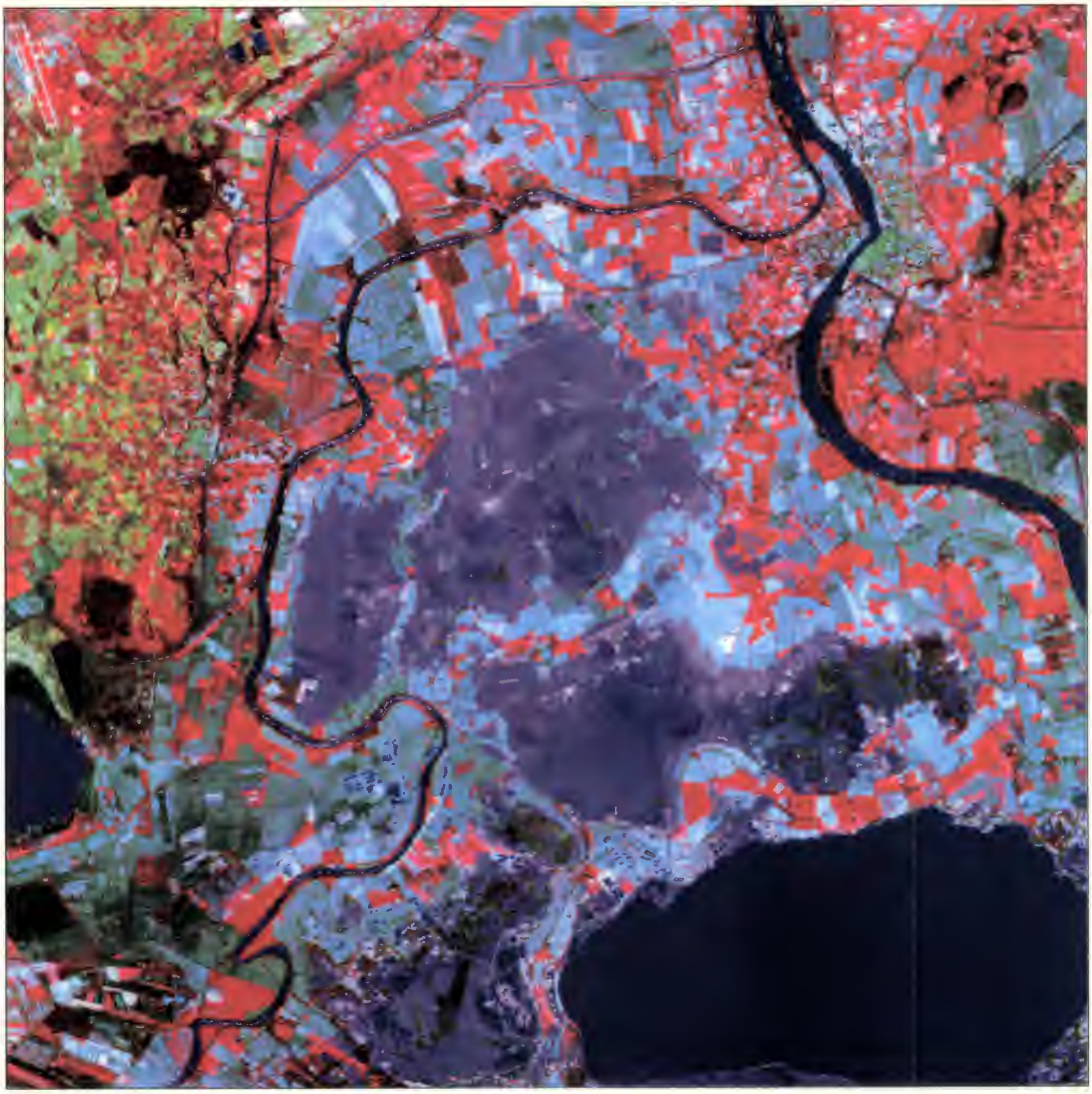
SP-1207

Satellite Data in Hydrology

Experience with ERS



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Contents

1. Introduction

1.1 Scope

Water is essential to human existence. The availability of a water supply is the first requirement for any settlement or agriculture. Similarly, flooding can represent a threat to many activities and must be controlled. Hydrology is the branch of science which addresses those components of the hydrological cycle affecting land areas. It underpins operational water supply and flood alleviation as well as furthering our understanding of the Earth system and climate over longer time scales.

Measurement and monitoring are fundamental to scientific understanding and are thus requisites for modelling and forecasting. In hydrology, measurements have generally been restricted to sets of point locations, such as soil moisture probes or gauging points on rivers. Despite the fact that hydrological techniques have developed to maximise the benefits from such data, the ability to measure spatially distributed variables has long been an aim in hydrology. Applications where the hydrological records are insufficient or where major characteristics of a river catchment have changed, are particular examples which would benefit from this capability.

Remote sensing offers the potential to observe variability over large areas consistently and almost instantaneously. To date, remote sensing has provided useful input, but has not yet played a major role in hydrology. The reasons for this include a lack of sensors which respond directly to key hydrological variables and also the influence of cloud cover on the availability of the information. In addition, realising the potential of remote sensing requires changes to the hydrological techniques used for analysis, changes that are still in the process of being developed.

The ERS satellites carry a range of sensors which offer considerable potential for developing the application of remote sensing to hydrology. These applications have reached a variety of stages. Some are already operational, with contractual links established between user organisations and suppliers of remotely sensed data, while others are either still at less mature pre-operational or research stages.

This document examines the requirements for hydrological data, how they are currently being used and the outlook for future developments towards operational applications.

1.2 Intended readership

This document is aimed at both current and potential users of ERS data in hydrology. It demonstrates the existing uses of ERS data in this field, considers the potential for further development and examines the issues affecting hydrological application of ERS data specifically.

1.3 Structure

Section 2 explores basic issues in physical hydrology, leading to the requirements for observation data. The basic capabilities of remote sensing sensors are then considered.

Section 3 considers how the observation system offered by the ERS satellites can be integrated with hydrological applications. The characteristics of the instrument types are discussed, followed by an analysis of what the ERS instruments in particular can achieve.

Section 4 considers what analysis is required to use ERS data effectively in hydrology applications and provides examples of key applications. These cover both the analysis of the remote sensing data and the hydrological techniques within which these data are being used. Consideration of hydrological techniques is important because new spatially distributed modelling approaches are likely to be critical in realising the full operational potential of ERS data in the longer term.

Sections 3 and 4 together demonstrate the potential for hydrological applications and the ways in which this potential may be realised. The contributions made to this process by ERS-1 and 2 are considerable because of the accuracy, stability and continuity of the mission. Section 5 thus shows the value of these characteristics and how they have provided a solid foundation for future developments.

Sections 6 and 7 cover the outlook for activities in this area and recommendations to encourage operational applications of remote sensing systems in the area of hydrology.

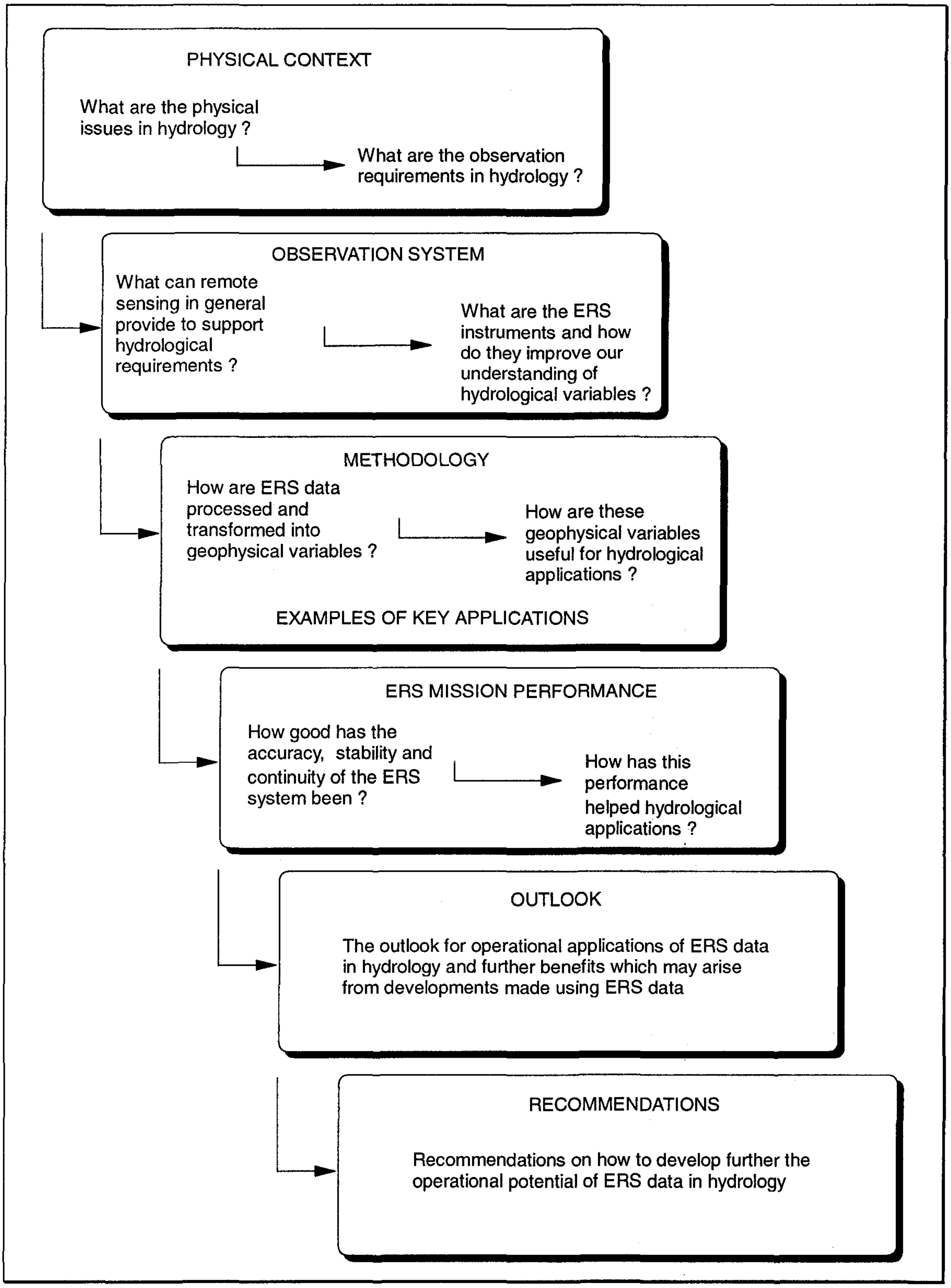
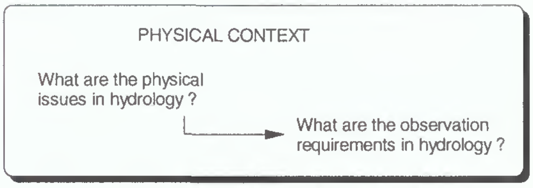


Figure 1-1: Methodology underlying the document structure

2. Physical Context



2.1 Physical issues in hydrology

Elements and scale

Hydrological science seeks to improve our understanding of the hydrological cycle in terms of its process and storage elements. The ways in which these processes and storages interact are driven by the structure of the land areas in which they exist. The main elements of structure, process and storage are summarised in Figure 2-1.

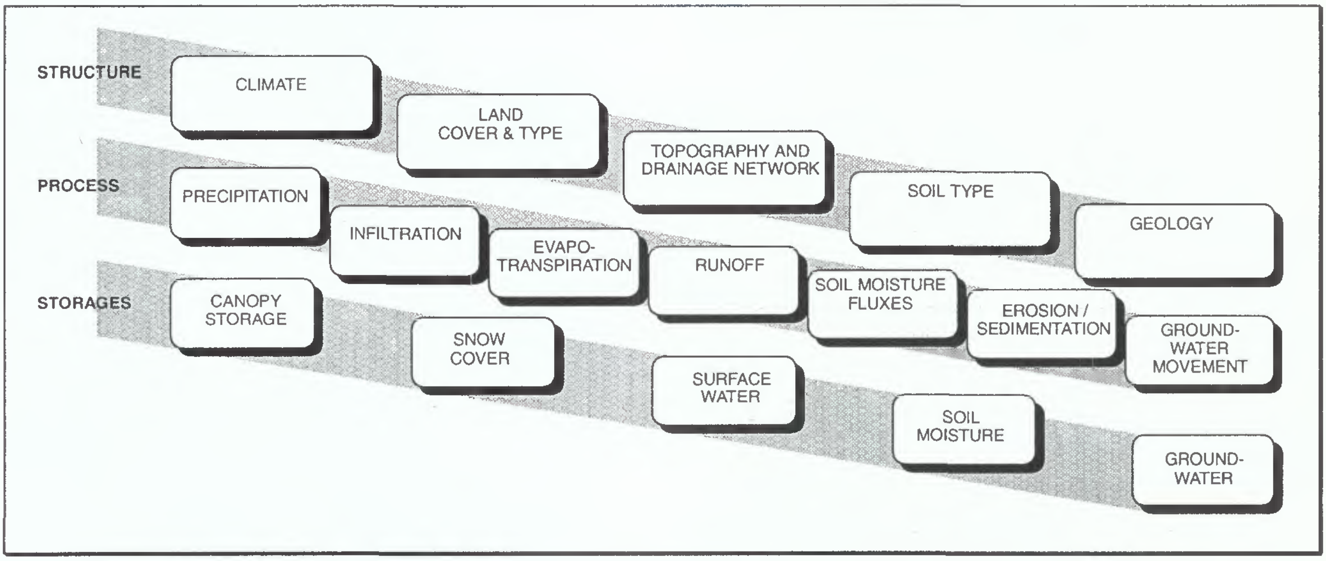


Figure 2-1: Structure, process and storage elements of the hydrological cycle

Hydrological investigations consider the elements in Figure 2-1 for a variety of applications and thus examine a wide range of spatial and temporal scales. As the scales change, the critical factors determining the success of the investigation also change. Figure 2-2 illustrates how scientific and operational applications vary according to the scale of investigation in hydrology. The left side of the diagram shows the scientific applications whilst operational applications are shown on the right.

For scientific applications, local scale plot studies are often the key to process understanding. Measurements and modelling activities at this scale are also essential foundations for work at larger scales. This is well illustrated by local scale studies which have been coordinated to examine representativeness at larger areas.

The catchment, though varying dramatically in size, is a natural framework for hydrological studies since it represents a semi-closed system. Catchments are often the basic units in water management. Large basins may be broken down into smaller sub-catchments for analysis. As part of large-scale work, regional and global scale basin studies are now gathering force within scientific research. This partly reflects the growing sophistication of General Circulation Models (GCMs), used to model the Earth's climate as a whole, which require an increasingly sophisticated treatment of the land atmosphere interface.

