Institute of Hydrology

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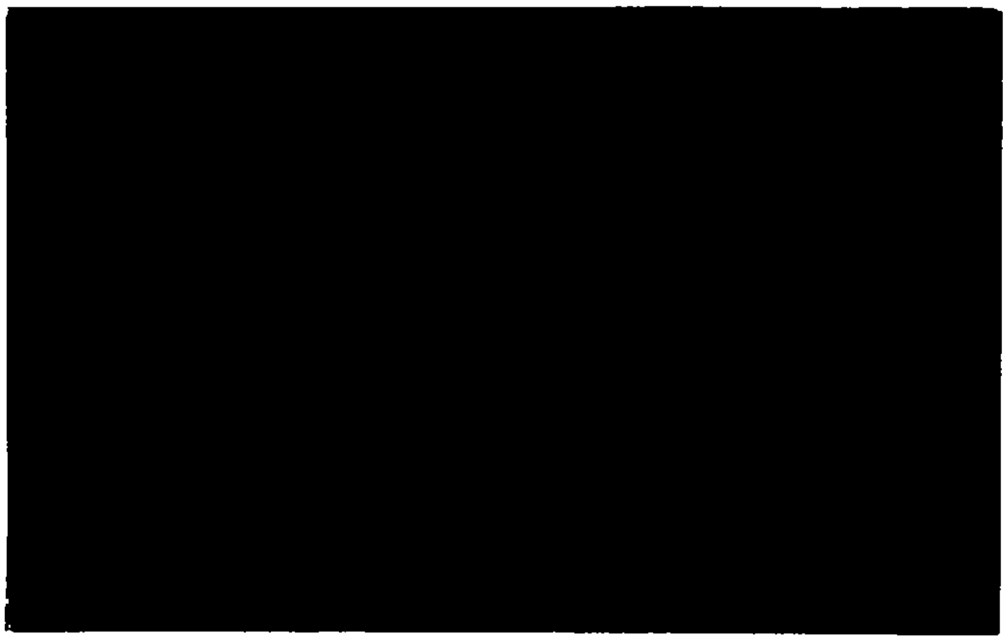

A REVIEW OF REMOTE SENSING WITHIN THE INSTITUTE OF HYDROLOGY

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Executive Summary

A review of current and possible future remote sensing needs in the Institute of Hydrology is given. The report begins by outlining past difficulties in using remote sensing for hydrological applications. This is followed by a description of current operational remote sensing systems, including instrument 'profiles' in an appendix, and a review of remote sensing applications for hydrological purposes with an extensive list of references. Finally, the results of the review of IH remote sensing needs are given, with individual needs outlined within an appendix. The report concludes with suggestions of future research and operational applications for the Remote Sensing Section.

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BACKGROUND

For some time now, the Remote Sensing Section at the Institute of Hydrology (IH) has been attempting to demonstrate to other sections within IH the value of remote sensing to hydrology. This has been done by communication between individuals, and the production and distribution of documentation outlining the expertise and facilities available within the section, and the type of work carried out. These attempts have met with a limited success.

Although much of the section's work is basic research, it is felt within the section that more applied work could be done in support of other projects within IH. To do this, it is necessary to improve the awareness of the usefulness of Remote Sensing in Hydrology within IH. One way of achieving this is to prepare a review of remote sensing activities within IH. This would be done in consultation with other IH sections in an attempt to:-

(i) Show how remote sensing can contribute to the particular section's work.

(ii) Identify areas of IH where remote sensing already successfully contributes.

(iii) Advise on the use of the final remote sensing product.

(iv) Identify areas of IH where remote sensing can contribute but does not at the moment do so.

(v) Advise on integrating remotely sensed data with other spatial data sets within IH.

This report outlines the finding of this review. It begins by outlining some of the problems of applying remote sensing to hydrological problems. This is followed by details of current satellite and aircraft remote sensing systems, a summary of what remote sensing can achieve, and a description of the facilities within IH for remote sensing. Finally past, present, and possible future use of remote sensing within IH, following discussion with other sections, is described.

INTRODUCTION

Remotely-sensed images have been used for many years to help solve a number of scientific and environmental problems, though their use by the hydrologic community has been much less than, for example, the meteorological and oceanographic community. There are a number of reasons for this:-

(i) Earlier satellite sensors were not designed specifically for hydrological applications. As a result, the temporal, spatial and/or spectral resolution that could be achieved were not suitable. However, the use of high spatial resolution sensors covering a range of frequencies on board such satellites as Landsat, SPOT, and ERS-1, and on airborne platforms have partly overcome these problems.

(ii) The cost of acquiring and analysing remotely sensed images is often prohibitive, particularly when this information can be obtained more quickly and cheaply by digitising existing maps. However, such maps can only give a limited amount of information, and are often out of date. Current information on a number of hydrologically relevant parameters e.g. detailed land use, soil moisture and temperature, can only be obtained by analysing remotely sensed images. The use of remote sensing becomes increasingly attractive when maps are unavailable and as the area of interest becomes larger.

(iii) Cloud cover is a problem when information is required on the temporal variations of hydrological parameters. The use of microwave sensors, such as on board ERS-1, will go a long way towards alleviating this problem.

(iv) Remotely sensed images do not generally directly measure the required hydrological parameters, and it is often necessary to conduct ground surveys, ideally at the same time as image acquisition, to provide calibration or 'ground truth' data.

Because of these various problems, there has been some degree of uncertainty or mistrust regarding exactly what remote sensing can offer the hydrological community. For example, when a land cover classification is done, it is often used for illustrative purposes only, and no use is made of the raster file that creates the hard copy output. This can, in part, be attributed to problems of integrating classifications based on remotely sensed imagery with other conventional spatial data sets and point values. Improved communication links between computer processors and the increasing use of Geographic Information Systems will, hopefully, overcome this.

In spite of these problems, data obtained from analysing remotely sensed imagery are increasingly being recognised as being useful to help solve hydrological problems. A number of recent reviews have been published of the potential role of remote sensing in hydrology (see, for example, Kuittinen, 1992; Engman and Gurney, 1991; Schultz and Barrett, 1989; Herschy *et al.*, 1988).

The calibrated remotely sensed data can be used singly or combined with other data sets. They can be used directly as hydrological parameters or to extrapolate results from small plot experiments to the area of interest. In this latter respect, IH is ideally suited, having many years experience of studying various small scale processes and, more recently, of manipulating spatial data sets, including those obtained from remotely sensed images.

CURRENT (OPERATIONAL) SENSOR/PLATFORM SYSTEMS

Remote Sensing involves the collection and interpretation of emitted and reflected radiation from a body; this radiation may cover different parts of the electromagnetic spectrum. Also, this information is collected without physical contact with the body.

The first characteristic of remote sensing suggests that a number of sensors covering different parts of the electromagnetic spectrum, may be employed, and that the radiation measured by these sensors may be emitted from the body of interest, as for gamma rays, or reflected from a natural e.g. the sun, or unnatural source, as is the case of radar systems. The second characteristic suggests that a number of sensor platforms may be employed, depending on the spatial and/or temporal resolution required for the particular application.

This chapter briefly outlines what sensor/platform combinations suitable for hydrological applications are currently operational, whilst the following chapter describes what hydrological applications are possible. In both bases, a more detailed review is given in a recent report to the National Rivers Authority (Briggs *et al*, 1991) and in other various publications (e.g. Curran, 1985; Drury, 1987; Blyth, 1981).

(i) Sensors

There are six commonly-used types of sensors. These provide or measure:-

Aerial photographs
Multispectral images
Thermal radiation
Microwave radiation
Gamma radiation
Laser images

These measure radiation in specific parts of the electromagnetic spectrum as indicated in Figure 1. Of these, the first four are used routinely at IH.

Aerial photographs
Aerial photography has been used for a long time in environmental management. Initially, these concentrated on the visible portion of the electromagnetic spectrum, but advances in photography and films allow near-infrared and thermal images to become available. A significant proportion of IH's remote sensing capability revolves around aerial photography.

Multispectral scanners
These measure spectral reflectances in a number of narrow wavebands. They generally provide the information in digital form, facilitating the use of rapid and sophisticated data analysis and classification techniques. A list of multispectral images used on a routine basis at IH is given in Appendix 1. These provide the largest proportion of IH's current remote sensing capability.

Thermal sensors
These measure emitted and reflected thermal energy from the earth's surface, and are mainly used to measure variations in temperature. This, in turn, can be used to infer variations in evapotranspiration, or the detection of groundwater seepage zones.

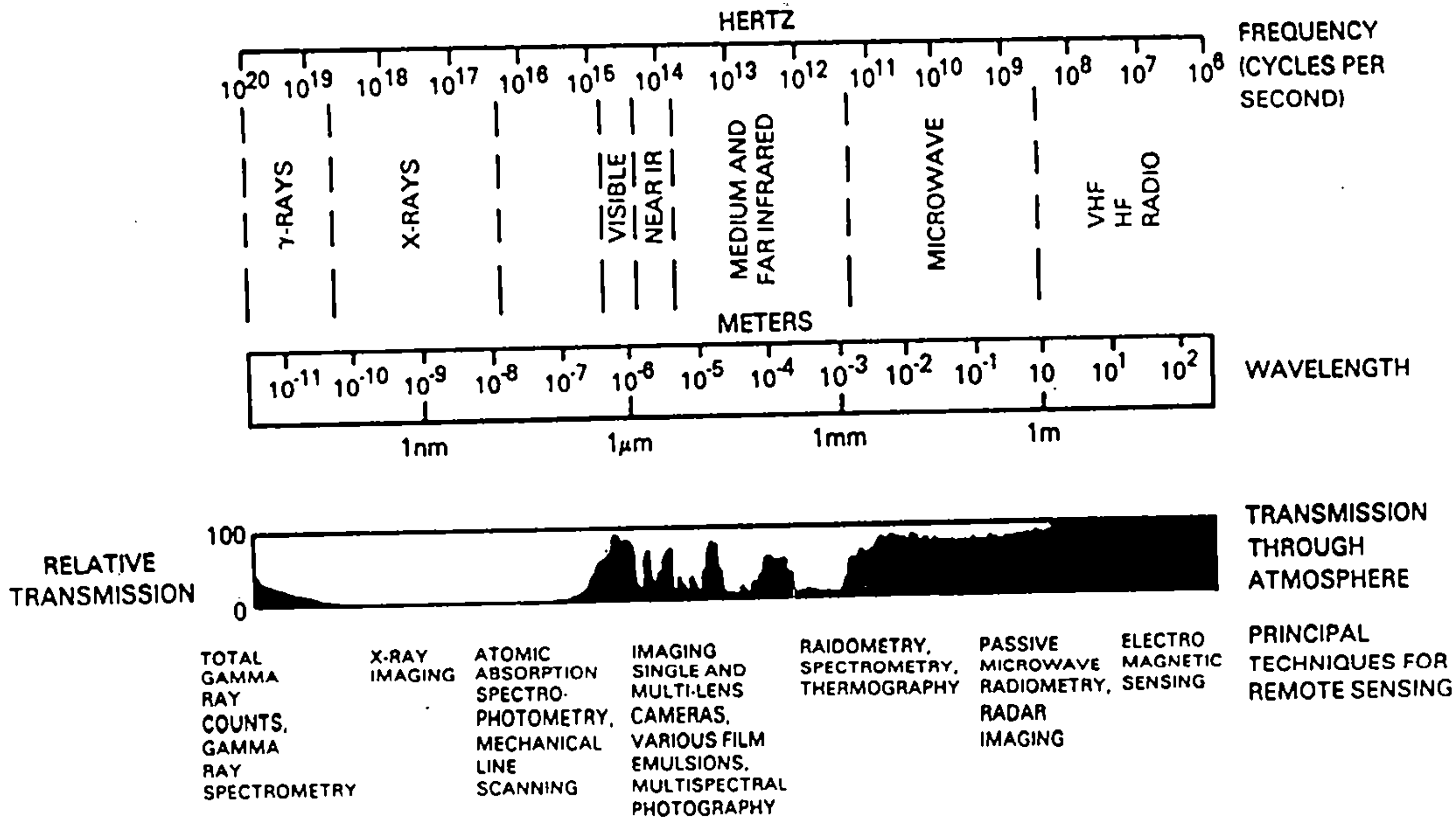

Fig. 1 The Electromagnetic Spectrum and Principal Techniques for Remote Sensing

Microwave sensors

These measure the dielectric properties of the Earth's surface which is strongly dependent on the moisture content. Analysis of microwave images can provide information on the areal extent of standing water, various properties of snow, and on the distribution of near-surface soil moisture. One important aspect of microwaves is that they can penetrate cloud cover, unlike visible and infrared radiation. Microwave systems may be passive, relying on reflected energy, or active, combining a source of energy and a sensor.

