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Operational applications of remote sensing in hydrology: success, prospects and problems*

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Abstract The use of remote sensing information in operational hydrology is relatively limited, but specific examples can be cited for determining precipitation, soil moisture, groundwater, snow, surface water and basin characteristics. The application of remote sensing in hydrology can be termed operational if at least one of two conditions are met: (a) the application produces an output on a regular basis, or (b) the remote sensing data are used regularly on a continuing basis as part of a procedure to solve a problem or make decisions. When surveying the various operational applications, simple approaches and simple remote sensing data sets are the most successful. In the data-sparse developing countries, many operational remote sensing approaches exist (out of necessity) that may not be needed in developed countries because of existing data networks. To increase the use of remote sensing in operational hydrology in developed countries, pilot projects need to be increased and information services must be improved. Increased utilization of GIS to combine remote sensing with other information will promote new products and applications. End user training must be improved by focusing on satellite data processing and manipulation. In developing countries the same improvements are needed plus some more basic ones. There is a need for international monetary assistance to establish long-term remote sensing data, improved database systems and image processing capabilities. There is also the need to set up innovative regional training centres throughout the developing world.

Applications opérationnelles de la télédétection en hydrologie: résultats, projets et problèmes

Résumé L'utilisation des informations issues de la télédétection en hydrologie opérationnelle est encore modeste, mais on peut cependant citer quelques exemples concernant les précipitations, l'humidité du sol, les eaux souterraines, la neige, les eaux superficielles et la caractérisation des bassins. Une application de la télédétection à l'hydrologie peut être qualifiée d'opérationnelle si au moins l'une des deux conditions suivantes est satisfaite: (a) l'application est réalisée en routine, (b) les données télédétectées sont utilisées continûment dans le cadre d'une procédure destinée à résoudre un problème ou à prendre une décision. Si l'on considère les différentes applications opérationnelles, on constate que les méthodes et les données les plus simples sont celles qui ont connu les plus grands succès. Dans les pays en voie de développement il y a de nombreuses applications de télédétection concernant les données qui ne sont pas nécessaires dans les pays développés en raison de l'existence dans ces pays de bons réseaux de mesure. Afin de développer l'utilisation de la télédétection dans les pays développés il est nécessaire de mettre en place davantage de projets pilotes et l'information doit être améliorée. Une utilisation accrue des systèmes d'information géographique en vue de combiner la télédétection avec d'autres sources

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d'information créera de nouveaux produits et de nouvelles applications. La formation des utilisateurs doit être améliorée et l'accent doit être porté sur la manipulation et le traitement des données satellitaires. Ces améliorations doivent aussi être apportées dans les pays en voie de développement en supplément à une formation de base. Il est nécessaire de créer un système international de financement permettant de recueillir des données télédétectées sur le long terme, d'améliorer les systèmes de bases de données et de promouvoir la formation dans le domaine du traitement des images. Il est enfin nécessaire de créer des centres régionaux de formation dans le tiers monde.

ACRONYMS AND ABBREVIATIONS

The following acronyms and abbreviations are not defined in the text; commonly used abbreviations are listed at the beginning of this issue of *Hydrological Sciences Journal*.

AVHRR	Advanced Very High Resolution Radiometer
B4	Bristol/Barrett, Beaumont, Bellerby
EOSAT	Earth Observation Satellite Company
ERS-1	First European Remote Sensing Satellite
ERTS	Earth Resources Technology Satellite
FRONTIERS	Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite Data
GOES	Geostationary Operational Environmental Satellite
IRS	Indian Remote Sensing Mission
MSS	Multispectral Scanner Subsystem
NESDIS	NOAA Environmental Satellite Data and Information Service
NEXRAD	Next Generation Radar
NOAA	National Oceanic and Atmospheric Administration
PERMIT	Polar-Orbiting Effective Rainfall Monitoring Interactive Technique
RAINSAT	Quasi-operational real-time (nowcasting) rainfall estimating scheme in Canada
SAR	Synthetic Aperture Radar
SPOT	Systèmes Probatoire d'Observation de la Terre
SSARR	Streamflow Synthesis And Reservoir Regulation
TM	Thematic Mapper
TOGA COARE	Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment
TOVS	TIROS-N Operational Vertical Sounder
WEFAX	Russian Meteorological Radar and Satellite Images (low resolution geostationary data)

INTRODUCTION

The science and practice of hydrology includes monitoring, assessing and forecasting the quantity and quality of water. Both historical and real-time hydrological data are collected, stored and analysed. The resulting information is provided to decision makers to effectively manage water resources for irrigation, supply, power and recreation purposes and to mitigate floods, droughts, pollution incidents and similar water-related hazards. An important prerequisite for performing these functions is the availability of accurate and reliable data. The International Conference on Hydrology (UNESCO/WMO/ICSU, 1993) recognized that a universal difficulty encountered in the science and practice of hydrology was associated with acquiring the required data.

Up until about 25 years ago, hydrologists relied mostly on conventional data network systems. However, because conventional networks are characterized by insufficient spatial and temporal coverage of the Earth's surface, remote sensing has increasingly been used to supplement existing conventional data networks.

The most important areas of application in hydrology and water quantity management include the following: (a) precipitation, (b) soil moisture, (c) groundwater, (d) evapotranspiration, (e) snow and ice, (f) surface water, and (g) basin characteristics. Although existing techniques for remote sensing applications in these areas are still mostly research oriented, there is an ever increasing number of operational applications located in different countries around the world.