Scientific studies of hydrology provide a basis for analysis and decision making. Industrial and governmental decision makers require the greatest

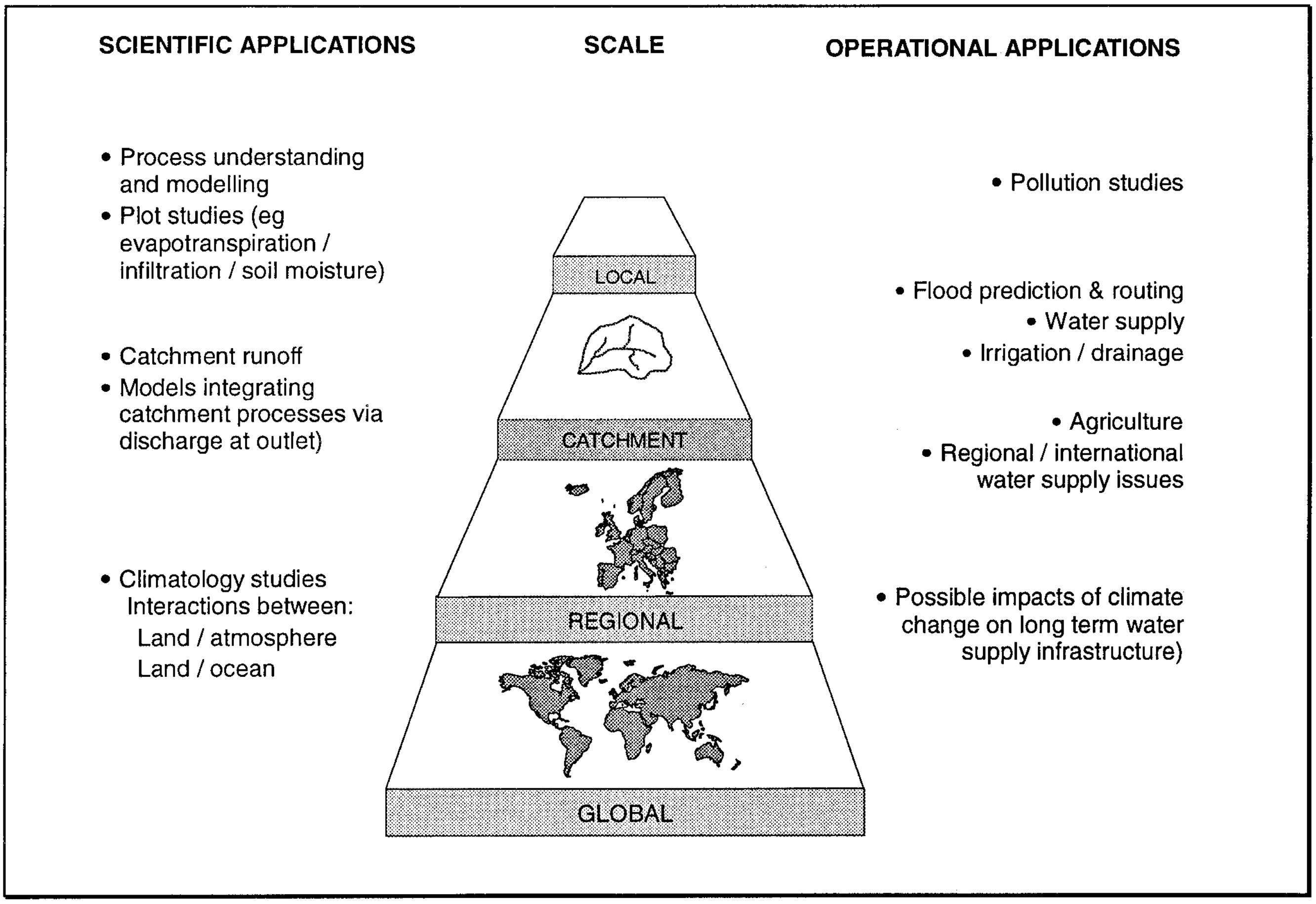


Figure 2-2: Scientific and operational applications at different hydrological scales

possible confidence in climate scenarios, and this needs a strong hydrological input. Operational applications of hydrology tend to concentrate at the catchment scale, but considerations of this type exist at most scales. For example, pollution control, agriculture and water supply all raise issues at local level, while international water supply issues and climate change have large-scale regional implications. Operational applications can either be related to the design of new hydrological schemes and the analysis of their effects, or to the management of existing facilities such as dams and other hydraulic structures.

Hydrological measurements

The hydrological activities discussed above have some common characteristics, but perhaps the most important is the requirement for measurements. This can be summarised in the following two quotations:

'*The complexity of hydrological phenomena makes it difficult to apply rigorous deductive reasoning. It is necessary to interpret observed data and from this analysis to establish the systematic pattern that governs these events. Without adequate historical data for the problem area, the hydrologist is in a difficult position.*' (Linsley et al. 1982)

'*Typical hydrologic problems involve estimates of extremes rarely observed in a small data sample, hydrologic characteristics at locations where no data have been collected (such locations are much more numerous than sites with data), or estimates of the effects of human actions on the hydrologic characteristics of an area.*' (Linsley et al. 1982)

In other words, as with many fields of endeavour, hydrologists are typically addressing problems with a lack of suitable data. Traditional methods for forecasting streamflows are generally based on point measurements, such as records of discharge at river gauging stations. Similarly, rainfall, soil moisture and snow cover are normally measured at points using raingauges, soil probes and snow depth gauges. The spatial situation must then be interpolated from these measurements.

The reason for the reliance on point data is that no effective, regular and consistent means of spatial measurement has been available. In addition, the models required to make full use of spatial data are computationally demanding, making them inaccessible to some users until recently.

The means to make spatial measurements of many required variables now exists through satellites, and the necessary computational power is readily available to most users with the emergence of powerful desktop PCs and network communications. There are obstacles to be overcome before spatially distributed, physically based methods can reliably be used in place of existing techniques. However many of the limitations to the development of these methods, which offer great potential in many of the 'typical' hydrological problem situations described above, are currently being resolved or addressed.

Unlike spatial distribution, traditional hydrological measurement techniques generally provide good temporal sampling and often record data continuously. Until recently, the main problem with such instruments has been data retrieval, but this is now a less important problem due to more advanced telecommunications links. Perhaps a greater problem with in-situ measurements is the monitoring and maintenance of the equipment itself. It is not uncommon for such instruments to be damaged by natural conditions or tampered with by people or animals.

2.2 Requirements for observations

Stated requirements in any field represent a balance between the desirable and the possible. Such has been the case in hydrology where the absence of techniques for measuring spatial variability consistently has meant that data requirements have concentrated on point or linear measurements.

Remote sensing offers new sources of suitable spatial measurement, and consistent time sequences are being built up to allow empirical methods to be used where necessary. However, the requirements listed below are expressed in terms of the needs of a physically based distributed model of the hydrological system at a catchment scale. The requirements can be considered in terms of both relatively fixed parameters and more rapidly changing variables.

Observations of hydrological system structure

Whether modelling a catchment or investigating processes within it, measurements of the fixed or

Element	Description
Climate	• Knowledge of long-term changes in weather patterns • Design specifications such as Probable Maximum Precipitation
Land cover and type	• Vegetation type and distribution — required across the catchment due to effects on interception, temporary storage of rainfall, possible effects of root channels on throughflow, effects on soil infiltration and importantly on evapotranspiration • Surface and subsurface characteristics — additional surface characteristics such as extent and location of urban areas and roughness for overland flow
Topography and drainage network	• Ground surface elevation — the variation in surface elevation across the catchment, the location of channels and potential source areas which may saturate during and following rainstorms
Soil type	• Soil type and distribution — required across the whole catchment, determining infiltration, levels of overland flow and throughflow, control of evaporation and often a determinant of vegetation types
Geology	• Type of underlying geology • Impermeable bed elevation — elevation to which water can percolate vertically before an impermeable barrier is reached

Table 2-1: Requirements for observations of structure

Element	Description
Precipitation	• Regular/continuous measurements of precipitation required • Traditionally measured by raingauge networks • Geostationary satellite data now used operationally to provide spatial data
Canopy storage	• Storage of precipitation in the vegetation canopy prior to evaporation or throughfall to the surface and infiltration to the soil
Infiltration	• Process by which water enters the soil from the surface
Snow cover	• Snow stored on the surface represents potential river discharge • Volume, distribution and temperature of the snow are key factors • Status of the snowpack & meteorological information can give ablation rate
Evapotranspiration	• Transfer of water from the land/snow surface or from the vegetation canopy to the atmosphere, normally measured indirectly • Data requirements a function of the extent to which the process is modelled physically and may include components of the radiation budget. • Meteorological data including wind and humidity combine with surface characteristics such as aerodynamic roughness
Runoff	• Movement of water over the surface towards the stream network • Includes monitoring/prediction of flood events
Surface water	• Areas of surface water including semi permanent features such as lakes and transient features such as variable source areas
Soil moisture	• Storage of moisture within the soil at a number of different levels • Distribution within the soil is a function of the soil type, layering effects in the soils and the meteorological history
Soil moisture fluxes	• Vertical flux in response to precipitation events and evapotranspiration uptakes • Lateral flux in response to the topography • soil wetness.
Erosion and sedimentation	• Soil erosion and resultant sedimentation cause the loss of valuable agricultural land and can destroy the effectiveness of reservoirs
Groundwater	• Water in geological structures (aquifers) underlying the soil column • Important to water supply and can be recharged artificially
Groundwater movement	• Controlled by the subsurface geology and pressure head

Table 2-2: Requirements for observations of process and storage variables

slowly changing aspects of a catchment or study area are essential. These represent the structure within which the model or investigation must operate. The following table summarises these requirements.

Observations of process and storage variables

Table 2-2 presents a range of storages and interacting fluxes. It is normal to monitor the storages and thus to infer the fluxes, but in some cases fluxes are measured directly, as with discharge.

Requirements for measurements of variables must include a specification of the temporal sampling interval. For many variables, the rate of change is a direct function of structural elements. For example, when measuring changing soil moisture after a rainstorm, the soil type and vegetation cover will determine whether the measurable effects of the rainstorm are dissipated within hours or days. The sampling interval must thus be specified accordingly.

Additional requirements relating to the operational environment are:

Reliability:	information must be available when required;
Timing:	information must be available at or close to the time required;
Timeliness:	information must be supplied within a given time after observation;
Accuracy:	information must be within the accuracy and representativeness tolerances necessary for the application;
Consistency:	changes in accuracy of measurement over time must be avoided.

Table 2-2 summarises the requirements for the key process and storage variables set out in Figure 2-1.

Requirements derived from hydrological models

Although it is appropriate to consider measurements at an elemental level for many applications, the way in which they are combined, ie through models, is also very important.

Many hydrological activities involve the use of models. The types of models used are illustrated in Figure 2-3. This illustrates that with the commonly used empirical approaches (black box and conceptual) at least some of the variables within the system are lumped together as effective parameters. This in turn makes it difficult to use the standard measurements specific in Tables 2-1 and 2-2 within the models. Only with the physical models are the variables described above used explicitly.

The fact that the majority of models used for operational purposes are empirically driven conceptual models is a reflection of the complexities of the hydrological system and the difficulties in obtaining representative spatial measurements. As a result the transition to physically based distributed models,

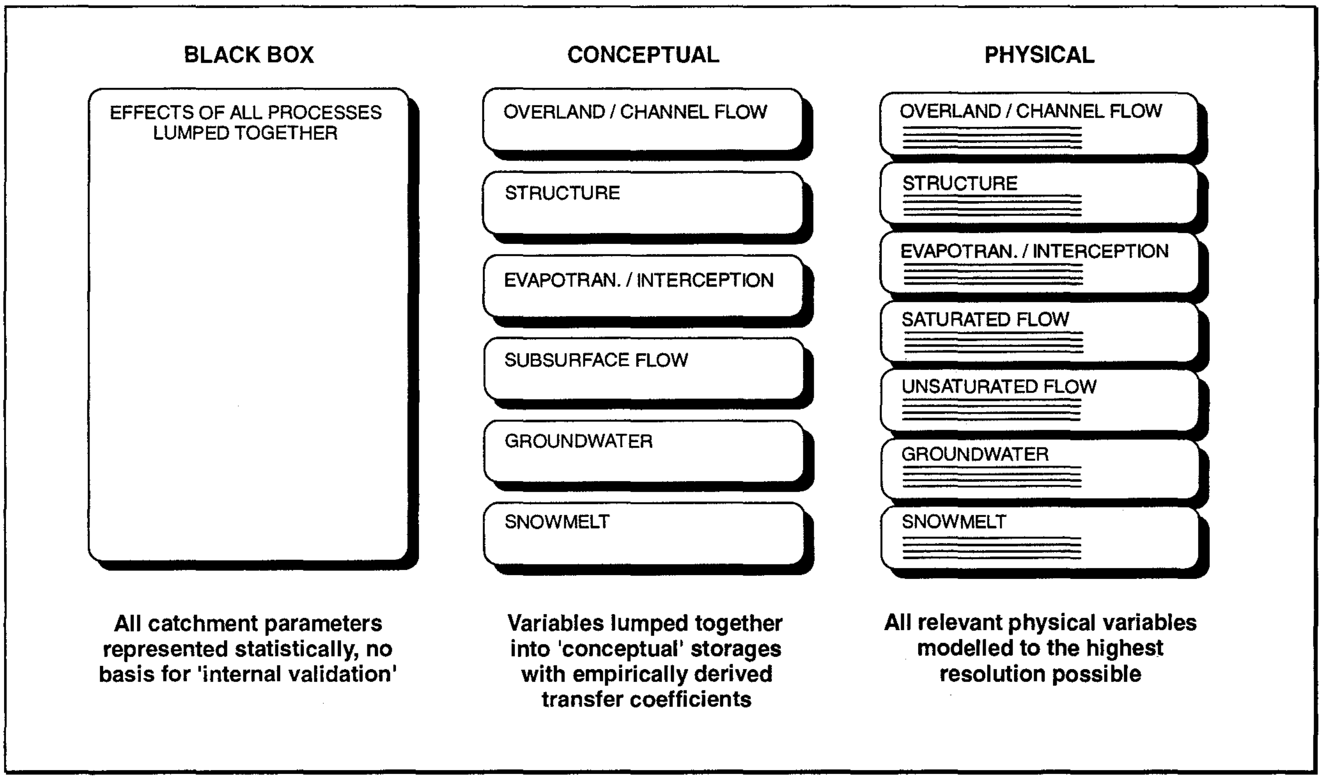


Figure 2-3: Types of hydrological model

which in principle have directly measurable variables, is difficult to achieve. To illustrate this, the following example can be considered. Physically based models represents volumes within a catchment with single point values. Consequently a volume which may be 100 x 100 m horizontally and 20 cm vertically or larger will only have a single value for variables such as soil moisture. For each variable represented in this way, two key questions arise:

1. Does a single set of values exist which will represent the variation within this volume across the full range of expected conditions (including extreme events)?