Gamma radiation

Gamma radiation originating from naturally-occurring radioisotopes in the soil are attenuated by soil water or snow lying on the earth's surface. Analysis of multi-temporal images will thus give information about changes in soil moisture distribution and snow extent. The technique is expensive as it can only be used by low flying aircraft, and needs careful calibration. It is not currently used at IH.

Lasers

These are used on aircraft systems, and involve measuring the reflected energy from a narrow beam of coherent visible or near infrared light using a photomultiplier tube. Although such systems have a number of hydrological applications, they are expensive to operate, and have not been used at IH.

Table 1 shows what hydrologically-relevant variables may be measured using the various sensor systems. The information given in this Table is only intended to give a general impression; possibilities may vary according to individual applications.

(ii) Platforms

The various types of sensors may be mounted on a variety of platforms ranging from ground-based systems on stationary tripods or mobile vehicles, through aircraft to satellites. Ground based systems are often used in sensor development prior to deployment in aircraft or satellites. The latter are operational and record images of a particular location at fixed time intervals. Aircraft surveys are carried out as and when required.

The type of sensor platform that is appropriate to a particular application depends on the spatial resolution required, the size of the area of interest, the frequency of image acquisition, and cost. For studying very small areas e.g. lysimeter-sized plots, it may be appropriate to use a ground-based system, to record continuous images of one area using a tripod system, or to sample several small areas using a mobile system. For small catchment areas, up to about 10 sq km, particularly if it is of a heterogeneous nature, an airborne system would be most appropriate. This is also the case when studying small areas e.g. the riparian vegetation within a catchment area. Using an airborne system, a ground resolution of down to about 2 m may be achieved. When studying large areas, satellite imagery is the most appropriate. Even here, a wide choice of spatial and temporal resolution is available, ranging from the SPOT satellite with a spatial resolution of 20 m and a repeat cycle of 26 days to the Meteosat satellite with a ground resolution of 2.5 km and 5 km, respectively for the visible and infrared bands, and a repeat cycle of 30 mins. Inevitably, the choice of satellite imagery to be used is a compromise with the temporal resolution being reduced as the spatial resolution increases. Figure 2 shows the spatial and temporal resolutions of commonly-used satellite sensors.

The cost of purchasing remotely sensed imagery varies enormously. At IH, the hardware and software required to receive and process Meteosat images has been purchased, so images for this satellite are received in real time free of charge. This is almost true of AVHRR images

Table 1 *The remote sensing of hydrologically-relevant variables*

	Aerial photographs	Multispectral scanners	Thermal sensors	Microwave sensors	Gamma radiation	Lasers
Rainfall		✓		✓*		
Snow						
(i) Extent	✓	✓		✓	✓*	
(ii) Properties				✓*	✓*	
Soil moisture		✓	✓	✓	✓*	
Surface temperatures			✓			
Land cover	✓	✓		✓		
Vegetation indices	✓	✓				
Topography						✓*
Surface water	✓	✓		✓		
Water quality						✓*

*Not possible at IH at present

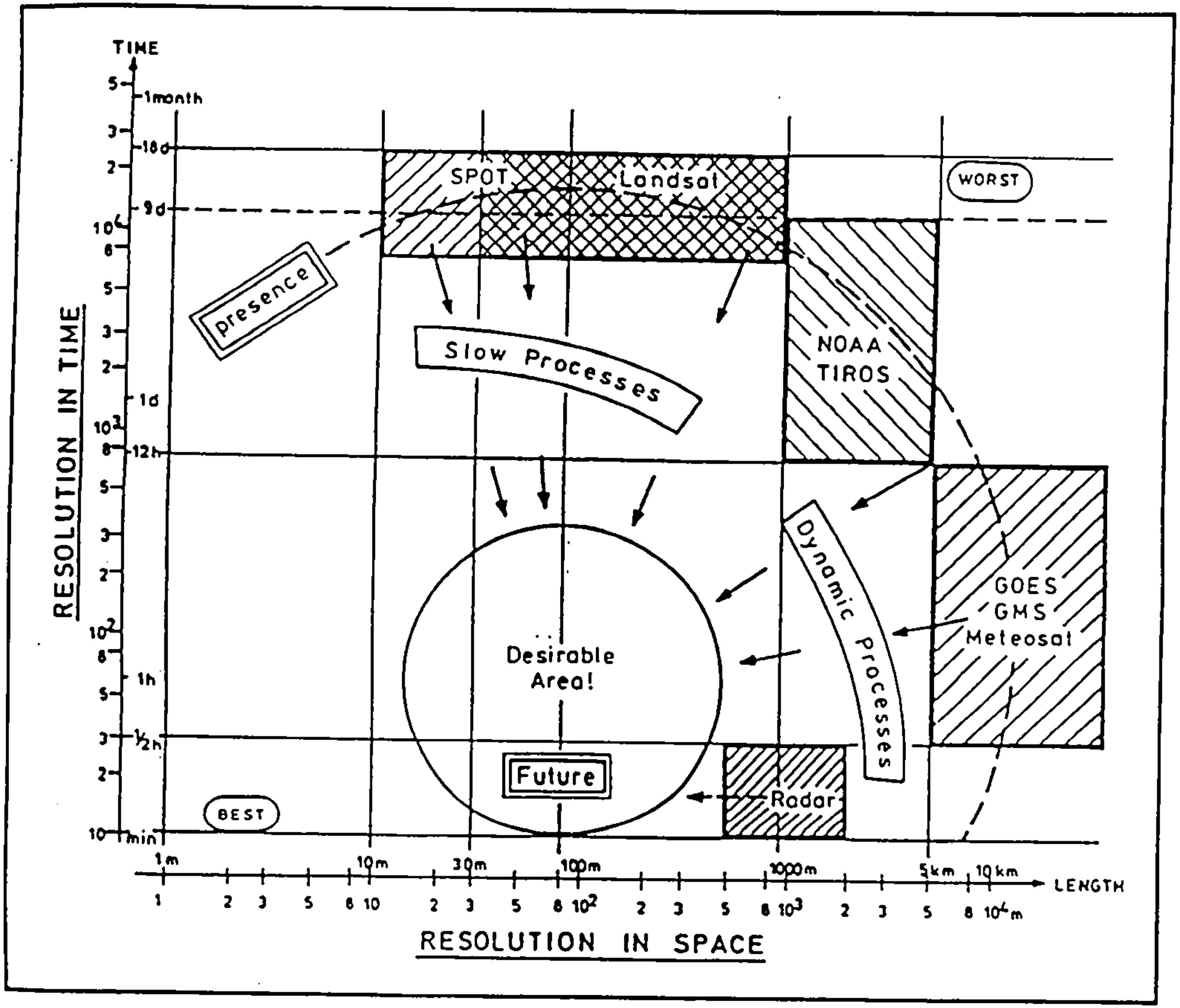

Fig. 2 Resolution in time and space of existing remote sensing systems and expected future trends

of Western Europe from the NOAA satellite. These are recorded by a receiver in the Department of Electrical Engineering and Electronics, University of Dundee who, being a NERC satellite station, make these images available in near real time to other NERC establishments at a token price to be determined. On the other hand, at the time of writing, a recent full scene Landsat image, covering an area of 185 km by 185 km in seven bands, will cost about £2,900. Less recent images, approximately four years old, are put into a 'cheap' archive, from which they may be purchased as cheaply as £500, provided they are used for research purposes only. Of particular good value if multi-temporal scenes of an area are required to study, for example, land use change, are the Landsat MSS (80 m ground resolution) images; these may be purchased for 500 US$ each.

REMOTE SENSING APPLICATIONS RELEVANT TO HYDROLOGY

This chapter concentrates on the techniques available for determining hydrologically relevant variables from remotely sensed images. The descriptions are summaries of those given in a recent report to the National Rivers Authority (Briggs *et al.*, 1991). The techniques are restricted to those that can be done routinely at IH, in some cases following some development time.

(i) Rainfall

Much work has been and continues to be done on estimating the areal distribution of rainfall using remotely sensed images. This includes the use of ground-based radar, though this is beyond the scope of this particular report. Detailed descriptions of the use of ground-based radar for rainfall estimation are given in a series of papers in a British Hydrological Society publication (BHS, 1989).

Satellite-based techniques for estimating precipitation rates rely on images in the visible/infrared and the microwave regions of the electromagnetic spectrum. In particular, visible and infrared images have been used for a number of years to such an extent that geostationary satellites such as METEOSAT and GOES are being used operationally for weather forecasting.

Techniques to estimate rainfall rates from visible/infrared imagery can broadly be divided into two types depending on the particular application. The two techniques are:-

(i) Cloud characteristics techniques
(ii) Life history methods

though as development has progressed, the differences between the techniques has become less distinct.

The estimation of rainfall by the identification of cloud characteristics (see pages 43-64 of Barrett and Martin, 1981) was the first technique to be developed, and is based on developing regressions of rainfall totals against such remotely-sensed variables as cloud brightness, temperature of the cloud tops, and stage of development of clouds (O'Sullivan *et al.*, 1990). Initially, the techniques utilized either the visible or infrared regions of the electromagnetic spectrum, though many current procedures utilize both regions. The methods are the least dependent on sophisticated software and hardware systems. However, they involve some degree of subjective interpretation, and the resulting rainfall estimates are not available in real time. They are mainly used to provide long-term (> 1 day) estimates of rainfall over large areas. A detailed review is given in D'Souza (1988).