The application of remote sensing techniques in hydrology is growing important mainly because of several unique aspects of remote sensing. First, remote sensing techniques have the capability to measure spatial information as opposed to point data. Second, remote sensing techniques can assess the state of the Earth's surface over large areas. Finally, remote sensing techniques, especially those which utilize satellite sensors, can be utilized to assemble long-term data sets (Engman & Gurney, 1991). Furthermore, although the expense associated with remotely sensed data may seem to be high at first glance, upon close inspection, the cost is very low when compared to acquiring the same spatial information using conventional means (Rango, 1994a).

According to Rango (1994a,b), the application of remote sensing in hydrology may be termed "operational" if: (a) the application produces an output on a regular basis, or (b) the remote sensing approach is used regularly and on a continuing basis as part of a procedure to solve a problem. Alternatively, according to Blyth (1993), for an application to be classified as operational, it is not essential that the technique has already been demonstrated operationally, but simply that current sensors and knowledge are adequate to make incorporation into an operational system feasible to a level where an improvement of that system can be expected. As such, there are numerous examples of operational applications of remote sensing in hydrology. The more narrow definition of operational by Rango (1994a) is used in this paper for the purposes of highlighting those applications that have progressed the most. It is also worth clarifying that this definition is different from the use of operational remote sensing data (e.g. from operational meteorological satellites) in hydrological research applications.

Blyth (1993) additionally points out that remote sensing will yield the most benefit when used at the earliest opportunity in any hydrological study requiring the selection of instrument sites. For instance, an optimum strategy for siting hydrological instruments may be developed only after a careful consideration of the basin characteristics. For example, Higuchi & Iozawa (1971) and Dozier (1989) illustrated that an optimum design of snow sampling regimes is possible when remote sensing is used to monitor snow accumulation and melt patterns. Remote sensing of other variables such as glacier areas and land cover is quite useful for locating instrument sites in mountainous regions because of the normally restricted access to these regions. In this way, remote sensing can also indirectly be useful in operational hydrological applications.

OPERATIONAL REMOTE SENSING APPROACHES TO HYDROLOGICAL MEASUREMENTS

Different remote sensing methods may be applied to measure different components of the hydrological cycle. In general, a combination of useful remote sensing techniques is found for each application. Some of the applications termed operational by the Rango (1994a,b) definition are identified for each of the major application areas.

Precipitation

Precipitation is one of the most important processes in the hydrological cycle. Precipitation data are important inputs to many environmental monitoring systems. The spatial and temporal variability of rainfall is necessary for the management of water resources such as rivers and reservoirs, irrigation and weather forecasting. Conventional raingauges provide direct measurement, yet only point rates and depths of rainfall are possible.

Most of the operational satellite applications for precipitation utilize visible or infrared imagery and include the following: The NESDIS Interactive Flash Flood Analyser technique (D'Souza *et al.*, 1990) provides indications of heavy rainfalls and has been used in the USA for nearly a decade for flash flood warnings. The FAO method (Barrett & Harrison, 1986) provides rainfall maps which are used operationally in the assessment of locust hazard in northwest Africa. The "B4" method (Barrett, 1993) uses real-time rainfall data from satellites to set rain/no-rain boundaries and rain rates over West Africa. The "B4" is also used to provide rainfall input for the Nile Forecasting System (Van Blargan, 1993). Two real-time (so called "nowcasting") rainfall estimation schemes (D'Souza *et al.*, 1990; WMO, 1992a) which use real-time satellite data include the large-scale RAINSAT in Canada, and the FRONTIERS systems in the United Kingdom (these have been used quasi-operationally). The Finnish Meteorological Institute is applying a Swedish algorithm (WMO, 1992a) to obtain precipitation estimates, and the PERMIT technique (D'Souza *et al.*, 1990) is used in Pakistan to obtain daily rain/no-rain boundaries.

Operational applications using passive microwave imagery include the following: NESDIS has been supplying precipitation products (including global precipitation from passive microwave imagery) to the US National Weather Service (NWS) Forecasting Offices and River Forecast Centers since 1978 (Scofield, 1991). Adler *et al.* (1991) combined infrared (IR) data with passive microwave data to produce monthly rainfall estimates over Japan. Negri *et al.* (1994) used the technique derived by Adler *et al.* (1991) to derive climatologies of convective precipitation for the TOGA COARE area. The Hungarian Meteorological Service combines IR data with passive microwave data (TOVS data) to forecast ultra-short range precipitation in the Carpathian basin (Csistar & Bonta, 1993). Other operational applications of TOVS data for rainfall monitoring exist in Russia, Japan, Finland and Italy (WMO, 1992a).

Operational ground-based radars such as NEXRAD provide real-time rainfall data for flash-flood warnings (Hogg, 1989; WMO, 1992a; Walton *et al.*, 1990). The Northwest Radar Project in the UK integrated the installed radar with operational flood forecasting and warning services (Collinge & Kirby, 1987).

Soil moisture

Remote sensing of soil moisture can be accomplished using visible, near infrared, thermal infrared, microwave and gamma radiation data (Engman & Gurney, 1991). However, the most promising techniques are based on the passive and active microwave data because of their all-weather and ground-penetrating capabilities. A main problem associated with visible, near infrared and thermal infrared techniques is cloud interference. Even though the microwave instruments show the most promise, interpretation of the data is complex because of soil texture, surface roughness, vegetation and geometry effects. As a result, it appears that operational remote sensing of soil moisture will involve more than one sensor. Furthermore, both active microwave and thermal infrared applications need much additional research before they can be used to reliably extract soil moisture information.

