal extent of snow is operationally measured in several countries (Rango and Martinec, 1982; Bowley et al., 1981; Dhanju, 1978; Schneider, 1981; Rango, 1981). This measurement alone is not completely satisfactory because snow varies in density and distribution as it is blown around by the wind, so there is not a constant relationship between the areal extent of snow and the amount of water in the pack. Most basins, however, do tend to follow a consistent pattern of melts so that a depletion curve often can be related to the amount of water that remains in a basin as the melt season progresses. The areal extent of snow estimation can be essentially automated. The degree of automation of snow mapping must be qualified by the requirement that a person must usually determine, either by photointerpretation or from on site observations, that snow covered portions of the basin are cloud free. Valley fog may be present and cause no problems if that part of the basin is known to be snow free and appropriate information has been fed to the computer. Estimates of areal snow cover from remote sensing can be used to update positions on depletion curves that are being maintained on the basis of some other monitoring system such as a gage network. The application of the update to the depletion curve is shown in Figure 19 by Anderson (1973).

Measurement of snow pack attributes in addition to areal extent has been performed in some areas. Operational programs exist to measure the water equivalent of snow using gamma-ray measuring devices. The gamma rays are attenuated proportionally to the mass of water between the gamma ray detector (which is carried above the snow) and the radioactive elements occurring naturally in the soil. In the USA, this method is primarily used in the plains of the North Central States (Carroll et al., 1983). There are, however, reports of mountain slope use in the USSR (Getker et al., 1979).

In some areas of the world, roads, railroads, and public utilities pass through isolated canyons where they may be subject to avalanche damage. When avalanches occur, communities depending on outside support may be isolated from the rest of the world during emergencies when external help is greatly needed. Monitoring of avalanches from space is discussed by Krakova (1980).

Ice cover on lakes and rivers can significantly affect flows in the rivers. Ice cover and the breaking up of ice cover impacts people living or working along the banks when ice jams cause flooding or when flowing blocks of ice cause mechanical damage to bridges and other structures. Ice cover also affects commercial and recreational traffic in lakes and rivers. Similarly, hydroelectric power generation is influenced by ice, which at

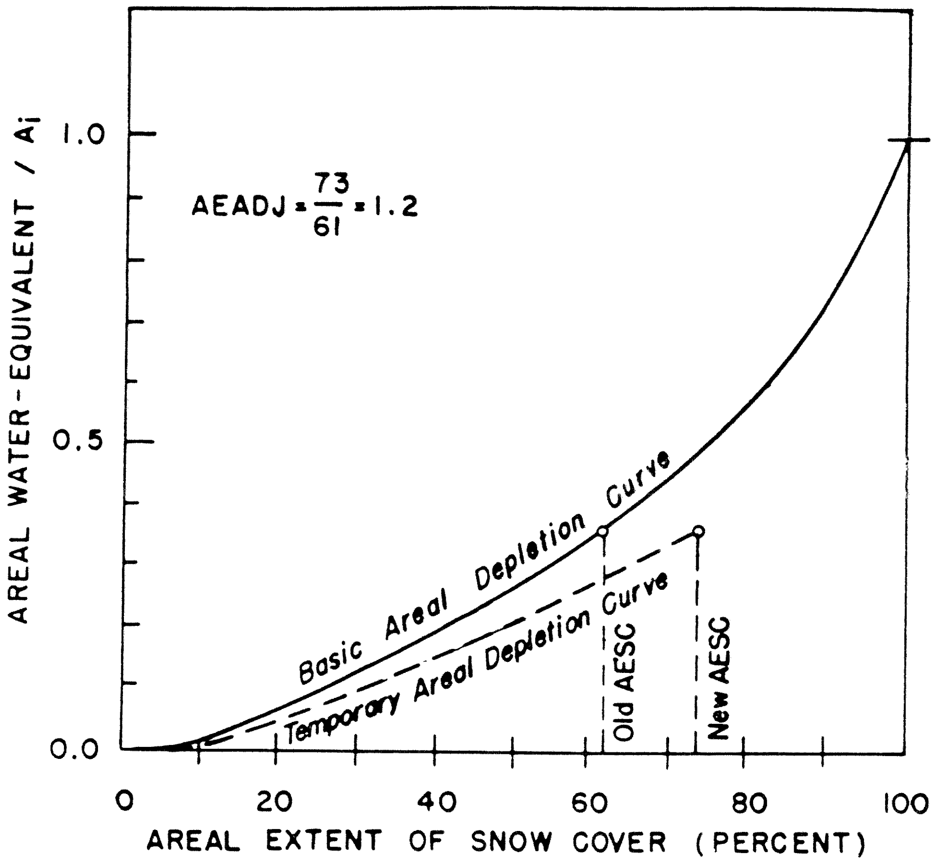


Fig. 19. Example of the effect of adjustment of the areal extent of snow cover on an areal depletion curve. AESC is Areal Extent of Snow Cover. AEADJ is the Areal Extent of snow ADJustment factor. A_i is the minimum water-equivalent of the snow existing on a basin when the areal extent of snow cover reaches 100 per cent (Anderson, 1973).

times controls the flow of water, and by the damage that may be done to generating equipment. Remote sensing measurements of ice cover have been performed routinely for large rivers and lakes (Schneider and McGinnis, 1981). Techniques used in Canada are described by Dey et al. (1977). Satellite imagery is used in the USSR to estimate the areal extent of glaciers, their movement, traces of avalanches, and the extent and location of river icings (Desinov, 1980).

4.2.5. Watershed definition and planning. In addition to generating maps showing relative locations of land features, water bodies, ice-cover on lakes, etc., map makers use remote sensing data to generate other types of maps. When aerial photographs or satellite images are made, objects which rise above the mean elevation of the surface tend to appear farther (in a radial direction) from the center of the picture (or away from the line of flight in the case of scanning devices) than their true relative horizontal distance. At the same time, objects or features that are below the mean elevation appear closer to the center (see Figure 20). Aerial photographs that are made for mapping purposes use techniques to minimize this effect; but, the displacement that is caused by differing elevations has its uses in the production of topographic maps. Topographic maps can be developed from stereo pairs of aerial photographs or images. A description of this process is found in the Manual of Photogrammetry (ASP, 1966). In addition to the topographic maps derived from stereo photography or imagery, maps derived from airborne imaging radars and thermal scanners show many geologic features which have an important influence on water holding and percolating properties that are not evident in aerial photographs. Most of the basin characteristics discussed in Section 3.1.3 can be obtained from these maps. Engineers with the appropriate imagery, who have training in photointerpretation, can select sites having surface geology appropriate for locating reservoirs, control structures, bridges, or canals. Once the sites are located, these same engineers can make decisions regarding the quantities

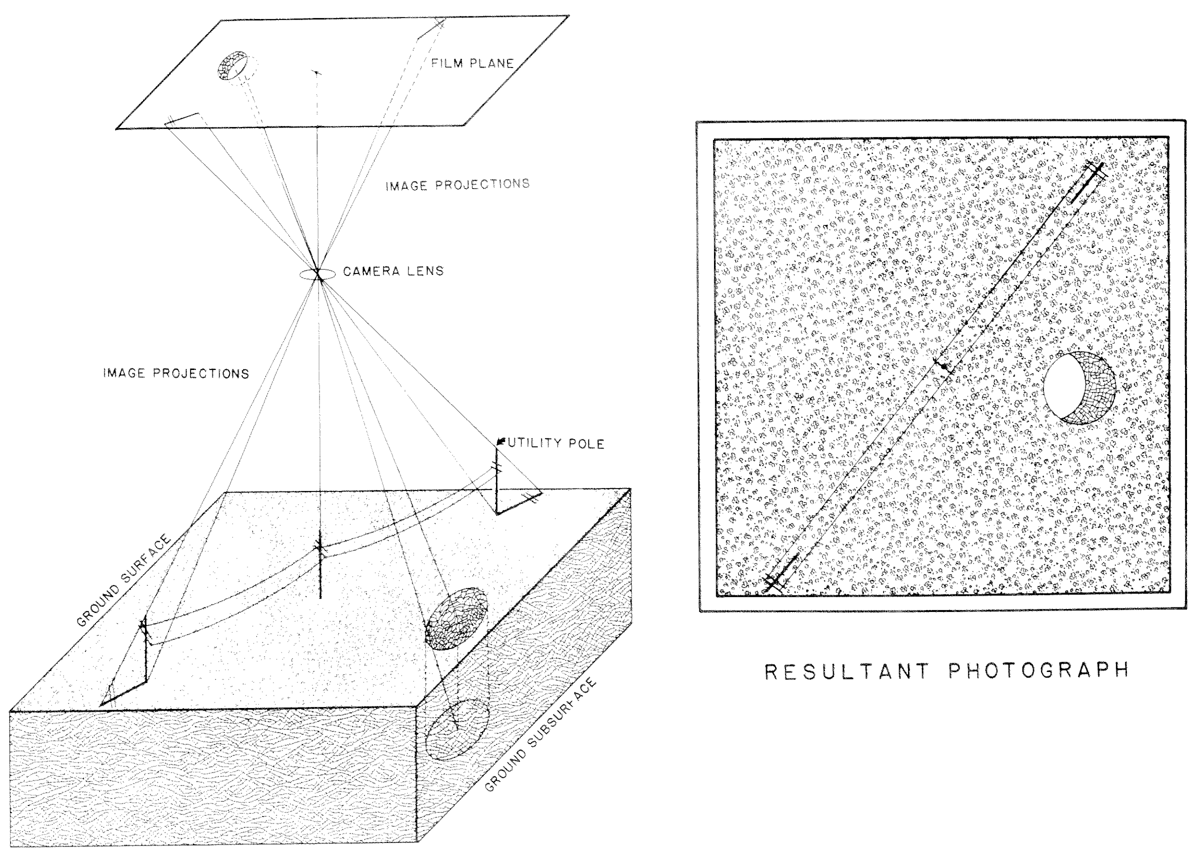


Fig. 20. Radial horizontal displacement of images on aerial photographs caused by objects projecting above or below the mean ground surface elevation.

of construction materials to be moved and, in some cases, locate sources of construction materials convenient to the construction site (McKim and Merry, 1979). The location of dam sites for flood control, water storage, or hydroelectric power is very important for developing countries. In 1978 it was estimated that only 2.6 per cent of the available hydropower had been developed in Africa, 14 per cent had been developed in Latin America, while nearly 80 per cent had been developed in North America (United Nations, 1978).

4.2.6 Infiltration and runoff coefficients. There are many factors of hydrological importance which are not evident on the maps, photographs, and imagery that have been discussed to this point. The infiltration of soils and the evapotranspiration of water from the surface depend on soil type, vegetation, and cultural development. To some extent, the type of soil influences the formation of surface features and can be suggested by topographic and geologic maps of sufficient detail if these maps exist. Lineaments associated with faults and fracture zones also suggest areas of high infiltration or recharge. These topics will be covered in a little more detail in Section 4.3.

In wilderness areas, vegetation and soils interact. Changes in vegetation often indicate a change in soil conditions. Vegetation observed over time, especially in an arid area where moisture is the limiting factor governing growth, is very indicative of the infiltration and moisture-holding capacities of the soil. The vegetation also affects the infiltration abilities of the soil, by protecting the soil surface from the pounding of rain which causes crust formation and by adding a humus layer which acts like a sponge to allow water to enter the soil. In populated areas, cultural practice or land-use will have a significant effect on both infiltration and evapotranspiration.

Land-use images or maps can be developed using multispectral scanners to classify land-use, vegetation, crop types, as well as trophic states of lakes, and other variables having distinctive spectral signatures (see Section 2.2). Maps which show some of the characteristics of the land such as those mentioned above are called thematic maps. Roofs, paved streets, packed soil in urban areas, and hardpan in arid areas all tend to be impervious to water. Grassy pastures, forests, and other similar vegetation tend to slow the surface flow of water causing it to infiltrate rather than run off. Ragan and others (Ragan and Jackson, 1980; Jackson and Bondelid, 1983) have employed these land use classifications to select runoff curve numbers which are related to basin infiltration. These runoff curves are used in a rainfall-runoff model to evaluate the flood potential that may exist in basins and for use in design flood studies (see Figure 21).

4.2.7 Irrigation and water consumption. In arid and semiarid regions, the presence of cultivated crops almost always indicates the use of irrigation. About 40 per cent of the world's food supply comes from such lands and half of the water that is stored or managed for irrigation is lost in transit to the crops requiring the water (Darves-Bornoz, 1981). Conservation of this water could allow a significant increase in the acreage to be cultivated. Losses from canals to surrounding soils are generally easy to find because vegetation grows that would not be present in an unirrigated area. Little or no volunteer vegetation (weeds) grows near lined canals in arid areas, and that which does grow, generally consumes water leaking

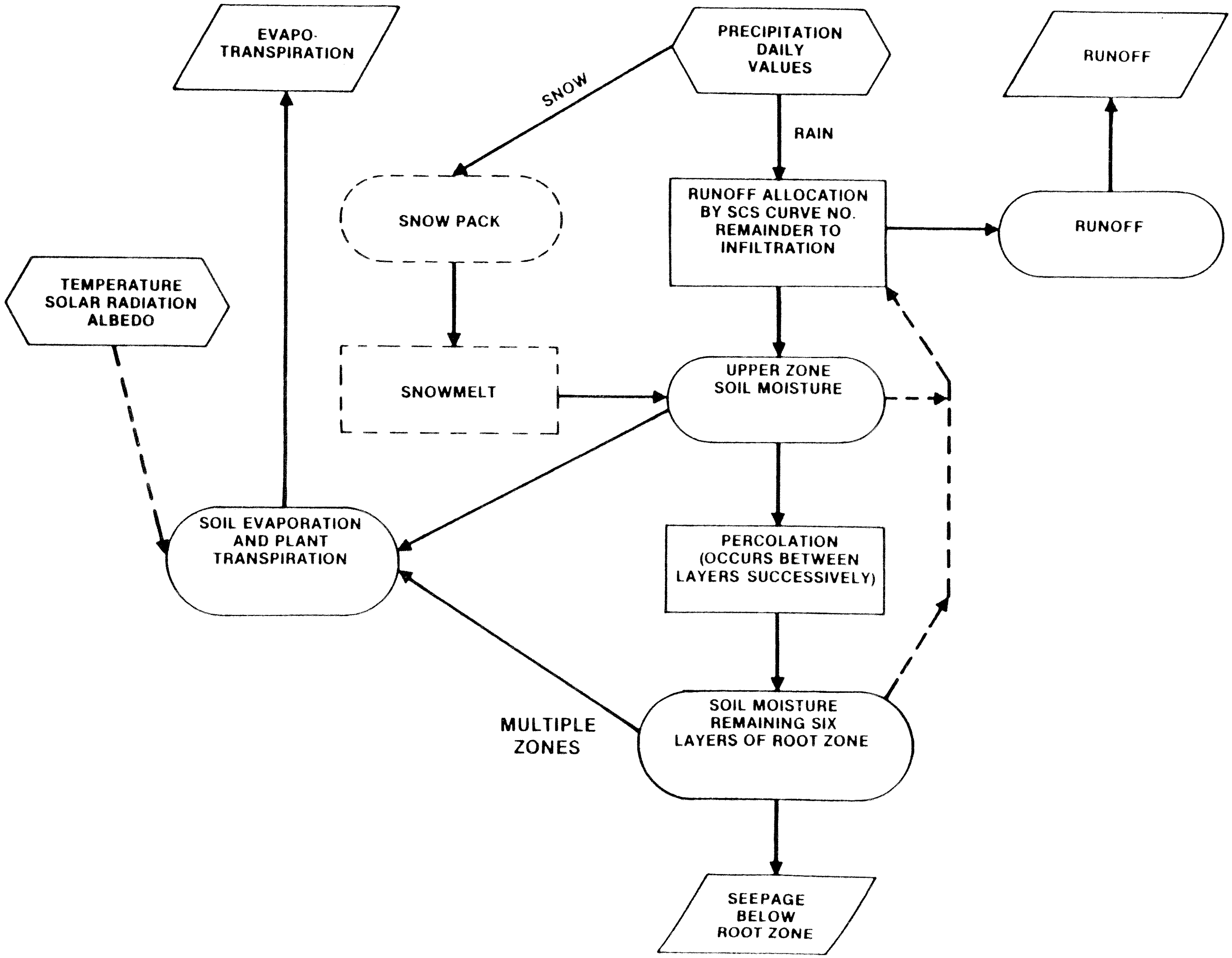


Fig. 21. Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model option 1 schematic diagram (Peck et al., 1981).

through the lining of the canal. Loss of water from natural stream channels is generally apparent from stream gage measurement at different reaches on a stream, but these observations do not identify where specific losses might occur. The presence of vegetation in desert areas can easily be detected with IR photography or, in many cases, with the near IR band sensors of the Landsat MSS or the thematic Mapper on Landsat 4 and 5, and the NOAA AVHRR.