Cloud indexing methods, utilizing the visible bands, were first investigated in the late 1960s (Barrett, 1970). Basically, the area of interest is divided into a number of grid squares or cells. Remotely-sensed images are used to identify the types of clouds and percentage areas within each cell. Look-up tables gives probabilities of rainfall and intensities of rainfall for each cloud type. Rainfall for a given period over a grid square is given by the sum of cloud area times the values in the look-up tables for each cloud type. Such techniques have been used successfully in support of desert locust control (Barrett, 1977), for water resource evaluation (Barrett, 1979), and for crop yield monitoring and harvest prediction (Moses & Barrett, 1986).

Cloud top temperatures, measured using satellite thermal infrared images, can also be used to estimate precipitation rates (Lethbridge, 1967). The approach adopted is to define temperature thresholds at which rainfall at different intensities occurs. The technique was found to be reliable for large areas (> 150 km sq) over long periods (> 1 day) (Richards and Arkin, 1981), and forms the basis of the derivation of a Global Precipitation Index from geostationary meteorological satellites.

Both of the above techniques have limitations. For the cloud indexing method, it has been found that clouds with similar appearances do not always precipitate equally, whilst the same could be said of clouds with similar top temperatures. This lead to the development of techniques using both visible and infrared imagery. Based on a no rain, light rain, and moderate/heavy rain differentiation, it was found that an overall error rate of 35% was obtained using both visible and infrared over Southern and Eastern parts of the USA (O'Sullivan *et al.*, 1990). When using visible or infrared images only, the overall error rates were 39% and 42%, respectively.

Examples of UK procedures for rainfall estimation using cloud characteristics include PERMIT (Polar-orbiter Effective Rainfall Monitoring Integrative Technique) (Barrett *et al.*, 1987), ADMIT (Automatic Drought Monitoring Integrative Technique) (Barrett *et al.*, 1987), and TAMSAT (Milford and Dugdale, 1987). Brief descriptions of the three methods are given in D'Souza, 1988 and a comparison of the results obtained over an area of west Africa given in Snijders, 1991.

Life-history methods (see pages 65-81 of Barrett and Martin, 1981) are based on the premise that most precipitation originates from convective clouds which can be distinguished from other types of clouds using satellite imagery. The clouds are determined using visible and/or infrared images, and their development over time monitored using sequential images. To do this, the interval between consecutive images must be short compared with the lifetimes of precipitating clouds. The rainfall patterns observed may be used for short-term applications such as flood warning.

Barrett and Martin (1981), in their review of life history methods, highlighted three different schemes. The first, and simplest, was developed by Stout, Martin and Sikdar, 1979. Visible and infrared images were used to identify areas of cumulonimbus cloud and their development monitored over successive 30 min images. A linear regression was developed between rainfall rate and the extent and change in cloud cover, the regression constants being obtained using rainfall rates derived by ground radar. The estimated error in rainfall rate for each 30 min period was 60-75%. Although simple to operate, the system has only been used in one location and considers precipitation only from cumulonimbus clouds.

Griffith *et al* (1978) describe a similar, but more complicated, technique to the above, the difference being in the conversion of cloud cover to rainfall. In this case, consideration is given to the cloud growth trend (i.e. growing or dissipating) and to the cloud top temperature. The technique has been widely used and several modifications to the original system implemented. In an application over the eastern Atlantic Ocean, nine possible values of the growth trend factor and three cloud top temperature thresholds are considered (Woodley *et al.*, 1980).

Scofield and Oliver (1977) have developed a rainfall estimation technique for use in monitoring storm rainfall. Basically, the system works by consideration of a number of criteria, significant rainfall is predicted if the following apply:-

(i) The cloud is convective.

(ii) The cloud is cold.
(iii) The existence of towers in the coldest part of the cloud.

If all the above apply, rainfall rates are estimated according to whether the cloud is growing, and whether there are overshooting tops, merging thunderstorms, and merging cloud lines. The system has been used in different regions of the world with some degree of success.

(ii) Snow

The mapping of snow extent from satellite images has been shown to be feasible to the extent that it is one of the few hydrological parameters which is measured by satellites on an operational basis. This is particularly so for those areas of the world (e.g. the Rocky mountains, the Himalayas, and Scandinavia) which experience substantial precipitation in the form of snow, and where over 50% of annual catchment runoff originates from melting snow (Bergstrom, 1975). In these areas, an assessment of the extent, depth, water equivalent, and onset and rate of melting, is crucial for flood alleviation, water resource evaluation, and hydroelectric power schemes. In the UK, where snow constitutes a much lower percentage of precipitation, routine monitoring using satellite imagery is not done, though studies in mid-Wales (Collin and Carlisle, 1989) and in northern England (Archer, 1981) illustrate that problems related to snowmelt occasionally occur in some parts of Britain.

As for all hydrological applications, there is at present no satellite/sensor combination dedicated to monitoring the extent of snow cover and its quality. In most situations, the best solution is to use a number of the possible satellite/sensor combinations. For example, the transient nature of snow cover in the UK means that the areas affected need surveying at frequent intervals. Unfortunately, the satellites that produce these frequent images are associated with very coarse resolutions, and it is useful also to use less frequent images from satellite/sensor combinations that give a finer ground resolution. This is particularly so for monitoring lying snow in the UK, where the areas affected are likely to occur in relatively small upland catchments with large variations in topography and patchy snow cover. The problem is exacerbated by cloud cover, when the visible and infrared images cannot be used and reliance has to be made on microwave imagery.

The most widely used images for snow monitoring are the visible and infrared bands on the Landsat (Baumgartner *et al.*, 1986) and NOAA satellites (Collin and Carlisle, 1989). The Advanced Very High Resolution radiometer (AVHRR) onboard the NOAA series of satellites, providing 4 images a day in 4/5 channels at a ground resolution of 1.1 km at nadir (Lauriston *et al.*, 1979) is particularly suited for snow mapping in large areas, > 1000 sq km (Rango and Martinec, 1986). Such images form the basis of an operational snow monitoring package for the UK (Lucas and Harrison, 1989). Using such images, algorithms have been written to discriminate between clouds and snow, to map the spatial distribution of snow, to identify snow obscured by forest canopies, and to partition the snowpack into zones of complete or partial snow cover. Also, it is possible to differentiate between areas of snow melt and accumulation (Lucas and Harrison, 1989).

For smaller areas, or where snow cover is highly variable, it is more appropriate to use images from the Landsat series of satellites. The latest satellites produce images every 16 days in 7 wavebands with a ground resolution of 28.5 m. Unfortunately, the use of these images for this particular application is limited by their infrequent availability. As an alternative, aerial photographs may be obtained when conditions allow, and the snowline simply overlaid onto a base map.

For satellite imagery, snow covered areas can be easily identified in the visible bands, preferably the red, 0.6-0.7 um, band. Partitioning the snow pack into zones of complete or partial cover is done using a Normalized Snow Cover Index. This is basically the difference between reflectance values in the near infrared and red bands, and provides a measure of the quantity of photosynthetically active radiation absorbed by vegetation canopies. Areas of snowmelt and accumulation can be defined using atmospherically corrected thermal infrared imagery and through multitemporal comparison of imagery. Very little information may be obtained about quality aspects of snow in the visible and infrared bands. Areas of cloud cover may be separated from snow covered areas. For AVHRR images, this is done using brightness temperatures as given by the thermal bands, whereas for Landsat images, one of the near-infrared bands is used.

If the area of interest is affected by persistent cloud cover then, in theory, night time images in the visible bands can be used, provided that the moon is sufficiently bright (Foster, 1983). However, this is limited to a small number of satellites having sufficient light sensitivity in the visible wavelengths.

(iii) Soil Moisture

All the available remote sensing wavebands can provide information of value to the interpretation of soil moisture variability, but it is essential that the physical basis behind the use of each waveband is understood to enable their advantages and limitations to be carefully matched to their application.

Visible/near infrared wavelengths are most suitable for studying the effect of soil moisture variability on both natural and cultivated vegetation, but under limited situations the reflectivity of bare soil can highlight soil moisture anomalies such as waterlogging or irrigation. Idso *et al.*, (1975) established a bare soil albedo/soil moisture relationship to calculate evaporative losses from bare fields based on the finding that wet soil albedo is roughly half that of the same dry soil. However Evans (1979) in his study of Fenland soils, found that the effect of changing soil type and roughness, coupled with rapid drying of the thin surface crust (Hoffer and Johannsen, 1969) limited the application of aerial bare earth studies to local qualitative comparisons. Handley (1980) reports on the use of aerial photography for identifying derelict and despoiled land in Merseyside, one measure of the environmental stress being poor drainage.

Vegetation reflectance provides a much more practical indication of soil moisture as it responds to water availability within the whole of the root zone rather than a very thin surface layer as in the case of bare soil. For perennial and natural vegetation, water availability often determines the distribution of vegetation species (Harris *et al.*, 1991) whilst for most free crops a marked change in reflectance results from stressing due to water shortage or waterlogging.

Considerable interest has been shown in the use of visible/near infrared remote sensing for irrigation monitoring and scheduling. Werner (1971) compared an irrigated and non-irrigated green crop over a full growing season and found that the red reflectance was most closely correlated with soil moisture. Richardson and Everitt (1987) compared irrigated and non-irrigated grass and found that water stress was first detected as a lowering of near infrared reflectance as leaf turgor reduced, followed by an increase in red reflectance as leaf chlorophyll was lost. Collier (1989) carried out similar measurements on cotton, whilst Danson *et al.*, (1990) studied sugar beet in Suffolk. Vegetation indices based on the ratio of red/near infrared reflectance (Steven *et al.*, 1990) are frequently used to express crop vigour and may provide an indication of soil moisture availability. In many cases, visual interpretation of aerial photographs will enable the separation of an irrigated and non-irrigated crop, but for more extensive studies Landsat data has been successfully used to estimate irrigation area (Heller and Johnson, 1979, Kolm and Case, 1984) whilst Sharma and Bhargava (1988) identified areas of soil salinity and waterlogging which were caused by excessive irrigation. Thompson and Wehmanen (1979) also used Landsat data to produce a moisture stress index for wheat during drought conditions in the USA.

When applying these techniques, care must be taken with interpretation of green crops as other factors such as fertilizer application (Blakeman, 1990) can produce changes in leaf reflectance similar to the effect of irrigation. Also, unless a complete canopy cover exists, reflectance from underlying soil will have a major effect on the overall signal. High resolution imagery which enables the effects of plants and soil to be separated is therefore likely to be most successful. The combination of increased soil moisture plus nutrient can produce marked vegetation flushes which enable drainage paths from farm slurry pits, sewage works etc. to be readily traced using aerial photography.

For heathland and wetland situations, the most important control over species distribution appears to be the depth to groundwater and its fluctuation with time. Once the vegetation/hydrology relationship has been established for a particular area, it is possible to invert the process and use wetland vegetation as an indicator of moisture or moisture change. Gurnell and Gregory (1986) used this relationship to categorise a heathland catchment in the New Forest in terms of storm runoff potential to use in hydrological models, whilst van Diggelen *et al.*, (1991) monitored the effects of groundwater extraction on species distribution within a wetland nature reserve. Remote sensing thus provides a permanent record of vegetation change over time caused by changes in groundwater levels.

For applications in the UK, it will generally be necessary to use airborne remote sensing to achieve the necessary spectral and spatial resolution for small-scale studies. Christensen *et al.*, (1988) successfully used aircraft multispectral scanner data for vegetation classification for wetland change detection, and Shih (1990) used aerial colour infrared photographs for locating artesian wells by the spectral reflectance of soils and vegetation around the wells.