Jackson & Schmugge (1989) found that for large river basin and global studies, satellite passive microwave soil moisture measurements are closer to operational applications than active microwave measurements because of their relative insensitivity to surface roughness and the availability of a rather simple method to handle vegetation effects. Furthermore, if the planned Earth Observing System becomes operational at the turn of the century, more suitable spatial and temporal passive microwave satellite data should be available.

Only a few soil moisture applications have been operational. The FAO (WMO, 1993b) has coordinated the use of visible/near-infrared imagery to estimate soil moisture through precipitation indices on an operational basis. Russian scientists have used passive microwave soil moisture imagery from aircraft to develop an operational system for irrigation scheduling (Reutov & Shutko, 1986). The NWS hydrologic runoff forecasting programme (Carroll & Schaake, 1983) uses real-time aerial soil moisture values obtained from the NWS operational airborne gamma radiation snow survey programme in the upper Midwest United States (Jones & Carroll, 1983). Jackson *et al.* (1996) suggest that the optimal sensor system for future operational soil moisture sensing may include both an active and a passive instrument.

Groundwater

Remote sensing techniques used to map areas of groundwater include aerial and satellite imagery in the visible, infrared and microwave regions of the electromagnetic spectrum. In particular, satellite imagery enables viewing very large areas and achieves a perspective not possible from ground surveys or even low-level aerial photography. Although remote sensing is only one element of any hydrogeological study, it is a very cost-effective approach in prospecting and in preliminary surveys. Due to the intervening unsaturated zone of soil, most remote sensing data cannot be used directly, but require substantial interpretation. As a result, inference of the location of aquifers is made from surface features. Important surface features include topography, morphology and vegetation. According to Engman & Gurney (1991), groundwater information can be inferred from landforms, drainage patterns, vegetation characteristics, land use patterns, linear and curvilinear features and image tones and textures. Structural features such as faults, fracture traces and other linear features, and particularly intersections of lineaments, can indicate the possible concentration of groundwater.

Several operational applications for groundwater have been reported. Zevenbergen & Rango (1992) combined Landsat TM imagery with conventional maps for groundwater development in the Nile Valley and Delta as input to a groundwater master plan for Egypt.

El-Baz (1993) used Landsat TM imagery to discover potential aquifers in the Arabian Desert at a junction of two known ancient Wadis. Sabins (1983) used radar imagery for groundwater exploration in Indonesia. Dutartre *et al.* (1993) used radar imagery and SPOT imagery for hydrogeological prospecting over the Kuturn area northwest of El Fasher, Sudan. Many villages in India suffer from a severe shortage of drinking water. In attempts to solve this problem, India has doubled its success rate of obtaining drinking water from new wells through the use of satellite mapping of IRS data (Corbley, 1994). In addition, India creates 1:50 000 hydrogeomorphic maps with IRS data (Corbley, 1994).

Evapotranspiration

Relative to the water balance (both local and regional), evapotranspiration (ET) is a significant and often the dominant water flux at the Earth's land surface (Engman & Gurney, 1991), especially in arid and semiarid regions. ET is sensitive to the following causative factors: (a) solar radiation, (b) air temperature, (c) wind velocity, (d) vapour pressure gradients, (e) soil moisture, (f) soil temperature, and (g) surface characteristics (Kuittinen, 1992). McCuen (1989) stated that based on a number of studies, the first four of these factors are believed to be the most important. Estimates of the ET component are required for various purposes, including irrigation scheduling, reservoir loss estimates, water and energy balance calculations, runoff predictions, inputs to soil erosion models, and meteorological and climatological studies (Engman & Gurney, 1991; Bailey, 1990).

In order to remotely estimate ET, remote sensing techniques are used to measure several important variables that comprise or affect the ET. The incoming solar radiation can be estimated from satellite observations of cloud cover primarily from geosynchronous orbits using visible, near infrared and thermal infrared parts of the electromagnetic spectrum (Pinker *et al.*, 1995; Brakke & Kanemasu, 1981; Tarpley, 1979; Gautier *et al.*, 1980). The surface albedo may be estimated for clear-sky conditions from measurements covering the entire visible and near infrared waveband, whereas measurements at narrow spectral bands can be used to determine vegetation cover (Jackson, 1985; Brest & Goward, 1987). The soil moisture may be estimated using the measurement of microwave properties of the soil (microwave emission and reflection or backscatter from soil). However, there are uncertainties in such soil moisture estimates due to factors such as surface roughness and vegetation cover (Engman & Gurney, 1991). The surface temperature may be estimated from Landsat MSS or NOAA-AVHRR measurements at thermal infrared wavelengths of the emitted radiant flux (Engman & Gurney, 1991). The surface temperature can be input to models that calculate the ET over a region. Kustas & Norman (1996) indicate that Seguin *et al.* (1991) have operationally calculated ET using one-time-of-day temperature measurements over a region. Upon review, this application is promising but so far not a true operational application.

Snow

Snow is the occurrence of precipitation in the solid form. The water stored in snow is held in cold storage on a basin for an extended period of time before it enters into the runoff process. During this varying time period, the snow in storage can be augmented by additional snow accumulation, redistributed by wind, changed in its internal structure, and affected by meteorological factors (Rango, 1993). The snowpack is removed from the basin by ablation processes usually lasting several months depending on the amount of snow and location. The snowmelt process takes place at various rates depending on the aspect, slope, elevation, vegetation cover and atmospheric conditions (Rango, 1993).

Predicting snowmelt runoff is required for various purposes including water supply, flood control, hydropower generation and water allocation for irrigation (Rango, 1994a). The hydrologist generally wants to know how much water is stored in a basin in the form of snow (Engman & Gurney, 1991). Remote sensing of snow can be accomplished using gamma rays, visible and near infrared, thermal infrared and microwaves (Rango, 1993).