2. If this set of values does exist, how can it be measured or derived effectively?

Simple answers to these questions do not exist and continuing research is required. It is, however possible to suggest that as remote sensing techniques develop, these should become instrumental in enabling the development of more advanced models. It has long been recognised that such models offer hydrologists a range of new opportunities, such as modelling catchments with poor in-situ records, or where changes have occurred. To date, these opportunities have only been partly realised. If remote sensing can assist in this regard, it will have made a valuable contribution to hydrology.

3. Observation System

OBSERVATION SYSTEM

What can remote sensing in general provide to support hydrological requirements ? → What are the ERS instruments and how do they improve our understanding of hydrological variables ?

3.1 Remote sensing techniques and hydrology

A remote sensing instrument measures the energy reflected or emitted by its target. This requires an initial energy source which may be provided by the instrument (as with radar) or by the sun (as with visible and infrared instruments). On the path between the source and the target and on the return path to the sensor (together the transmittance path) additional factors may influence the sensor's measurements. The nature of these effects is a function of the wavelengths measured by the sensor and their interactions with atmospheric and possibly vegetation characteristics. These effects can be considerable and thus in order to achieve the accurate and repeatable results necessary for many applications, the effects must be controlled. The operation of a visible/infrared and radar remote sensing instruments is illustrated in Figure 3-1.

By adopting a range of wavelengths, specific signatures of different surfaces and surface conditions can be identified. Sensors using solar energy as a source operate in the ultraviolet, visible and infrared wavelength bands between about 0.3 and 10 μm. Microwave sensors operate at wavelengths between about 1 mm and 1 m.

Once the appropriate corrections have been applied, the operation of a remote sensor provides a set of measurements of target response, with each individual value representing the individual response from an area whose size is governed by the instrument's spatial resolution. This information is normally presented in the form of an image field showing the spatial distribution of different responses.

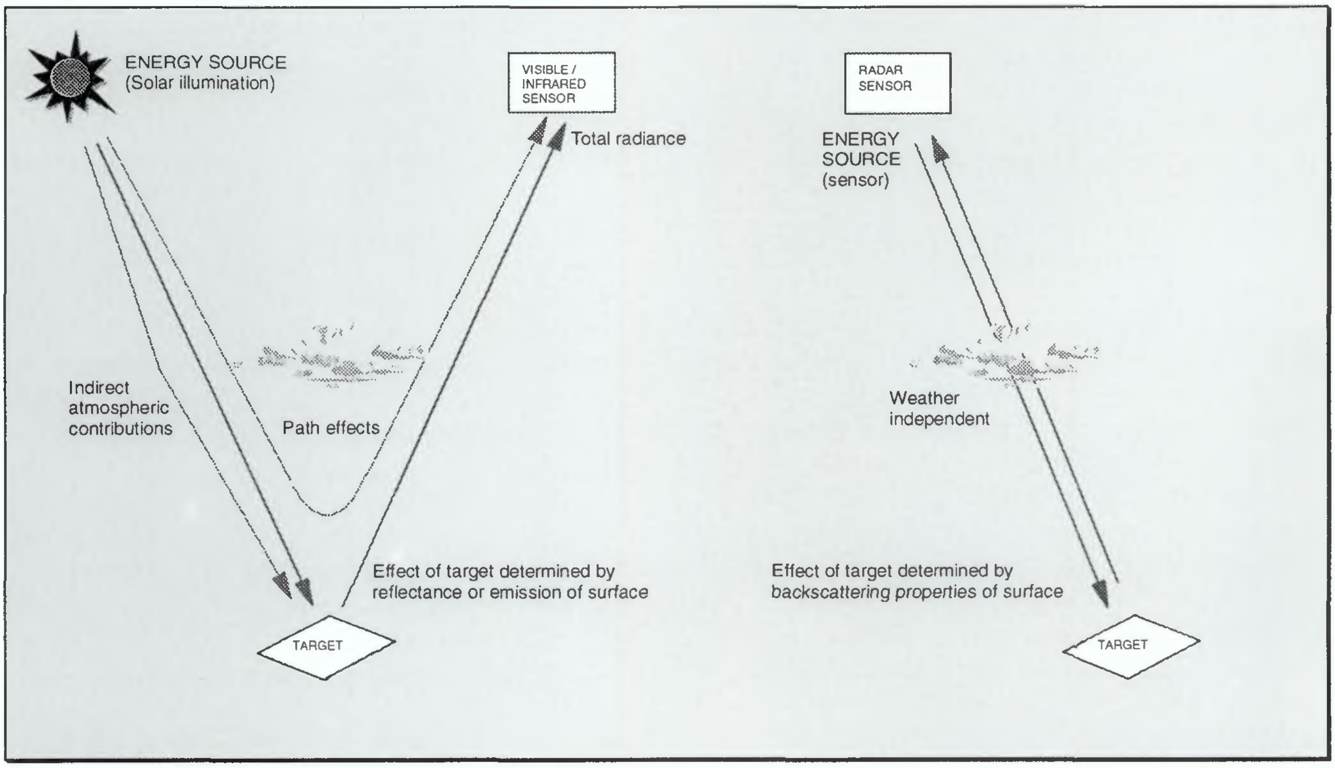


Figure 3-1: Basic elements of remote sensing (visible/infrared and radar)

	Active	Passive
Microwave (1 mm to 1 m wavelength)	SAR (eg. ERS-1/2, JERS-1 and Radarsat) Scatterometer (eg. ERS-1/2) Radar Altimeter (eg. Geosat, ERS-1/2, Topex/Poseidon)	Imaging passive microwave radiometer (eg. DMSP SSM/I)
Optical (0.3 to 10 μm wavelength)	Lidar (eg. airborne laser ranging is used for floodplain determination)	High-resolution radiometers (eg. Spot, Landsat) Lower-resolution radiometers (eg. ATSR, AVHRR)

Table 3-1: Remote sensing instruments with hydrological applications used on low Earth orbiting satellites

The next stage is to go beyond this level and to relate the measured target response to quantitative hydrological variables. The techniques for making these transformations will be considered further below. In summary the areas in which remote sensing can support hydrology, following *Barrett & Herschy, 1989*, are:

- *Precipitation:*
  rainfall monitoring
  severe storm/flash flood forecasting and evaluation
- *Snow hydrology:*
  cover and water equivalent mapping, measurement and monitoring
- *Evapotranspiration:*
  estimation and monitoring
- *Runoff:*
  surface water inventory and monitoring, eg. of rivers , lakes, marshes and reservoirs extremes of surface water presence or availability, ie floods and droughts sedimentation patters and rates in reservoirs, and deposition in rivers
- *Soil moisture:*
  measurement, though mainly for unvegetated or sparsely vegetated localities
- *Groundwater:*
  . mapping and assessment
- *Water quality:*
  pollution monitoring
- *Hydrological forecasting* of the above parameters and phenomena and numerous dependent variables
- *Data collection* from in-situ sensors and/or the relay of information from elsewhere.

The list above is based on the possible use of a number of remote sensing sources. These include airborne as well as satellite sources from geostationary and low Earth orbits (such as the orbits of the ERS-1 and ERS-2 satellites). All of these sources can provide valuable hydrological information, but unlike airborne sources, satellite sources offer the potential for regular and consistent observation.

Weather satellites in geostationary orbit, such as Meteosat, offer very frequent observations (currentky every 30 minutes) which are of particular value for monitoring rapidly changing phenomena but are limited in the spatial resolution they can provide. Satellites in low Earth orbit can provide much higher spatial resolution, though the revisit time for a location is much longer (for example 3 to 35 days). The nature of the contribution to hydrology is therefore dependent on the types of instruments carried on the satellite, their resolution and their swath width. Remote sensing instruments which have hydrological applications can broadly be classified as shown in Table 3-1.

3.2 The ERS missions and their instruments

There are two ERS satellites (ERS-1 and 2), both of which carry almost identical payloads. The ERS-1 satellite was launched on 17 July 1991 and ERS-2 on 21 April 1995. The ERS satellites carry a payload of three main instruments directly relevant to hydrology, the Active Microwave Instrumentation (AMI), Along-Track Scanning Radiometer (ATSR) and Radar Altimeter. The AMI provides the capabilities of two different instrument types, a SAR and a Scatterometer. Similarly, the ATSR contains both an InfraRed Radiometer (IRR) and a Microwave Radiometer (MWR). The capabilities relevant to hydrology are:

- *Synthetic Aperture Radar (SAR).* This can operate in either image mode or wave mode and provides data day or night, irrespective of weather conditions. It uses an incidence angle of 23° and a frequency of 5.3 GHz. In image mode, which equates to normal SAR operation, the signals retrieved are vertically polarised and have a ground resolution of about 25 m. The responses are processed to provide a radar image. The wave mode is used to provide two dimensional spectra of ocean surface waves.

- *ATSR*. The IRR provides measurements of sea surface temperature, as well as cloud top temperature, cloud cover, water vapour and land surface temperature. The version of the instrument on ERS-2 (ATSR-2) carries three additional visible channels intended for vegetation related applications.

- *Scatterometer*. This is designed to measure sea surface wind speed and direction at the ocean surface, but is also being used for land applications where backscatter is being correlated with surface cover and moisture condition. The frequency of the instrument (5.3 GHz, with vertical polarisation) is sensitive to land surface characteristics such as vegetation cover and surface soil moisture content. Its low spatial resolution (50 km) corresponds to a wide swath and frequent coverage, making it suitable primarily for global monitoring.

- *Radar Altimeter*. This active microwave instrument provides accurate sea and ice surface elevation. Information on significant wave heights, various ice characteristics, an estimate of sea surface wind speed and gravity information from the sea bed can also be derived. Land applications of altimetry are currently limited, but examples such as lake level monitoring and large scale DEM determination are being developed.

Although the ERS instruments were optimised for oceanographic applications in keeping with the emphasis of the mission's original objectives, all have been used successfully for land applications. The ERS instruments used for hydrological applications represent a wide range of approaches to sensing, but have some features in common, notably:

— they are highly calibrated and stable instruments;
— they have designated successors on future satellite missions, allowing current work to become the basis for future development. This is an especially important feature for operational uses.

The ERS-1 mission has been divided into a number of mission phases. Each phase is a period within which the orbit characteristics and priorities for sensor operations are set for a specific objective and left unchanged. These were designed to enable the various mission objectives to be achieved.

The first two phases covered the launch, early orbit and commissioning periods which were successfully completed by 12 December 1991. Since this time, the main mission phases have been as follows:

- *First ice phase* (December 1991 to March 1992). Optimised for Arctic ice experiments, this phase was characterised by a 3-day repeat cycle with high repetition, especially of SAR data in the polar and marginal ice zone;

- *Multi-disciplinary phase* (April 1992 to December 1993). This provided a 35-day repeat cycle with a much greater density of radar altimeter data and at least twice the frequency of coverage of SAR imaging at middle and high latitudes;

- *Second ice phase* (January 1994 to March 1994). This had the same characteristics as the first ice phase;

- *Geodetic phase* (April 1994 to March 1995). Two 168-day repeat cycles, one shifted 8 km from the other, allowed a high density of altimeter measurements to be recorded improving the availability of data for solid Earth applications. The SAR followed a similar profile to the multi-disciplinary phase;

- *Second multi-disciplinary phase* (March 1995 to the end of the mission). This has the same characteristics as the first multi-disciplinary phase.

Despite a design life of 30 months, the good health of ERS-1 after four years of life allowed for the possibility of tandem operations with ERS-2 which was launched on 21 April 1995. The tandem phase began on 17 August 1995 following the successful commissioning of the ERS-2 SAR and the Radar Altimeter.

During this tandem phase, the satellites are kept in a 35-day repeat cycle with a 30-minute offset in the same orbital plane (i.e. a 1-day offset in ground revisit for ERS-1 and ERS-2). The orbit maintenance scenarios are intended to optimise baselines for specific applications such as elevation mapping and change detection. As well as the opportunities for interferometry and increase spatial sampling from the two satellites, the tandem mission offers the possibility to compare observations from instruments of the two satellites to assess accuracy of measurement.

The sections which follow address the application of the ERS instruments to hydrological applications. In each case, a brief description of the instrument operation is given, followed by a table which describes its application to the observation of hydrological variables. These variables are derived from those required to run a comprehensive physically based distributed model.

3.3 ERS instruments and their hydrological applications

SAR

The ERS SAR is sensitive to a number of factors of interest to the hydrologist. These include

— soil moisture;
— vegetation cover;
— surface roughness;
— surface slope.

The SAR's response to soil moisture relies on the dielectric properties of the soil, which vary significantly according to its moisture content. Water has a dielectric constant of about 80 at microwave frequencies and a moist soil can have values in excess of 20. Dry soils have values in the order of 3 to 5 *(Engman and Gurney, 1991)*. The range between the dielectric constants of wet and dry soil can give rise to a change in radar backscatter of 10 dB or more *(Schmugge, 1990)*, which represents a considerable part of the instrument's 21dB dynamic range.

The soil type is also important because, for example, the difference between wilting point and field capacity is much larger in clay soils than in sandy soils. The degree of penetration of the signal into the soil is a function of the soil composition as well as its moisture content. This can be considerable in very dry sandy soils, but in general it is the moisture levels of the top 5 cm which influence the SAR measurements.

SAR response to vegetation cover is a function of the attenuation of the transmitted and backscattered microwave signal by the canopy This is controlled by the angle of the signal beam, its polarisation and its frequency, together with the structure, height, density and wetness of the vegetation canopy.

The effects of surface roughness on an image are related to the geometric structure of the surface pattern and the degree of alignment with the SAR viewing geometry. Similarly, the overall slope of the ground surface and its alignment with the beam will affect the response.

A SAR image of an area will initially represent the combined effects of these characteristics and in order to extract one, the others must be controlled. Slope is often controlled at the initial processing stage. Examples of methods for controlling other factors such as vegetation and surface roughness are considered in Chapter 4 (e.g. *Examples 2 and 3*).

Table 3-2 describes the capability of the ERS SARs for measuring a range of hydrological parameters and variables.

Scatterometer

The use of spaceborne scatterometers for land applications is a very recent but developing area. As a result, the range of applications is still limited but those applications which exist are relevant to the important field of global change monitoring .