Middle infrared radiation is strongly absorbed by the presence of moisture in soil and vegetation, with water absorption at 1.45 and 1.95 micrometers. However, absorption by atmospheric water prevents the use of these wavelengths for remote sensing, so the intervening regions are used, the most common being those selected for Landsat TM bands 5 (1.55 to 1.75 micrometers) and band 7 (2.08 to 2.35 micrometers).

Musick and Pelletier (1986) carried out laboratory tests to establish whether band ratioing of Landsat data would improve measurement of bare soil water content. The best results were obtained with TM5/7 with good sensitivity to soil moisture throughout the moisture range. Further work (Musick and Pelletier, 1988) showed that the effects of soil type were almost eliminated by expressing soil moisture relative to field capacity. Everitt *et al.*, (1987) used an airborne video camera to study middle infrared reflection and found that wet soil, dry crusted soil and dry fallow soil could be differentiated, the irrigated wet soil appearing particularly dark as a result of water absorption. The technique should be useful for studying local soil moisture anomalies such as the effectiveness of field drainage, water seepage, irrigation etc, but as with visible/near infrared techniques, only the thin surface soil layer is observed and the effects of changing soil roughness and illumination angle will restrict the extent of comparative or temporal studies.

Current evidence as to the usefulness of mid-infrared reflectance for determining leaf water content as an indicator of soil moisture is inconclusive. Laboratory measurements by Ripple (1986) showed that mid-infrared reflectance was governed primarily by leaf moisture content, but he confirmed that soil reflectance was an important factor when leaf cover was less than 100%. Baret *et al.*, (1988) found that mid-infrared reflectance was most influenced by the geometry of the vegetation canopy whereas other studies have demonstrated a better relationship with dry phytomass rather than actual leaf water content (Everitt *et al.*, 1989, Shibayama and Akiyama, 1989). Hunt and Rock (1989) concluded that indices derived from near-infrared and mid-infrared reflectances were not sensitive enough to be applied to real field situations and that thermal infrared sensing would have to be included as the only practical methods of detecting water stress over large areas. Further work is required before mid-infrared/vegetation/soil relationships are better understood.

Thermal infrared measures surface temperature which can best be related to soil moisture via the thermal inertia method. Wet soil has a higher thermal capacity than dry soil so it exhibits a smaller diurnal range of temperature, appearing cooler during the day and warmer at night. Models to derive surface soil moisture and evaporation over bare earth and short grass were developed during the European TELLUS project to test data from the Heat Capacity Mapping Mission satellite (De Paratesi, 1981). Whilst the models performed satisfactorily using aircraft thermal data (Rosema *et al.*, 1978) cloud cover proved the impracticality of obtaining the necessary consecutive day/night thermal data from an orbiting satellite. For bare soil, Schmugge *et al.*, (1980) found that the effect of surface evaporation reduces the amplitude of the diurnal temperature cycle, thus complicating the calculation of soil moisture when the soil surface is moist, but once the surface layer has dried, a good measure of soil moisture within the 0-4 cm layer is possible.

Because the remote sensing of bare soils is seasonally very restrictive, most applications of thermal mapping have looked at vegetated surfaces to relate evaporation rates to available soil moisture. Nieuwenhuis (1986) calculated evaporation of crops from aircraft thermal data and derived soil moisture via SWATRE soil water model. As evaporation is crop dependent, coincident visible/near infrared data was used for crop classification. This appears to be the best approach for obtaining a quantitative measure of soil moisture using thermal remote sensing.

Qualitative measures of the spatial extent of soil moisture anomalies have been widely recorded using single flight thermal surveys. Low-cost thermal video cameras are available in the UK for use in light aircraft (Stove *et al.*, 1987) and thermal infrared linescanners are operated by air survey companies. Clyde Surveys Ltd (1987) have produced a report outlining the applications of thermal linescanner data for the water industry and give examples of field drainage surveys, waterlogged areas, spring detection, chemical discharges into waterways, leaks from pipelines, etc. Although not essential, it is recommended that coincident visible imagery is recorded with thermal surveys to aid interpretation of the data. The combination of thermal and reflected radiation will provide a better indication of soil moisture distribution than the use of either individually.

Active microwave or radar can achieve high spatial resolutions from both aircraft and satellites, their backscattered signal being directly affected by the electrical properties of soil which is moisture dependent (Schmugge, 1990). For soil moisture studies, satellite systems are felt to be technically more suitable than aircraft because satellites are inherently more stable than aircraft and their narrow radar beam width greatly reduces problems caused by varying incidence angle. European aircraft experiments such as AGRISCATT (Blyth and Andrews, 1990) have demonstrated the immaturity of aircraft radar, so such systems cannot yet be recommended for operational applications.

Because of their cloud-penetrating capability, satellite radars can monitor land surface changes as frequently as the satellite orbit permits. Repetitive monitoring enables soil moisture changes to be studied whilst unwanted effects, such as those caused by variations in surface roughness are reduced as they are largely time invariant. Although in a very early stage of development, this is an area of great potential as a number of satellite radars will be launched within the next 5 years. The first of these was the European ERS-1 satellite (Guyenne, 1989) which was successfully launched in July 1991 and is now returning very high quality radar images with a ground resolution around 25 m. Within the next 3 years, ground-based experiments such as those being undertaken by Institute of Hydrology will determine the utility of orbiting satellites for soil moisture monitoring. To make full use of this data for hydrological monitoring it will be necessary to develop better soil water models to allow prediction of soil moisture conditions within the root zone from remotely sensed measurements made within the top few centimetres of soil. Such development forms an important part of the IH ERS-1 Special Topic studies.

(iv) Surface Temperatures

Land surface temperatures, obtained from the analysis of remotely-sensed images, have been used in a number of relevant applications. These include the detection of heat losses from urban areas (Birnie *et al.*, 1984), water availability for agricultural purposes (Cihlar, 1980), the detection of frost hollows in fruit growing areas (Caselles and Sobrino, 1989), areal estimates of evaporation (Carlson and Buffum, 1989), the detection of icy road conditions (Thornes, 1989) and the mapping of areas of very low temperatures (Collier *et al.*, 1989).

Estimating land surface temperatures from remotely-sensed images presents greater difficulties than the estimation of sea surface temperatures. Whilst for the latter, it is generally only necessary to correct for atmospheric effects (see below); for the former variations in surface emissivity, variations in land surface temperatures over one pixel (picture element), and differences between air temperatures just above the land surface and actual land surface temperatures all present problems.

Two regions of the electromagnetic spectrum have been used operationally for the determination of surface temperatures; passive microwave and thermal infrared. Whilst the microwave method overcomes the problem of cloud cover, complications due to the presence of snow and water bodies limit its applicability (McFarland *et al.*, 1990), particularly for the detection of frozen ground surfaces. Also, the ground resolution associated with passive microwave imagery, typical pixel size 50 km, limits its application to global studies.

The thermal infrared technique for determining surface temperatures utilizes images in the 10.5 μm to 12.5 μm range. The most suitable images are those provided by the Advanced Very High Resolution Radiometer (AVHRR) sensor on-board the NOAA series of satellites. These satellites have the potential to provide four images a day in four/five wavebands (two visible, one infrared, and one/two thermal), with a ground resolution of 1.1 km at nadir (Lauriston *et al.*, 1979). However, actual data capture rates depend on prevailing cloud cover conditions. NOAA data can be currently received and processed quickly, a few hours after satellite overpass.

The detection of sea surface temperatures has been one of the major applications of satellite thermal remote sensing. For this, it is generally only necessary to correct the sea surface brightness temperature, as given by the sensors on board the satellite, for atmosphere effects. These are caused by absorption and scattering of radiation by particulate matter or gases within the layer of atmosphere between the emitting surface and the sensor. The method of correction is based on the fact that, since these atmospheric effects vary with wavelengths, the problem can be minimized. In the AVHRR sensor on the latest NOAA satellites, the original 10.5 - 12.5 um channel has been separated into a 10.5 - 11.5 um and a 11.5 - 12.5 um channel. Atmospheric correction by the use of images in two such bands is known as the 'split-window' technique.

A major problem when attempting to determine land surface temperatures from remotely sensed images is the effect of emissivity. Unlike water bodies, for which the emissivity is close to 1.00 with little variation, land surfaces exhibit large variations in emissivity (Griggs, 1968). Neglecting this variation may result in appreciable errors in the estimates of land surface temperatures (Becker, 1987). A number of theoretical formulations have been developed to solve the problem (see, for example, Becker and Li, 1990; Wan and Dozier, 1989). Alternatively, derived emissivity values from ground-based radiometers for different land surfaces may be used to correct the observed brightness temperatures over the area of interest according to the distribution of land cover. Another approach is to correct the brightness temperatures observed by the satellite using measured ground or air temperatures (McClatchey *et al.*, 1987). Both of the latter techniques suffer from the fact that, whilst the ground observations are point values, the brightness temperatures are averaged over a considerable area (1 sq km in the case of the AVHRR sensor).

(v) Land Cover

The mapping of land cover is probably the most widely used remote sensing application. The types of land cover that are identified depend, to a certain extent, on the type of image involved and on the particular application. For example, an ecologist's perception of a land cover classification would be very different to that of a hydrologist's. For the latter, a land cover classification would consist of open water, forestry, permanent grassland, arable land including temporary grassland, and urban areas. Such a classification, perhaps in combination with a soils map, a digital terrain model, and a geological map, could be used to extrapolate results from small plot studies to the catchment scale. Such an approach for catchment water balance purposes has been demonstrated by Roberts and Roberts (1992), and could be extended to estimate catchment chemical and sediment losses, provided that the required data from small plot studies were available.

Alternatively, land use classifications could be used, again perhaps combined with other classifications, to identify suitable areas of study or to judge the representitivity of existing study sites. Another possibility is in the study of the effects of land use change, where the analysis of multi-temporal images will give an indication of the size of the areas affected. As with all remote sensing applications, the type of image used depends on the spatial and temporal requirements of the particular application.

Aerial photography probably remains the most widely used remote sensing medium for land use mapping. Such photographs are widely available, are economic to buy, and have a sufficiently fine spatial resolution to map small features e.g the riparian vegetation, within the area of interest. Disadvantages of using aerial photography include the manual effort involved in digitising, the relative coarseness of the spectral resolution attainable by the use of filters, the difficulty of converting the image to digital form, and hence the effort entailed in transforming the data to map projections or as input to a Geographic Information System. On the other hand, aerial photography is often a more economical way to providing 'ground truth' against which to calibrate other remotely sensed images, than are ground surveys.

Imagery from multispectral scanners in digital form has a number of advantages over photographic products. In the first place, the scanners operate in distinct spectral regions designed to highlight differences in the reflectances of land cover types. Also, since the data are in digital form, they may be subject to detailed analysis using computer software written specifically for this purpose. This includes image enhancement and the combination of reflectances in different spectral bands. On this latter point, a very useful index for land classification purposes is the Normalized Difference Vegetation Index (NDVI). This is basically the difference between reflectances in the near infrared and the red region of the electromagnetic spectrum. Green vegetation has a high reflectance in the infrared region and a low reflectance in the red; for non-vegetated surfaces the reverse is true, so the NDVI is an index related to crop cover.