There are numerous operational applications for snow cover, snow water equivalent assessments and seasonal snowmelt runoff forecasts. The NWS Office of Hydrology in Minneapolis uses NOAA-AVHRR and GOES imagery to provide periodic snow cover extent maps on about 4000 basins in North America (Carroll, 1995). Kumar *et al.* (1991) used satellite snow cover data as input to the snowmelt runoff model for use in operational forecasts of daily snowmelt runoff in the Beas and Parbati rivers in India. Harrison & Lucas (1989) used NOAA imagery of the UK to produce daily and weekly snow area maps. Andersen (1991) reports on using NOAA-AVHRR snow maps for planning of hydropower generation in Norway. The NWS has an operational airborne gamma-ray spectrometry programme to obtain snow water equivalent values for the upper Midwest USA and Canada (Carroll,1995). Furthermore, Norway, Finland and Russia also use airborne gamma-ray spectrometers to measure snow water equivalent (Rango, 1994a). Goodison & Walker (1993) use passive microwave imagery to operationally produce snow water equivalent maps of the Canadian prairies.

Satellite snow cover data are being used regularly in the SSARR model in the Pacific northwestern USA (Engman & Gurney, 1991). The NWS updates the snow accumulation and ablation model component of their hydrologic simulation model using airborne and ground-based snow water equivalent data (Carroll *et al.*, 1993). India has developed computer models which use IRS satellite data to determine how much water will melt from the seasonal snow cover. This information is used to predict water use for irrigation and power generation (Corbley, 1994).

Surface water

Surface water which may occur in the form of lakes, ponds, reservoirs, rivers, streams and areas temporarily covered by water is a major hydrological basin storage component. The India Department of Agriculture uses IRS, Landsat and SPOT data to monitor the impact drought is having on crops, soils and surface water resources and issues weekly drought reports to local governments. The objective is to detect the problems in advance and take steps to minimize resource losses (Corbley, 1994). McKim *et al.* (1972) operationally used ERTS-1 (Landsat) imagery to map surface waters in the national programme for the inspection of USA dams. The US National Oceanic and Atmospheric Administration (NOAA, 1994) used passive microwave data from the Defense Meteorological Satellite Program series satellite to monitor flooding from the Great Flood of 1993 in the Midwest USA. Furthermore, EOSAT (1993) and Radarsat International Inc. (COSPAR, 1993) merged SAR data from ERS-1 with multispectral data from Landsat and SPOT, respectively, to monitor the 14 July 1993 floods in St Louis, USA.

Basin characteristics

Physical basin characteristics include basin boundary (shape), area, drainage density, length, slope (topography), land cover, soil type, vegetation canopy and channel cross-sectional properties. Basin characteristics are required for the estimation of hydrological model parameters. All hydrological models that are to be applied at the basin scale require parameters that link the hydrological processes describing the input, storage and output of water to the physical characteristics of the basin. Most of the basin characteristics are either fixed or change only seasonally. Furthermore, conventional estimates of basin characteristics have often been from inaccurate or obsolete maps. Remote sensing techniques, especially satellite-based, offer promising potentials of mapping basin characteristics on a timely and repetitive basis as needed. Data from satellites like Landsat TM and SPOT with their high spatial resolution are of particular value.

There have been several operational applications for basin characteristics. The Forest Survey of India is using IRS data to map the entire country's forest lands each year; India has experienced a severe deforestation problem in the last 20 years. Furthermore, India has input IRS data into a Geographical Information Systems (GIS) to classify its 20% wasteland into 13 categories, many of which will be targeted for reclamation. Also, India has turned to satellite imagery to plan new infrastructure such as roads to meet the demands of the growing cities (and as a way for urban planners to keep pace with rapid urban growth) (Corbley, 1994). The UK Institute of Terrestrial Ecology (ITE) produced the first computer compatible digital land cover map of Great Britain using Landsat TM data in April 1993 (Fuller, 1993). The ITE has a wide range of users of the land cover map which include organizations concerned with environmental impact assessments, pollution control and water resources management. Furthermore, the map is integrated with other data in Decision Support Systems and GIS such as the "Countryside Information System" (CIS). The administrators use the CIS for the assessment of quantitative information and thus in the decision-making process (Fuller, 1993).

Ritchie (1996) reports on additional operational methods for obtaining basin characteristics using airborne laser altimeters. The low altitude laser measurements can be used to produce topography, stream channel and gully cross sections and vegetation height, cover and distribution.

PROBLEMS IN APPLICATIONS OF REMOTE SENSING IN OPERATIONAL HYDROLOGY

Current limitations of operational utilization of remote sensing

In each of the major components of the hydrological cycle, there are examples of the operational application of remote sensing data or at least the operational potential. Because there are many notable examples, and because there is wide geographical distribution of operational applications, it is apparent that technical problems are not holding back additional operational remote sensing applications. Most of the problems limiting the operational application of remote sensing in hydrology are either financial or organizational in nature as opposed to technical. Financial problems result in limitations of funds necessary to: (a) further develop the technology of remote sensing for hydrologic applications, (b) acquire, process, distribute and utilize remote sensing data, and (c) train and maintain personnel. Organizational problems result in: (a) a gap between the scientist (collecting the data) and the decision-maker (using the data), (b) a lack of an interdisciplinary approach, (c) a lack of interagency collaboration, and (d) barriers between national government agencies and international organizations (UNESCO/WMO/ICSU, 1993). In general, there is a problem of lack of awareness of remote sensing among managers and decision makers. According to Vaughan (1994), even in Western Europe, people in high posts often do not appreciate the usefulness of maps and spatial data. According to Konecny & Vetrella (1994), the problems stem from the fact that government and users have an organizational structure that does not take into account the capabilities of remote sensing. For a long time, the thrust in remote sensing has come from the providers of data rather than the users. Although this situation is slowly changing, it is still dependent on the support of government.