In most of the developing nations of the world, it is important to get maximum use from available irrigation water. When the quantity of water available for irrigation, the consumptive use of the crop, and the acreage currently under cultivation are all known, then the surplus or deficit of water can be estimated. If there exists a surplus in the available water, then the number of additional acres that can be brought under cultivation can be determined. When snow packs, reservoirs, or groundwater provide the primary source of water, farmers and agricultural economists can base planting strategies and market forecasts on estimates of available water (Estes et al., 1975; Heller and Johnson, 1979). Estimates of the area of cultivation, areas of available snow, and the quantity of stored surface water are all obtainable (to some degree of accuracy) from satellite imagery or aerial photography.

At times, the effect of water management policies (which often reflect land ownership policies) become apparent by the contrast in the vegetation reflection bands (bands 6 and 7 of the Landsat Multispectral Scanner) across political boundaries. Water control managers can seek to improve management policies by comparing areas they manage with nearby areas to see if their areas appear favorable, using the water management indicators portrayed by remote sensing imagery.

4.2.8 Identification of sources of pollution. Variation in the spectral signature in areas of homogeneous land-use or on water are sometimes observed. The cause of the changes in the reflected radiation is sometimes a result of variation in soil type, soil moisture availability, or suspended sediment in water, but it could also be caused by the presence of pollution. Consequently, sources and current locations of pollutants are often identifiable. When the remote sensing system is such that variations in the reflected or emitted energy received at the sensor (due to variations in the atmosphere, the solar angle, and the surface texture) can all be recognized or controlled, then signatures of reflected surface radiation can suggest types and levels of pollutants. This, in general, can only partially be accomplished, leading to some disagreement concerning the magnitude of the error and the use of methods for monitoring pollution (Witzig and Whitehurst, 1981). There are some sensors that are less influenced by environment than others. An airborne laser is currently being flown to identify oil spills and algae populations (O'Neil, et al., 1981). There is little question that remote sensing can indicate areas where more precise ground measurements might be taken. Using the indications of the source of pollution located on the remote sensing image, a ground survey can often further identify the type and cause of pollution which can then be corrected by a mix of legal and engineering remedies. In the Union of Soviet Socialist Republics, satellite images acquired with snow on the ground are used to identify sources of pollution (especially around large cities), the level of the pollution, and how the pollution is distributed (Vasilenko et al., 1981). Analysis of a multispectral image can suggest remedies to some pollution problems by indicating local areas where holding ponds or levees might be placed.

Mapping of pollution using airborne multispectral scanners was described by Polcyn and Wezernak in 1970. The concentration of colorless chemicals has been estimated based on correlations with suspended particulate matter (Rogers et al., 1976). Oil spills in coastal waters are routinely monitored by the United States Coast Guard who are developing a fourth generation system called AIREYE, consisting of a side looking radar, a three channel UV scanner, and an aerial reconnaissance camera (Manning et al., 1980).

Chemical pollution in rivers exists primarily because water is such a universal solvent with the capability of carrying, in solution or in suspension, a large variety of materials for either transport or disposal. Water is also used in many areas as a universal coolant. Water taken from streams and ponds to cool buildings and power plants is sometimes evaporated, but in a significant number of industries, is returned to ponds and streams much warmer than when it was taken out. Increasing the temperature of water influences the amount of sediment that it carries, the rates at which it dissolves minerals (some of which are in control structures and bedrock), and perhaps most significant, the amount of dissolved gases that it can hold. Cold water can hold more dissolved oxygen than warm water. Oxygen is required by most of the aquatic life preferred by man. Changes in the water temperature can have a large effect on aquatic life which, in turn, influences the environmental balance of the water system. If the balance is shifted, toxic bacteria or undesirable fish sometimes take control away from the existing fish population causing a deterioration in the value of the water for many useful purposes.

Several countries have statutory limits as to the amount of heat (or change in temperature) that can be added to natural waterways. Increases in water temperature increase the thermal radiation of the water surface. Scanners can identify heat release plumes and expose their sources. When potentially polluted water surfaces are small or narrow, an airborne survey is required rather than satellite imagery in order to achieve the necessary spatial resolution.

Almost all rivers naturally carry a certain sediment load. This sediment complicates river development because plans for reservoirs must consider the effects of siltation, and plans for bridges, levees, and bank-side development must take into account shifts in the river bed and the possibility for undercutting of control structures. Hydroelectric plant development must consider the abrasive effect of sediment on turbines, tunnels, etc. Scouring of the river bed may be difficult to control, but sediment contributions from all the contributing watershed can be controlled by ponds, dikes, vegetation, cropping practices, etc. Sediment contribution is of concern not only because of the detrimental effects on channels and reservoirs, but also because of the loss of topsoil from agricultural lands.

Campbell (1979) discusses the use of the Universal Soil Loss Equation to assess the potential for soil loss from agricultural fields. The universal soil loss equation is:

$$A = RKLSCP,$$

where:

A = Average annual soil loss per unit area.
R = Rainfall factor.
K = Soil erodability factor.
L = Slope length factor.
S = Slope steepness factor.
C = Cropping management factor.
P = Erosion control factor.

Topographic maps and land use inventories, both potentially remote sensing products, may be used to determine many of these factors. Cropping practices are likely to be more evident in large scale air photos than in satellite imagery. Turbidity changes in rivers indicating increases or decreases in sediment load, are easily seen in most types of photography or imagery. Munday et al. (1979) propose a method for quantifying the sediment load using Landsat digital data. The study they performed used data acquired over the Bay of Fundy in Canada. They defined chromaticity coefficients using data from Landsat MSS bands 4-6, i.e.

$$x = \frac{N_4}{N_4 + N_5 + N_6} \text{ and } y = \frac{N_5}{N_4 + N_5 + N_6}, \quad (3)$$

where N_i is the radiance in the i^{th} band. x and y then form the independent axes of their chromaticity diagram. The coordinates of x were then transformed by:

$$x' = x + \Delta x ,$$

where Δx is an atmospheric correction derived from x for a given standard atmospheric condition and the achromatic point (.333, .333) on the chromaticity diagram. When x' was regressed with the log of the sediment concentration, a correlation of $r = 0.965$, with a mean standard error of 44 per cent (absolute) was observed for 108 different points collated from nine Landsat passes (Munday et al., 1979).

4.2.9 <u>Assessment of flooded areas and flood plain mapping</u> Remote sensing imagery can furnish help in times of disasters. Areal extent of flooding can be depicted (van Es et al., 1975; Lowry et al., 1981; Berg et al., 1981). Breeches in levees constructed for separating clean and polluted water generally can easily be seen. Using airborne (and possibly spaceborne) imaging radars, escape routes that are still accessible for escaping areas subject to flooding can be pictured, even though rain clouds are still in the area. Damages can be rapidly assessed using images of flooded areas, allowing appropriate planning to be done and relief supplies to be ordered.

In some cases, an analysis can differentiate perennially flooded areas from those periodically flooded or never flooded. This information is required to develop flood plain maps (Sollers et al., 1978, Dhanju, 1980). Frequent inundation is usually indicated by the geomorphology and the vegetation existing in a given area (ASP). Wolman (1971) discusses many alternative means of estimating flood plains.

Propagation of the flood wave through the basin may be monitored by a sequence of satellite images (Goskomgidromet, 1982).

4.2.10 Temporal variations in basin characteristics. Just as a moving picture provides more insight into processes than do still photographs, repetitive imagery provides a series of map-like pictures showing changes in infiltration potential caused by urbanization or the building of reservoirs, drainage patterns, irrigation, the filling or emptying of reservoirs, and changes in reservoirs and stream channels due to siltation (Munday, 1979; Moore, 1980). The ability to continuously monitor the environment is available on a relatively coarse scale with geosynchronous satellites on an hourly basis, on a finer scale with the polar orbiting weather satellites on a daily basis, or on a much finer scale with the Landsat satellite on a 16-18 day basis.

4.2.11 Integrated use of remote sensing for water resource management. Several studies have been made of the potential for obtaining data needed for water management projects through remote sensing practices (Peck et al., 1981 and 1983; Johnson et al., 1982; Kalinin, 1974; Middleton and Munday, 1980; and Rango et al., 1983). Peck et al. (1981) examined several runoff models to investigate the potential use of remote sensing data. The models they examined were the Antecedent Precipitation Index model (API); the Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS) model; the soil moisture accounting model from the National Weather Service River Forecast System (NWSRFS); the Storage, Treatment, Overflow, Runoff Model (STORM); the Stanford Watershed Model IV; the Streamflow Synthesis and Reservoir Regulation (SSARR) model; and the NWSRFS Snow Accumulation and Ablation model. For each model the inputs, parameters, states, and outputs were examined. In Figure 21 (shown earlier) one can see where the SCS curve number which was discussed in Section 4.2.5 is used in the CREAMS model. Figure 22 and Table 2 show the schematic for the NWSRFS model and the findings of Peck et al. (1981) related to remote sensing applications. They concluded that the primary data available from remote sensing to calibrate and run rainfall-runoff models which simulate all phases of the hydrologic cycle in a basin are: rainfall, identification of impervious areas, water surface areas, areas of riparian vegetation, areal extent of snowfall, and water equivalent of snow.

4.3 Hydrogeology and groundwater

Groundwater hydrology, or hydrogeology, is concerned with water in the saturated zones beneath the surface of the Earth. Groundwater information most useful to water resource managers includes: the presence or absence of groundwater in designated areas, the depth to groundwater, the quantity and quality of water available for development, recharge rates to the aquifer, the possible impact of pumping on land subsidence, areal extent of the aquifer, locations of recharge and discharge areas, and the interaction between withdrawals at wells and natural discharge into rivers. Whereas this information is generally sought by hydrogeologists using conventional methods, remote sensing can help in the planning of conventional measurements and can be used to estimate some hydrogeological variables quantitatively and others qualitatively. In the following paragraphs we will discuss the observable features most helpful in providing information to water managers.

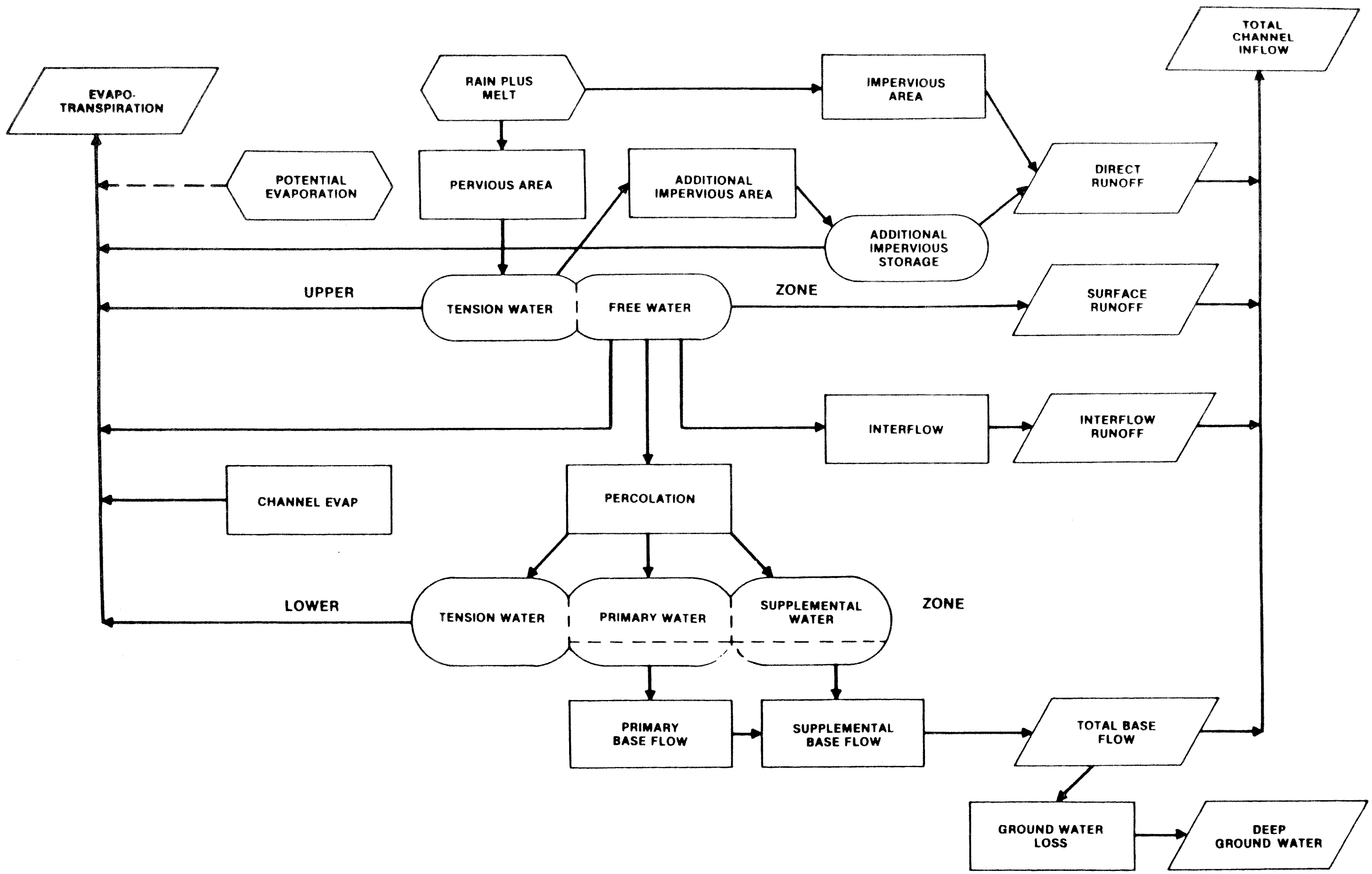


Fig. 22. National (United States) Weather Service River Forecast System (NWSRFS) Sacramento Soil Moisture Accounting Model schematic diagram (Peck et al., 1981).