There are two basic classification methods that can be used - unsupervised and supervised. In the former, a clustering algorithm is used to divide the total population of picture elements (pixels) in the area of interest according to their distribution in multispectral space (Belward *et al.*, 1990), without any user input. The user must then decide how the resultant classes relate to his perception of 'ground truth'. In a supervised classification (Schowengerdt, 1983), the user defines representative pixels of known land class; their mean spectral response is then use to define the spectral properties of each class and 'unknown' pixels are matched and assigned to the most 'similar' class. A relevant example to IH of applying this latter technique is ITE's land cover classification of the whole of the UK. This is based on Landsat TM images, covers over 30 different land classes and is at 25 m ground resolution.

A particularly relevant aspect of land cover to hydrology is the extent of urbanisation. The change in catchment response to rainfall inputs following urbanisation has been the subject of much research and has led to the development of predictive rainfall runoff models. These vary in their complexity from simple techniques (Lloyd-Davies, 1906) through hydrograph methods (Watkins 1962) to the more advanced models that are in general use (Colyer and Petwick, 1976). Most of the latter include modules that calculate surface runoff for a given rainfall intensity and duration. This depends on several catchment characteristics including soil type, catchment wetness and, most importantly, the percentage of impervious surface within the catchment. This latter parameter has usually been assessed, for a given catchment, using large scale maps, aided by on-the-ground surveys and the manual interpretation of aerial photographs. However remotely sensed data has been used to assess this parameter and can be considered a viable operational technique (Finch *et al.*, 1989). The majority of examples have made use of the different spectral reflectance properties, usually in the visible and near infrared, of the various types of urban land cover such as roads, roof, and grass.

The application of remotely sensed data from satellites to mapping urban areas was an early use made of the data (Jackson *et al.*, 1976) when it first became available at the beginning of the 1970's with the launch of Landsat 1 carrying the Multispectral Scanner (MSS). The percentage of impervious area was directly estimated from Landsat MSS data for use in the US Army Corps of Engineers STORM model (US Army Corps of Engineers 1976). The comparison between measured storm discharges and those discharges simulated using a conventional approach and the Landsat approach showed that the two simulations could be equally good whilst the cost benefit of the Landsat approach was between 2.5:1 and 6:1. Although estimates of impervious areas for incorporating in hydrological models continued to be reported from the USA (Slack and Welch 1980, Rango *et al.*, 1983, Forster 1985) it was pointed out that the spatial resolution obtained by space borne sensors was not really appropriate (Welch 1982). A spatial resolution of at least 30 m is required for the USA whilst even higher resolutions, at least 10 m, is needed for Europe. Landsat MSS data has a nominal spatial resolution of 80 m and, although it can reliably map urbanised areas of 5 hectares or larger (Jackson *et al.*, 1980), it is not capable of the detail required for urban rainfall-runoff models in the UK.

Landsat 4 was launched in 1982 and carried a new instrument, the Thematic Mapper (TM). This provided remotely sensed data with a spatial resolution of 30 m which achieved the spatial resolution required for the USA. It has also been used in Europe (Richter and Schultz 1988). However it was not until 1986 and the launch of the French satellite SPOT that a spatial resolution appropriate to the European environment was available. The sensors on the SPOT satellite can provide data at 20 m spatial resolution in three spectral bands or 10 m spatial resolution in a single spectral band. The latter is best regarded as akin to black and white photography and so the amount of radiometric information is limited. Multispectral SPOT imagery has been successfully used to map changes in urban areas in southeast England (Quarmby and Cushnie, 1989) and may be appropriate to hydrological models of urban areas on a regional scale (Finch *et al.*, 1989).

The method used to analyse the digital data from sensors has been to classify each picture element (pixel) into a single land use class, such as road, grass, deciduous woodland, roof. The underlying assumption with this method is that the spectral radiance recorded by the sensor for that pixel corresponds to the spectral radiance of a pure land class. This is frequently not so in practice as pixels often correspond to a mixture of land classes and this is more likely to happen with coarser spatial resolution systems. Increasing the spatial resolution can help to decrease the number of mixed pixels. In addition there have been promising attempts recently to estimate the individual spectral contributions made by different land classes within mixed pixels (Fisher and Pathirana, 1990). These methods are still experimental but do offer the possibility of improving estimates of the effects of different urban land cover types using remotely sensed data from satellites.

A source of high resolution remotely sensed data from satellites that has recently become available is from the Soviet space programme. The American and European civilian space programmes have relied on systems that acquire digital data that is transmitted to earth whilst the satellite remains in orbit. The Soviets have used a system of cameras mounted in satellites that are in low earth orbit. The entire satellite returns to earth to allow the film to be recovered and processed (Piskulin, 1989). The colour film can then be digitised for computer processing. The KFA-1000 system has a resolution as high as 5 m that may be useful for monitoring urban areas (Van Genderent, 1989).

Sensors mounted on aircraft provide high spatial resolution that has been analysed to provide estimates of land cover in urban areas. Digital processing of aerial photographs has been described in several studies (Scarpace and Quirk 1980, Downey *et al.*, 1989). High altitude aerial photography, digitised by a laser imaging processing scanner was used to estimate the percentage impervious area (Draper and Rao, 1986). The estimates were part of the input to a hydrological model that used a single linear reservoir with a precipitation excess equation. The results compared well with those derived from conventional aerial photograph interpretation.

An alternative to aerial photographs are data from multi-spectral scanners mounted on aircraft. Data from this kind of system has been used successfully to estimate the percentage impervious areas of urban catchment in the UK (Finch *et al.*, 1989). Nine catchments contributing flow to individual drains in a trunk sewer were examined at Kidlington, Oxford. The remotely sensed data, acquired using a Daedalus 1268 Airborne Thematic Mapper, were used to differentiate between vegetated and non-vegetated surfaces and these components were classified to give areal estimates of each vegetation type and the areas of roof, roads and paths for input into the WASSP model (Department of the Environment 1981). The estimates were found to compare well with those from a conventional survey using large scale maps, aerial photographs and on-ground survey particularly where the land cover was relatively homogeneous.

(vi) Water Quality

A number of remote sensing techniques can be used to measure parameters that are directly or indirectly related to water quality. For most freshwater applications, the relatively low spatial resolution and uncertain coverage of satellite sensors limits their use, and airborne surveys are likely to be more applicable.

As with most remote sensing techniques, direct measurements are limited, and ground truths or predictive techniques have to be used to provide the required parameter. One exception to this is surface water temperature which can be derived from radiances measured in the thermal infrared. For airborne sensors, the use of internal temperature reference plates to calibrate the observed radiances will generally ensure relative accuracies of 0.1°C and absolute accuracies of 0.3°C. In contrast, satellite imagery has to be carefully corrected for atmospheric effects, and the resulting accuracies likely to be lower. The mapping of surface water temperatures has many possible hydrological applications such as tracking sewage and power station discharges, the identification of groundwater sources, and the mapping of lake or coastal currents. The latter could equally be done by tracking floating targets using multitemporal aerial photography or visible/near infrared images from airborne scanners.

No comprehensive ways have yet been found to measure the levels of chemical pollutants in water. However, images in the visible and near-infrared bands can be used to determine dissolved organic carbon, suspended mineral particles, and the concentration of phytoplankton chlorophyll. These determinations are based on characteristic reflectances of the various components in natural waters (see pages 4.4 to 4.5 of Briggs *et al.*, 1991). In the case of sediments, these reflectances are very dependent on the types of soil; information regarding this is required in order that accurate surveys may be made. Sensors having high spectral resolution such as the Moniteq PII/FLI or CASI are very useful in this respect. The Compact Airborne Spectrographic Imager (CASI, see Appendix I) will be used extensively onboard the NERC aircraft during the course of the Land Oceans Interaction Study (LOIS) initiative.

When using indirect remote sensing methods to derive water related parameters, great care must be taken to eliminate other contributory factors. An obvious example of this relevant to water quality modelling in the detection of algae as a surrogate for nutrient concentrations. In this case, it is necessary to consider which nutrient, usually phosphorus, is limiting algal growth, and to 'normalize' the concentrations of other nutrients. Also, it is necessary to consider the temperature and movement of the water. As with sediment monitoring, it is necessary to collect and analyse water samples to provide ground truths for absolute concentration determination by remote sensing.

The simplest way of detecting algol growth by remote sensing is by utilizing the green chlorophyll reflectance peak. This technique can only be used for relatively high chlorophyll concentrations under clear sky conditions. Under more difficult conditions, a variety of multi-band algorithms have been devised that predict water quality parameters from the relative change in water colour (page 4-7 in Briggs *et al.*, 1991).

(vii) Other hydrologically-relevant parameters

Two vegetation parameters relevant in particular to estimates of evapotranspiration is albedo and leaf area index. Albedo is defined as the ratio of the reflected to incoming solar radiation, and its determination will enable an estimate of the amount of solar energy that is available for evapotranspiration. A number of investigations have been conducted, but there is, as yet, no effective way to remotely sense albedo. There are three main problems:-

(a) Remote sensors collect only a small portion of light in the specific electromagnetic bands of the sensor. For the determination of albedo, it is necessary to consider radiation over all portions of the electromagnetic spectrum.

(b) Remote sensors collect radiation only in the field of view of the instrument, whereas light reflected in all directions need to be estimated/measured.

(c) Corrections are required for the effects of the atmosphere on the reflectances recorded by the sensor.

Studies are being conducted on methods to overcome these difficulties (see, for example, Brest and Goward (1987)).

Leaf area index is normally expressed as a function of the Normalized Difference Vegetation Index (NDVI), the difference between measured reflectances in the near infrared and red parts of the electromagnetic spectrum (Curran *et al.*, 1992). However, variations in a number of environmental factors - solar angle, understorey vegetation, atmospheric conditions, phenology - cause variability in the relationship, and it is generally necessary to collect 'ground truths' and to develop site specific relationships between these and the remotely sensed data.

A final hydrologically-relevant parameter that may be obtained by remote sensing is altitude though, for most purposes, this information may be obtained from existing maps. When no maps are available, estimates may be obtained using stereo images from the SPOT satellite. The high spatial resolution of the sensor on board this satellite will provide values with errors in the range 5-20 m in both the vertical and horizontal planes.

FACILITIES AVAILABLE TO THE SECTION

This chapter describes what facilities are available and what remotely sensed images may be accessed by IH Remote Sensing Section. Reference will be made to the applications described in the previous chapter and to IH requirements in the next chapter.

(i) Image Analysis System

The section has access to an in-house analysis system, an I²S (International Imaging Systems) Model 75. This is hosted by a Micro-Vax, and is housed in room 43, directly beneath the computer suite. The hardware consists of several VT2000 terminals, a colour monitor, a D-scan printer and a 35 mm camera for producing black-and-white and colour hard copy outputs from screen dumps, and a digitiser that can be used for maps/drawings up to A4 size. In addition, larger maps or drawings may be digitized on the Calcomp 9100 and transferred to the system via the network. The image analysis software, System 600, provides a wide range of routines. These include functions for geometric and radiometric transformations, image inspection, classification, and analysis. Additional routines have been written by NERC scientists and these are also available on the system.