Scatterometers operate in the microwave domain and the ERS Scatterometers share key components with the ERS SARs operating on the same frequency of 5.3 GHz. For its intended application of observing ocean winds, the Scatterometer measures the effects of small wind induced ripples on the ocean surface. These are converted, via a model, into the required wind speed estimates. The ERS Scatterometer has multiple antennas which observe the target with different incidence angles and thus provide different measures of backscatter for each angle. The antennas face 45° forward, 45° backward and side orthogonal to the satellite's track

As well as the intended ocean application, the responses from these antennas can also be used to provide quantifications of soil and vegetation conditions. The Scatterometer provides this information at much lower resolutions than the SAR, the resolution is 50 km, but the wide swath pattern allows for a much higher temporal frequency of observation. The low resolution may appear a handicap, but as well as being compatible with the grid pattern of GCMs it is also similar to the DMSP SSM/I passive microwave sensor, which is widely considered for large-scale soil moisture studies.

PARAMETER	SAR CAPABILITY
	OVERLAND AND CHANNEL FLOW
Water surface elevation and extent	• Possible to estimate water elevation in large channels and areas of standing water. • Identification of water is possible for channel sizes >30 m while measurement is only possible for channel widths >60 m. • In windy or variable conditions, water discrimination is hindered. • Water can easily be identified using its low coherence from SAR interferometric products (even with high winds). • Weeds, floating/submerged vegetation, turbulence and sediment complicate detection and delineation of flooded areas.
Overland flow roughness coefficient	• Backscatter is affected by surface roughness thus the response may allow some indication of the overland flow roughness. • Specification of this parameter is always difficult and it is unlikely that good results would be obtained.
Channel flow roughness coefficient	• Channel roughness is affected by bed material and may thus be inferred from surrounding soils and geology. • Water surface patterns over a rough bed could indicate roughness for large channels.
Channel morphology	• Channel width and slope may be measurable using interferometric DEMs. • Dry and wet season channels may also be identifiable in large channel systems, showing the possible movements in the channel over time in a braiding river. • In the case of heavily braided gravel rivers, good relations between SAR measured channel width and discharge have been achieved, as shown in Chapter 4 (Smith, 1995).
Drainage network	• Identification of the drainage network for a catchment via surface water detection. • Effectiveness limited with incised channels, but high incidence angle on ERS SAR limits this problem.
	STRUCTURE
Ground surface elevation	• Interferometric processing of SAR data can provide measurements of the ground surface elevation. • Accuracy from this method is currently comparable to that of DEM generation from Spot stereo pairs. Vertical accuracies of 10 m have been achieved.
Impermeable bed elevation	• This is a geological parameter which can only be inferred from the visible surface exposures. • SAR can penetrate dry sandy soil to considerable depths (depending on the frequency), and give an indication of the depth to the impermeable layer.
Soil type distribution	• Indications of soil type may be possible with bare soil, but in general, the response to the radar. is dominated by the condition of the surface.
Vegetation type distribution	• The basic vegetation type can be determined using SAR, particularly when multitemporal images of the same area are used. • The ability to distinguish vegetation types is enhanced when the data are used in conjunction with other data sources.

Table 3-2a: Suitability of ERS SAR for measuring hydrological parameters & variables

PARAMETER	ERS SAR CAPABILITY
EVAPOTRANSPIRATION AND INTERCEPTION	
Vegetation aerodynamic resistance	• Derived from vegetation type
Vegetation canopy resistance	• Derived from vegetation type
Canopy storage capacity	• Indications of biomass can indicate likely precipitation interception levels
Root distribution with depth	• This parameter can only be inferred from the vegetation type • Even in situ measurements are often difficult for any sizeable area
Meteorological and precipitation data	• SAR gives no direct measurements in this area, but can be used to give an indication of recent rainfall events via surface moisture patterns
UNSATURATED FLOW	
Soil moisture tension / content relationship for each unsaturated soil layer	• This parameter is a function of the soil type and distribution. It can thus be inferred, but cannot be measured directly by SAR
Soil saturated conductivity for vertical flow	• This parameter is a function of the soil type and distribution. It can thus be inferred, but cannot be measured directly by SAR
Soil moisture in the unsaturated zone	• The response of soil is dependent on its moisture content in an effective surface layer whose thickness is of the order of 5cm • Soil moisture can only be measured in soils without heavy vegetation cover, since vegetation will dominate the response unless it is controlled
SATURATED FLOW	
Conductivity for horizontal flow	• This parameter is a function of the soil type and distribution. It can thus be inferred, but cannot be measured directly by SAR
Initial phreatic surface	• This can be defined only when close to the surface, depending on the nature of the overlying unsaturated zone • It may also be extrapolated from the near surface moisture estimates • The exception may be in very sandy soils where penetration may extend to the saturated surface if no wet layers are present above it
GROUNDWATER	
Definition of recharge areas	• It may be possible to define areas of groundwater recharge indirectly, based on the instrument's ability to detect areas of different geology
Identification of lineaments	• It may be possible to identify areas of groundwater seepage, based on areas with high moisture contents, eg seepage / spring lines
Pumping and recharge data	• In general, it is not possible to identify initial groundwater levels using SAR
SNOWMELT	
Initial snowpack cover and depth	• SAR can be used to determine the depth of the snowpack, or to monitor changes in the depth of new snow • Some limitations are imposed by the incidence angles of the ERS SAR, particularly in high terrain
Degree day factor	• This is an empirical factor which is used in conjunction with measured air temperature to give estimates of heat flux for a given location and time
Initial snow temperature	• SAR may give an indication of the wetness of the snowpack

Table 3-2b: Suitability of ERS SAR for measuring hydrological parameters & variables

PARAMETER	SCATTEROMETER CAPABILITY
OVERLAND AND CHANNEL FLOW	
Water surf. elevation & extent	• It may be possible to identify large areas of flood inundation using Scatterometer data
EVAPOTRANSPIRATION AND INTERCEPTION	
Vegetation aerodynamic resistance	• Although it is unlikely that resistance can be identified directly, regional biomass estimates could be useful in parameterising climate models • Work in this area is continuingit may be possible to identify vegetation structural parameters more directly related to aerodynamic resistance than biomass
UNSATURATED FLOW	
Soil moisture in the unsaturated zone	• Area estimates of soil moisture may be obtained. These could be used to support regional or global models since the resolution is broadly compatible
SNOWMELT	
Initial snowpack cover & depth	• Monitoring snow cover and permafrost extent are being considered as applications, but have yet to be proven

Table 3-3: Suitability of ERS Scatterometer for measuring hydrological parameters & variables

Table 3-3 describes the capability of the ERS Scatterometer for measuring a range of hydrological parameters and variables.

ATSR

The ATSR consists of two instruments, an InfraRed Radiometer (IRR) and a passive MicroWave Radiometer (MWR). The emphasis here is on the IRR, an imaging radiometer which operates in the thermal IR and visible areas of the spectrum, and offers valuable inputs to hydrological applications. The instrument was specifically designed for the measurement of sea surface temperatures to very high levels of accuracy. It has two features which allow it to achieve this accuracy:

- a high level of channel accuracy and calibration;
- a conical scan which provides two views of the surface, one looking vertically downwards and the other looking ahead of the vertical.

The comparison between the two views provides an effective basis on which to provide corrections for the effect of the atmosphere on the instrument observations.The main areas in which ATSR can contribute to hydrology are:

- vegetation cover/type;
- land surface temperature

The ATSR-1 instrument on ERS-1 provides four thermal channels. The ATSR-2 instrument on ERS-2 features three additional channels in the visible range. The ATSR bands are similar to those used on the NOAA AVHRR series, for which vegetation indices are well established. To these, ATSR can add improved radiometric performance. The use of the instrument for vegetation indices involves the determination of dimensionless reflectances from the raw instrument data. These are dependent on the high relative accuracy of the instrument between channels. Understanding the nature of the vegetation surface is the key to many hydrological parameters, particularly those related to evapotranspiration.

Examples of the use of ATSR for land surface temperature have also been reported, for example by *Labed, Li & Stoll, 1993*. In this example it was noted that the high radiometric resolution of the ATSR instrument made it possible to observe the detailed thermal structure of the ground surface over the Sahel. This capability can be very valuable in determining the location of moisture rich areas and identifying hydrological structures, particularly in arid (non-vegetated) zones.

Table 3-4 describes the capability of the ERS ATSR for measuring a range of hydrological parameters and variables.

PARAMETER	ATSR CAPABILITY
OVERLAND AND CHANNEL FLOW	
Initial water surface elevation/extent	• Can be measured in cloud free conditions, but applications are limited by the pixel size (about 1km)
Overland flow roughness coefficient in each axis	• No-except from general indications of the surface conditions
Drainage network	• Overall structure of the drainage network can be determined for large catchments
STRUCTURE	
Soil type distribution	• Soil type may be inferred from the vegetation type and local conditions
Vegetation type distribution	• Vegetation indices have been developed with AVHRR data, such as NDVI • Similar indices can be derived from ATSR, and especially ATSR-2 with its visible channels
EVAPOTRANSPIRATION AND INTERCEPTION	
Vegetation aerodynamic resistance	• Derived from vegetation type
Vegetation canopy resistance	• Derived from vegetation type
Canopy storage capacity	• Derived from vegetation type
Root distribution with depth	• Derived from vegetation type
UNSATURATED FLOW	
Soil moisture tension / content relationship for each unsaturated soil layer	• Vegetation studies may indicate this via long term soil information
Soil moisture in the unsaturated zone	• Indications from vegetation type and condition
SATURATED FLOW	
Initial phreatic surface	• Possibly from vegetation type and condition
SNOWMELT	
Initial snowpack cover and depth	• Snow coverage and depth can be estimated. This has been done operationally in support of hydro electric power schemes in areas with extensive snow cover using AVHRR, a similar instrument
Meteorological and precipitation data	• Estimates of land surface temperature

Table 3-4: Suitability of ERS ATSR for measuring hydrological parameters & variables

PARAMETER	RADAR ALTIMETER CAPABILITY
OVERLAND AND CHANNEL FLOW	
Initial water surface elevation and extent	• Radar Altimeter data have been used successfully for monitoring lake levels • When combined with ATSR or AVHRR data, this can be extended to estimate lake volumes
STRUCTURE	
Ground surface elevation	• With suitable processing, it is possible to produce global and regional scale DEMs using radar altimeter data
SNOWMELT	
Initial snowpack cover and depth	• The ability of radar altimeters to map sea ice and also ice sheet topography has been demonstrated • For smaller ice sheets and glaciers, the main limitation is the spatial sampling interval and the complexity of the response over land areas with high relief

Table 3-5: Suitability of ERS Radar Altimeter for measuring hydrological parameters & variables

Radar Altimeter

Radar altimeters are generally intended for oceanographic and cryospheric applications and their use for land applications is currently limited to a small number of specific areas. They are designed to measure precisely the altitude of the satellite above the surface at a set of points in time. Using this information, a profile of the surface shape, and in particular the ocean surface can be derived, since the position of the satellite is known to a high level of accuracy.

The ERS Radar Altimeter operates by timing the 2 way delay for a short duration pulse to be transmitted to the ground vertically and reflected back. The characteristics of the return signal can also provide valuable information on the nature of the surface encountered, for example the responses from ice and open water are distinct.

Altimeters have been used for some land applications, including measurements of lake surface height and low resolution global topography. In the former case, the accurate determination of changes in level are used to estimate changes in the volumes of storage in freshwater lakes and reservoirs. This can contribute to water balance studies as part of global change research and also to water supply considerations in areas where stage measurement devices are not available or accessible on reservoirs.

Table 3-5 describes the capability of the ERS Radar Altimeters for measuring a range of hydrological parameters and variables.

3.4 Access to ERS data

ERS data can be obtained from archive, through normal processing channels and in some cases in near real time (about 3 hours after observation).

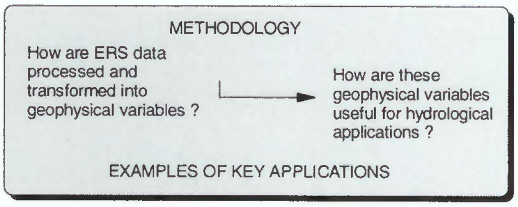
More information on availability of ERS data and the services available can be obtained from the ESA establishment ESRIN:

ERS Help Desk
ESA/ ESRIN
via Gallileo Galilei
00044 Frascati, Italy

Tel: +39-6-941.80 600
Fax: +39-6-941.80 510

4. Methodology

4.1 Issues



The ways in which satellite data are used to solve problems can vary considerably in complexity. At one extreme is the simple identification of a single discrete object on the image. At the other is the measurement of spatial variability across the whole image. In the latter case, the variable may have to be extracted from a response which represents the covariation of a range of phenomena.

It is not possible to use 'raw' ERS data directly from the satellite for hydrological applications. Even after initial processing a series of corrections and transformations to the data are normally required, the nature and complexity of which depends on the instrument. The general process is illustrated in Figure 4.1.