Cudlip (1994) points out that although the number of people being trained in remote sensing is about right, the field of training does not always match the current shortages. There is a definite shortage of trained technicians for routine data processing tasks. In particular, the staffing of satellite receiving stations is proving difficult. Although several stations have been built in developing countries, they are not being used due to the lack of suitably trained personnel. Thus, a special remote sensing training effort is necessary in developing countries (Demerliac, 1994).

Status in developed countries

Most developed countries have the necessary resources and capabilities to collect, store, analyse, distribute and operationally apply remotely sensed data for hydrological purposes. These countries have available to them the latest in remote sensing technology, data transmission systems, computer hardware and software and a highly developed set of procedures for data collection and quality assurance (UNESCO/WMO/ICSU, 1993). However, there are still some personnel problems that hinder the operational utilization of remote sensing in hydrology. In general, there is a resistance to change from traditional ways of doing business combined with an unwillingness to confront new technologies. These problems can be found in developing countries as well, but there even more serious problems prevent the operational applications.

Status in developing countries

Many developing countries do not have the financial resources or the organizational capabilities to benefit from the available remote sensing technology. There is a competition for scarce financial resources in some countries which are struggling to provide the basic amenities of life to their people (UNESCO/WMO/ICSU, 1993). According to UNESCO/WMO/ICSU (1993), many developing countries do not have access to new remote sensing technologies because of their high initial cost, lack of high level skills (needed to process and apply them) and lack of personnel training capabilities. According to the World Meteorological Organization (WMO, 1993a), the reason is the lack of efficient and reliable information systems such as global telecommunications and the related use of electronic mail, electronic bulletin boards and computer-to-computer file transfers. Other problems which contribute to the inability to benefit from the available remote sensing technology include language difficulties, insufficient dissemination of UNESCO and WMO publications to end users (UNESCO/WMO/ICSU, 1993) and organizational problems. An example of the last problem is the fact that operational hydrology is carried out in several agencies with little or no coordination between agencies. Additionally, there is a reluctance to share data even between closely-related agencies.

In the past, remote sensing has been presented too much as a tool in itself without enough operational application examples being stressed. The decision makers are also often not aware of the economic usefulness of remote sensing and they need to be targeted in training programmes just as much as technicians. It may be necessary to design two-tiered training programmes where both scientist-technicians and managers are trained in remote sensing. Such training would be separate except for introductory and summary sessions when the technical and management sides are both present.

Geographical or climatological regions where remote sensing data is most applicable

Because most techniques attempt to measure surface features, remote sensing works best in areas with little to obscure the surface (Rango, 1994b). Remote sensing tends to work best in arid and semiarid regions because vegetation cover is sparse and does not seriously obscure the soil surface. Furthermore, in the area of snow hydrology, snow mapping applications also tend to work best where there is little vegetation to obscure the snowpack (Rango, 1994b).

Data acquisition and distribution capabilities of countries

According to the World Meteorological Organization (WMO, 1992b), there are approximately 700 established satellite receivers operated by WMO Members throughout the world. The large number of receivers is a result of the widely varying geographical location of the countries and their meteorological regimes. Furthermore, another factor contributing to this large number of receivers is the rapid technological advances in satellites and in the equipment available for receiving, processing and presenting satellite data.

A survey conducted in 1990 by the World Meteorological Organization (WMO, 1992b) through National Meteorological Services revealed information concerning the status of satellite receiving equipment within WMO Regions. There are six Regional Associations (RA) and they are as follows: RA I: Africa; RA II: Asia; RA III: South America; RA IV: North and Central America; RA V: South-West Pacific; and RA VI: Europe. Four categories of satellite receiving equipment were surveyed: low resolution polar-orbit data (APT); high resolution polar-orbit data (HRPT); low resolution geostationary data (WEFAX); and high resolution geostationary data (HR). The goal for the WMO Regions is that each WMO Member

Table 1 Status of satellite receiving equipment within WMO regions (WMO, 1992b).

	WMO regional associations*					
	I	II	III	IV	V	VI
Total number of members	55	30	13	25	16	37
% members equipped with APT receivers	80	80	85	76	38	57
% members equipped with HRPT receivers	46	13	27	15	20	31
% members equipped with WEFAX receivers	46	25	12	25	37	46
% members equipped with HR receivers	11	15	4	5	21	28

* I: Africa; II: Asia; III: South America; IV: North and Central America; V: South-West Pacific; and VI: Europe.

should be equipped with at least one polar-orbiting satellite data receiver and one geostationary satellite data receiver. However, there is a Voluntary Co-operation Programme of WMO which coordinates the needs of WMO Members from developing countries with available resources from WMO Members from developed countries. A fact highlighted in the survey is the lack of satellite ground receiving equipment registration with the national telecommunication administrations and International Telecommunication Union's International Frequency Registration Board. Registration is advised in order to protect and preserve the present allocation. Furthermore, the present allocation is limited and new technologies are constantly vying for frequency allocation. Table 1 shows the results of the WMO survey and indicates the geographical distribution of equipment (WMO, 1992b).