The image analysis system can process remotely sensed images from all platform/sensor combinations. In practice, most of the section's work in the past has concentrated on satellite images from Landsat, Spot, AVHRR, Meteosat, and ERS-1, and aircraft images from the Daedalus scanner and CASI used in the NERC aircraft campaigns. The final product, whether a visual representation of an area, a classification, a calculated parameter or flux may be given as a hardcopy as indicated above, or transferred as a raster file covering any specified area at the required ground resolution. The file can then be used as input to other applications such as models or GIS. High quality hard copies are possible by transfer to plotters such as the Phase III or Versatec on the distributed computing system at IH.

This system may be used for all the applications involving digital images except for rainfall estimates described in the previous and next chapter.

(ii) NERC Remote Sensing Archive and Airborne Campaigns

The section has free access to the NERC remote sensing archive at Keyworth. This contains all the remotely sensed images, both satellite and airborne, that have been used in the past within NERC. Although most of the images cover areas of the UK (the whole of the UK has been covered by at least one recent cloud free Landsat image), there are also images from various overseas locations. A listing of all available images or, alternatively, for selected areas can be obtained. IH Remote Sensing Section is compiling its own list of images used.

The section regularly acquires images over selected areas of the UK from the NERC airborne campaigns. The cost of data from the airborne campaigns is covered from central NERC funds if the proposal has been approved by the steering committee. However, it would also be possible to commission data acquisition if there were sufficient funds from a commissioned project.

Alternatively, the section has a modified aircraft door containing four camera housings for acquiring visible and near infrared aerial photographs (not thermal), and a housing for a video camera.

(iii) **Meteosat Receiver**

The section has the capability for receiving and analysing real-time images from the Meteosat satellite. This has recently been updated so that it is capable of dealing with images from two different parts of the globe. One half of the system is being dedicated to providing half-hourly cloud top temperatures over the UK for the next three years for Bob Moore's HYREX project (see Appendix 2). Software exists for the estimation of convective rainfall from Meteosat images using a cloud temperature threshold algorithm. Additional software may be obtained or developed for the other proposed/possible requirements outlined in Appendix 2.

(iv) **University of Dundee NOAA Receiving Station**

Network access, via JANET, to the NERC satellite station at the University of Dundee has been obtained. This will enable near real-time AVHRR images of western Europe to be obtained at a nominal cost (to be decided). These can be analysed on the image analysis system, for a number of hydrological applications.

(v) **Arc-Info Geographic Information System**

The section has access to the workstation and PC version of the Arc-Info Geographic Information system. This will facilitate the overlapping and comparison of remotely sensed and other spatial data sets.

(vi) **Stereo Photograph Viewer and Magellan Global Positioning Systems**

The section has a stereo viewer for analysing aerial photographs. This is particularly useful for delineating areas of interest such as water catchment areas, where the exaggerated vertical scale enables the identification of catchment boundaries. The section has two Magellan GPS receivers. These allow their location to be obtained, anywhere in the world. They are used for obtaining accurate locations, either to transform images to the map projections, or to locate other features such as boreholes. The accuracy obtained depends on the mode of use but varies between 5 and 200 m.

(vii) **NERC Equipment Pool for Field Spectroscopy**

The section also has access to the NERC Equipment Pool for Field Spectroscopy based at Southampton University. These instruments allow ground measurements of spectral characteristics to be made. The section has a Milton spectroradiometer for similar, but broad band, measurements.

REVIEW OF THE IH REMOTE SENSING NEEDS

This review was conducted mainly by one to one discussions with individuals following consultation with Division and Section Heads. Prior to these discussions, a short note was circulated outlining the expertise within the RS Section, the facilities available, and the type of work that can be undertaken. In one instance, Flow Regimes Section, a presentation of possible remote sensing applications was given to the section followed by a discussion of possible future needs. All of the sections within IH with a possible interest in remote sensing were covered though, in the time available, it was not possible to talk to everyone. Nevertheless, it is felt that a good general picture of present and future needs has been obtained.

The response from all the sections was extremely positive and frank, so that the findings can form the basis of future work within the remote sensing section. Another gratifying aspect is that a number of applications were initiated during the course of these discussions. Although most of these were of a short term nature, two, in particular, have the potential to be particularly beneficial to large ongoing commissioned studies.

The results of the review are given in Appendix II. They are shown by Division and, within each Division, by Section. For each possible application, the person concerned is indicated and an index based on:-

1 = ongoing, 2 = proposed, 3 = speculative

The findings are summarised in Table 3 under general application headings and using the index described above. They are split into UK and overseas applications, this is because of the different degrees of availability/cost of images in the two situations (see previous chapter). The rest of this chapter describes the responses for each general application and highlights (underlines) areas where the remote sensing section are or should be involved. If necessary, concept notes will be written to reinforce involvement in these areas.

(i) Rainfall

The results of the review showed a large possible need for areal estimates of rainfall, particularly for large-scale overseas modelling purposes. As indicated in the previous chapter, two Meteosat receiving systems are now operational, one of which will be dedicated to collecting cloud top temperatures over the UK at half hourly intervals over the next three years under Bob Moore's HYREX project. <u>It is proposed that every effort should be made to utilize the other system in support of these needs using algorithms developed elsewhere or, if need be, using alternative site specific algorithms developed at IH</u>. This applies particularly to those applications identified by the Land Use and Water Efficiency Section of the Hydrological Processes Division (Appendix II).

(ii) Snow

The identification of the areal extent of snow and its parameters is not a major requirement within IH. There are, however, two positive overseas proposals, one under the BOREAS study in Canada, and the other under the proposed TUNDRA project. <u>The role of the remote sensing group in both these studies needs to be defined</u>. In the UK, there is a small general interest for mapping snow extent for input to flood models. <u>One possible way of doing this using existing facilities is by identifying suitable snow covered scenes using the Meteosat images acquired for the HYREX project, and then analysing AVHRR images acquired from Dundee over the JANET network for identifying snow cover over areas of</u>

interest.

(iii) Soil Moisture

There is a general interest in the distribution of near surface soil moisture for both overseas and UK applications. This is an application currently under development in the remote sensing section by Ken Blyth, as principal investigator using ERS-1 Synthetic Aperture Radar (SAR) under a NERC special topic. This special topic is scheduled for completion towards the end of 1994; it is proposed that this research be continued with stronger ties with interested parties within IH. Complementary to this research, a core and menu proposal for the use of passive microwave for soil moisture determination on a global scale is being considered. On a more local scale, the 1993 NERC airborne campaign over Plynlimon, mainly designed to study the distribution of near-surface soil moisture by vegetation inference has been postponed. It is expected that this will now take place in spring 1994.

(iv) Land Cover

The mapping of land cover for input to hydrological models is a major requirement within IH. For the UK, most of these requirements are for a general classification for relatively small catchment areas. Now that agreement has been reached with ITE for access to their UK Landsat classification, it is envisaged that future requirements be provided by access to this data set, though IH Remote Sensing Section may have some advisory role e.g. in the integration of the various ITE classes into hydrologically significant land uses.

There are some instances that the ITE Landsat classifications cannot be used. This applies particularly to the identification of impervious surfaces within urban areas. This is done using high spatial resolution aircraft imagery. A useful exercise in this respect would be a comparison of urban areas from the ITE classification and those from past aircraft campaigns e.g. at Kidlington and Bracknell. Another example of this is the proposal by the Agrohydrology Section to identify variations in cereal yield within individual fields. A proposal is to be put into the 1994 NERC aircraft campaign to acquire multispectral images over Battle Farm, Benson. This also applies to the clear-felling in the Hafren Forest at Plynlimon (Hydrochemistry Section); this will be done during the 1993 NERC airborne campaign, now scheduled for spring 1994.

Perhaps the most promising application for UK land use mapping is under the LOIS initiative. An early decision is required on what role IH Remote Sensing Section has to play in fulfilling these needs.

For overseas applications, IH requirements for land classifications were equally great, ranging from the small research catchment to the global scale. For the former, two significant applications were initiated during the course of this review; these are the Landsat classifications of areas of Nepal (Water Quality Systems) and of Zimbabwe (Agrohydrology). It is anticipated that these applications will continue with the purchase and analysis of further images and extending the classifications to other areas, should funding be obtained. It is anticipated that the availability for spatial data sets, including land cover, for mesoscale applications will increase, as new formulations for mesoscale hydrological modelling are developed. The spatial land cover can best be obtained using a combination of AVHRR (for homogeneous areas) and Landsat or SPOT (for heterogeneous areas) images. Such an approach is currently being used by Jon Finch for areas of Niger. For global scale applications, it is anticipated that existing datasets will mainly be utilised, though the remote sensing section may have a role to play in acquiring and interpreting these data sets.

An important aspect of land use in UK and overseas applications is land use change. Such changes may be monitored by analysing multi-temporal remotely sensed imagery. In particular, it is proposed to purchase and analyse Landsat MSS images of Zimbabwe and Niger to study the timing and extent of land degradation and desertification.

Although IH Remote Sensing section has not been involved with the identification of vegetation parameters such as albedo and leaf area index in the past, this may be an area of future research, with its important relevance to evaporation losses (Global Processes Section). A tentative start has been made in this respect with the analysis of multi-seasonal Landsat images of Savernake Forest in Wiltshire.

(v) Surface Temperatures

Surprisingly, there seems to have been only a small response to the mapping of surface temperature considering its success in various applications in the past. In particular, the mapping of cold seawater currents has been used successfully by Jon Finch recently to identify areas of groundwater discharge off the coast of Qatar. This is similar to the application proposed by the Flow Regimes Section. The spatial variation in surface temperature has been used extensively at IH in the past to give estimates of the areal distribution of evaporation. It is anticipated that this research will continue, with possible extension to larger areas and input to large scale models.

(vi) Aerial Photography

The analysis of aerial photography continues to be an important aspect of IH Remote Sensing Section's work. Current and future applications include the delineations of catchment boundaries by the analysis of stereo pairs (numerous examples), the mapping of the riparian zone (Experimental catchments and Flood and Storm Hazard), and multi-temporal agricultural land use in Jersey (Water Resources Systems).

In conclusion, the review has highlighted a number of possible future research topics and applications of remote sensing within IH. Although in some instances, it is difficult to decide when research stops and applications begin, an attempt has been made below to list these proposals under separate headings.