Table 2. Capability of remote sensing to acquire data required for NWSRFS hydrologic model

REMOTELY SENSED VARIABLE	PRESENT CONFIGURATION*	MINOR MODIFICATION OR ADAPTATION
SOIL MOISTURE	1. No 2. No 3. No	1. No 2. Update upper zone free water (UZFWC) and tension water (UZTWC) 3. Define upper zone free water maximum (UZFWM). Some information on Potential Evaporation (PE) demand curves
IMPERVIOUS AREA	1. N/A 2. No 3. For % impervious area (PCTIM)	1. N/A 2. No 3. Objective procedure to determine % impervious area (PCTIM)
LAND COVER	1. N/A 2. No 3. In model segmentation (forested versus non-forested) and for RIparian Vegetation Area, RIVA	1. N/A 2. No 3. Objective techniques for model segmentation and riparian vegetation. Also, to define seasonal PE demand curves.
AREAL EXTENT SNOW COVER **	1. No 2. Subjective update of areal extent of snow cover 3. No (**Used in NWSRFS Snowmelt Model)	1. No 2. Redesign to use R S observations of Areal Extent Snow Cover and Water Equivalent directly--leaving heat budget and liquid water components as is 3. Aid in developing areal depletion curve and SI, the minimum water equivalent above which the snow cover is always 100%
AREAL EXTENT FROZEN GROUND	1. No 2. No 3. No	1. No 2. To adjust the rate of loss of upper zone soil moisture, UZFWC 3. To define winter values for UZFWM and the daily depletion of UZFWC (UZK)
WATER EQUIVALENT SNOW COVER**	1. No 2. Subjective update of water equivalent 3. To develop areal depletion curve (**Used in NWSRFS Snowmelt Model)	1. No 2. Objective procedure to update water equivalent (WE) and areal extent of snow cover 3. Objective techniques to develop areal depletion curve, and for checking water balance

*1. Input; 2. Update; 3. Calibrate (Peck et al., 1981).

Groundwater occurs beneath the surface of the Earth in water-bearing formations. Practically all the groundwater in these formations comes from surface water through the recharge zones. The storage capacity of groundwater reservoirs depends on their extent, which depends on the geological properties of the area. Groundwater forms the baseflow for many streams and is the source of water for springs and seeps. Wells from which groundwater is pumped form the only source of water in many areas for the major part of the year.

Surface water forms a system that can be directly seen and touched, but groundwater by its very nature is not available for direct observation. The areal extents of groundwater reservoirs and their depths from the surface are determined primarily by inference. Vertical measurements are primarily available at wells. The detection of water movement within the ground is difficult because groundwater generally moves slowly and response times for the groundwater system are long.

Some of the hydrogeological terms associated with the physical system of groundwater are shown in Figure 23.

Remote sensing has been applied to:

(a) Find likely areas for the existence of groundwater.

(b) Find indicators of the presence of groundwater.

(c) Indicate the quality of groundwater existing near the surface or at points of natural discharge.

(d) Indicate regions of groundwater recharge and discharge.

(e) Suggest areas where wells might be drilled.

(f) Monitor aquifer changes as groundwater development proceeds.

4.3.1. Surface indicators of groundwater. Finding areas likely to contain water by using remote sensing involves identifying certain indicators such as: favorable geologic structures, evidence of past surface water activity, existence of transpiring vegetation in unirrigated areas, and presence of active discharge from seeps and springs.

The first two indicators have much in common. Specific details of soil and topographic effects are discussed by Maxey (1964). He notes that the permeability of the soil influences how much water from precipitation remains available for relatively rapid rates of evaporation. In highly permeable areas, water rapidly infiltrates to the groundwater table. Geologic forms composed of highly permeable materials are identifiable by remote sensing methods because of their geomorphological appearance, or, in rocky areas, because of the occurrence of linear features and fracture zones.

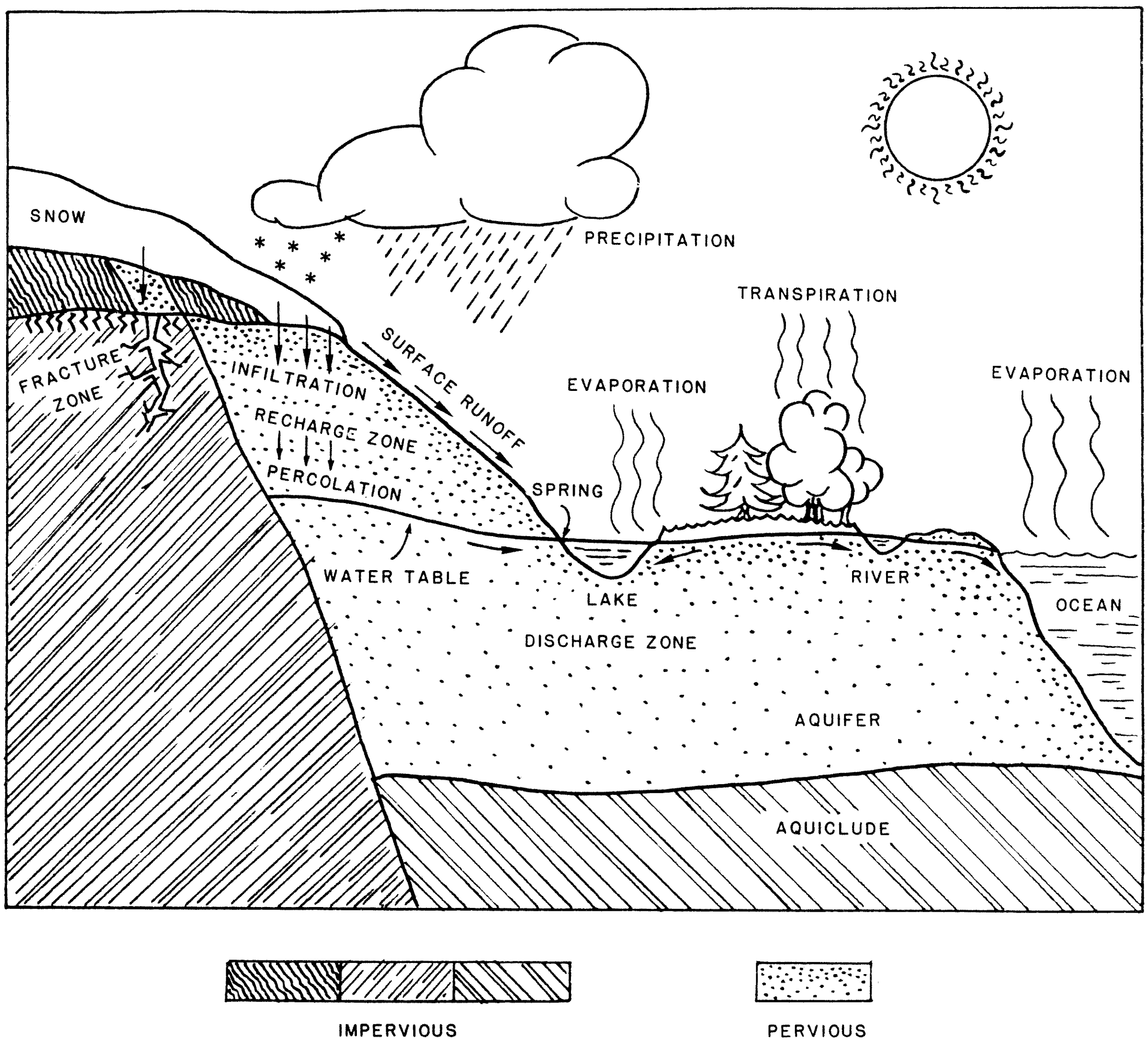


Fig. 23. Schematic cross-section showing occurrence of groundwater

Geomorphology, the study of land surface formations, has been aided for many years by aerial photography. Rivers, lakes, and glaciers are significant in the formation of land surfaces. Flood plains, playas, alluvial deposits, and glacial moraines all generally form very permeable areas, ideal for storing water. The presence of these landforms (which are generally identifiable in air photos and satellite images), even in arid areas, often suggests the existence of groundwater.

Certain generalizations can be made about various geologic formations or rock types. The following paragraphs are a limited set of these attributes.

Alluvial deposits. In some alluvial fans and piedmont deposits, confining beds may form, giving rise to springs and artesian wells. In large river valleys like the Gengetic basin and the Mekong basin, huge groundwater reservoirs are found. Ox bows and old river channels are indicators of the presence of alluvial deposits. Extensive studies have been carried out on this topic (Unesco, 1975; and Lloyd, 1981). Alluvial deposits on coastlines generally yield significant water; however, salt water intrusion into these aquifers often limits the value of the water.

Glacial deposits. Glacial moraines consist of sand, gravel and other debris which allows water to percolate. For additional information see Rahn and Moore (1981).

Rocky areas. The primary water-bearing areas in rock formations are found along fault or fracture lines. These areas are often indicated by lineaments or lines in the surface geology of the area. In addition to having fracture lines, carbonate rock formations often have many solution channels and caverns. The channels allow a rather rapid passage of water, and caverns can hold significant quantities of water. Sinkholes and springs are indicators of water availability.

Lineaments which can be detected in both visible imagery and radar imagery are sometimes associated with fault zones and fracture zones. Both of these zones form highly permeable areas for groundwater recharge. Sinkholes and solution channels have also been located using multispectral scanners (Coker, 1969).

Indicators of the existence and quality of groundwater near the surface are provided by vegetation growing near discharge points or having roots that extract water from an aquifer. Both the type and vigor of the vegetation are indicators of the water quality. Where seeps, springs, or seasonal lakes exist, residue from evaporated water supplies evidence of minerals that were present in the surface water, and would be expected in available ground water.

The broad view obtainable by aerial photography or satellite imagery (as opposed to the comparatively limited information obtainable from a ground survey) shows the relationship of springs, seeps, and rivers to other locations on the ground, helping to infer the form of the hydrogeologic system. This is very helpful in selecting sites capable of successful groundwater development.

Locations of well sites. The combination of surface indicators of groundwater, subsurface geology implied by surface features, and topography can be especially useful in areas which have not been mapped, (and can still be helpful in addition to maps in areas where available) to suggest potential well sites. When there are several prospective sites, the data can suggest the site with the best relative conditions for storing and distributing water which may be found.

Moore and Mayers (1973) have used thermal data to identify areas of artesian wells and natural springs in South Dakota, USA, and Parizak (1971) discusses the increased productivity of wells located near fracture zones. The development of guide maps using digitally processed and photographically enlarged Landsat data is discussed by Zall and Russell (1981). Foster et al. (1980) determined lineament density from Landsat data for Arizona, USA, and established a correlation with the well grid.

General groundwater explorations. Landsat data have been extensively used in some regional studies, particularly for arid areas where the need for exploring groundwater is urgent. Ellyett and Pratt (1975) have reviewed use of visible and near IR band sensing methods for hydrogeological investigations in Australia. Groundwater exploration in Africa (Zall and Russell, 1979) and studies in Botswana (Gurnay et al., 1982) are directly based on detailed interpretation of Landsat data for identification of hydrogeological features. In a case study of Andhra Pradesh, India, Bedi (1977) has delineated, from Landsat data, geomorphic features such as flood plains, filled-in valleys, and undulating terrains.

In western Egypt studies were carried out, taking into consideration the oasis area where depressions are connected with long geological faults (El Shazly, 1977). The deltaic region of the Nile River was also investigated. Vincent et al. (1978) have identified areas of high fracture density as potential exploration sites. Areas which have sharply truncated vegetation patterns and are adjacent to isolated linear fractures were also identified as potential areas. Techniques such as the ratio of the intensity values of different Landsat spectral bands were used for enhancing the structural features.

Identification of coastal springs. Fresh water is lost from land areas to sea water in many places. The springs are indicative of the location of groundwater, and the amount of flow from springs is indicative of the volume. Recovery of this water for use before it mixes with briny sea water can generally show economic benefits. Temperature differences in coastal waters, river banks, and islands allow us to use thermal IR data for locating subsurface sources of water. Guglielminetti et al. (1975), using data from thermal scanners flown over southern Italy, have identified fresh water springs in the coastal areas and their outfall into the sea. In the Gulf of Oman on the Arabian coast, thermal imagery has helped in identifying points of freshwater discharge into the sea and in preparing rough estimates (in the range of 2240-14950 m^3/day) of the outfall.

Changes due to development. When groundwater has been located and developed, groundwater tables will generally be lowered, outflow into streams reduced, artesian well flows decreased, etc. Changes in the area can be monitored to identify any changes which might be attributed to the development. Traditional methods for detecting change include the use of observation wells, records of discharge of springs and rivers, and records of local crop yields. These methods have not generally been integrated into a single picture to identify which areas are most affected by a lowered water table caused by groundwater development. Imagery in the near IR parts of the spectrum can show the variation in the health of the vegetation over the basin as well as the presence or absence of seeps and swamps. This information can serve as both a graphic and numerical lattice on which to integrate the isolated traditional measurements listed above.

4.3.2 Subsurface indicators of groundwater (geophysical methods). There are many techniques used by hydrogeologists that are based on remote sensing principles which are standard and are described in general texts on groundwater. Many, but not all, of these techniques require the sensor to contact the ground, but the method is still "remote" in that inferences are made about hydrologic quantities or qualities which are distantly removed from the sensor. Most of the techniques can be used to obtain areal values by extrapolation of point measurements (e.g., from samples taken at bore holes). Because these methods are well-covered in standard texts (for example, Mandel and Shiftan, 1981), only a list of the methods and their principal applications will be given here.

Category: Electrical resistivity

Applications: Two-layer problems not involving great depth, e.g., identification of aquiferous and non-aquiferous zones and layers in alluvial deposits.

Category: Electromagnetic and magnetometric

Applications: Detection of geological features influencing the recharge and storage of aquifers: faults, shear zones, concealed dikes, extent of igneous rock, differences between clay and gravel/sand deposits.

Types: Radio broadcast frequency
Audio-frequency magnetometric
Turam and galvanic inductive Turam
Magneto-telluric resistivity
Magnetometric profile

Category: Seismic

Applications: Determination of depth and thickness of layers and identification of those layers with known structural features. Provides supporting information for other hydrogeological measurements.

Category: Gravity survey

Applications: Detection of unconsolidated fill, in buried valleys. Usually used in conjunction with other hydrogeological data.

4.4. Operational status of remote sensing in hydrology

The emphasis of this report is on operational systems. Scientists in many countries are experimenting with remote sensing measurements that hold great promise for water resource applications such as soil moisture measurements made with microwave radiometers, theories for estimating rainfall using satellite borne active and passive microwave sensors, and with planned improvements in the resolution of current imaging systems (Jackson et al., 1982; Atlas and Thiele, 1981). However, in this report we have tried to limit our scope to techniques that have been tried and are in common use or that have been adequately tested but have not been put into common use because institutional constraints have prevented their implementation.

In the following summary we present techniques which have been reported as being operational. Some flexibility has been given to the criteria for being operational, to try to allow experts in various fields to expose those techniques which they feel are ready for operational use but which have not yet been implemented on a fully operational basis.