The availability and access of remote sensing data needed for operational hydrological applications is difficult except when these applications are conducted by large meteorological services who have mandated responsibilities in those fields (WMO, 1993a). High-rate digital acquisition stations are required for near-real time applications; otherwise, data are obtained from archives and thus only for post-analysis applications. High geometrical resolutions are required for many operational hydrological applications, and are available from operational satellites such as Landsat and SPOT. However, the technical complexity of acquisition and distribution of these images, in developed or developing countries, seriously limit the access to these data to a few selected projects. Furthermore, passive microwave radiometry, which could eventually be extremely valuable in hydrology, is not available at present with a fine enough resolution and at the appropriate wavelength (WMO, 1993a).

Cost of data

The financial aspects of remote sensing data include the direct cost of acquiring data, cost trends and policy, and thus the capabilities of countries to purchase the data. In the developed countries, funding is provided mainly by national institutions and international grants. However, there is a need for better coordination in order to make the best use of the funds available (UNESCO/WMO/ICSU, 1993). In many developing countries, there is a severe problem regarding financial constraints and it has worsened over the last 10 years (UNESCO/WMO/ICSU, 1993). Sufficient funds are not available to support either hydrological research or adequate conventional data collection let alone remote sensing activities. Thus, there is a need for support of sustained hydrological research and data collection (including remote sensing), particularly those efforts in the humid, semiarid and arid parts of the tropical world (UNESCO/WMO/ICSU, 1993). According to the Food and Agriculture Organization (FAO, 1989), the developing countries stand to benefit most from the remote sensing technology. They urgently need reliable resource inventories and maps to provide a basis for more rapid, geographically balanced and ecologically sound economic development (FAO, 1989). According to the World Meteorological Organization (WMO, 1993a), most experimenters have received data free of charge, in connection with an Announcement of Opportunity process and most of them are financially supported by their national space agencies. When this support expires, only national meteorological centres connected to the Global Telecommunication System will continue to receive data free of charge.

Computer data processing capability

Impressive developments have occurred in the field of image handling systems (WMO, 1993a). The traditional hardcopy-oriented approach has been replaced by a software approach. Hardware/software systems have been developed which allow for image enhancement, multi-channel image handling, multi-temporal image sequencing and merging of images overlaid with other information (radar images, bulletins, maps, etc.) (WMO,1993a). Geographical Information Systems (GIS) are used to supply all necessary background information, including data from Digital Elevation Models (DEM). Furthermore, modern technology provides reasonably inexpensive workstations able to support these applications. The WMO and national and international aid-to-development programmes are active in supporting developing countries for the acquisition and maintenance of processing facilities. For example, the National Resources Institute in the UK provides a comprehensive service for the interpretation and analysis of remotely sensed imagery, from both satellite and airborne platforms. The latest technology, including workstation and PC-based image processors, is used in conjunction with GIS software to address a variety of environmental issues.

Manpower and training capability

UNESCO/WMO/ICSU (1993) has identified a number of problems affecting the manpower and training capabilities of various countries. They are (a) inadequate number and quality of qualified hydrologists and technicians, (b) the "brain drain" affecting trained staff is too high, (c) there is an imbalance between technology and skills of the users, and (d) UNESCO, WMO and other relevant publications do not reach a sufficient number of end users. However, UNESCO/WMO/ICSU (1993) point out that the developed world has tried to make adjustments in the educational system to adapt to the rapid and unpredictable changes taking place; this is reflected in the increasing variety and contents of training courses and improved training methods. Where staff and teaching facilities are still inadequate, poor results are attained from education and training courses. Furthermore, there is a need for an educational network which would put basic material and data products at the disposal of educational entities (Fea, 1994). However, the training opportunities and documents resulting from UNESCO (IHP) and WMO (OHP) programmes have greatly contributed to the countries' manpower and training capabilities. The requirements and standards for remote sensing education and training vary, qualifications are not universally recognized and few training programmes exist (Vaughan, 1994). However, the European Association of Remote Sensing Laboratories, which has been involved in education and training programmes for many years, has so far taken the main initiatives in Europe by identifying gaps in the existing programmes, analysing needs and developing training materials (Konecny & Vertrella, 1994). Cudlip (1994) recognized that training courses tend to concentrate too heavily on technology and image processing. The aim should be to raise the general level of awareness of remote sensing technology across the disciplines and to provided specialist training for scientists and engineers (Mather, 1994).

A STRATEGY FOR ACCEPTANCE OF REMOTE SENSING IN OPERATIONAL HYDROLOGY

In order to bridge the gap between scientists and decision-makers, an important strategy is to integrate the remote sensing information through a national archive to support the decision-making process and to facilitate the education of decision-makers (UNESCO/WMO/ICSU, 1993). Another important strategy is to provide effective mechanisms for coordination among decision-making agencies. A way to encourage coordination is to establish joint programmes among the agencies for publications, meetings and training (UNESCO/WMO/ICSU,1993). Furthermore, an awareness of the needs for interdisciplinary collaboration in hydrology and water resources is required so as to avoid overlaps and duplication of activities between agencies and disciplines in the same country. To accomplish this strategy requires overcoming financial constraints and modification of current organizational and institutional arrangements at both national and international levels. There is also a need to implement the World Hydrological Cycle Observing System (WHYCOS) to facilitate access to global data and support hydrological services in need (Rodda *et al.*, 1993).

In order to improve the use of satellite data, particularly in developing countries, the World Meteorological Organization (WMO, 1993a) recommends the following strategies. First, well-designed pilot projects should be promoted, involving the end user from the onset since they will have to ensure the continuation of the activity if the pilot project is successful. Second, improved information services should be developed to allow users, particularly from developing countries, to be able to survey existing information, know where it is and how to access it. Data from different sensors or from more than one satellite can be combined with a GIS to produce new products and applications. Third, education and training should reach the end users instead of stopping at an intermediate level (often due to language difficulties). Databases of training events, distribution of computerized training packages and assimilation of satellite-focused education and training within the framework of the current local education and training organization should be considered.