The four steps shown in Figure 4-1 are in most cases well established, but a number of issues are raised at each stage:

- The ERS instrument performs the measurements and downlinks them to the ground station. This process is well established and reliable, the only variability is in the availability of the sensor at a particular time and location.
- Initial processing, reformatting and calibration of data. Most correction techniques and basic

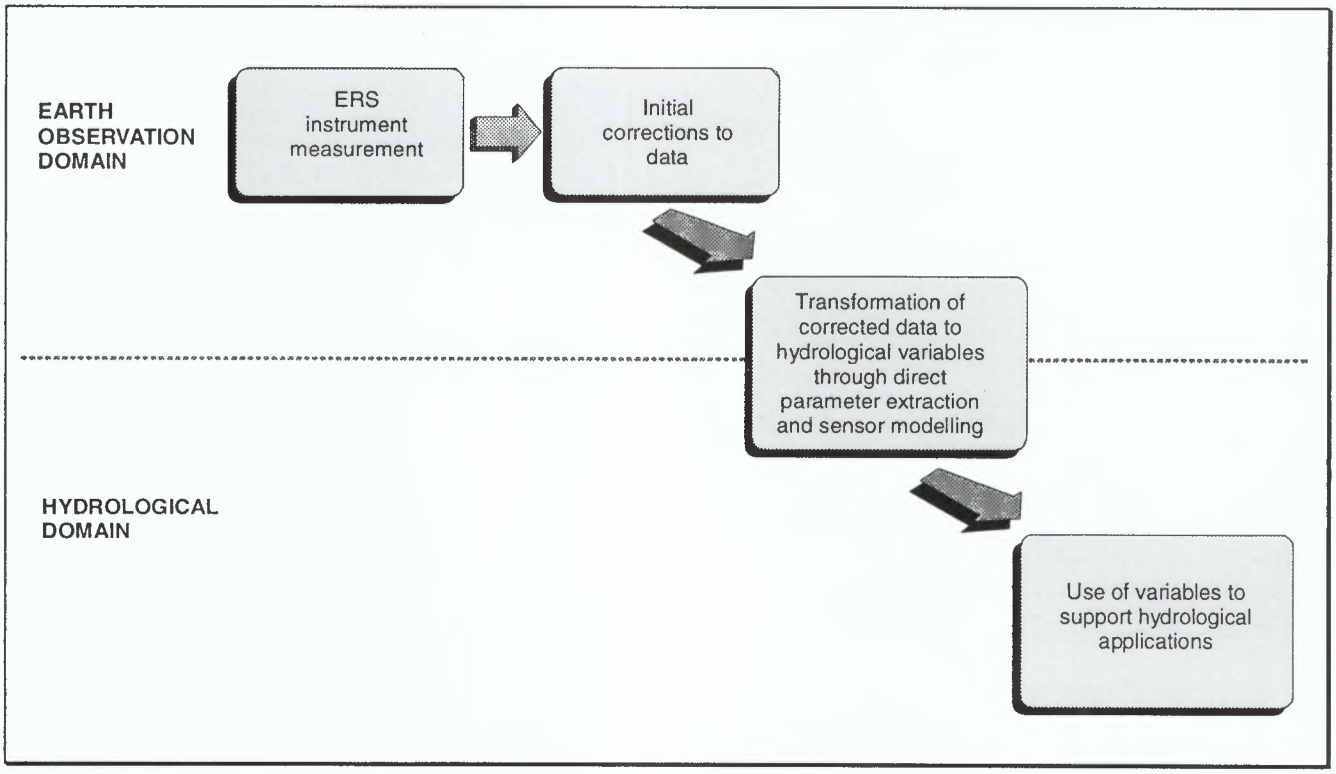


Figure 4-1: Basic data transformations for ERS data

processing such as SAR processing are well developed. The initial processing is complex.

- Transformation of the data to basic hydrological variables: ERS data do not measure hydrological variables directly and must thus be converted to usable information. Techniques for this are developing and are currently the subject of intensive research. Some operational techniques are already available. The complexity varies considerably according to the application, but care is always advisable when interpreting SAR imagery because the apparent meaning may differ from more conventional optical imagery. This is partly due to the noisy aspect of the SAR image, resulting from speckle, compared to the noise-free optical image.
- The use of the variables to help solve hydrological problems. Once in the hydrological domain, the need is to develop the techniques which can make optimum use of the hydrological information derived from ERS data.

In addition to the basic issues, the following points are also particularly important:

- *Spatial resolution*: This is partly determined by the nature of the instrument, but as will be shown, it is also a function of trade offs made when processing the data. The aim is to obtain data with sufficient radiometric resolution on a scale which is still appropriate for the application;
- *Temporal frequency of observation:* Many hydrological variables vary rapidly and require either continuous or very frequent measurement. This is again largely a function of the satellite and instrument characteristics, but decisions may have to be made on the use of techniques such as multitemporal analysis in relation to the frequency of change being considered;
- *Frequency and polarisation:* The ERS SARs operate in a single frequency (5.3 GHz) and with a single (vertical) polarisation. Although the incidence angle can be changed using Roll Tilt Mode, for normal operations it is fixed at 23. It should be noted that the nature of the surface interactions and thus the measurement capabilities are closely linked to these characteristics.
- *Timeliness of data:* Due to rapid changes which may occur and the need to act on these quickly, the period for which the data are useful is often very short and rapid dissemination of processed data is therefore required. This may affect the way in which the data are processed as it may preclude the use of multitemporal analysis or even complex processing methods;
- *Need for long-term observations:* The complexity of most hydrological systems often requires an empirical approach to analysis based on long and consistent hydrological records. The short duration and variability of many remote sensing sources currently makes it difficult to use remotely sensed records in this way.

Methodological issues are thus of two types, those which emerge from the remote sensing domain (such as the most appropriate way to derive average backscatter from SAR), and those which emerge from the hydrological domain (such as the conversion of the averaged backscatter to soil moisture and the spatial representativeness of the resultant data in models).

The issues are thus considered in two separate sections below. The first examines the corrections and transformations used to provide a basis for the extraction of geophysical information from the data.

The second examines the conversion of corrected instrument data into usable hydrological information. The hydrological results which can be achieved by using this geophysical information are then illustrated with several examples.

4.2 ERS data analysis & interpretation

Remote sensing data sources must provide reliable and representative estimates of hydrological variables in order to be of value to hydrologists. The initial measurement obtained by a sensor represents the amount of energy received from the target. In order to translate this into a meaningful measurement, most of the following must be taken into account (depending on the sensor):

- correction for any specific sensor characteristics/ calibration;
- location of each of the pixels of the image onto a suitable map projection;
- correction for the effects of topography;
- correction for the effects of the atmosphere;
- extraction of the effects of the required variable from effects resulting from other sources.

The following sections describe the basic processing of SAR data together with some additional techniques which enhance the value of the data for hydrological applications.

Basic processing of SAR data

This section examines the process of transforming the digital numbers received from the satellite into usable geophysical information. The emphasis is on user issues, and thus the later stages of the processing chain are examined in more detail.

A SAR operates by transmitting radio frequency pulses and coherently detecting the return signal reflected from the target area. The basis of the Synthetic Aperture is the use of the satellite motion along the ground track to create the effect of an antenna much larger than the 10 m x 1m antenna actually used. This method makes it possible for space based systems to achieve high resolutions while limiting size and weight to realistic levels. The trade off for the use of this technique is a high data rate and complex processing to reconstruct the responses for a series of 'sub-apertures' to provide the final image. Until recently, the

PROCESSING STAGE	CHARACTERISTICS	USER ISSUES
Digital number	• The initial data are reconstituted from those received from the satellite, with the addition of the auxiliary data necessary for processing	• No user applications at this data level
Pre-processing	• Multi-looking normally applied for speckle reduction (3 looks for the standard PRI) • Conversion from slant to ground range applied for PRI images • System corrections applied (eg. corrections for antenna pattern) • Standard result is a 100 km image (or subset) with 15 bit intensity values for each pixel	• The three look PRI image is suitable for most applications • Interferometry requires Single-Look Complex (SLC) image
Geocorrection	• The PRI image is oriented as received by the satellite, and thus its orientation varies according to the pass type • In the geo-corrected image each pixel is correctly oriented and located to the required map projection	• Need to modify the PRI image to ensure that each pixel is correctly oriented and located to a selected map projection
Terrain correction	• The effects of terrain are removed for areas of moderate of high relief • This is important to avoid misleading or mislocated values	• In areas of moderate or high relief, the effects of slope angles on radar returns must be taken into account • These effects include increased response from facing slopes and areas of shadow with no response
Atmospheric correction	• Although water droplets within the atmosphere can affect radar, this is at shorter wavelengths than used by the ERS SAR • Ionospheric effects may affect some applications (as with the Radar Altimeter)	• No need for correction as wavelength large enough to avoid interference from water droplets • For very high accuracy aplications such as interferometry, atmospheric corrections (incl. ionospheric corrections) may be necessary
Backscatter derivation	• For many quantitative applications, averaged backscatter values are derived from the basic pixel data. This is often necessary to achieve the required radiometric resolution	• To determine geophysical variables, an averaged backscatter ((0) is required. This issue is explored further below

Table 4-1: User considerations in the processing of SAR data

processing required specialist hardware and could be expected to take an extended period of time. In some cases, optical SAR processors were used which, while very rapid, lacked the flexibility of their digital counterparts and generally produced only photographic print type output.

Recent developments in both data storage capacity and especially in desktop processing power have made digital SAR processing a less specialist activity than it was. A number of packages are now available which will allow users to undertake their own SAR processing where necessary, though for most users, the centrally produced images are still suitable.

A basic characteristic of any SAR data is the presence of speckle. Speckle gives the images a grainy effect and aggravates classification. It results from the coherent nature of the radar waves which cause random constructive and destructive interference and thus produces random bright and dark areas on the image. Although it is not possible to remove this effect completely, there are techniques which can reduce the problem. One of the most common is to process the data using multiple looks. This involves producing several independent images of the same area by using different portions of the synthetic aperture. The independent images are then averaged to produce a single, smoother image, but at a spatial resolution which is reduced as a function of the number of looks used. The reduction in speckle is inversely proportional to the square root of the number of looks *(cf Lillesand & Kiefer 1994)*. The selection of processing technique is thus linked to the balance between resolution and speckle reduction.

For certain applications, and in particular interferometry, the phase information is important and as a result complex valued single-look images are used. For general use, the standard ESA product is the PRecision Image (PRI) image which is a three look image representing a useful balance between resolution and speckle reduction.

The key elements of SAR processing are summarised in the Table 4-1, along with the issues which face the user at each stage.

The most common stage at which the user will acquire data is at the PRI level. Since September 1992, PRI processed products have included corrections for the antenna pattern and compensation for range spreading loss (deviations from the mid swath reference sensor to target distance in different parts of the image area) i.e. those factors which are facets of the instrument and satellite configuration. From this point, correction is necessary to orient the image correctly and then to fit it accurately to a suitable map projection.

Changes in the terrain angle relative to the SAR incidence angle can affect the nature of the response and this may need correction. For example, a slope facing the sensor will increase the average return to the sensor for a given surface type. There may also be areas of shadow, which are those areas not seen by the radar pulses because they are obscured by an obstruction. In these areas, no effective backscatter is measured and they must be excluded from the image. In some cases, it is possible to use data from ascending and descending passes in which case, it may be possible to reduce the loss of information due to layover and foreshortening because the satellite will have viewed the area from two opposite angles. This approach has been demonstrated by *Rott, 1995.*

Once an image has been suitably corrected, the remaining issue relates to the calculation of backscatter This is effectively an averaging process which represents a trade-off between radiometric resolution and spatial resolution. The standard approach to this calculation is given by *Laur, 1992* and takes into account the calibration constant for the instrument, the actual angle of incidence to the target of interest and the average intensity for the selected number of pixels. *Laur, 1992* suggests a value of 500 pixels as a minimum for averaging, but further research has allowed this figure to be refined for particular applications.

This issue of averaging has been examined in a hydrological context by *Bally & Fellah, 1995* and *Example 1* describes their analysis and gives an example of the way in which the analysis can be used to derive the available combinations of accuracy and resolution.

In many cases, the use of a single SAR scene may not be sufficient to provide the hydrological information required. A number of possibilities exist within the remote sensing domain for using multiple SAR images in conjunction with other data sources and specific techniques such as interferometry. The outputs from these techniques can then be used in conjunction with in-situ and hydrological techniques.

Example 1: Impact of observation scale on SAR radiometric resolution

Kader Fellah, SERTIT (cf. Fellah et al, 1996, Bally & Fellah, 1995, Fellah, 1995)

Using the intensity averaging technique (Laur, 1992), variations in the backscatter measurement due to radiometric resolution errors are a function of the number of pixels used for the derivation of the backscattering coefficient as illustrated in Figure 4-2.

In a study case, backscatter measurements were performed over a test site consisting of cropland using four different acquisition dates with georeferenced ERS-1 SAR Ellipsoid Geocoded (GEC) images. With a low number of pixels N, a high variability of the measured backscattering coefficient is noted. For higher values of N, the measured backscatter coefficient converges to one value. If the instrument noise is assumed to be negligible and if the area of investigation is perfectly homogeneous and flat, this value would be the expected backscattering coefficient for the area.

Interpreting a time series of these measurements at different scales of observation could lead to different or even contradictory results. Therefore a prerequisite in the temporal and spatial analysis of the backscattering coefficient's behaviour is the determination of the amount of pixels for which the backscattering measurement is statistically valid in order to relate this measurement to bio-geophysical information with a sufficient confidence level.

Depending on the statistical uncertainties in the SAR signal due to speckle, the radiometric resolution varies as a function of the product's Effective Number of Looks (ENL) and the spatial integration of pixel values within a certain area of interest corresponding to a specific observation scale. A study based on a statistical modelling of the SAR signal over natural surfaces has been investigated in collaboration with ESTEC, Earth Science Division. A relationship between SAR radiometric resolution and observation scale has been established and validated in the case of ERS-1 SAR product. The methodology and the validation of the SAR radiometric accuracy assessment are described in detail by *Bally & Fellah, 1995*. Table 4-2 illustrates the impact of the spatial integration of pixel values on the radiometric resolution. Confidence levels are presented versus the number of pixels within an area of interest.

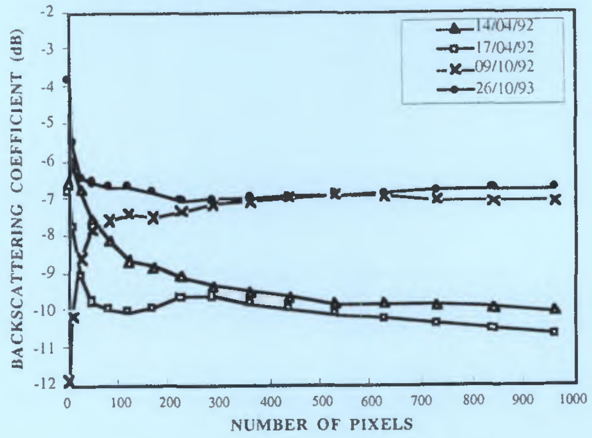


Figure 4-2: Backscattering coefficient versus the number of pixels from data extracted from ERS-1 SAR GEC products for a cropland area on four different dates

The following example illustrates the use of the relationship between radiometric resolution and observation scale. In this example, the following requirements are established:

- Required measurement accuracy is 5% for soil moisture retrieval between a range of 10% to 40% (*Evans, 1995*);
- Using an ERS-1 PRI product and the experimental results over the Flevoland test site (*Borgeaud et al, 1993*), the above requirement corresponds to a backscattering coefficient measurement accuracy of 0.5 dB.
- At pixel scale, the confidence level for ± 0.5 dB accuracy bounds is very low (15%). A ± 0.5 dB measurement accuracy cannot be achieved with a suitable confidence level unless intensity averaging is applied with a consequent sacrificing of spatial resolution. If the number of pixels is larger than 214 in the mid swath region, the required accuracy bounds are obtained for the measurement with a confidence level of 90%. This corresponds to an area of interest of at least 3 ha which represents the minimum spatial scale of observation to requirements for use in hydrological applications.