The techniques listed are limited to overland or shoreline applications. They do not include applications which are exclusively oceanic or which are based on remote data-transmission from in situ sensors alone.

4.5 Tabular summary of current operational applications

(See pages 66 through 83.)

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
1. Determination of watershed physiography**	USA	Consultants, Gov't. agencies such as USGS,SCS	Landsat/MSS, aerial photos	As needed	MSS bands 80 m	Not avail.
2. Profiling of stream channel cross-sections, check subsidence	USA, Canada, Australia	USGS	Airborne laser coupled with high accuracy inertial guidance	Single pass high frequency sampling rate	Near IR ±0.5 ft	Not avail.
3a. Estuarine processes	Taichung Taiwan	MRSO	Color air photos & airborne MSS	4/yr	Visible,UV Thermal-IR 20m x 20m	$30k
3b. Estuarine processes	China	Remote Sensing Center, MWREP	Landsat/MSS, aerial photos IR scanner	As needed	MSS bands 80 m	Not avail.
4. Evapo-transpiration mapping using the TERGRA algorithm	As requested	ICW, Wageningen Neth.	Meteosat, TIROS	1/day (around noon)	Visible & IR	Not avail.
5. Evapotranspiration using the TELL-US	USA Sahel	EARS, Neth.	Aircraft, satellite IR data	At least 2/day	IR	Not avail.
6. Assessment of water volumes in swamp impoundments	USA	USGS	Landsat	As needed	MSS bands 80 m	Not avail.
7. Flood plain mapping**	USA India China	USA-NESDIS for NWS, USACOE, FEMA, USGS; India-ISRO China-MWREP	Landsat/MSS, low altitude aerial photos TIROS	As needed	MSS bands 80 m approx.1 meter AVHRR 1 km	Not avail.

**This application is widely used in many countries.

A P P L I C A T I O N S

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
1. Not avail.	Yes	EROS	$35 per scene	Ground surveys	Maps, air photos	Hydro Science Branch Goddard Space Flight Center, Greenbelt, MD 20771, USA	126
2. Not avail.	No			Ground surveys	Maps, air photos	Ass't Div Chief for Res.,Nat'l Mapping Div., USGS, Reston, VA 22092, USA	47
3a. $10K	Not indicated			Sea water sampling,physical parameters measurement	Physical parameters measurement of sea water	MRSO library Taipei, Taiwan	97,103, 108,111, 117
3b. Not avail.	Yes	EROS China	$650/CCT	Ground surveys	Some ground truth	Yellow River Water Conservancy Committee, Zhengzhow; Nanjing Hydraulic Inst., China	97,103, 108,111, 117
4. Not avail.	Yes	ESA	Depends on form of data used	Ground truth data	Climatic station	EARSel Work Gp 7 EARSel, 292, rue Saint-Martin 75003 Paris, France	24,48,66, 75
5. Not avail.	No			Ground surveys	Climatic station	EARSel (same as 4 above)	24,48,66, 77,101,131
6. Not avail.	Yes	EROS	$35/ scene	Aerial surveys	Ground truth ground data net	USGS,WRD, Tampa, FL, USA	70
7. Not avail.	Yes	EROS, USDA, NESDIS	$35/Landsat scene Air photo $5 BW $15 color+	Photo interpretation	Ground truth	Hydro Science Branch Goddard Space Flight Center, Greenbelt, MD 20771, USA	39,58, 143,174, 175

(+ enlargements or additional processing available at a higher price)

*The numbers identify references in the list beginning on page 108.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
8. Monitoring of flooded areas**	Manitoba, Canada	AES for Manitoba Gov't.	Airbourne SLAR 20,000 ft.	As needed	5-20 meters 1.2 GHz & 9.0 Ghz	Not avail.
9a. Ground water surveying**	USA	USGS-EROS Data Center	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
9b. Ground water surveying**	Egypt India	RSC, Cairo, Egypt ISRO, India	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
9c. Ground water surveys in karstic regions	Hungary	VITUKI, Budapest, Hungary	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
10. Management of major regional aquifers**	NE Africa & Arabian Peninsula	RSC, Cairo, Egypt	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
11. Inventory of dams & surface waters	USA China	USA-USACOE China-MWREP	Landsat imagery, air photos	As needed	MSS bands 80 m	$1300/Landsat scene
12 Monitoring of infestations of aquatic vegetation**	USA	USCOE	Air photos	As needed	False color IR scale 1:60K-1:20K	Not avail.
13a. Irrigated crop-land inventory	USA high plains	USGS	Landsat/MSS	Seasonal	MSS bands 80 m	Not avail.

**This application is widely used in many countries.

A P P L I C A T I O N S

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
8. Not avail.	?			Aerial or satellite imagery after sky clears.	Maps, ground data if avail.	SURSAT Project Office Sir Wm.Logan Bldg. 8th Fl. 580 Booth St. Ottawa,Ont,Canada K1A 0Y7	95
9a. One scientist in field 10 - 100 km^2/day	Yes	EROS	$35/scene	Air photo-interpretation	Ground truth, maps	User Services, NOAA, EROS Data Center, Sioux Falls, SD 57198, USA	3,41,42,44, 94,96,106, 119,121, 135,151
9b. Not avail.	Yes	EROS	See price list	Aerial survey	Ground truth, maps	RSC, 101 Kasr El Eini Street, Cairo, Egypt;	"
	Yes	NRSA	$10/scene	"	"	ISRO, Ahmedabad, 380 053 India	146
9c. Not avail.	Yes	EROS	See price list	Aerial & ground surveys	Ground truth, maps	VITUKI, Hydro. Inst., P.O.Box 27, Budapest, H-1453, Hungary	119
10. Not avail.	Yes	EROS	See price list	Aerial surveys	Ground truth, maps	Remote Sensing Center Cairo, Egypt	44
11. Not avail.	Yes	EROS	$730/photo interpretation scene or per CCT	Ground survey	Ground truth, training set	USACOE Seattle Dist. PO Box C3755 Seattle, WA 98124, USA; Yangtze Valley Planning Office, WuHan., China	60
12 $11/acre	---No---			Ground survey	Ground checking	US Army Engineer Waterways Experiment Station. P.O. Box 631 Vicksburg, MS, USA 39180	92
13a. Not avail.	Yes	EROS	See price list	USDA statistical reports	Ground truth, training set	Ass't Div. Chief for Research, Nat'l. Map. Div., USGS, 12202 Sunrise Valley Dr., Reston, VA. 22092, USA	49,68

*The numbers identify references in the list beginning on page 108.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
13b. Irrigated crop-land inventory	Libya	Environmental Res.Inst. of Michigan/FAO	Landsat/MSS, air photography	Seasonal, then biannual	MSS bands 30-80 m	Not avail.
14. Data base assessment for development of comprehensive regional development plan**	Africa Mali	US Agency for International Development	Landsat/MSS, air photography	Seasonal, then biannual	Landsat MSS bands 80 m	$250K-600K
15. Land use mapping for planning (hydrological aspects)	USA	Montgomery County Park & Planning Commission, Maryland, USA	Landsat/MSS, high altitude air photography	Annual	MSS bands 80 m stored in 4.59 acre cell	8¢-10¢/acre $20K minimum
16a. Precipitation estimation	Global	Ruhr Univ.,Bochum F.R. Germany	Meteosat	30 minutes	Thermal IR	Not avail.
16b. Precipitation estimation	USA	NOAA	GOES	30 minutes	Visible & IR	Not avail.
16c. Precipitation estimation	Global	Subscribers	GOES	30 minutes	Visible & IR	Not avail.
16d. Precipitation estimation	Global	Gov't agencies	GOES, TIROS	15 min	Visible & IR	Not avail.
16e. Precipitation estimation	Global	Subscribers	Avail. imaging satellite	As avail.	Visible & IR	Not avail.
16f. Precipitation estimation	Global	NOAA-USDA	TIROS, GOES	2/day or as avail.	Visible & IR	Not avail.

**This application is widely used in many countries.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
13b. Not avail.	Yes	EROS	See price list	Ground survey	Ground truth	ERIM, PO Box 8618 Ann Arbor,MI 48107,USA	
14. Not avail.	Yes	EROS	See price list	Ground survey, aerial survey	Ground truth, training set	ERIM, PO Box 8618 Ann Arbor,MI 48107,USA	
15. \$3-4 per km^2 \$20K min	Yes	EROS	See price list	Ground survey, aerial survey	Ground truth, training set	College of Engrg. Univ. of Maryland College Pk., MD. 20740, USA	79,120
16a. Not avail.	Yes	ESA, NCDC, Japan	See price list	Not avail.	Some ground truth	Ruhr-Univ. Bochum Universitatsstrasse 150 4630 Bochum, F.R. Germany	15,87, 145
16b. Not estimated	Yes	NCDC	Real time service negotiated (RTSN)	Rain gages, ground based radars	Rain gages, ground based radars	E/RA3,Satellite Applications Lab., NESDIS, Wash. D.C. 20233, USA	9,15, 107,139
16c. Not estimated	Yes	NCDC, EROS	RTSN	Ground surveys, hydromet data	Ground truth	Cropcast-Earth Sat. Corp., 7222 47th St. Bethesda, MD.,20815 USA	67
16d. Not avail.	Yes	NCDC	\$100/CCT	Hydromet data which is often not avail.	Ground truth, hydromet data where it exists	Office of Weather Research & Mod., NOAA/ ERL, Boulder, CO, USA	15,62,74
16e. Not avail.	Yes	NCDC, ESA	RTSN	Hydromet data which is often not avail.	Ground truth, hydromet data where it exists	Dept of Geography University of Bristol Bristol, BS8 1SS, UK	9,11,13 15
16f. Not avail.	Yes	NCDC	RTSN	Hydromet data which is often not avail.	Ground truth, hydromet data where it exists	NOAA/NESDIS, AISC Rm 135 Page Bldg 2 Whitehaven St. NW, Wash. D.C. 20235, USA	

*The numbers identify references in the list beginning on page 108.

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	CURRENT OPERATIONAL FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
17a. Precipitation estimation**	Japan Kanto & Kyushu districts	Agency governing dam, river and road control	Ground based radar	5 min	5 cm wave-length, 3 km Rn 100-120,2.8° Rn 120-198,1.4°	Not avail.
17b. Precipitation estimation**	Switzer-land	Swiss Met. Institute	Ground based radar	10 min	5.6 cm wave-length 2 x 2 km^2 Rn 230 km,1.4°	Not avail.
17c. Precipitation estimation**	USA	Office of Hydrology	Ground based radar	10 min.	10cm wave-length 2° Az X 3 km Rn 230 km	Not applicable
17d. Flood forecasting based on precip. estimation	Poten-tially global	Ruhr Univ. Bochum, & German Weather Svc., F.R.Germany	Ground based radar	10 or 15 min.	5.4 cm wave-length	Not applicable
18. Monthly runoff estimation for design purposes	World-wide	Ruhr Univ. Bochum F.R. Germany	Polar orbiting satellite	Two images per day	Thermal IR	Not avail.
19a. Regional environmental assessment**	Jonglei Canal Project, Sudan	Permanent Joint Committee of Nile Water, Egypt & Sudan	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
19b. Regional environmental assessment**	Qattara Depression Egypt	Ministry of Egypt	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
19c. Regional environmental assessment**	Africa	US AID Mali	Landsat, aerial photography	As needed	MSS bands 80 m a few meters	Not avail.

**This application is widely used in many countries.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
17a. Not avail.	---- not ---- ---indicated---			Rain gages	Rain gages	Japanese Met. Agency 1-2-3 Ote Machi Chiyoda-ku, Tokyo, Japan	76
17b. Not avail.	---- not ---- ---indicated---			Rain gages	Rain gages	Swiss Met. Service	82
17c. Not avail.	Yes imagery since 1/1971	NCC	$21/roll of film	Rain gages	Rain gages	HRAP Project, NWS, W/OH3, Silver Spring MD 20910, USA	61
17d. Not avail.	--- not --- --indicated---			Rain gages	Rain gages	Ruhr-Univ. Bochum Universitatsstrasse 150 4630 Bochum-Querenburg F.R. Germany	116
18. Not avail.	Yes	Inst.fur Weltraum Forschung Bochum	Depends on form of data used	Not avail.	Ground truth	Ruhr-Univ. Bochum, Universitatsstrasse 150 4630 Bochum-Querenburg F.R. Germany	145
19a. Not avail.	Yes	EROS	See price list	Ground surveys	Ground truth	RSC, 101 Kasr El Eini St. Cairo, Egypt	43
19b. Not avail.	Yes	EROS	See price list	Ground survey	Ground truth, training sets	RSC, 101 Kasr El Eini St. Cairo, Egypt	41
19c. $250-600K	Yes	EROS ERIM	$730 per scene on CCT	Ground survey	Ground truth	ERIM, PO Box 8618 Ann Arbor, MI 48107, USA	

*The numbers identify references in the list beginning on page 108.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
19d. Regional environmental assessment**	Suez Canal Zone Egypt	Ministry of Reconstruction, Egypt	Aircraft		a) 4 Lens Camera; I^2S (400-800 nm) b) Single channel IR-Thermal Scanner (Bendix LN) c) 3.5-5.5 & 8.0-14.0 µm	Not avail.
20a. Assessment of consumptive use	Calif. USA	Kern County Water Agency	Landsat/MSS	Seasonal	MSS bands 80 m	$500K
20b. Assessment of consumptive use	Algeria	World Bank	Landsat	As needed	MSS bands TM channels	Not avail.
21. Peak flow estimates from land use classifications	USA	NASA/USACOE	Landsat/MSS 80 m	1/season	MSS bands 80 m	~$2400/small basin
22. Estimation of infiltration (runoff curve numbers)	USA	USDA/Univ Md.	Landsat/MSS	As needed	MSS bands 80 m	Job specific
23a. Distributed rainfall runoff modelling system (specifically oriented to remote sensing input)	Denmark	Danish Technological Institute	Primarily Landsat MSS bands	As avail.	MSS bands 80 m	Variable
23b. Lumped parameter rainfall runoff modelling system (specifically oriented to remote sensing input)	USA	NASA,USDA	Landsat, ITOS, GOES	As avail.	MSS bands, Visible, IR	Variable

**This application is widely used in many countries.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
19d. Not avail.	----Contact RSC----			Ground survey	Ground truth, training set	RSC, 101 Kasr El Eini St. Cairo, Egypt	40
20a. Not avail.	Yes	EROS	See price list	Ground survey, Agricultural Reporting Service	Ground truth, training set	Kern County Water Agency, Bakersfield, CA, USA	49
20b. Not avail.	Yes	EROS	See price list	Ground survey	Ground truth, training set	ERIM, PO Box 8618 Ann Arbor, MI 48107,USA	
21. ~$2400/ small basin	Yes	EROS	$730/CCT	Land survey	Conventional hydro data, ground truth	Res. Branch, HEC Davis, CA 95616, USA	51
22. About $2K/ Landsat scene	Yes	EROS	$750/CCT scene	Land survey	Ground truth, USGS maps, Soils maps	USDA-ARS, Hydro. Lab. Beltsville, MD. 20705 USA	79,120
23a. Not avail.	Yes	EROS	$730/CCT	Hydromet data	Hydromet data	Dansk Hydraulisk Institut, ATV Agern Alle 5 2970 Horsholm Denmark	32
23b. Not avail.	Yes	EROS, NCC	$730/CCT	Hydromet data	Hydromet data	Hydex Corp. 11150 Main St. Fairfax VA, 22030 USA	81,113, 114