According to Torlegard (1994), remote sensing technology developments and education should be more demand driven in the future, but it is difficult for clients/users to formulate requirements. This is an interactive process. The information requirements of the users have to be established rather than the remote sensing requirements. Users should not have to be experts in the field of remote sensing (Cudlip, 1994). When designing training programmes, the needs of the users should be carefully considered. For instance, courses organized in institutions and universities in Europe may not correlate with the level of activity or applications in, for example, individual African countries. What may be needed instead are well targeted, well prepared, *in situ* courses. These need to be designed to suit both the equipment available and the particular problems of the users (Vaughan, 1994). At the end of training, the newly-trained user would profit from having a project at home to work on. On the other hand, sometimes it is necessary to teach training courses in developed countries. At that time, the developing nations must make sure to send the end users who need the hands-on experience and not use the training course as a reward for seniority. The attendee must truly be a user of the data. However, if a two-tiered training course approach is developed, then both the end user on the technical side and managers on the administrative side may both be appropriate participants.

Another possibility exists for upgrading remote sensing training in the area of hydrological applications. A way should be found to provide more rewards or incentives for the scientists who serve as instructors. At present, there is very little incentive for the scientist-instructor to leave research activities for up to six weeks to serve as a instructor in a training course. With a better reward system, more scientists on the cutting edge of remote sensing research would become available as instructors.

ELEMENTS OF SUCCESSFUL REMOTE SENSING IN OPERATIONAL HYDROLOGY

In order for the smooth and rapid transfer of new developments in remote sensing into operational status, strategies for anticipating future trends are essential (WMO, 1993a). The remote sensing instruments planned to be on board the new generation of operational satellites scheduled up to the early 2000s have already been decided and some are currently being tested on satellites in an experimental mode (WMO, 1993a).

The high rate of development in the communication and computing technologies continues to have significant benefits for satellite data utilization; they offer the capability to receive, process, disseminate and display increasingly large amounts of data faster and faster, while at the same time reducing costs and system size. Rapid advances are also being made in education and training systems and technologies with the experimental use of Computer-Aided Learning systems. The World Meteorological Organization (WMO, 1993a) further reports that small but quite powerful and affordable desk-top workstations are now in general use in the more advanced developing countries and are penetrating into the least developed countries.

Financial resources

In order to maintain applications of remote sensing on a long-term operational basis, it is necessary to have sufficient financial resources available. International agencies need to provide funds and leadership to assist developing nations in establishing and maintaining long-term remote sensing data capabilities (UNESCO/WMO/ICSU, 1993). However, the World Meteorological Organization (WMO, 1993a) reports that such programmes are being severely cut and launch schedules significantly deferred now in almost all satellite operating countries due to economic pressure for the resources to be directed elsewhere (for instance to social welfare programmes). A reliable source of funding or a strategy for procuring funding for operational remote sensing is a very critical need.

Regional remote sensing centres

The establishment of regional remote sensing centres is an international effort which aims to ensure that all countries have sufficient remote sensing capabilities by transferring technology and providing the appropriate technical assistance. At the same time the regional approach conserves limited resources and allows a number of countries to share the cost of technical assistance. Furthermore, the technology transfer process includes demonstration projects and establishment of international databases to support projects on regional and global scales (WMO, 1993a). According to UNESCO/WMO/ICSU (1993), capacity building programmes should be flexible in approach and give due consideration to differences between countries and their corresponding needs in time and space.

According to the World Meteorological Organization (WMO, 1993a), its Executive Council Panel of Experts on Satellites (ECSAT) studied techniques to improve the use of satellite data through more effective education and training. Central to the techniques is the concept of training of instructors at the Regional Meteorological Training Centres (RMTCs) in order to provide "on-the-spot training". ECSAT has proposed a strategy for education and training in satellite matters with the strategic goal to systematically improve the use of satellite data for meteorological and hydrological applications over the next 10 years in all member countries, with a focus on meeting the needs of developing countries. In order to achieve this goal, there are three major strategic objectives. The first strategic objective is to build on the existing infrastructure (includes functional responsibilities, organizational structure, management principles and data quality control) in a way that the initiatives are consistent with the users' capabilities to absorb and sustain them independently in their own operational environment. With regard to implementing new technology in developing countries, three main areas requiring training include: (a) the operation and maintenance of the facilities, (b) the use of the information, and (c) the infrastructure supporting the facilities. The second strategic objective is to focus on the developing countries with particular attention to systematically improving level of expertise of instructors at all RMTCs in the use of satellite data. The third strategic objective is to anticipate future trends in satellite data applications and in education and training techniques so the new developments can flow through to operational users quickly and efficiently.

In order for ECSAT to implement the above proposed strategy, they have highlighted two important points. First is the establishment of specialized satellite application training centres at six RMTCs (strategically located around the globe). And second is that each satellite operator participating in the space-based subsystem of the Global Observing System cooperate with at least one of the six specialized RMTCs with regard to satellite training programmes, facilities and expertise required. Furthermore, while the strategy aims to serve the full spectrum of needs, from the least developed to the most developed countries, it is intended to be applied in such a way that the focus is always on the needs of the developing countries (the least developed will benefit more than the others). Thus, the gap in satellite data utilization capability between the least developed and the more developed countries should become continually narrower.