Radiometric resolution: bounds around mean intensity (+/-) (dB)										Number of ERS-1 pixels		
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0			
Confidence level, (%)										near range	mid swath	far range
15	30	43	55	66	74	81	86	89	92	1	1	1
17	34	49	62	73	81	87	91	93	95	5	5	4
19	38	54	68	78	86	90	94	96	97	7	6	5
28	53	71	84	92	96	98	99	99	99	12	11	10
34	62	81	92	97	99	99	99	99	99	18	16	14
39	69	87	96	99	99	99	99	99	99	24	21	19
59	89	98	99	99	99	99	99	99	99	61	54	48
75	97	99	99	99	99	99	99	99	99	121	107	95
84	99	99	99	99	99	99	99	99	99	182	161	143
89	99	99	99	99	99	99	99	99	99	242	214	190
93	99	99	99	99	99	99	99	99	99	303	268	238

Table 4-2. Confidence intervals of area of interest extent in pixels for radiometric resolution ranging from 0.5 dB to ± 5 dB

Use of multitemporal datasets

Just as multispectral imagery can be used to enhance the classifications achieved with visible/infrared instruments, the use of ERS SAR data from more than one date can be used to enhance classification performance.

Studies using ERS-1 SAR data have shown that four dates represented a suitable compromise between classification performance and the number of images required. This number was derived using principal components analysis (*Wooding et al, 1993*). As the number of images increases, the timespan covered also grows and thus the possibilities increase that changes in the surface characteristics may impose themselves on the analysis.

Sets of multitemporal SAR data can also be used for change detection by allocating images from different dates in false colour composite displays. With careful interpretation, this approach can provide information on the spatial pattern of changes which occurred in the periods between the image acquisitions.

Integration of SAR and optical data

Optical data, such as Landsat TM or Spot XS, are the established data for use in land use classifications and related applications. It is also the case that near IR is viewed as a valuable basis for determining land and water boundaries. The main technical problem with these data sources is unreliability due to cloud cover.

As a result, the optimum approach is often to combine the optical data with SAR data. This can be done in a number of ways. The traditional approach to integration has been to use a visual approach with the combination of the SAR data being either one of a red/green/blue or an intensity/hue/saturation combination.

Another approach is to use the most recently available optical data to provide a land cover type classification. The SAR data can then be used to provide soil moisture estimates by applying empirical relationships specific to each of the land cover types under consideration.

SAR interferometry

The technique of SAR interferometry can be used to provide digital elevation maps, to monitor ground displacements and also to help determine ground cover/landuse. It involves using the phase information contained in two complex valued images, normally SLC products taken from different locations (less than 1200 m apart for ERS), together with an accurate knowledge of the satellite location for the two observations.

The technique can be used to provide topographic maps and to estimate surface change detection (*Werner et al. 1993*).

With a suitable and known baseline separation between the satellite observation positions, interferometry can be used for the generation of DEMs. It is also preferable that the period between the observations is minimised to ensure that as little surface change as possible occurs. This has been achieved both during the 3-day repeat cycle of ERS-1, and more recently and effectively by the tandem operation of ERS-1 and ERS-2 satellites. The main sources of error in this technique are the determination of the baseline between sensor positions during acquisition, non parallel orbit tracks, decorrelation caused by baseline length, thermal noise, temporal decorrelation and surface change. The high standards applied to the design, operation and consistency of the satellites thus help to make the technique as effective as possible.

Secondly, interferometry can provide an estimate of the displacement along the line of sight which can be used to detect changes in the surface between the first image date and the second. This has been applied to the effects of earthquakes (e.g. *Massonnet et al. 1993*), volcanic activity, landslides, glaciers and other ice movements. The change is observed either by decorrelation in the interferometric phase resulting from *random surface changes* or coherent phase shifts caused by locally uniform surface movement.

An additional use of interferometry is based on the fact that interferometric correlation between the images varies according to the land cover type. The correlation is low for forested canopies because of the dominance of volumetric scattering, but much higher for areas with lower or non existent cover. This can be very valuable at certain times of the year, such as the autumn, allowing separation of classes which would otherwise be very difficult. Agricultural fields under active cultivation cause almost complete decorrelation. SAR interferometry can thus assist with land use classification *(Wegmüller et al. 1995, Werner et al. 1993)*.

4.3 Benefits in hydrological measurement and analysis

The benefits of ERS data in hydrology are realised in two stages. Firstly there are direct benefits of measurement which include many applications where the main requirement is only for measurement and monitoring. In other applications, however there is a need to go beyond measurement to modelling and forecasting. Here, the ability to measure, particularly in the spatial dimension is vital, but progress is also a function of the development of *modelling techniques*.

This section considers the contribution of the ERS data by examining examples of its measurement capabilities. The following section considers how these might be used for modelling and forecasting.

The examples given are in the following areas (Table 4.3). Note that the instruments specified were those used in the example rather that a list of possible methods.

Soil moisture

The ability to measure surface soil moisture remotely has long been a goal in remote sensing. Accurate *measurements* of this variable can provide a range of opportunities which can be realised through modelling techniques. These opportunities exist at scales from small to medium catchment up to regional and global climatology studies.

It is important to recognise that soil moisture is a complex variable which is highly heterogeneous and scale dependent. Subsurface moisture can exist in a number of forms. The main division is between the unsaturated zone where both air and water are present in the soil pores and the saturated zone where

Example	**Primary ERS Instrument**	**Other Complem. Instruments**	**Application Scale**
Soil moisture	SAR		Local
Soil moisture Land surface cover	SCATT	NOAA AVHRR	Regional
Wetlands	ATSR	Radar Altimeter (potential)	Regional
Flood monitoring Floodplain delimitation	SAR	Spot XS	Catchment
Discharge measurement	SAR		Local/catchment
Discharge forecasts Hydrological modelling Snow cover	SAR		Local/catchment

Table 4-3: Examples of areas where ERS and other complementary instruments are used.

the hydrostatic pressure is equal to the atmospheric pressure. Within the unsaturated zone, water can exist as vapour, hygroscopic moisture, capillary water (in smaller pores) and gravity water (in larger pores).

The basic measurement of soil moisture by ERS SAR was described above (Section 3.2). This showed how the backscatter was proportional to the dielectric properties of the soil and thus to overall moisture content at and near the surface. It also described the other factors affecting the backscatter response.

Controlling factors such as vegetation cover and surface roughness is the key to operational applications in this area. The most common approach is to derive empirical relationships between SAR backscatter and soil moisture for classified areas within which the unwanted variability is relatively constant. There must also be the assumption that the temporal change in unwanted variability within the area is limited over the period for which the relationship is derived. It can be seen that this approach requires a means of classification and if possible some ground controls to ensure the applicability of the relationship.

An approach which is considerably more difficult, but may yield dividends in the longer term is the use of physically based models to describe the effect of vegetation and roughness on the backscatter. The results of these models could then be used to isolate the variable required, in this case, soil moisture. Examples of this type of work are *Schmugge & Jackson 1992* and *Oh et al. 1992*. This research is not likely to become operational before the end of the ERS era. As multifrequency and multipolarisation SARs become available, operational applications will increasingly and more quickly become feasible.

Example 2 is a case study which has examined soil moisture variations over non homogeneous agricultural areas using the ERS-1 SAR. It illustrates the use of multitemporal ERS-1 SAR data and the normalisation of surface combinations to allow standard moisture relationships to be used. The images illustrate the measurement of spatial variability and the links between the SAR measured soil moisture and other key aspects of soil moisture.

Example 2: Relationships between soil moisture and SAR backscatter

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University of Munich, Luisenstraße 37, D-80333 München

Introduction

Within a project sponsored by DARA 72 ERS-1 SLC SAR images of an agricultural area in the Upper Rhine Valley were integrated into a GIS structure after proper pre-processing. The GIS contained information on field boundaries, land use for each field, soils and the results of continuous soil moisture and rainfall measurements on single fields in the test site (approximately 50 km and very flat). The GIS was used to establish relations between ERS-1 SAR backscatter and measured surface soil moisture for different land uses. Since backscatter depends on soil and surface properties, statistical relations between temporal backscatter profiles of different soil surface complexes were established. This allowed equalisation of the multitemporal ERS-1 SAR images to a reference backscattering behaviour of corn growing on loamy sand. Since surface soil moisture had been measured in-situ for this soil surface complex the ERS-1 SAR images could be converted into reference surface moisture images.

To achieve this aim, a segmentation of the entire ERS-1 SAR image of the test site on a field and even subfield basis was necessary to be able to distinguish different soil surface complexes and to study their backscattering behaviour.

The approach

An approach based on statistical analysis was chosen to determine the spatial distribution of surface moisture over a non homogeneous area. It was based on the relation between measured soil moisture and the backscatter of ERS-1 SAR data as shown in Figure 4-3. The good correlation between the two parameters includes the influence of surface roughness, plant geometry and temporal dynamics of the different soils, due to the use of different suction curves for each field.

To determine the relative influence of these parameters on the backscattering signal, a statistical analysis was carried out based on the following assumptions and methods:

- the absolute values and the temporal behaviour of backscatter are different for different land uses and soil types due to the influencing factors mentioned above;
- a corn field on loamy sand with in-situ soil moisture measurements was taken as a reference to which all other soil surface combinations were compared and finally equalised;
- the meteorological conditions in the test site were spatially constant (which was proven for rainfall by using 20 raingauges, cf. Fig. 4-8);
- correlations between the backscatter of the reference field and all soil surface complexes (not necessarily complete fields) were determined. All combinations of the main land uses and soil types were taken as soil surface complexes. Assuming linear relations between the backscatter on the reference corn field and the soil surface complexes, this leads to a matrix of gain and offset values for 16 combinations of:

  cover types: corn, winter barley, summer barley, meadows
  and soil types: strongly loamy sands, loamy sands, sandy loams, loams

- the result of this analysis was a set of correction values to alter the backscattering coefficients for each soil surface complex in the test site to the behaviour of corn on loamy sand and therefore to relative backscatter values;
- based on these relative backscatter values, the reference surface moisture could be derived from the relationship underlying Figure 4-3 for each date of the ERS-1 SAR time series.

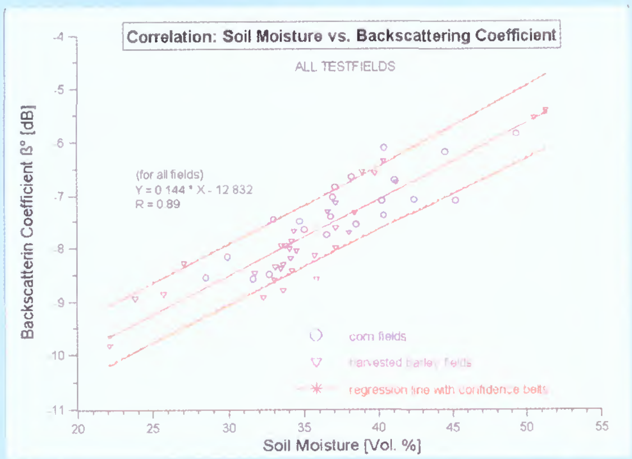


Figure 4-3: Correlation between soil moisture and ERS-1 SAR backscattering coefficient

To verify this approach a comparison of the temporal backscatter profiles of different surface covers and different soils was made.

Performance of the approach

The average backscattering coefficient for each ERS-1 SAR image during the commissioning phase (July until December 1991) was determined for all summer barley pixels in the test site separating three groups according to the soil type. The average power for each group was then converted into backscatter values. This procedure was done for the main land use types in the test site as well.
A regression analysis was then carried out between the backscatter of the selected reference (corn field on loamy sand with in-situ soil moisture measurements) and the backscatter values of the other soil surface complexes in the test site, which are covered with the main land use types. These were conducted using all the multitemporal ERS-1 SAR images.

The complete results of the statistical analysis for all examined combinations of land cover and soil type in the test site were tabulated, including the gains and offsets of the regression lines, the regression coefficient and the number of pixels included in the analysis for each combination. The values listed in these matrices serve as a basis to convert the backscatter of all pixels in the multitemporal ERS-1 SAR dataset according to their membership to one of the combinations.

The result of this conversion was the reference backscatter value of all pixels, giving a set of equalised ERS-1 SAR backscatter images for the dates under consideration. These images in turn can easily be transformed into reference surface moisture images by applying the relation underlying Figure 4-3.

Results

Figures 4-4 to 4-7 show three typical situations in which the distribution of the surface moisture has been determined for the complete test site.

The first image (Fig. 4-4) shows the distribution on 27 July 1991 (day 208). At this date the situation was characterised by recent rainfall events during the last three days. This led to an almost homogeneous spatial distribution of surface soil moisture.

Figure 4-5 (29 August) shows the consequences of strong evapotranspiration and almost no rainfall during the last three weeks. The image shows relatively low reference surface soil moisture values throughout the test site. The usual range lies between 20 and 35% volume depending mostly on the plant cover. Corn fields tend to show larger soil moisture values. This is according to observation, since the fully developed corn plant does not extract water from the surface layer for transpiration and is a very efficient shield against surface evaporation. The only striking difference is in the west centre part of the image, where the corn fields have been irrigated because of the low water holding capacities of the underlying soils. There, the reference surface moisture is much higher and lies in the range between 35 to 45 %volume.

In Figure 4-6, almost one week later than the previous image, the effect of no rainfall and strong evapotranspiration at the same time is even more visible. Only the fields under irrigation can keep their top soil moisture content, all other field are drying up.

Figure 4-7 shows the distribution of the reference surface moisture distribution on 15 November 1991 (day 319) and can be considered the end of the spatial and temporal dynamics of the surface moisture development of 1991. In October the available energy for transpiration had fallen almost to zero, the plant growth had almost stopped and the preceding rainfall events filled the soil moisture reservoirs. Therefore, a homogeneous distribution of the reference surface moisture can be expected since the differences due to plant cover and soil type have been equalised. The dominant reference surface soil moisture lies between 40 and 50% volume and is therefore very close to saturation (for a sandy loam soil). Differences due to land use and irrigation practices cannot be detected.

The interpretation of Figures 4-4 to 4-7 has shown that the spatial distribution of the reference surface moisture is determined by many features which can be expected. The most striking effect is the detection of irrigated areas in August. Nevertheless many features are difficult to interpret and evaluate since experience with such detailed surface moisture distribution maps is very sparse.

Conclusions

The reference surface moisture, as defined in this project is a value which can be determined quite easily even on larger agricultural areas if the relationships found in this study are stable. It is a parameter of potentially high practical value, because it is closely related to the soil suction in the top layer of the soil.