*The numbers identify references in the list beginning on page 108.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
24a. Not avail.	1978-1980+ (+ more recent data are being prepared)	Inst. f. Met und Geo.		no equivalent	none	Kunzi,Patil,Rott IEEE-Trans on GeoSci Rem.Sens GE-20:452-467	90
24b. $2050/yr or $0.23/km^2	Yes	NESDIS	See price list	Snow courses Aerial surveys	Base map	Hydro Sciences Branch, Code 924, GFSC Greenbelt, MD. 20771 USA	124,127
25a. Not avail.	Yes	EROS	See price list	Aerial survey Land survey	Ground truth	Water Research Inst. Nagoya Univ., Furo-cho, Chikusa-ku, Nagoya 464, Japan	100
25b. Not avail.	Yes	EROS	See price list	Aerial survey Land survey	Ground truth	Water Research Inst. Nagoya Univ., Furo-cho, Chikusa-ku, Nagoya 464, Japan	
25c. $3,500K/yr	Since 1975	ESA Frascati (Rome)	See price list	Field measurements	Ground truth	ENEL (Milan, Italy) or CNR Piazzale Luigi Sturzo 31, 00144 Rome, Italy	
26. Not avail.	Yes	NESDIS EROS, ESA	$30 per scene	This technique shows improvement over snow course estimates	Precipitation, river discharge, degree days	Hydro Sciences Branch GSFC, Greenbelt, Md. 20071, USA or Fed Inst. for Snow & Avalanche Res. Weissfluhjoch/Davos Switzerland	124,127, 137,145
27a. $13/ flight line mile $15K min.	Since 1981-82	WDCAGSI	??	Snow courses	One-time ground soil moisture calibration	Airborne Snow Survey Program, NWS, 6301 34th Ave. So. Minneapolis, MN 55450 USA	26

*The numbers identify references in the list beginning on page 108.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
24a. Mapping of snow & ice cover & pack condition & water equivalent	Global	Institut fur Meteorologie und Geophysik, Univ. Innsbruck, Austria	Nimbus-7 SMMR	2/day	37 GHz & 18 Ghz 30 x 30 km^2 60 x 60 km^2	Not avail.
24b. Mapping of snow**	USA, India, Pakistan, Norway, Hungary	USA-NOAA, NASA India-NRSA Norway-NVE	NOAA-AVHRR Landsat-MSS GOES-VISSR	Daily or monthly	Visible 80 m or 1 km	Depends on the number of basins & work volume
25a. Monitoring perennial snow fields or glaciers**	Japan	Water Research Institute, Nagoya University	Landsat	As needed	MSS Band 4 (0.5-0.6 µm) 0.1 km	Not avail.
25b. Monitoring perennial snow fields or glaciers**	Nepal Himalayas Karakorum	Water Research Institute, Nagoya University	Landsat/MSS	As needed	Composite color imagery	Not avail.
25c. Monitoring of alpine glaciers (surface & equilibrium line variations)**	Italy	CNR-IFC Milan, CNR-ISDGM Venice	Landsat/MSS	1/year 80 m	MSS bands	Not avail.
26. Snow melt runoff forecasts using snow cover data	USA Switzerland	USA-NASA, SCS Switzerland-SFISAR	Landsat/MSS VISSR visible AVHRR visible	Daily	Visible (0.6-0.7 µm) 80 m-1 km	Not avail.
27a. Water equivalent of snow cover**	USA Northern Plains; Canada & Norway	USA-NWS, USACOE, USDA; Geological Survey of Canada; Norway-NVE	Low altitude aircraft, NaI(Tℓ) scintillation detector	3/spring plus as needed	0.5-5.1 Mev 1 km	Not applicable

**This application is widely used in many countries.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
27b. Water equivalent of glaciers & ice fields	Japan	National Institute of Polar Researches	Landsat/MSS	As needed	Composite color imagery	Not avail.
28. Ice cover mapping	USA, Canada	Coast Guard	Airborne radar, Landsat	As needed	K band, SLAR, MSS bands	Not avail.
29. Soil moisture mapping	Africa Sahel	EARS Delft, Netherlands	Meteosat, HCCM, NOAA, Scanners	1-2/day	Day-visible, day & night-thermal IR band	Not avail.
30a. Water Pollution survey (chemical/bacteriological)	Tatu River Taichung Taiwan	MRSO	Color film, multiband camera IR scanner	2/yr	Visible, UV Thermal IR 5 m X 5 m, 20 cm	$20K
30b. Water pollution survey (chemical/bacteriological)**	Tanshui River Taipei, Taiwan	MRSO	Airborne MSS system	2/yr	Visible, UV Thermal IR 5mX5m, 20 cm MSS bands	$40K
30c. Water pollution survey (chemical/bacteriological)**	Egypt, Lake Qarun	RSC, Cairo, Egypt	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
30d. Water pollution monitoring (chemical/bacteriological**	Canada	Saskatchewan Research Council	Airplane 1500 m alt. for 5 hrs	Every 15 minutes	Color film ±5 m depth	$30K
30e. Water pollution monitoring (chemical seepage from tailing ponds)	Canada	Saskatchewan Research Council	Airplane 6000 m alt. Camera, IR scanner	1/yr for 5 yrs	Thermal IR, aerial false color, aerial color film ±5 m	$20k

**This application is widely used in many countries.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
27b. Not avail.	Yes	ESA, NCDC	See price lists	Snow courses In some areas there is no other way.	Runoff records	Water Research Inst. Nagoya Univ, Furo-cho, Chikusa-ku, Nagoya 464, Japan	
28. Not avail.	---not--- ---indicated---			Air and sea ice surveys	Ground truth (when avail.)	US Coast Guard International Ice Patrol; Governors Island, New York, NY, USA	
29. Not avail.	Yes	ESA, NOAA	see price lists	Ground survey	Climatic stations	EARS Ltd, PO Box 449 2600 AK Delft, Neth.; ESOC,Darmstadt,F.R.G.	24,48, 131
30a. $10k	Not indicated			Ground sampling analysis	Water sampling analysis, hydro data, waste water discharge.	MRSO Taipei, Taiwan	103,108, 111,117, 130
30b. $20K	Not indicated			Ground sampling analysis	Water sampling analysis, hydro data, waste water discharge.	MRSO	103,108, 111,117, 130
30c. Not avail.	Yes	EROS	See price list	Ground samples	Ground truth	RSC, 101 Kasr El Eini St., Cairo, Egypt	2
30d. $30K(Can)	Yes	Sask. Res. Council	$30 (Can)	Physical measurement	Current measure flowmeter	Sask. Res. Council Saskatoon, Saskatchewan,Canada	134
30e. $20K(Can)	Yes	NAPL	$2K (Can)	Drilling test holes		Sask. Res. Council Saskatoon, Saskatchewan, Canada	133

*The numbers identify references in the list beginning on page 108.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
30f. Water pollution monitoring & tracking (chemical/ bacterial)	Venice Lagoon Italy	CNR-ISDGM, Venice, Italy/ JRC, Ispra, Italy	Aircraft MS camera, IR scanner, Landsat/MSS	Aircraft on request	Visible, near IR, thermal IR	Variable
30g. Water pollution oil spill	Sweden, Netherlands	Coast Guard	Aircraft	Periodic monitoring	SLAR (x-band), UV, IR	Variable
30h. Water pollution (algae control)	Canada, USA	EPA, NASA, CCRS	Aircraft	As needed	N_2 laser & Ne laser fluorosensor	Not avail.
30i. Water pollution measurements (lake trophic classification)	USA	EPA, DNR (Wisconsin), State of Vermont	Landsat/MSS	In situ sampling	MSS bands 80 m	Not avail.
30j. Water pollution survey (algae & sediment control)	Lake Balaton, Hungary	VITUKI, Budapest, Hungary	Aircraft/MKF6 Landsat/MSS	Monthly in growing season	5 m MSS bands 80 m	Not avail.
31a. Water pollution (thermal-power plant discharge)**	China	Remote Sensing Center, MWREP	Landsat/MSS	As needed	MSS bands 80 m	Not avail.
31b. Water pollution (thermal-power plant discharge)**	Chinshau N. Taiwan. Kaoshiung, S. Taiwan.	MRSO	MSS thermal IR	4/yr	Visible, UV, thermal IR 20m x 20m	$40K
32a. Water pollution (suspended sediments)**	Canada China	Canada Centre for Remote Sensing, NASA, VA Inst of Marine Science; China-MWREP	Landsat/MSS	Every 18 days when avail.	MSS bands 80 m within ± 40% concentration over range	Not avail.

**This application is widely used in many countries.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
30f. Variable	Since 1975	CNR (Venice) or ESA Frascati (Rome)	See price list	In situ measurements	Sea-truth data	ISDGM	
30g. Variable	?	?	?	Surface patrols	?	Swedish Space Corp. Tritonugen 27, S17154 Solna, Sweden	97,111
30h. Not avail.	?	?	?	In situ measurements	Ground truth for calibration	Canada Centre for Remote Sensing, Ottawa, Canada	111
30i. Not avail.	Yes	EROS	$730/CCT scene	In situ measurements	Ground truth for calibration		108
30j. Not avail.	Yes	EROS	See price list	In situ measurements	Ground truth for calibration	P.O.Box 27, Budapest, H-1453, Hungary	23,57
31a. Not avail.	Yes	China	?	In situ measurements	Ground truth for calibration	Electric Power Design Institute, Beijing, China	
31b. $15K	---not indicated---			Thermograph, remote sensing thermometer	Ground truth, water temperature profile from surface down	MRSO	
32a. Not avail.	Yes	EROS	$730/CCT scene	In situ measurements	Ground truth for calibration	Remote Sensing Center Va. Inst. of Marine Science, College of Wm & Mary, Gloucester Point, VA. 23062 USA	108

*The numbers identify references in the list beginning on page 108.

CURRENT OPERATIONAL

APPLICATION	COUNTRY OR REGION	ORGANIZATIONS INVOLVED	SENSOR PLATFORM	FREQUENCY	SPECTRA & RESOLUTION	TOTAL COST $ USA
32b. Water pollution (finding primary sources of siltation)	USA China	USA-US Geological Survey, EROS Data Center; China-MWREP	Landsat MSS	As needed	MSS bands 80 m	$850
33a. Bathymetric mapping	USA,China shallow water, mainly coastal	USA-National Ocean Survey, NOAA; China-MWREP	Airplane 10,000 ft 80 % overlap for stereo view; Airborne MSS, IR scanner,Landsat/ MSS, Air Photo	Single pass "	Aerial color film, special filter MSS bands,Vis Near IR, Thermal IR	20% of cost of conventional method; Chinese est. not received.
33b. Reconnaissance for bathymetric mapping	USA-global	USA-DMA, NOS	Landsat	As needed 10 yr cycle	MSS band 4, TM channels 1 and 2, 300 m	Not avail.

**This application is widely used in many countries.

APPLICATIONS

COST PER CYCLE	----ARCHIVED SENSINGS--- AVAILABLE	WHERE	COST	ALTERNATE METHODS	ANCILLARY DATA REQUIRED	OTHER SOURCES OF INFORMATION	REFERENCES*
32b. $850	Yes	EROS	$730/CCT per scene	Extensive water samples	Limited water samples	USGS, EROS Data Center, Sioux Falls, SD 57198 USA; MWREP, Beijing, China	105
33a. 20% of the cost of conventional method;	Yes USA only	NOS		Hydrometry	Some ground truth	Chief, Photogrammetry Br., NOS, 6001 Exec. Blvd., Rockville, MD. 20852 USA	47,88
Not avail. for China	Yes	China	$650/CCT	Hydrometry, 10 ships at 16 pt.	Some ground truth	Pearl River Water Conservancy Committee, Guangzhow, China	
33b. Not avail.	Yes USA only	DMA		None	None	Defense Mapping Agency, Hydrographic Topographic Center, 6500 Brookes Lane, Wash. D.C. 20315 USA	47,88

*The numbers identify references in the list beginning on page 108.

4.6. Integrated regional studies

The continents with the largest arid areas are Africa, Asia, and Australia. In order for society to exist in or near these dry areas, cooperation with areas having more water must exist. However, regional cooperation should not be limited to dry areas but can be beneficial wherever water is considered a valuable resource or a potential hazard. One of the primary goals for hydrologists that has been stressed throughout this document has been to find ways to control or store water when and where it is abundant, and to distribute it when or where it is in demand. Accomplishment of this goal requires that an assessment be made to classify areas where water is in excess, for at least part of the year, and create the means to store and then distribute the water when and where it is needed. Data are required, including spatial and temporal distributions of expected precipitation, the type of precipitation (rain or snow), the annual variability of precipitation, the existing demand for water both in the areas of excess and in the areas of deficiency, the geology and topography of the area and its suitability for reservoirs and canals, and the evaporation and transpiration losses that might be expected from water stored in or transported by those structures. The suitability of the land for agricultural purposes should also be determined. In any region, there is a limit to the total water available and, ideally, its use should be optimal for the majority of the inhabitants. The cost of storing and distributing water is often very large. Cooperation among water development planners in the region is required to see that existing resources in water and money are not over spent or doubly spent by planners operating independently, each not knowing of the development plans of the others.

A region, in the context used here, is a logical sized unit which hydrologically interacts. Examples would be: land encompassed in a large river basin such as the Nile, Mekong, or the Mississippi River basins; areas bordering rivers used as intergovernmental boundaries where the development of the water in the river must often be mutually agreed to; or areas composed of several governmental units having common hydrological and economic problems.

In the first paragraph in this section, quantitative descriptions of the climatology, topography, geology, consumptive use of water resources, population, and agricultural practices of the region were inferred, if not listed, as being required for development. The primary step in a regional development plan is to assess existing conditions as a baseline against which anticipated improvements can be compared. Social and economic benefits can then be projected and a realistic plan drawn up. The projection of the development costs requires data in addition to weather and runoff observations, that is, those data necessary to determine the cost of land acquisition, construction, relocation of roads, etc. In this context these also are hydrological data. Finally, when the baseline and the construction costs have been established, the climate, the terrain, and the soils can be considered in the light of the water resources available to the entire region to determine alternative development options and associated benefits. This sequence of planning may indicate that a change in crops, or a change in crop versus livestock ratio is needed to optimize the general standard of living, or that some resettlement of population must take place. Some displacement of persons, roadways, and other facilities is almost always required in the land to be flooded by reservoirs. Trade-offs can be examined between the potential loss of arable land to flooding behind a reservoir and the benefits obtained by being able to irrigate additional areas. The value of archeological sites or areas held in special esteem by the local population can be weighed against the value of alternate areas having other attributes.

In sum, the regional study is an effort to collect all the data required to effectively plan the best use for the water resources of the region. Examples of such studies include the possibility of diverting into Central Asia the rivers of the USSR currently flowing toward the Arctic Ocean (Voropaev, 1979); the taking of water from water-rich areas of North America to arid agricultural regions further south (Biswas, 1978); the water conservancy projects of China (Vermear, 1977); and the water storage projects of India (Murthy, 1978).

To carry out regional studies, several countries having similar problems have formed regional councils to assist in data acquisition and planning. For example, Palgen (1979) describes the African Remote Sensing Council.