Ground truth networks

In the application of remotely sensed data for hydrological problems, the advantages of both ground-based and aerial measurements are best combined. "Ground data are used to adjust or calibrate the transfer function to ensure convergence of the remotely sensed and point data" (Blyth, 1993). For instance, the UK developed procedures for the calibration of weather radar based on fitting multiquadratic surfaces to the calibration factor values, conventionally defined as the ratio of rain gauge to coincident weather radar grid-square estimates of rainfall. Using a gauge density of one gauge over 120 km^2 area, the application of simple rain gauge calibration to the radar data improves the accuracy by 12%, and the use of the more sophisticated surface fitting method increases this further to 22%, on average. GISs are essential to relate the spatial and temporal remotely sensed data to ground validation information.

Key ancillary support systems

In order for the application of remote sensing to be successful, key ancillary support systems must be available. Beyond the initial computer data processing of the digital remote sensing imagery, GISs are used to supply all other important information (spatial, temporal and statistical) and further integrate and analyse the remote sensing information (Baumgartner & Apfl, 1996). A GIS is an organized collection of computer hardware, software and geographic data designed to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced information (Johnson *et al.*, 1992). The information pertaining to various spatial or temporal features is stored typically as attributes in tabular files linked to the feature, often in special databases (Data Base Management Systems—DBMS). It is essential that efficient synergistic processing techniques be developed to cope with the large multisensor data volumes and to allow efficient GIS integration. Remote sensing technology and GISs are both tools for managing spatially distributed information in large quantities and at a variety of scales. Both increase the capabilities of human decision-makers and planners to grasp relationships at large scales and in more complex settings than has been possible before. Remote sensing data from the Landsat and SPOT programmes have been used successfully in a GIS environment for base map production, automated DEM extraction, terrain visualization and map revision.

RECOMMENDATIONS

There are several key recommendations for both developed and developing countries with the goal to increase the use of remote sensing in operational hydrology. Although most of the developed countries are not suffering from financial constraints as badly as some of the developing countries, both share some organizational problems.

Key approaches to include in developed countries

There is a need for modification of current organizational and institutional arrangements at both national and international levels. First, there is need for better coordination and removal of barriers between the national government agencies and international organizations that provide the funding for hydrological remote sensing and operational hydrology. Second, there is a need for interagency and inter-disciplinary collaboration in research on hydrology and water resources so as to avoid overlaps and duplications of activities between agencies and disciplines. Third, there is a need to bridge the gap between the scientists (including satellite systems planners collecting the data) and the decision makers (end users specifying data requirements) by integrating remote sensing information/capabilities through a national archive. Fourth, there is a need for the research hydrologist to continue development of hydrological models based on remote sensing inputs, demonstrate technical and economic benefits from using remote sensing and to improve the design of pilot projects (involving applications of remote sensing). An improvement in the design of pilot projects could be accomplished by involving the end users (decision makers) from the onset since they will have to give authoritative long-term validation of applications demonstrated theoretically and thus ensure the continuation of the activity (i.e. operational application) if the pilot project is successful. This may be accomplished through (a) improved information services in order to allow the end users to know where the information is located and how to use it; (b) utilization of GIS to combine remote sensing data with other information to produce new products and applications; and (c) education and training of the true end users through database of training events, distribution of computerized training packages and assimilation of satellite-focused education and training. Fifth, there is need to provide effective mechanisms for coordination among decision-making agencies. The second and fifth recommendations may be accomplished through joint programmes among their respective agencies for publications, meetings and training.

Key approaches to include in developing countries

In addition to the organizational and institutional modifications recommended above for the developed countries, there is also a need for continued international financial assistance and modification of national financial arrangements in developing countries. First, there is a need for international agencies to continue to provide funds and leadership to assist developing nations in establishing and maintaining long-term remote sensing data (acquisition and distribution) networks. Second, there is a need to facilitate the accessibility to new remote sensing technologies by developing efficient and reliable information systems especially for satellite related activities. Third, there is a need for national and international aid-to-development programmes to continue to actively support the acquisition and maintenance of processing facilities. Fourth, there is a need to continue effective and innovative education and training capability programmes and documents such as those resulting from UNESCO (IHP) and WMO (OHP) programmes, thus encouraging the developing nations to emphasize developing skills and professional attitudes. Fifth, there is a need to continue the establishment and development of regional remote sensing centres around the world, which is an international effort to ensure technology transfer (through demonstration projects and establishment of databases to support projects on regional and global scales), to provide the appropriate technical assistance and to train instructors at the RMTCs to provide "on-the-spot training".

CONCLUSIONS

The cases of remote sensing information being used in operational hydrology are relatively limited, but good examples have been identified for determining precipitation, soil moisture, groundwater, snow, surface water and basin characteristics.

There are several improvements that can be instituted to increase the use of remote sensing in operational hydrology both in developed and developing countries. These include increasing coordination between national government agencies and international organizations, improving interagency and interdisciplinary collaborative research, bridging the gap between scientists and decision makers and continuing work by researchers to develop hydrological models based on remote sensing inputs, demonstrate technical and economic benefits from using remote sensing and conceive better pilot projects involving applications of remote sensing.

In the developing countries, the acquisition of funding for remote sensing is equally important to technical improvements. International agencies need to continue to provide funds for long-term remote sensing data networks. Funding is also necessary to develop remote sensing data processing facilities, to promote technology transfer in the form of training and technical documents and to set up regional remote sensing centres around the world. Scientists and government agencies of the developed countries can be instrumental in transferring the remote sensing technology and in obtaining the funding necessary for the developing countries.

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