Research

1. Develop algorithms for the utilization of Meteosat images for the areal distribution of rainfall.

2. Continue and extend the ERS-1 microwave study on the distribution of soil moisture.

3. Determine the usefulness of passive microwave data for the distribution of soil moisture on a global scale.

4. Research in providing estimates of albedo and leaf area index.

5. Continue and extend studies of areal evaporation to larger areas and inputs to large scale models.

6. The integration of land classifications based on AVHRR, Landsat and SPOT imagery for mesoscale modelling.

Applications

1. Snow determinations for the BOREAS and TUNDRA projects.

2. Snow determination for the UK using METEOSAT and AVHRR images.

3. An advisory role in the use of the ITE Landsat classifications.

4. A comparison of urban areas from the ITE Landsat classification and results from airborne campaigns.

5. A NERC aircraft campaign over Battle Farm, Benson.

6. Riparian vegetation mapping for the LOIS initiative.

7. Further land classifications of overseas areas, particularly Zimbabwe and Nepal.

8. Advisory role on the acquisition and interpretation of global data sets.

9. Analysis of multi-temporal Landsat MSS images of Zimbabwe and Niger.

10. Acquisition and analysis of multi-temporal aircraft images of Jersey.

11. The mapping of water extent and areas of flooding using ERS-1 imagery.

Table 3 Finding of the IH remote sensing review

	United Kingdom			Overseas		
Application/Index	1	2	3	1	2	3
Rainfall	1	-	1	2	2	6
Snow	-	1	2	1	1	-
Soil Moisture	1	1	2	1	3	-
Land Cover	7	2	8	5	4	10
Surface Temperatures	-	1	-	-	1	-
Aerial Photographs	2	1	1	2	1	1

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Appendix I Remote Sensing Sensors

1. Advanced Very High Resolution Radiometer (AVHRR) - NOAA
2. High Resolution Visible Imager (HRV) - SPOT
3. Visible and Infrared Spin Scan Radiometer (VISSR) - METEOSAT
4. Thematic Mapper (TM) - LANDSAT
5. Synthetic Aperture Radar (SAR) - ERS1
6. Daedalus AADS 1268 (ATM) - NERC Aircraft
7. Compact Airborne Spectrographic Imager (CASI) - NERC Aircraft

Instrument Profile Number 2.

Acronym :	**AVHRR**
Full Name :	**Advanced Very High Resolution Radiometer.**
Platform :	The NOAA satellite series.
Operator/Sponsor :	National Oceanographic & Atmospheric Administration (NOAA).
Country :	USA.
NRA Applications :	Flood Monitoring. Hydrological Modelling. Chlorophyll Monitoring. Land Cover Mapping. Snow Mapping. Land Surface Temperature. Sea Surface Temperature. Cloud Temperature.
Frequency Bands :	1. 0.58-0.68 2. 0.725-1.1 3. 3.55-3.93 4. 10.5-11.3 5. 11.5-12.5µm
Resolutions :	1.1km to 4.6km (Scan angle dependent).
Swath Width :	1600km.
Orbit (Height/Type) :	833 - 870km; Sun-synchronous; 7.00a.m. & 2.00p.m. equator crossing times.
Repeat Interval :	c.1 day.
Launch Date :	1978 - 1990s.

Further Details :
The NOAA satellites are a series of weather satellites originally designed to produced operational weather data.

Selected References.

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Instrument Profile Number 3.

Acronym :	**HRV**
Full Name :	**High Resolution Visible Imager.**
Platform :	Systeme Probatoire d'Observation de la Terre (SPOT).
Operator/Sponsor :	Centre National d'Etudes Spatiales.
Country :	France.
NRA Applications :	Surface Water Mapping. Topographic Mapping. Operational Land Use Studies. Inventory Monitoring. Flood Monitoring.

Frequency Bands :	1. 0.5-0.6μm	2. 0.6-0.7μm	3. 0.78-0.9μm	1. 0.51-0.73μm
	--------Multispectral Mode		----------	Panchromatic Mode
Resolutions :	20m	20m	20m	10m

Swath Width :	110km. (2x 60km swaths with overlap)
Orbit (Height/Type) :	Sun-synchronous.
Repeat Interval :	26 days (2.5 days with off-nadir viewing).
Launch Date :	1986

Further Details :
The SPOT satellite's payload includes two HRV instruments which can both be oriented across track by + or - 27 degrees so as to produce stereoscopic images of a given scene from subsequent orbits; an important aid in the production of high-resolution topographic maps.

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Instrument Profile Number 4.

Acronym :	**VISSR**
Full Name :	**Visible & Infrared Spin Scan Radiometer.**
Platform :	Meteosat.
Operator/Sponsor :	European Space Agency (ESA).
Country :	Western Europe.
NRA Applications :	Operational Weather Data. Real-time Storm Monitoring. Severe Storm Warning.

Frequency Bands :	1. 0.4-1.1μm	2. 5.1-7.μm	3. 10.5-12.5μm
Resolutions :	2.5km	1.0km	5.0km

Swath Width :	Entire Earth Disc.
Orbit (Height/Type) :	36000km; Geostationary.
Repeat Interval :	30 Minutes.
Launch Date :	1978

Further Details :
A similar, 2-band instrument is included in the payloads of the American GOES (Geostationary Operational Environmental Satellite) series of weather satellites which have been in operation since 1975.

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Instrument Profile Number 5.

Acronym :	**TM**
Full Name :	**Thematic Mapper.**
Platform :	Landsat.
Operator/Sponsor :	EOSAT/NASA.
Country :	USA.
NRA Applications :	Drainage Basin, Channel and Snow Mapping. Suspended Sediment Monitoring. Hydrogeological Research. Vegetation, Crop and Land Use Inventories. Flood Monitoring.

Frequency Bands :

1.	2.	3.	4.	5.	6.	7.
0.45-0.52μm	0.52-0.60μm	0.63-0.69μm	0.76-0.90μm	1.55-1.75μm	10.4-12.5μm	2.08-2.35μm

Resolutions :	All 30m except band 6 which is 120m.
Swath Width :	185km.
Orbit (Height/Type) :	705km; Sun-synchronous; 9.30am node.
Repeat Interval :	16 days.
Launch Date :	1972-1990s.

Further Details :
Landsat satellites also carry a multispectral scanner (MSS) which has a resolution of 80m.

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Instrument Profile Number 6.

Acronym :	**SAR**
Full Name :	**Synthetic Aperture Radar.**
Platform :	ERS-1.
Operator/Sponsor :	European Space Agency (ESA).
Country :	Western Europe.
NRA Applications:	Flood Monitoring. Soil Moisture Estimation. Coastal Ocean Studies. Ice Studies.
Frequency Bands :	C band.
Resolution :	30*30m (in wind mode).
Swath Width :	100km.
Orbit (Height/Type) :	785km; Sun-synchronous; 10.30am equator crossing time.
Repeat Interval :	3 days. (Possible changes to 17 and 35 days)
Launch Date :	1991

Further Details :
The SAR is carried as part of ERS-1's Active Microwave Instrument (AMI). The Shuttle Imaging Radars, SIR-A and -B, are further examples of satellite-borne SAR systems which have been successful in a number of water science applications.

Future satellite-borne SAR systems will include those on board the planned JERS-1 (Japan) and Radarsat (Canada) due for launch in 1994 and 1995, respectively.

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Instrument Profile Number 9.

Acronym :	**ATM.**
Full Name :	**Airborne Thematic Mapper. (Daedalus AADS 1268.)**
Platform :	Airborne; NERC Aircraft
Operator/Sponsor :	Daedalus Enterprises Inc. (US). Global Earth Sciences Limited (UK).
Country :	US/Europe.
NRA Applications:	Water Resources Management. Pollution Studies. Land Cover Classification and Inventories. Flood Delineation.
Frequency Bands :	11 bands including the same wavelengths as Landsat TM (See Profile Number 5).
Resolutions :	~1m to 20m (Altitude dependent)
Swath Width :	72 degrees.

Further Details :
AADS 1268 (ATM) is one of a well-established series of Daedalus line scanner systems. Within the broad applications mentioned above, these systems have, for example, been used in Environmental Impact studies, Effluent Mapping, Pollution Monitoring in Waterways, Pipeline Leak Detection, River Current studies and Ship Traffic Monitoring.

Selected References.

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See also references under Instrument Profile Number 5.

Instrument Profile Number 10.

Acronym :	**CASI.**
Full Name :	**Compact Airborne Spectrographic Imager.**
Platform :	Airborne; NERC Aircraft.
Operator/Sponsor :	ITRES Research.
Country :	Canada
NRA Applications:	Water Quality Analysis. Chlorophyll Concentration Mapping. Vegetation Stress Assessment.
Frequency Bands :	Mode 1: 'Full Spectral': 288 bands: 0.4-0.9μm Mode 2: 'Full Spatial': 8 bands: 0.4-0.9μm
Resolutions :	1m to 10m (Altitude and No. Bands dependent)
Swath Width :	1km. (2m resolution)
Operational Altitude :	2000m.

Further Details :
The CASI instrument employs a 288 by 612 two-dimensional detector array which avoids any need for scanning optics; the array simply moves with the platform, operating in a so-called 'push broom' mode.

The CASI's specifications and applications are a development of the earlier airborne multispectral radiometer, PMI/FLI (Programmable Multispectral Imager/Fluorescence Line Scanner), operated by Moniteq Limited.

Selected References.

Borstad GA, and Hill DA, 1989, **Using visible range imaging spectrometers to map ocean phenomena.** Proc. SPIE vol 1129, Advanced Optical Instrumentation for Remote Sensing of the Earth's Surface from Space, Paris, France, 27-28 April, p130-136.

Gower JFR, Borstad GA, Gray LH, and Edel, HR, 1988, **The Fluorescence Line Imager: High-resolution imaging spectroscopy over water and land,** Proc. 4th Int. Colloq. on Spectral Sigantures of Objects in Remote Sensing, Aussois, France, ESA SP-287, p273-278.

Appendix II The Results of the Remote Sensing Review

1. ENVIRONMENTAL HYDROLOGY DIVISION

(i) Water Quality Systems
(ii) Agrohydrology
(iii) Hydrological Modelling
(iv) Hydrochemistry
(v) Experimental Catchments

2. ENGINEERING HYDROLOGY DIVISION

(i) Climate Change Impacts
(ii) National Water Archive
(iii) Hydrologic GIS
(iv) Flow Regimes
(v) Flood and Storm Hazard
(vi) Distributed Modelling
(vii) Urban Hydrology

3. APPLICATIONS RESEARCH AND POLICY DIVISION

(i) Water Resources Systems

4. HYDROLOGICAL PROCESSES DIVISION

(i) Global Processes
(ii) Sustainable Dry Land Use
(iii) Land Use and Water Efficiency

ENVIRONMENTAL HYDROLOGY

Water Quality Systems

AJ(1) Landsat classification of areas of Nepal (Gareth Roberts). The classification to be used to determine the representivity of a number of research catchments and to extrapolate water quality and sediment loss results to larger areas.

Agrohydrology

CHB(1) The identification of catchment boundaries in Zimbabwe using aerial stereo photographs (Gareth Roberts).

CHB(1) Land classification of Zimbabwe catchments to advise on land management issues (Jon Finch).

CHB(3) Weekly rainfall totals over Zimbabwe from Meteosat.

CHB(3) Identification of waterlogged areas to determine rice growing in reservoirs/tanks eg. in Sri Lanka, and for determining success of soil erosion deterrents using ridges.

RJW(3) Land-use of UK to extrapolate results from process studies of insecticide losses.

CHB(2) Proposal for a NERC airborne flight over Battle Farm, Benson to ascertain, with field surveys and data from the farmer, contributing factors for variations in cereal yields as a result of variations in hydrological parameters.

Hydrological Modelling

RJM(1) High resolution rainfall forecasts over south west Britain as part of the HYREX project. Meteosat images received at IH in the form of cloud top temperatures at half hour intervals (Jon Finch) are used with weather radar and climate station data in a simplified dynamic model of a cloud column to forecast rainfall on a 2 km space grid at 15 minute intervals.