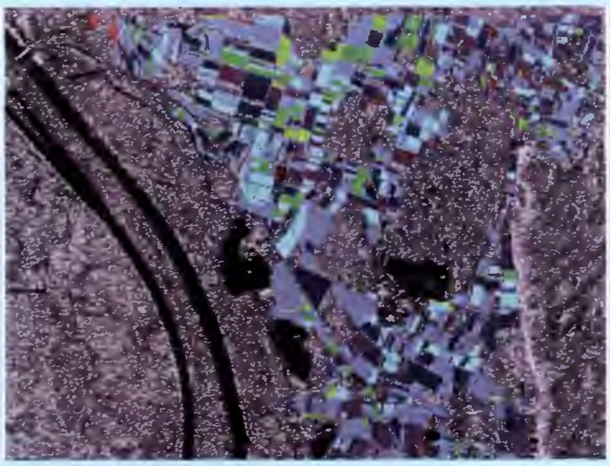


Figure 4-4: Surface soil moisture map of the testsite Freiburg, 27 July 1991

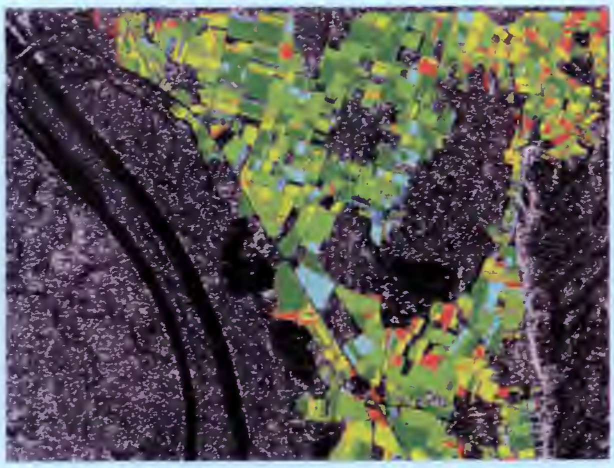


Figure 4-5: Surface soil moisture map of the testsite Freiburg, 29 August 1991

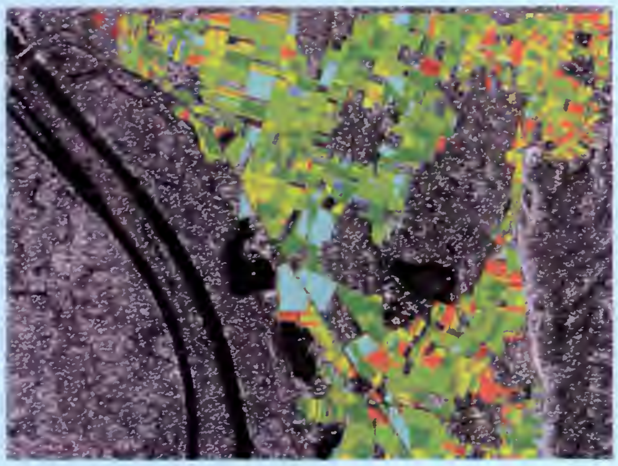


Figure 4-6: Surface soil moisture map of the testsite Freiburg, 4 September 1991

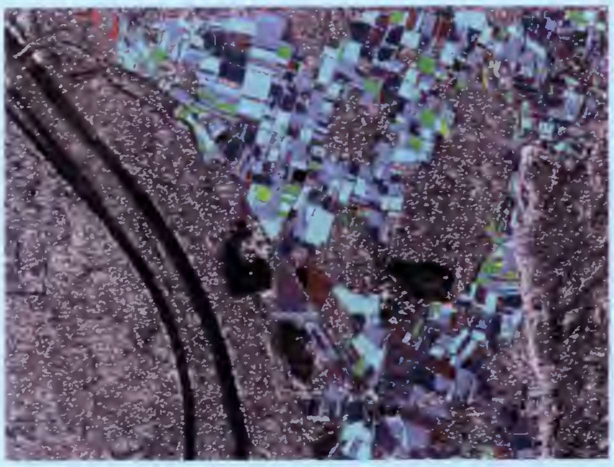


Figure 4-7: Surface soil moisture map of the testsite Freiburg, 15 November 1991

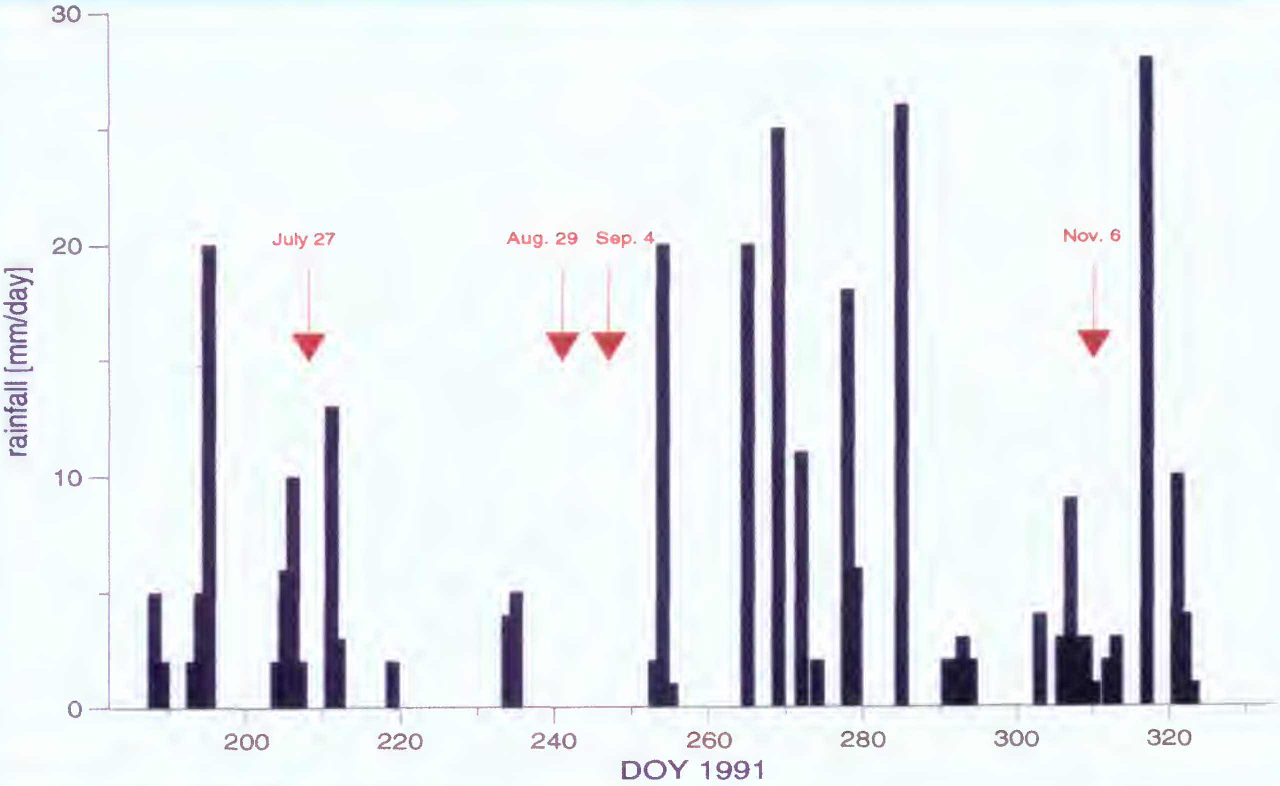


Figure 4-8: Rainfall during the commissioning phase in the testsite Freiburg 1991

The soil suction is an even more important parameter than the soil moisture, since it determines the availability of water for the plant and mainly the actual infiltration capacity, one of the key parameters needed for effective forecasting of floods. Continued effort is needed to stabilise the relationships found for different plants and soils, and in modelling efforts to explain the differences in temporal backscatter signatures of different soil surface complexes.

Regional soil moisture and vegetation conditions

ERS instruments offer considerable capabilities in resolving the type and condition of surface cover at a range of resolutions. The ERS-1 SAR for example has been used for operational monitoring of agricultural activities at medium to high resolutions. The ERS Scatterometer is a microwave instrument which offers many of the benefits enjoyed by the SAR, such as all weather operation and a sensitivity to surface moisture. It differs in that it is a low-resolution instrument offering daily coverage due to its wide swath. The frequent sampling is particularly important in semi-arid areas, where the effects of individual rainstorms on surface moisture are often short lived due to rapid infiltration and high evaporation.

Example 3 illustrates the use of the ERS Scatterometer to determine soil moisture conditions at lower resolutions over large areas in arid and semi-arid regions. This work was undertaken as part of the HAPEX-Sahel programme, one of the aims of which was to examine scaling effects (ie relating surface measurements to grid squares of global models) and methods for deriving surface characteristics at regional scales.

The problem of separating vegetation and soil moisture effects on backscatter is similar to Example 2, but here the approach to the solution is different. In this case, the effects of vegetation were expressed in terms of a 'water cloud' model, parameterised by the optical thickness and single scattering albedo. The necessary values in this model were obtained using NOAA AVHRR data and ERS Scatterometer measurements at different viewing angles. This model was then used to obtain estimates of soil moisture. MSAVI is the Modified Soil Adjusted Vegetation Index (*Qi et al, 1994*) which is a vegetation index adapted to estimate vegetation cover over semi arid areas.

Example 4 shows an example of the use of ERS Scatterometer data to map canopy density in Siberia. In this case, an index was derived which takes into account both the backscattering strength and mechanism in order to improve the correlation between canopy density and the Scatterometer measurements. The concept was demonstrated for a single month (July), but the potential demonstrated suggests that the technique can be developed to provide the capability to monitor canopy density change over time at this large regional scale.

Example 3: Soil moisture in the Sahel from Scatterometer

Yann Kerr, CESBIO

The aim of this study was to use the information provided by the ERS-1 Scatterometer over land surfaces in arid and semi-arid environments to infer soil moisture in the presence of vegetation. The area considered was a 5050 km^2 centred at Banizoumbou, Niger Republic, which has a 4-month rainy season from June to September.

Driven by dielectric properties and surface roughness, the soil contribution is attenuated by a factor which depends on canopy characteristics (water content, shape, height, density) and Scatterometer viewing conditions. To describe the influence of vegetation on the signal, a semi-empirical 'water cloud' model (a first order radiative transfer solution) was used. The optical thickness (τ) and the scattering albedo (ω) were the parameters used to quantify the vegetation contribution to the measured signal. Through a simulation analysis for different soil moisture and incidence angle conditions, the importance of τ and ω on the signal partition between vegetation and soil conditions was shown. To quantify the effect of vegetation on the signal, information on the green vegetation from NOAA AVHRR visible and near infrared data was used with ERS Scatterometer data in a water cloud model to extract τ and ω. The temporal evolution of the different contributions to the signal was then compared for different angular ranges. The semi-empirical model was then applied within suitable angular ranges to retrieve soil moisture.

The values of τ and ω were obtained with an rms of 0.318 dB data and a correlation coefficient of 0.98. In Figure 4-9, the temporal evolution of the oblique optical thickness (*x*) agreed well with MSAVI behaviour ($x = \tau/\cos\theta$ where θ is the incidence angle). This allowed the introduction of a quantitative relationship between a vegetation index and the dielectrical and structural properties of vegetation. This had the advantage of relating the vegetation index properties accessible by optical remote sensing to the optical thickness measured independently through the backscattering coefficient.

The temporal evolution of the single scattering albedo (shown as + in Figure 4-9) first increases with vegetation growth from day 211 and remains almost constant for different time intervals (days 243 to 258 and 262 to 303). This is probably because single scattering albedo is related to the plant water content which has a small temporal variability when the vegetation is mature.

The main objective of estimating t and q is to eventually assess the influence of vegetation dielectric and structural properties on backscattering coefficient.