The WMO publication on "Statistical Information on Activities in Operational Hydrology" (WMO,1977) is designed to serve as a convenient, permanent and regularly up-dated compilation of statistical information on activities in operational hydrology, which has been collected from Members of WMO and supplemented where appropriate by published information from elsewhere.

It indicates,in a fairly tangible way, the status of progress and contains some information on future plans with respect to operational hydrology activities of Members at the national, regional and global levels. It should prove valuable at all these levels for planning and co-ordination purposes.

5. PRACTICAL CONSIDERATIONS FOR THE USE OF REMOTE SENSING IN HYDROLOGY

5.1 Data availability

For unique applications of remote sensing, project plans must include details for acquiring the remote sensing data. However for applications requiring either aerial photography using standard aerial films, filters, and cameras, or imagery in the spectral bands available on weather satellites such as GOES, or the NOAA orbiting satellites, or on land survey satellites such as Landsat, the imagery can be obtained at very low rates (compared with the cost of acquiring the data as a custom job) from national or international agencies such as the European Space Agency, or from the EROS Data Center in the United States. Data available from archives will usually be useful for calibration and developmental work. There is not space in this report to contain comprehensive price lists and ordering details; however, the following addresses indicate where comprehensive information can be obtained.

5.1.1 Landsat, Skylab, and NASA remote sensing data. Satellite imagery, aerial photography, and computer compatible tapes can be ordered from:

User Services
EROS Data Center
Sioux Falls, South Dakota 57198, USA

Data that are ordered will usually be delivered within three weeks if they are on file. There is usually a delay of about 10-14 days between the time of acquisition of a scene and the time when it is available to a user. In special cases such as natural disasters, however, this time has been reduced. The data processing system for the Thematic Mapper is not in place yet; but there is a preliminary system running that is able to supply about one scene per day.

The resolutions available from these data are roughly as given in Table 3.

Aerial photographs at the EROS Data Center have been collected in an organized fashion for areas in the United States, and some limited international data are available. Because this report is written primarily for developing countries, we recommend that readers contact the EROS Data Center and ask if data for your area of interest are available.

Table 3. Resolution and Frequencies Associated with Remote Sensing Satellites

Vehicle	Sensor	Spectrum	Spatial Resolution	Frequency
Landsat*	RBV	0.5-0.6 µm	80 - 100 meters	18 days
		0.6-0.7 µm	"	"
		0.7-0.8 µm	"	"
Note: there was a wider spectrum on the RBV on Landsat 3.				
	MSS	0.5-0.6 µm	80 - 100 meters	18 days
		0.6-0.7 µm	"	"
		0.7-0.8 µm	"	"
		0.8-1.1 µm	"	"
	TM	0.45-0.52 µm	30 meters	16-18 days
		0.52-0.60 µm	"	"
		0.63-0.69 µm	"	"
		0.76-0.90 µm	"	"
		1.55-1.75 µm	"	"
		10.40-12.50 µm	120 meters	"
		2.08-2.35 µm	"	"
HCMM 4/26/78-9/30/80	Scanning Radiometer	0.5-1.1 µm	600 meters	2 passes/day
		10.5-12.5 µm	"	"

Skylab These data were collected during three separate periods when the spacecraft was manned between 1973 and February 1974. The products are described in Johnson Space Center Document JSC 09016. U.S. Gov't. Printing Office Stock Number 3300-00586. SKYLAB carried six high precision cameras, an Earth terrain camera, an Infrared Spectrometer, a multispectral scanner with 13 channels, a microwave radiometer, scatterometer, and altimeter, and an L band radiometer. There is a separate order form for the SKYLAB data.

* Landsat data have been collected since 1972; however, some of the CCT's of the earlier years are no longer available.

Most of the data available from the EROS Data Center can also be ordered from:

European Space Agency
Earthnet User Services
Via Galileo Galilei
000 44 Frascati, Italy

Remote Sensing Division
National Research Council
Bangkok 9
Thailand

Australian Landsat
1416 Oatley Court
P.O. Box 28
Belconnen, A.C.T. 2616
Australia

Instituto de Pesquisas Espacias (NPE)
Departmento de Producao de Imagens
ATUS Banco de Imagens Terrestres
Rodovia Presidente Dutra, KM 210
Cachoeira Paulista-CEP 12630
Sao Paulo, Brazil

Academia Sinica
Landsat Ground Station
Beijing
Peoples Republic of China

Canadian Centre for Remote Sensing (CCRS)
User Assistance and Marketing Unit
717 Belfast Road
Ottawa, Ontario KlA OY7, Canada

Director, National Remote
Sensing Agency
Balanger
Hyderabad 500 037, India

Remote Sensing Technology Center (RESTEC)
7.15.17 Roppongi, Minato-ku
Tokyo 106, Japan

Director, National Institute for
Telecommunications Research
ATTN: Satellite Remote Sensing Centre
P.O. Box 3718
Johannesburg 2000
Republic of South Africa

Comision Nacional de Investigaciones
Espaciales (CNE)
Centro do Procesamento
Dorrego 4010
(1425) Buenos Aires, Argentina

5.1.2 METEOSAT (geosynchronous data for Europe and Africa)

Data from Meteosat can be ordered from:

Meteosat Data Services
Meteosat Data Management Department, ESOC
Robert-Bosch-Strasse 5
D-6100 Darmstadt
F.R. Germany

The data have the characteristics given in Table 4.

Table 4. Meteosat (European Space Agency) Characteristics

Vehicle	Sensor	Spectrum	Spatial Resolution	Frequency
Meteosat*	Imaging radiometer	0.4-1.1 μm	2.5-5 km	30 min
		5.7-7.1 μm	5 km	"
		10.5-12.5 μm	5 km	"

*Data have been archived since March 18, 1983.

5.1.3 NOAA, GOES (geosynchronous data for North and South America), and Nimbus Coastal Zone Color Scanner (CZCS)

Data from the GOES, NOAA meteorological satellites and the Nimbus (NASA) CZCS can be ordered from:

National Climatic Center
Satellite Data Services Division
World Weather Building, Room 100
Washington, D.C. USA 20233
Telephone: (301)-763-8111

The data have the characteristics given in Table 5.

Real time data are available from what is called the "GOES tap". It includes some data from European and Asian geosynchronous satellites as well as from the two over the United States. Access to these data by developing countries is best done by installing a ground station in the interested countries (or region if several countries want to share costs and data).

Table 5. Characteristics of U.S. Weather Satellites

Vehicle	Sensor	Spectrum	Spatial Resolution	Frequency
GOES	VISSR	0.55-0.75 μm	1, 2, 4, 8 km	30 min*
	"	10.5-12.6 μm	7.4 km	30 min
TIROS	AVHRR	0.58-0.68 μm**	1 km	roughly 2/day
		0.725-1.10 μm	"	"
		3.55-3.93 μm	"	4/day
		10.3-11.3 μm***	"	"
		11.5-12.5 μm****	"	"
Nimbus	CZCS	0.433-0.453 μm	"	1/day
		0.510-0.530 μm	"	"
		0.540-0.560 μm	"	"
		0.660-0.680 μm	"	"
		0.700-0.800 μm	"	"
		10.5-12.5 μm	"	"

* Note that there are currently two GOES satellites in the Western Hemisphere, one at 75° West and one at 135° West. The products from these two satellites are offset by 15 minutes.

** TIROS-N .55-.90 μm.

*** TIROS-N (NOAA 6 - NOAA 8) 10.5-11.5 μm.

**** Only available on NOAA 7 but is expected on future NOAA satellites.

Specifications for ground stations may be obtained from:

User Affairs Unit
NESDIS
Room 3306A
FOB #4
Washington D.C. 20233, USA

Negotiations to communicate data received by NESDIS in the USA to another country would have to be conducted with:

Division Chief, Satellite Service Division
NESDIS
World Weather Building Room 607
Washington D.C. 20233, USA

5.1.4 Other data. Some data are also available from the

World Data Center A for Rockets and Satellites
Code 601
Goddard Space Flight Center
Greenbelt, Maryland 20771, USA
Telex no.: 89675

However, much of the data archived here are related more to astronomy and satellite performance, than to water resources.

Snow and ice data are available from the

World Data Center A for Glaciology (Snow and Ice)
Institute of Arctic and Alpine Research
University of Colorado
Boulder, Colorado, 80309, USA

Climatic data are available from the World Data Centers. World Data Center A is colocated with the United States National Climatic Data Center. Information on data accessible through the World (Climate) Data Center program may be obtained by contacting:

Director, World Data Center A
National Climatic Center
Federal Building
Asheville, North Caroline 28801 USA

Director, World Data Center B
Chief, Administration of
Hydrometeorological Service of USSR
Pavlik Morozov St.
12 Moscow D-376 USSR

Additional sources of information are listed in World Wide Directory of National Earth Science Agencies and Related International Organizations published by the US Geological Survey (Circular 834) in 1981 which can be obtained by writing to:

Distribution Branch
Text Products Section
U.S. Geological Survey
604 South Pickett St.
Alexandria, VA 22304 USA

5.1.5 Radar data. Data for ground-based weather radars are generally of local interest only and, when stored, are stored in archives in the countries where the radars are located.

5.2 Data systems and costs

Table 6 gives a brief price list. For more detailed information and for special service, contact the agencies directly. Possible techniques for determining remote sensing costs have been discussed by Cheeseman (1973) and Ramey (1970). It must also be remembered that besides the data acquisition costs, there are other costs involved such as data analysis system and dissemination costs. So, in evaluating any remote sensing systems all these costs must also be included.

5.3 Support facilities

Chapter 2 discussed the capabilities of remote sensing and Chapter 3 indicated the data requirements of hydrology. The sensings were given in terms of an image on a photographic negative or an electrical signal converted to a magnetic record of a brightness, a temperature, or a series of numbers stored as magnetic signals in a computer or on a tape. Before these sensings can be converted to the kinds of data described in Chapter 3, or used in the

Table 6. Abbreviated Price List for Satellite Products

Agency	Satellite	Sensor	Frequency	Data Archived Since	Product	Cost*
EUROPEAN	METEOSAT	Visible	30 min	1 December 1978	$(20\ cm)^2$ film pos	9 DM 13.50 DM
SPACE	"	and	"	"	$(40\ cm)^2$ film pos	18 DM 27 DM
AGENCY	"	Infrared	"	"	$(20\ cm)^2$ paper pos	9 DM 13.50 DM
	"	"	"	"	CCT	75 DM 112.50 DM
	METEOSAT	"	"	"		for each additional file accessed on the tape 32 DM and 48 DM (Prices as of 9/80)
EROS DATA CENTER**	Landsat	MSS and RBV	18 days	July 1972	70 mm film pos	$26
			"	"	70 mm film neg	$32
			"	"	10 inch film pos	$30
			"	"	" " " neg	$35
			"	"	40 inch col paper	$175
		MSS	"	"	CCT full scene (9 track tape)	$650
		RBV	"	"	Full scene	$1300
			"	"	Single subscene	$650
		TM**	16-18 days	July 20 1982	Full scene	$3400 (Prices as of 10/1/83)
NCDC/	TIROS&	VHRR****	2/day	early 70's to 78		
NESDIS	TIROS-N	AVHRR	2-4/day	October 1978	10 in film pos	$10.75 transparency $8.50 print
	"	"	"	"	30 in paper pos	$18
	"	"	"	"	CCT 7 or 9 track 1600 bpi or less	$99 ***
					9 track 6250 bpi	$154
	GOES	VISSR	30 min each	early 70's	Selected scenes	Same as TIROS
					Geographic coordinates added	$1 per image (Prices as of FY 83)

Prices are generally given in U.S. dollars. For ESA the prices are in Deutsch marks.

* For the ESA data, two prices are given, one for the ESA member states: Belgium, Denmark, France, Germany, Ireland, Italy, Netherlands, Spain, Sweden, Switzerland, and the United Kingdom; and another price for non-ESA purchasers.

** The Thematic Mapper channel spectra were listed earlier in this section. Special acquisition services are available at extra cost. Contact EROS Data Center for details.

***The above prices are for full tape-to-tape copies only. Selective copies will cost $20 for each input tape that is mounted, plus the $99 per output tape ($154 for 6250 bpi tapes).

applications given in slightly more detail in Chapter 4, some processing must usually be done. This processing was described in Section 2.4. The processing for specific applications varies and could require a little or a great amount of sophisticated equipment. This equipment is found in various support facilities prepared to perform various levels of processing. Many details of data processing are presented in the Manual of Remote Sensing (ASP, 1983).

The support agencies prepared to process data can be roughly divided into four classes.

1. National and international data acquisition agencies who design the data acquisition platforms such as the satellite, the sensors to be carried on the platform, and the means to receive data and convert the raw information to standard or customized format for use by themselves or others. This includes governmental agencies of the United States, Union of Soviet Socialist Republics, India, Japan, and the European Space Agency. The international data coordination agency is the World Meteorological Organization (WMO) and its World Weather Watch (WWW) program.

2. Large governmental or commercial agencies who collect required data from air photos, radar, or satellite imagery to produce a variety of local, national and international maps. These companies (or agencies) must maintain expertise in photography, photointerpretation, the uses of stereoplotters with associated equipment, and in mosaicking and printing all types of maps.

3. The third class consists of institutions which are often associated with governments or universities, which emphasize numerical processing of data on computers as opposed to the graphical processing specialized in by class two.

4. The fourth class consists of many consultants who have expertise in remote sensing practices and applications and often act as a bridge between classes one through three and users not familiar with remote sensing capabilities.

Many of the agencies in the first group overlap into the other three groups in an effort to educate the public and build a market for their products. The EROS Data Center and the NESDIS information center in the United States are continuing to develop new and better ways of applying the Landsat and the NOAA and GOES type satellite data respectively. This work includes improved techniques to remove unwanted noise from sensor signals, improved navigation of satellite data, practical ways of estimating rainfall, transpiration, soil moisture, water pollution, etc. Questions related to the services offered should be sent to the addressees listed in Section 5.1.

Many countries which do not own their own satellite systems still fund centers to develop appropriate remote sensing practices. An example of this is the Remote Sensing Center in Cairo, Egypt.

There are many mapping centers, both governmental and non-governmental. It is not the function of this report to promote any one private company over another, but lists of companies having mapping potential can often be identified by inquiry directed to the United States Agency for International Development, the World Bank, the United States Geological Survey, or members of the International Association of Hydrologic Sciences (IAHS) Committee on Remote Sensing and Data Transmission for Hydrology (ICRSDT); by checking advertisers in journals such as Photogrammetric Engineering and Remote Sensing; or in Europe by reference to the EARSeL Directory. The address of the IAHS- ICRSDT is

A. Ivan Johnson
7474 Upham Court
Arvada, Colorado 80003, USA.

The address of the EARSeL Secretariat is

292 rue Saint-Martin
75003 Paris, France

The IAHS committee has members from nearly all major countries throughout the world where remote sensing applications are being made. The EARSeL Directory lists academic, governmental and commercial institutions throughout Europe and describes the facilities available to them.

In the third group are many academic institutions which have available extensive data processing facilities. As the cost of data processing devices is reduced, more small companies are finding themselves in a position to process satellite data "on order" from computer-compatible tapes, to contour specific values, to develop thematic maps, or to receive data directly on a down link from a weather satellite.