RJM(1) Land classifications for selected catchments from Landsat images (Gareth Roberts). These are used in distributed flood forecasting models formulated on the weather radar 2 km grid. The urban fraction is used to introduce a partial impervious area controlling runoff production whilst different evaporation formulations can be used for forested and grassland areas in model water balance calculations.

Hydrochemistry

CN(1) Needs estimations of the extent of forestry practices - clear felling and afforestation - to model catchment streamflow losses mainly in the Plynlimon area but may be extended to other parts of the UK. The NERC airborne campaign over Plynlimon will be used to enhance Landsat classifications of the clear felling within the Hafren forest (Gareth Roberts).

Experimental catchments

JAH(2) Determination of snow parameters for NRA funded project with RJH.

JAH(1) Areal distribution of soil moisture for detecting contributing areas during low flow conditions. This may be obtained by analysing the NERC aircraft images.

GJLL(2) Channel characteristics (bank erosion) using low level coloured aerial photography.

GJLL(2) Determination of riparian vegetation using images from the CASI scanner on board the NERC aircraft under the LOIS initiative. Also, possible use of multi-temporal Landsat images for changes in land use.

JAH(1) Landsat classification of the upper Tees (Gareth Roberts).

KG(1) Norfolk Wetlands classifications using Landsat imagery (Gareth Roberts).

KG(1) New forest plantations in the Wye catchment using aerial photography (NERC airborne campaign).

RCJ(3) Snow cover in various Scottish catchments in relation to altitude and aspect. This could be done using real time Meteosat and near real time AVHRR (1 km resolution) images.

RCJ(3) Multi-temporal land classifications for various catchments in Scotland for natural forest regeneration and clear felling used for modelling suspended sediment.

RCJ(2) Land classifications of 4 River Basins - 1 in Nepal, 1 in Bhutan, and 2 in India, for relating river chemistry and biology to land use, soils, geology, etc. The proposal is under consideration of funding by the CEC and ODA.

ENGINEERING HYDROLOGY

Climate Change Impacts

Requirement for inputs to large scale (50 km by 50 km grid cell) hydrological models. Remote sensing possibilities:-

NWA(3) Daily rainfall data from Meteosat over east Africa and Europe.

NWA(3) Vegetation indices (NDVI, forestry/non-forestry) for East Africa and the whole of Europe. These are likely to be obtained from existing data sets and are to be used in evaporation formulations developed in the Hydrological Processes Division of IH.

National Water Archive

IGL(3) Rainfall inputs to large overseas catchments - regressing areal extent of cold cloud temperatures to runoff records. Liaison with David Grimes, Department of Meteorology, University of Reading.

IGL(3) Possibility of applying IHACRES to Plynlimon using catchment characteristics (vegetation, contributing areas) obtained during the NERC 1993/94 airborne campaign.

Hydrologic GIS

NAR(3) Interested in stronger ties between Remote Sensing Section and spatial data base. In particular, need to evaluate the ITE land classification e.g. the extent of urbanisation obtained from aircraft imagery.

Flow regimes

AG(3) Studies of the development of low flows on land use, particularly extent of urbanisation and water bodies, in the UK. Will probably utilize the ITE land classification, but may need land use change and more localised classification for selected catchments.

ARY(2) Stream temperatures in the Lambourn catchment from the NERC 1994(?) airborne campaign. Joint proposal with BGS (Helen Jones) to study aquifer recharge into the Lambourn.

AB(2) Areal evaporation estimates in Zimbabwe required for drought monitoring purposes. Being done in collaboration with John Stewart.

AB(3) Normalized Difference Vegetation Index for southern Africa to be obtained from NUTIS.

AG(3) Need a land classification for Western Europe, particularly France and Germany. Will probably be obtained from existing data sets.

AG(3) Rainfall rates over mountainous regions e.g. the Philippines.

Flood and storm hazard

DWR(3) Stream drainage networks digitized from aerial photographs used for comparison with networks generated from a DTM and from digitizing maps. The latter tends to underestimate the true network whilst the DTM takes no account of soils or geology.

DWR(3) Estimates of the areal extent of rainfall over GCM squares using different scales of input data. Initial work will be confined to the HYREX data sets, but may possibly use additional data from the Meteosat receiver.

Distributed modelling

PSN(3) Input parameters for large scale catchment (> 10,000 sq km) models initially in the UK but possibly overseas in the future. Will probably use existing spatial data sets, with a possible need for the areal extent of snow.

PSN(3) Rainfall/runoff modelling for flood events and sediment losses in the UK under the LOIS initiative. Will probably use existing spatial data sets, notably the ITE land classification.

PSN(3) Large scale soil moisture distributions.

Urban hydrology

JCP(1) Identification of urban areas. Inter-comparison of various urban classifications including digitized large scale maps, analysis of aircraft and satellite remotely sensed images, and ground surveys. Also, an interactive urban classification of remotely sensed imagery based on shapes would be of interest.

APPLICATIONS RESEARCH AND POLICY

Water Resources Systems

RBB(3) Estimating shallow groundwater recharge in arid zones. Spatial rainfall inputs to the area of interest by Meteosat images using the algorithm appropriate to the type of rainfall and area. Spatial variation in shallow groundwater recharge by vegetation inference using multi-temporal images from high resolution satellite sensors such as Landsat and SPOT. Such an application has already been done by Jon Finch for areas of Botswana.

RBB(3) Detection of changes in agriculture from traditional methods using shallow groundwater (spate) irrigation to more recent pumped irrigation from deep groundwater sources. This may be achieved by the analysis of multi-temporal high resolution images, as traditional methods produce only seasonal crops whilst pumped irrigation can, in theory, lead to all year agricultural production. Associated with pumped irrigation is the problem of soil salination, and it may be possible to detect the onset of this by vegetation inference.

RBB(3) Updating inventories of borehole locations using aerial photographs.

RBB(3) Determine sources of pollution by monitoring the quality of water courses e.g. the occurrence of blue-green algae as a result of nitrate and phosphorus runoff from agricultural areas. The analysis of multi-temporal aircraft photographs/images to determine the effects of alleviation schemes.

RBB(3) Shallow groundwater discharge (low flow springs and vegetation/soil indicators of shallow groundwater in sabkhas).

JRB(2) Field by field classification of Jersey by aerial photography at a number of times in a year. Estimates have been provided by Ken Blyth using the IH aircraft door. The classification to be used to extend SVAT functions for various vegetation types over a large (whole of Jersey?) area.

HYDROLOGICAL PROCESSES

Global processes

CRL(1) Vegetation patterns (1 m resolution) in a 1000 m by 1000 m square surrounding the towers in Niger. This has already been digitized and now needs to be registered to a base map and transferred to the appropriate data base (Gareth Roberts/Jon Finch).

CRL(2) Surface ponding and snow cover at fine resolution (aircraft images) required for the Tundra project. Also, there is a possibility of using the IH aircraft door, though technical difficulties make this unlikely.

RJH(1) Convective rainfall (mm/day) and land use maps of west Africa from AVHRR and Landsat images. The two spatial data sets to be integrated to produce soil moisture distributions for mesoscale modelling. The rainfall estimates are being obtained from Reading University whilst the land use estimates are being done at IH (Jon Finch).

RJH(1) The identification of snow for mesoscale modelling in the BOREAS study in Canada. Various snow parameters - water equivalent, density, variation of snow depth - required over grid squares. John Stewart to coordinate IH Remote Sensing Section's role.

RJH(2) Areal extent of snow cover and its relation to altitude, aspect and type of slope (concave or convex) for flood forecasting over the UK.

RJH(3) Various vegetation parameters - percentage vegetation cover, leaf area index, albedo, canopy roughness - for input to Soil Vegetation Atmosphere Transfer Functions. Gareth Roberts to coordinate when more concrete proposals appear.

IRW(3) Quantify seasonal and spatial variability of tropical forest albedo. Ground truth all-wave albedo available. Also, possibility of adding narrow band satellite simulators.

IRW(3) Rainfall distribution within GCM grid squares over the Amazon Basin.

Sustainable dry land use

JMR(3) Land classifications of limited regions of the Amazon using Landsat and SPOT to determine how vegetation differences, soil moisture differences and hence moisture stress varies with topography.

JB(1) Degradation processes in Zimbabwe. Need to integrate land use (Jon Finch), soils, a digital terrain model, and geology into a Geographic Information System. Also, an interest in temporal variations in land use and rates of degradation. This may be obtained most cheaply by utilizing Landsat MSS images if the spatial resolution (80 m) is considered adequate.

JB(2) Need to integrate a digital terrain model, a land classification, geology, and extent of irrigated area for groundwater recharge estimates in Crete. The first two parameters will be provided elsewhere, but there are possibilities of IH Remote

Sensing Section contributing to the extent of irrigated area either through multi-temporal ERS-1 microwave imagery (Ken Blyth) or via vegetation indices from Landsat or SPOT (Jon Finch/Gareth Roberts).

MGH(2) Hydrological process studies in Amazonia within the Lambada - Baterista experiment. Remote Sensing could provide the soil moisture distribution, streamflow contributing areas, and land cover, including land use change. Initially, remote sensing would be used in the site selection process, and subsequently for scaling up from the small basin studies. A study proposal, including a remote sensing input, is currently under discussion within IH.

MGH(1) Classification of West Wood, Savernake Forest using multi-temporal Landsat images (Gareth Roberts). The classification will be compared with the information obtained from a Forestry Commission compartment map to determine whether it is possible to differentiate between tree species, age, and condition. This is really a test of the method, to see whether deciduousness can be readily detected; in Amazonia, this may be very subtle.

RR(3) The areal distribution of near-surface soil moisture for agricultural scheduling-irrigation, ploughing, and planting. Also, together with surface temperature, to provide an areal distribution of actual evapotranspiration using a two layer model.

SJA(3) Desertification in the Sahel - changes in time could be determined by the analysis of multi-temporal remotely sensed imagery. Landsat MSS, 80 m resolution, would seem to be the best option.

Land use and water efficiency

HMG(2) Water balance studies in Africa. For Lake Malawi, spatial rainfall inputs to be provided by James Milford, Reading or in-house by Jon Finch (estimates of costs involved have been made). Vegetation cover (forest/non-forest) to be provided possibly from existing data sets (Department of Geography, Reading). It is possible that extended land cover will be required for some sub-catchments. Similar requirements will be required for modelling the Zambezi.

HMG(2) Real time management of water resources in southern Africa. Joint proposal between IH, NRI (Jim Williams), and Reading University. Possible role for IH Remote Sensing Section in estimating areal distribution of rainfall. John Stewart to coordinate.

MR(1) The spatial distribution of near surface soil moisture in particular over the River Ock catchment at Abingdon. Of particular relevance are the areas of grassland based on existing Landsat images at IH (Gareth Roberts), and Ken Blyth's work on ERS-1 microwave images, involving two instrumented sites under grassland at Newbury and Lechlade. Also, a general interest in the results of the NERC airborne campaign over the grassland areas of Plynlimon.

MR(1) A requirement for a catchment boundary for the Coalburn catchment using stereo aerial photographs. Gareth Roberts to provide once the photographs have been obtained.

JDC(1) Estimates of the spatial variation in rainfall, vegetation, and soils in Niger for inputs to calculations of aquifer recharge. Jon Finch to provide the necessary data. Similar data will be required for India if the Western Ghats project gets underway.

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