Much of the non-governmental or governmental contract work for research in remote sensing is done by the organizations in this group. For example, a lot of the experimentation using mobile land-based radar to get hydrological data from snow packs and soils has been done by or in conjunction with the University of Kansas.

The fourth class of processors includes many small companies or individual consultants who get contracts with the facilities listed in classes one, two, and three and combine the expertise of the contractee with the facilities provided by the contractor. Many of these individuals or companies can be identified by the same methods for identifying those in classes two and three.

5.4 Evaluation of results

A major problem in evaluating results from remote sensing occurs when there is not a clear understanding and mutual agreement on what data will be supplied and how those data are to be applied. In this section, data forms or formats, accuracies, and standards and criteria for comparison will be discussed.

Hydrological measurements, the need for data, and current means to get them were discussed previously in Chapter 3, and forms and analyses were discussed in Section 2.4. Because a clear understanding of what can be done and how the data are used is so important to the successful use of remote sensing, additional emphasis on data forms and formats is given here. Data are used in many different ways but can be grouped into four large classes for purposes of discussion. The first group comprises data used for routine, reoccurring, cyclic processing such as runoff forecasts and water supply outlooks. These data include basin means of: precipitation, snowpack water equivalent, temperature, and evaporation. Because many basins and many time intervals are often processed at one control center in a rather routine manner, one number, in the proper dimension, is desired to represent each process (rainfall, evaporation, temperature) in each basin for each observation period. In a distributed model, one number for each process may be desired for each grid square or sub-unit. In many cases, storages of surface and groundwater also fall into this category for which one number represents the total storage, input, release, or withdrawal for the time period.

The second group consists of flow data. One number is desired at each of several points, to indicate the volume of flow past that point during the observation period. A third group includes data such as pollutants and their sources. In this class, a number representing a concentration and numbers representing a location on the ground in some coordinate system are required. The best means of receiving and processing these data is a three dimensional array, e.g., two dimensions for spatial coordinates and one for rainfall accumulation. This group can be expanded to include values sensed in different spectral bands for developing land use maps. The dimension of the data array must be two more than the number of characteristics to be associated with the two dimensional coordinates for ground location.

The fourth group consists of data for floodplain mappings, explorations, or pilot studies. These processes have not been so easily modeled on a computer, and the integration performed by the eyes and brain of an interpreter is required. Information obtained from remote sensing for these purposes will frequently be checked against what is on the ground, with the remote sensing data suggesting where more intensive ground sampling might be required. In these cases, imagery and thematic maps are likely to be preferred over digital data. Some interpreters would like to use the digital data described in the third group to generate their own thematic maps to aid them in their interpretation of the imagery. Success in using these types of data depends on the training and experience of the interpreter, who may also be a geologist, civil engineer, or hydrologist, in charge of a project or part of its advisory staff.

Evaluation of data requires some standard against which to compare the data. Great care must be taken that the accuracy (and the error) of the standard is considered in making the evaluation. If an accuracy or error term is stated by those who provide a set of data, then a statement should be included by the provider of the data about the standard used to estimate the error and its associated accuracy. When a user requires knowledge about data accuracies, he should request from the data supplier information on the accuracy of the data and how the accuracy is estimated. To illustrate, Farnsworth and Canterford (1980) discuss rainfall accuracies available from remote sensing techniques in terms of an equivalent raingage density, and indicate the errors assumed to be inherent in raingage networks as a function of storm area, duration, and variability.

5.4.1 Comparisons against standards. Data that are remotely sensed are frequently obtained to replace or expand data previously measured either by a network of points, or by a transect. When new types of data are evaluated for accuracy, they are generally compared with data obtained by previous methods. The sampling cells used in remote sensing are often several orders of magnitude larger than those associated with the in situ measurements used in conventional methods. The sensing cells have been called picture elements (pixels), footprints, or in the case of radar, bins (these bins are a function of the beam width and range resolution). For instance, rainfall may be measured by a raingage having a diameter of 1.0 foot (0.3 meters) and by a radar with a bin that is one or two degrees in azimuth wide (which becomes wider like a piece of pie as the range from the radar increases), and is one to five km in length. These same measurements might also be compared with that from a GOES satellite with an IR pixel which is on the order of eight km on a side. If the remote sensors were all looking at the area (volume) containing the raingage and if the rainfall were uniform over the area of the sensing element and over the duration of the observation, then all the reports should, within the errors of the system, be the same. All of the sensors give the effective areal average of the process that they measure. The area of the raingage is so small that it is effectively a point, while the area of the remote sensing cell is large enough that a fair degree of variability can exist. Being a point, the raingage could have any value within the range of values occurring in the remote sensing sampling cell. The remote sensor will measure just one value, the mean for the cell. If a storm system only partly fills the cell, then the estimate will be the same as for some less intense storm which uniformly fills the cell. The remote sensor also generally is used to monitor many cells during an observation period. In effect, it takes a series of snapshots of a process which can be spaced at fairly wide intervals during the reporting period. When a storm is highly variable over space and time, it is easy to see why it is hard to compare the information from a remote sensing system with that from a raingage(s). In the absence of extreme wind speeds, a well exposed and calibrated raingage will surely be the most accurate for the 0.3 meter diameter circle that it monitors, but how well can it monitor a point 10, 100, or 10,000 meters away? Many of the local variations in rainfall intensity are smoothed when the measurement is taken over a larger interval or for several minutes. Additional details on comparison of points with areas is given under sampling frequency in Section 3.4.1.

The point in raising this issue is that it is important to remember that simply because point observation estimates from a measuring system may not agree exactly with the estimates from a remote sensing system, does not mean that the remote sensing system is not as accurate for the area and observation period for which its measurements apply. Only from analyzing the errors inherent in both systems can reasonable evaluations be made, and the analysis may well show the remote sensing system to have the smaller error. Because of the difference in sampling characteristics between the in situ and remote sensor, the user generally will achieve the best solution by incorporating the information from both in such a way that the strengths of each are maximized.

5.5 Project planning.

When a project is being considered and the data acquisition needs are defined, the following issues should be considered in choosing one of the following possible alternatives: to use remote sensing as the main data source (with necessary ground truth sampling), to incorporate remote sensing with in situ data, or not to use remote sensing at all.

1. Can remote sensing, by itself or in conjunction with available in situ observations, supply more complete data for the project because of the additional spatial and temporal sampling afforded by the remote sensor?

2. Does remote sensing provide data that are available in no other way?

3. Does the project require data from areas where in situ techniques cannot be used, such as snowline sampling in remote mountainous areas?

4. Can remote sensing data be collected at more relevant times than those offered by other data acquisition methods?

5. Do remote sensing data increase the efficiency of in situ sampling by indicating where ground truth sampling must be concentrated?

6. Can remotely sensed data be collected more quickly or more accurately than data obtained by alternate methods?

7. Are remotely acquired data more suitable for data application needs, i.e. areal data rather than point data?

8. Have past projects shown that remote sensing gives a high correlation with the information required for the project, or have additional data generally been required?

9. Are remote sensing techniques cost effective?

As much as possible, the form and specific application of the data from the remote sensing system should be evaluated before the data acquisition system is put in place and data are collected. The United States Army Corps of Engineers has outlined a reasonable approach (USACOE, 1979). The schematic in Figure 24 is taken from their publication.

When the format for the data, the standard for comparison or accuracy assessment, and the desired accuracy are set forth before the data are acquired, there is less problem with the interpretation and use of the data after they have been gathered.

5.6 Cost benefit studies.

The cost versus benefit analysis of remote sensing data acquisition should not be justified on the cost/benefit ratio of the entire hydrologic project but on the basis of comparing the use of remote sensing data by itself (possibly with other data types) with the use of only non-remote sensing

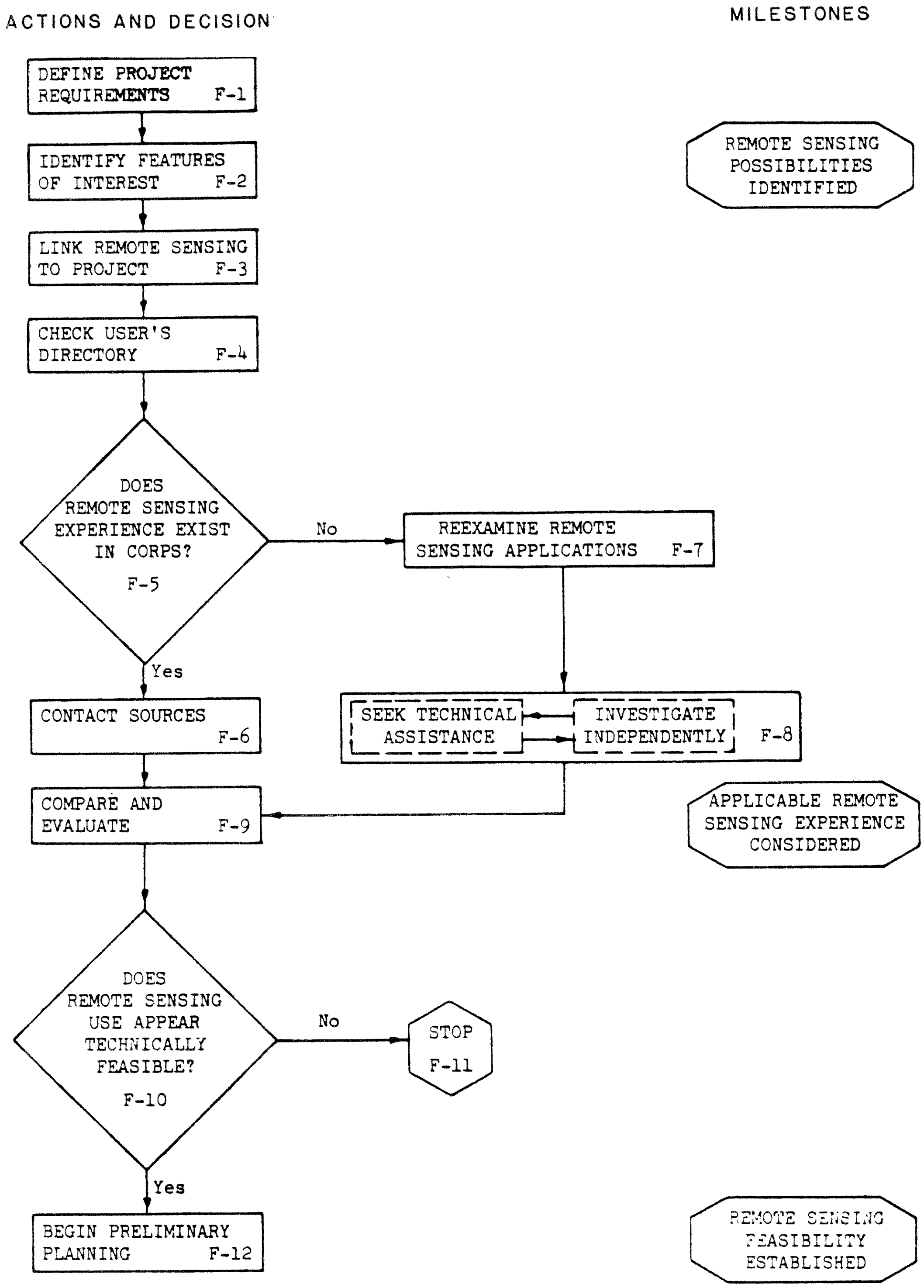


Fig. 24. Flowchart for determining the technical feasibility of applying remote sensing by the United States Army Corps of Engineers (United States Army Corps of Engineers--Remote Sensing Applications Guide, October 1979, Office Chief of Engineers, Washington, D.C. 20314, p. 3-2).

data. However, there may be projects, which have been disallowed because of the high cost of data acquisition, that could be acceptable if remote sensing data were satisfactory, and could provide the same level of information at a lower cost. There are some projects for which there are no other means of gathering data. In these cases, the comparison analysis recommended above cannot be performed, and the full project cost/benefit analysis is appropriate.

The parameters for cost benefit analysis of a project are: the useful life of the project, the annual maintenance costs, the initial investment costs plus the interest on that money over the life of the project, and finally the estimated benefits (Kuiper, 1971). One means of assessing the benefits attributed to hydrological forecasts is discussed by Day in WMO 341 (1973). Once a decision is made to go ahead with data acquisition, the cost/benefit ratio for evaluating the benefit of remote sensing is just the ratio of the cost of data gathering by remote sensing methods (including ground sampling), to the cost of gathering data of sufficient detail and accuracy exclusively by conventional methods. Cost effectiveness of remote sensing is discussed in CPUOS (1965). The cost of acquiring hydrological data by remote sensing can be divided into remote sensing data collection (see Section 5.2), data processing and analysis (described in Section 2.4), and dissemination, which is highly dependent upon the location and application and will not be discussed further here.

Among the costs or benefits to be considered are the speed in collecting the data versus any penalties incurred for project delays caused by lack of data; the estimated advantages (if they exist) for continued monitoring by remote sensing; the added benefits that could accrue by the display (in the synoptic views acquired by aircraft or satellite sensing) of the local roads, waterways, power lines, gas pipe lines, and the environmental monitoring of water resource development.

If hardware such as a computer is required for remote sensing processing, then the additional uses to which the computer might be put should be included in the overall estimate of benefits.

In some cases, the remote sensing system may totally replace an existing data gathering system. In other cases, existing data are insufficient and the remote sensing system is considered to supplement the existing condition. In this situation, the costs are the total cost of acquiring and maintaining the total system. The benefits of more accurate data are difficult to assess. Watkins summarizes some of the studies related to the economic benefits of remote sensing (Watkins, 1978). The value of improved hydrologic data are not central to this report and for more information on this topic the reader is referred to NOAA-NWS (1982).

5.7 Information, education, and training

5.7.1 Information. No single comprehensive work on remote sensing in hydrology has yet been written. If one had, the task of the authors of this Report would have been much simpler--and this document would have been much more complete. However, some volumes provide useful introductions to the science of remote sensing. For example, the Manual of Remote Sensing (American Society of Photogrammetry, 1983) has a chapter devoted to remote sensing applications in hydrology and in the marine environment (including water pollution). Other examples include: paper collections edited by Salomonson and Bhavsar (1980); Deutsch et al. (1981); and Fraysse (1980); and a general but brief review, the Applications of Remote Sensing to Hydrology, prepared for the WMO by Wiesnet et al. (1979). Additional WMO publications in this area include Satellites in Meteorology, Oceanography, and Hydrology (WMO, 1982b); Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use (WMO, 1982a); and Information on Meteorological Satellite Programmes Operated by Members and Organizations (WMO, 1975). A text entitled Remote Sensing Applications in Hydrology has been planned for a series of Remote Sensing Applications texts edited by E.C. Barrett and L.F. Curtis, and is expected to be published by Chapman and Hall of London, England. A useful guide to technology and application is found in material assembled by the United States Army Corps of Engineers in Remote Sensing Application Guide (USACOE, 1979).

Appropriate texts in Russian include: Remote-sensing Methods in Hydrology by Kalinin et al.,(1977), Applications of Aerial Methods in Ground Water Studies, by Kell,(1962), Satellite Imagery in the Study of Land Water (Kuprianov and Prokacheva, 1976), and Review: Satellite Imagery in Hydrological Investigations by Kuprianov and Prokacheva (1979).

Other publications of interest to the hydrological community include user's guides for individual satellite systems (e.g., Landsat, Nimbus, METEOSAT), and information sheets containing regular updates of satellite status and products. These include the Landsat Data Users Bulletins published by NOAA at the EROS Data Center, the Nimbus users guide published by NASA at GSFC in Greenbelt, Maryland, USA, and the GOES user's guide published by NOAA-NESDIS Washington, D.C., USA.

Useful entries into the paper and article literature in this field are afforded by the computer libraries of publications held by some national remote sensing centers. The Canada Center for Remote Sensing in Ottawa maintains one of the most extensive and easily accessible of these. The address of the Canadian Center is:

G. Thirlwall
RESORS
Canada Centre for Remote Sensing
240 Bank Street, 5th Floor
Ottawa, Ontario K1A Oy7
Canada

The purpose of these centers is to provide coverage of remote sensing as a whole. Therefore, they have had no more interest in hydrology than other areas of application, and such computer libraries all fall far short of the comprehensive ideal our discipline urgently needs. Reports on satellite research (including applications of satellites in hydrology) undertaken in major government laboratories make up some useful series of occasional publications (e.g., the NOAA Technical Memoranda - an example of which is the Scofield and Oliver reference found in the reference section of this report). The Land and Water Resources Division of the Food and Agriculture Organization (FAO), Rome, prepares and circulates a useful series of information leaflets on water sciences under the title of "Water Briefs". Some of these series have addressed the potentialities of remote sensing techniques. A similar news sheet devoted exclusively to remote sensing in hydrology might be a useful innovation. Some publications from FAO's Remote Sensing Center also address topics of hydrological significance. The address for FAO is:

Food and Agriculture Organization
Land and Water Resources Division (or Remote Sensing Center)
Via delle Terme di Caracalla
00100 Rome, Italy

Symposia in remote sensing have proliferated in recent years. A few have focused specifically on hydrology, including the XXII COSPAR Symposium on the Contribution of Space Observations to Water Resource Status and the Management of These Resources held in Bangalore, India (Salomonson, 1980) and the AWRA Wm. T. Pecora V Symposium in Sioux Falls, South Dakota in 1979 (Deutsch et al., 1981). Hydrology is becoming increasingly important in general remote sensing symposia such as the University of Michigan series. Remote sensing is also figuring more in symposia on hydrology, e.g., at the IAHS meetings in Exeter, UK (1982) and Hamburg, F.R. Germany (1983). These proceedings will be published in 1984 and can be ordered from the IAHS at 2000 Florida Avenue, N.W., Washington, D.C. 20009, USA.

There are several journals emphasizing remote sensing activities, including Remote Sensing of Environment (Elsevier Science Publishing Co., Inc.); Photogrammetric Engineering and Remote Sensing (American Society of Photogrammetry); the IEEE Transactions on Geoscience and Remote Sensing (Institute of Electronic and Electrical Engineers); the Canadian Journal of Remote Sensing (Atmospheric Environment Service of Canada); and the International Journal of Remote Sensing (published in London by Taylor and Francis).

There are several active groups or committees devoted to disseminating information on remote sensing in hydrology. These include the American Geophysical Union (AGU) Committee on the Hydrologic Sciences, the Hydrospherics Committee of the Remote Sensing Applications Division of the American Society of Photogrammetry (ASP), and the previously mentioned committee of the International Association of Hydrologic Sciences on Remote Sensing and Data Transmission. Both the World Meteorological Organization (WMO) and the United Nations Educational, Scienctific, and Cultural Organization (Unesco), through the International Hydrologic Program (IHP), have rapporteurs on remote sensing in water resource applications. An address for further information on the IAHS committee was given Section 5.3. The chairman of the AGU committee is:

Dr. Thomas J. Jackson,
USDA-SEA-ARS, Hydrology Laboratory
Rm. 139, Bldg. 007
Beltsville, Maryland 20705, USA

The chairman of the ASP Hydrospherics Committee can be reached at:

Chairman, Hydrospherics Committee
Remote Sensing Applications Division
American Society of Photogrammetry
210 Little Falls Street
Falls Church, Virginia 22046, USA

The current WMO rapporteur is:

Mr. Risto Kuittinen
Laboratory of Land Use
Technical Research Centre of Finland
Revontulentie 7
02100 ESPOO 10, Finland

From 1981 - 1984, he was assisted by:

Dr. David F. McGinnis
Land Sciences Branch
NOAA-NESDIS
Washington, DC 20233, USA

The rapporteurs for the Unesco/IHP program are the authors of this report. Their addresses are:

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ISRO
Ahmedabad 380 053
India

5.7.2 Education and training. These are so closely interwoven that it is convenient to treat them together. Education may be conceived as either relatively comprehensive instruction in a field, or familiarization with its general aims, method, and problems. Training is generally more concentrated and restricted in scope, but may treat selected topics in greater depth; its purpose is to develop practical skills which may be used subsequently in everyday operations. General education in remote sensing for hydrological applications is offered by a small but growing number of universities in several countries, e.g., the University of Maryland (College Park, MD. USA), and the International Institute for Aerial Survey and Earth Sciences, ITC, Enschede, The Netherlands. Special training for the use of remote sensing in regional offices is given by the staff of some national centers, e.g., training in the use of satellite imagery for flash-flood forecasting as given by the staff of the Satellite Applications Laboratory of NOAA-NESDIS in the United States. Courses in hydrological applications of remote sensing, specially designed for personnel from developing countries, have been provided at FAO, Rome, in 1980 and 1983, under the co-sponsorship of the United Nations and the Government of Italy. The IAHS Committee on Remote Sensing and Data Transmission is interested in arranging for a "hands on" training workshop (see Section 5.3 for the address of their chairman).

However, in general, it must be concluded that training in remote sensing for hydrology has been generally inadequate and, apart from the chief exceptions listed above, has concentrated mainly on uses of airborne imagery for the determination of basin characteristics, and radar data for severe storm monitoring, rather than on the present range of remote sensing possibilities in general, and uses of satellites in particular.

5.8 Organizational issues

Many of the problems introduced in the earlier parts of this chapter have stemmed from the historic lack of some international body with a specific task or vision to promote and coordinate remote sensing in hydrology. It is possible that the International Committee for Remote Sensing and Data Transmission of the IAHS, founded in 1981, may have an important role to play in such directions.

Among the more common results of the long standing deficiency are:

(a) A lack of awareness of satellite systems and capabilities among many potential users.

(b) A lack of knowledge of available data and data products, and the sources where these might be obtained.

(c) An urgent need for more "bridge-building" between satellite engineers, scientists, and users or potential users of satellite data and products for more efficient hydrological problem-solving.

(d) An inadequacy of funds for technique demonstration and development for operational applications.

(e) A need for areally broader and more integrated approaches to the potential uses of remote sensing for hydrological problem-solving. At present, remote sensing techniques are often used only fragmentarily in operational programs, and incompletely or not at all in some areas. However, in other areas considerable overlap or duplication of effort is evident. Clearly, political problems increase as the scales of operations broaden and cross local, regional, or even national boundaries. However, the practical and economic benefits of organizing some projects on larger rather than smaller scales would be so great that they deserve much closer attention than they are often given.

(f) A failure to reappraise existing operations in the light of new practices and technologies, often due to nothing other than civil service inertia.

(g) Generally inadequate or inappropriate provisions for remote sensing education and training.

(h) A sparseness of equipment or personnel of the right types to capitalize upon new possibilities in remote sensing for hydrological applications.

In view of the points listed above, it is not surprising that remote sensing in hydrology seems to hold great promise, but also generally unfulfilled potential. More than many other environmental sciences, hydrology is dominantly an applied science. In it, the needs of operational users are paramount. Administrators seem reasonably happy to countenance new approaches--but only if these have been developed to operational levels already. Meanwhile, the goals of pure research are different, and research funding is not normally afforded for the translation of research methods into operational techniques. Consequently, progress towards the everyday implementation of remote sensing in hydrology has been much slower than it could have been. It seems that remote sensing will not become much more widely and fully used by the hydrological community until and unless new international initiatives are made. Otherwise, judging by experience in other spheres of activity, remote sensing will go largely ignored by many of its potential users, who will not only proceed without its aid, but will also stunt its future development through their skeptical influence on others. Perhaps, one antidote to this would be an international center, or regional centers, committed to the use of remote sensing in hydrology, charged with the task of encouraging and coordinating activity in this field, publicizing its possibilities, and stimulating the types of research, education, and training which would serve the hydrological sciences best.

6. FUTURE NEEDS AND PROSPECTS

6.1 General

The need for data for hydrologic applications is expected to increase as population and industrial development continue to cause increased demands upon available water resources. The age-old problems of periodic flooding continue to bring damage and death even where remedial steps have been taken. The future needs which are practical to discuss here are those which have some reasonable probability of being addressed by remote sensing. Several lists have been compiled of observational requirements for hydrology. For example, see Table III in WMO 1977. Stating the needs in broader terms, the objectives for the Draft Plan of IHP-III (HYGRE/7/Part 1, Unesco, 1981) lists the "Main Objectives of IHP-III," and identifies a number of main objectives by which it might achieve its goal of helping "to solve the crucial hydrologic, water management, and water-related socio-economic development problems as can be foreseen in the second half of the decade 1981-1990 and in the following years." These objectives read as follows:

(a) To contribute to the progress of hydrology, other water sciences and related aspects of ecology and promote their applications to the solution of problems related to the development of human society;

(b) To improve knowledge of the processes involved in the hydrological cycle and to determine the manner in which these processes could be most appropriately described to meet the demands for the planning, design, execution and operation of water projects;

(c) To evaluate the influence of man on the hydrological cycle both in the form of direct actions such as those involved by water works or changes in land use and also in relation to indirect activities such as those leading to possible change in climatic factors;

(d) To develop procedures for the conservation of water resources and their protection against pollution within the framework of sound environmental management;

(e) To determine methodologies for the assessment and integrated management of water resources to meet the needs of economic and social development;

(f) To provide in cooperation with the international scientific community, a general frame-work for the development of hydrology and the scientific basis of water resources management, and to promote and facilitate the access of all nations, in particular the developing countries, to scientific and technological progress in this field;

(g) To promote education and training in hydrology and other disciplines related to water resources management, with increased emphasis at the technician level, in order to strengthen the endogenous capacity of Member States to solve their water problems;

(h) To develop procedures for providing information to decision-makers and the general public aimed at bettering awareness of matters related to water use, protection, and conservation, and increasing general as well as personal responsibility for the crucial water issues;

(i) To promote the development of scientific and technical information systems in the field of water resources;

(j) To achieve effective scientific and technological transfer through international cooperation between developed and developing countries, and also among developing countries;

(k) To enhance regional cooperation, in particular among developing countries, to enable the respective countries to better cope with water problems of common interest;

(l) To assist Member States, in particular the lesser developed ones, in the development of their research and educational programs relating to the study, assessment, planning and management of water resources and in building up appropriate infrastructures (with special reference to the role of National Committees for the IHP).

Remote sensing relates to these objectives, respectively, in the following ways:

(a) As a new and active research area, remote sensing has much to contribute to hydrology and related sciences, both pure and applied.

(b) Remote sensing can contribute to process studies by providing better measurements of key variables involved in the hydrological cycle, especially exchange processes such as precipitation and evaporation (Section 4.1).

(c) Monitoring environmental variation and change, whether natural or man-induced, is a major area of application of satellite imagery, both from Landsat and environmental-type satellites (Sections 4.2.10 and 4.2.11).

(d) Conservation, pollution monitoring, and management of the environment are areas of active concern to remote sensing scientists (Section 4.2.9).

(e) Integrated approaches to water resource assessment and management are already under development, e.g., the "assemblage approach" of the University of Maryland (Section 4.2.6).

(f) The need for centralization of information and technology transfer in remote sensing specifically for hydrological applications as identified already in this Report (Section 5.7).

(g) The need for increased training in remote sensing for hydrology has also been identified previously in this Report. An expansion in the numbers and scope of relevant courses is particularly sought (Section 5.7).

(h) Many remote sensing products are visually striking and are of contemporary interest in these days of active space exploration. It is not difficult to envisage them as key items in improved information systems and new publicity drives.

(i) New communication science and information technology systems in the field of water resources neglecting remote sensing would be inappropriate to the needs and opportunities at the end of the Twentieth Century. Remote sensing products and results will constitute an essential part of any information to be shared.

(j) Transfers of science and technology must be centered on areas of worthwhile innovation, of which remote sensing is one.

(k) Water-related problems are characteristically trans-national. So, too, are the operations and data provided by remote sensing satellites which could, therefore, serve as spurs to new international approaches to water-related problem-solving (Section 4.6).

(l) The rapid advance of computer technology should be capitalized on to enhance the effective utilization of remotely sensed data through improved data management and processing.

(m) Remote sensing is a rapidly expanding field in which further advancement is essentially guaranteed. It is essential that it should figure increasingly in hydrological research, operations, and education, and that appropriate infrastructures should be developed to encourage such expansions to take place to the benefit of Member States, especially the lesser developed ones.

6.2. Suggested Activities for Continued Development of Remote Sensing

Considering the general needs and opportunities outlined earlier in this Report, including the growing demands for potable water in the communities in the vast rural areas of developing countries, a number of studies and projects can be proposed. These (in logical, not rank, order) are as follows:

(a) A systematic evaluation of potential remote sensing inputs into current projects supported by international programs such as IHP and WWW, as and where appropriate, to determine which might benefit most therefrom.

(b) The establishment of a cumulative, exhaustive, centralized, and computerized bibliography on Remote Sensing for Hydrology listing sources of technical information and data.

(c) The preparation of a unified Directory of Remote Sensing Techniques for Operational Hydrology (a "how-to-manual"), by cooperating international users sponsored by WMO in cooperation with Unesco.

(d) A review of water use and consumption requirements for developing countries, or groups of developing countries, and an evaluation of the use of remote sensing methods for acquiring these data.

(e) Realistic evaluations of the benefits and costs of remote sensing in hydrology, so that types and areas of future implementation and further activity can be ranked according to priority.

(f) The formulation of blueprints for integrated regional remote sensing training and education programs for hydrology (modality or implementation studies examining all aspects of remote sensing implementation, including scientific, technical, cost, and other questions).

(g) An exploration of present and potential global and/or regional products which could be used in broad-area hydrological monitoring, e.g., in rainfall, soil moisture, snow and ice, and drought monitoring, etc., so as to capitalize more fully on the capabilities of existing satellite systems. We recommend that the work be done in cooperation with WMO, Unesco, FAO, and the World Bank.

(h) A call to WMO and other international organizations to emphasize problems of inter-compatibility between different data sets, including both remotely sensed and collateral data types.

(i) Studies on the development of remote sensing methods for groundwater exploration, with particular reference to potable water supplies for rural communities in developing countries.

(j) Promotion of seminars and workshops on the application of remote sensing to hydrology (floods and droughts).

(k) Remote sensing studies of the ecological and dynamical changes of inland water bodies.

(m) Encouragement of definition studies in cooperation with WMO and the various national and multi-national space agencies on the needs, economic feasibility, and requirements for a hydrological satellite ("HYDROSAT") system, and hydrological sensors for deployment on existing satellite systems for the benefit of the hydrological and water resources communities.

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