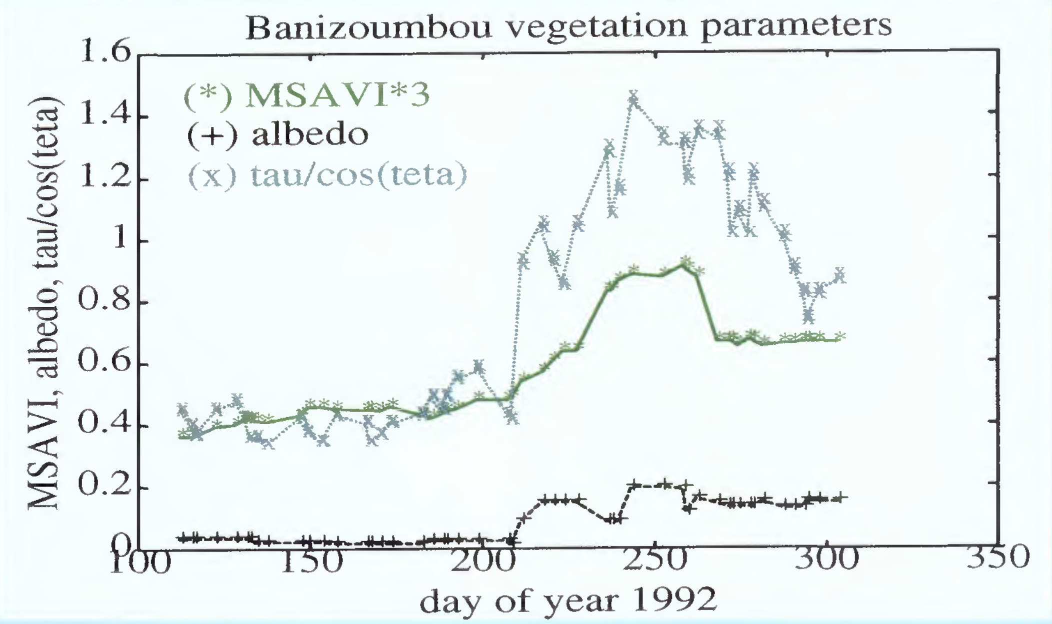


Figure 4-9:Vegetation changes over time

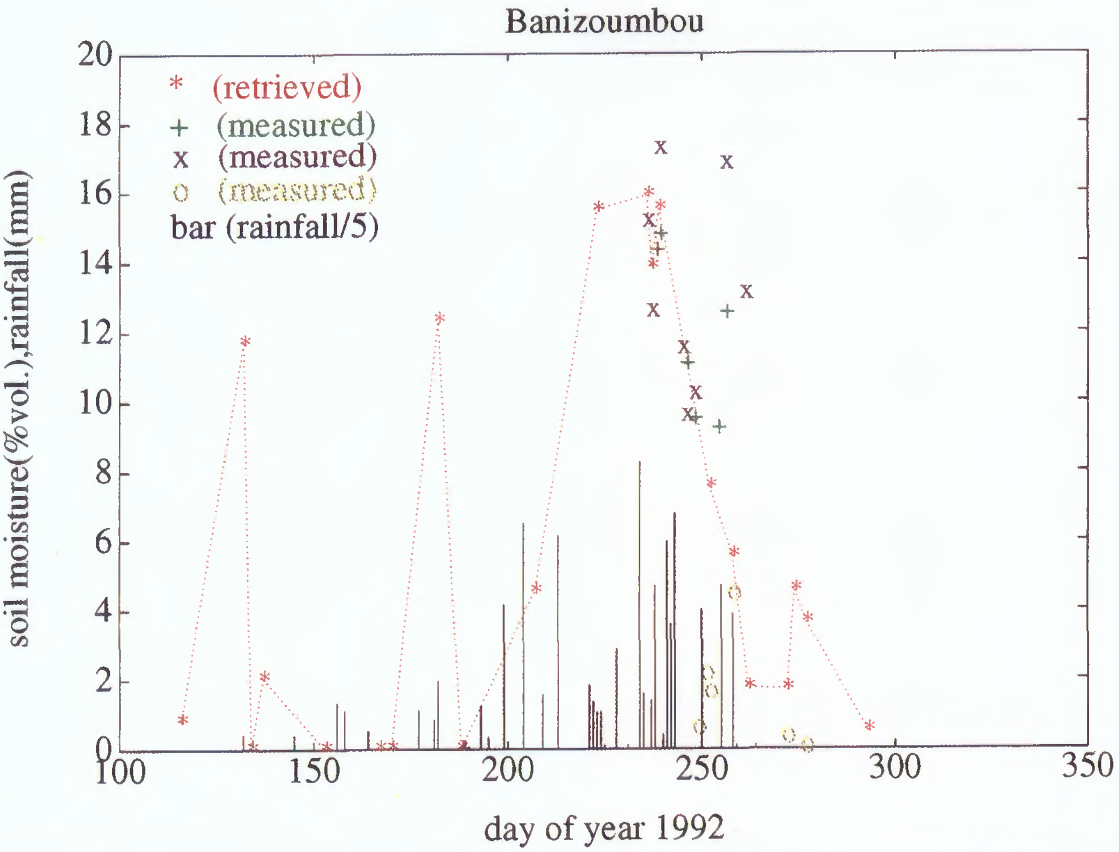


Figure 4-10: Soil moisture changes over time

Once this relationship is derived, it is possible to estimate soil moisture through vegetation cover. Figure 4-10 shows the temporal evolution of the estimated soil moisture together with ground measurements made by three teams during the HAPEX-Sahel programme.

* indicates values retrieved from the scatterometer using the above method. Errors are attributed to mis-matches between Scatterometer penetration depth and measurement depth and time separations between in-situ and Scatterometer measurements.

Example 4: Canopy density in Siberia from Scatterometer

Volkmar Wismann et al, IFARS

In this example, an application of the ERS Scatterometer to the determination of canopy density was made. In-situ data for the analysis were obtained from the records of 30 WMO observing stations distributed throughout the area, which specify their local vegetation characteristics.

The index used to relate the Scatterometer response to canopy density was the Radar Backscatter Index (RBSI). This was derived by taking the ratio of the averaged Normalised Radar Cross Section for incidence angles of 40 to 57 (NRCS) to the slope index. The slope index is a measure of the relationship between NRCS and incidence angle, and thus adds information on the backscattering mechanism to the indication of back scattering strength given by NRCS itself.

A very good correlation was found between the RSBI and the canopy density. This correlation was used to produce the map of canopy density in July given in Figure 4-11. The boundaries between the forest and the tundra in the North and between the forest, wheat belt and Kazakstan steppe in the south are well depicted on the map. The latter were classified as areas of negligable canopy density due to extremely low RSBI values. When comparing this map to a forest map of this area, many of the details agree very well, such as the dense forest along the Ural mountains, especially on the western slope, the variability of the vegetation along the river Ob in the West Siberian Lowland and the different forest types and densities in the Central Siberian Plateau. The small and isolated forests north of Semipalatinsk (51°N-80°E) were also detected.

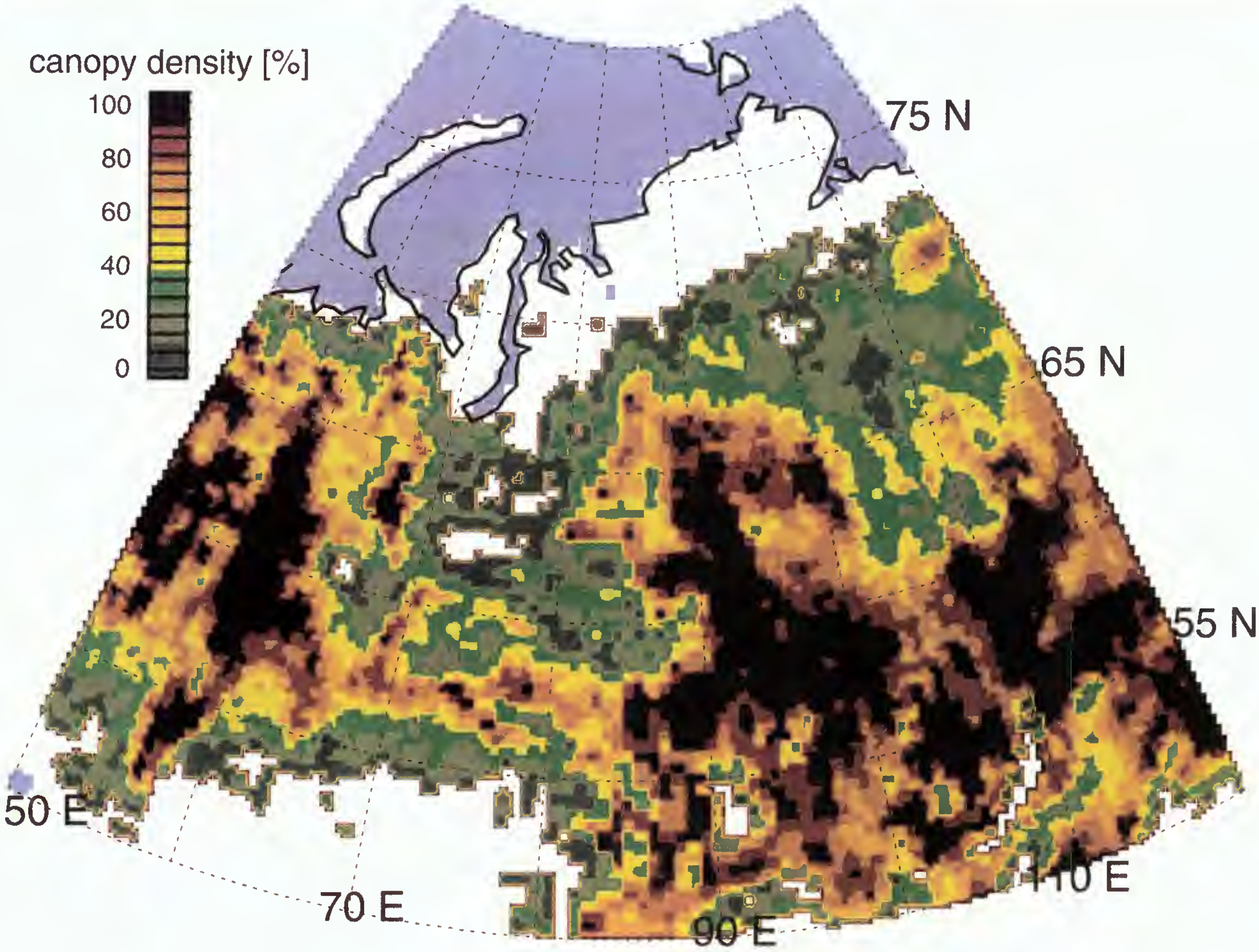


Figure 4-11: Canopy density map of the Siberia test area derived from ERS-1 Scatterometer measurements

Wetland monitoring

The ATSR has been used for a number of land applications, building on the experience gained from many years gained with the similar AVHRR sensor. The ATSR, with its more advanced radiometric capabilities offers the potential to develop medium-resolution land applications further.

Example 5 shows how ATSR data have been used to monitor the varying extent of the wetland. Although cloud cover has been a problem, the presence of the thermal channels on ATSR, together with the size of the swath, make it suitable for this application. ERS SAR data have also been used for wetland studies at higher resolutions, as illustrated by the examples of *Henebry & Kux, and Corves (ESA 1995).*

Earlier work on monitoring lake levels and wetlands quoted by Blyth, 1993 suggests that the following accuracies have been achieved using altimetry prior to ERS-1 (Seasat and Geosat):

- Lake levels to ± 25 cm *(Mason et al, 1990)*
- Water levels in wetland regions to 1015 cm *(Cudlip et al. 1990)*

It was also necessary to know the elevation of adjacent areas accurately to reduce the effects of orbit errors. Accurate orbit determination with ERS and Topex/Poseidon missions is allowing these techniques to be developed further. Preliminary results showed accuracies to better than 10cm using the ERS-1 Radar Altimeter *(Mason et al, 1990).*

Radar Altimeter instruments, in combination with radiometers such as ATSR have also been applied to monitoring lake levels. In this case, the Radar Altimeter is used to give a very accurate indication of the lake level. Data from the radiometer are then used to estimate the surface area of the lake. These data, together with estimates or data on the subsurface shape of the lake can be used to give an approximate value for the lake volume. By monitoring the changes in these values over time, the status of the world´s surface freshwater storages can be monitored, making a valuable contribution to the science of global environmental change from a hydrological perspective.

Flood monitoring and floodplain determination

The areas liable to be flooded by a river are traditionally determined using historical records of previous flood events to estimate likely flood discharges and routing procedures to estimate the characteristics of the flood wave as it passes through the river system. One of the main inputs to this approach is in-situ measurements of flood extent and corresponding estimates of river discharge.

Although these techniques are well developed, there are a number of limitations associated with them. Firstly, the in-situ measurement techniques are often difficult and thus expensive to provide. It would therefore be advantageous to minimise the number of such measurements necessary and also to optimise their use. There are also difficulties associated with measuring the precise topography of the floodplain and any discontinuities which may exist. These affect the accuracy with which the localised extent of flooding can be predicted for a given discharge.

The use of ERS SAR data has been shown to be of value in a number of ways in assessing the potential for flooding in an area. Many of these examples are given in ESA, 1996. Taken together, they illustrate the following important aspects of flood monitoring with SAR:

- ERS SAR can be used to determine areas which have flooded during an event.

- Typical weather conditions during flood events emphasis the value of the ERS SAR all weather capability.

- The flooded area information can be used for immediate flood relief and to assess insurance claims. Monitoring during a flood event can be used to design flood prevention infrastructure also to provide insurance hazard assessments.

- Successful applications of ERS SAR data for these assessments are not made in isolation. In the examples cited above, at least some of the following sources were used in conjunction:
  - — topographic base maps
  - — soil maps
  - — hydrographic network maps
  - — in situ soil moisture measurements
  - — Landsat data (as a base reference and to improve classification)
  - — Spot maps (for land classification and to provide a DEM).

Example 5: Remote Sensing of the World's Largest Wetlands

Charon Birkett MSSL

Wetlands have been estimated to cover 6% of the world´s land surface. Found over a wide range of latitudes, they are important elements of the hydrosphere and biosphere. They are important ecosystems, and often play a significant role in the regional hydrology. In addition, wetland extents vary substantially both seasonally and inter-annually. The hydraulic response tends to be relatively slow (from weeks to months) and such changes can in principle be used as a proxy indicator of regional climate. However, most wetlands exist in areas where in situ monitoring is difficult and in these situations, remote sensing can play an active role

The Sudd is a seasonally inundated wetland situated on the White Nile. With an area of tens of thousands of square kilometres, it is one of the world´s largest wetlands. Only around half of the inflow of the river at the head of the wetland emerges at the tail; the rest evaporates from the swamp. This fact has led to the proposal and partial reconstruction of the Jonglei Canal to bypass the Sudd and provide more water to the Nile downstream.

The Sudd has become a case study to investigate the potential for systematic remote sensing of wetlands. The study initially concentrated in the use of satellite imagery to monitor the variation of wetland extent. The results showed that the vegetation covered wetland is best observed at thermal wavelengths and that contrast between the vegetation covered marsh and the surrounding land is at its best either in the early morning or afternoon. Analysis of a time series of images revealed the magnitude of the changing inundated areas, ranging from 10 000 km^2 to 40 000 km^2 However, the cloudy nature of the images, particularly at times of minimum extent, hindered the analysis, Current research therefore is looking at methods of combining synergistic imagery and radar altimetry to look for ways of using the altimetry alone, which is not affected by clouds, to predict the extent of inundation. Correlations between the image derived areas, and the extent of the marsh as displayed by the changing shape and intensity of radar echoes are currently being researched.

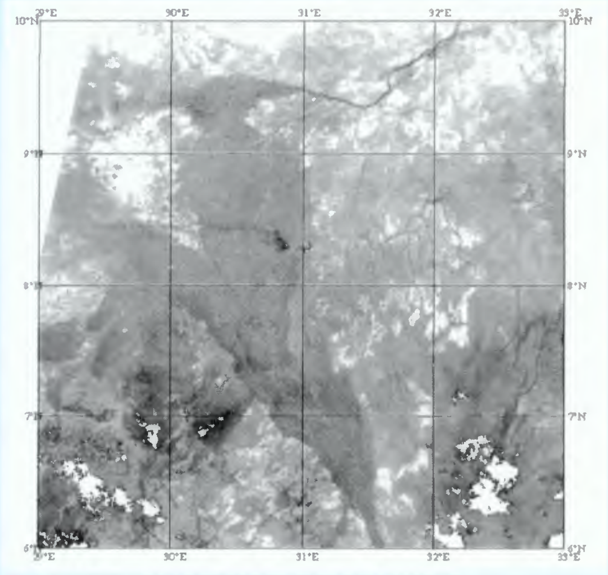


Figure 4-12: ATSR image of the Sudd wetlands

Figure 4-12 shows an ATSR-1 image depicting the Sudd near its time of maximum extent on 6.12.1992. The channel 4 (11 micron) image was taken at 10 am local time and shows good contrast between the vegetation covered Sudd and the surrounding land. The inundated area, derived by applying a simple thresholding technique to the image brightness histogram, is approximately 29 000 km^2.

This DEM may be available from traditional cartographic sources, but if it is not, it can be obtained using SAR interferometry as well as from Spot.

An important means of integrating the data types listed above is to use a GIS. This allows combinations of different 'layers' of information to be viewed and can also provide a basis for modelling work. Many of the examples below have used this approach, which also represents an important link between satellite data and the operational user community, since many of these users already operate sophisticated GIS as part of their routine activities.

The example also illustrate the increasing number of examples where ERS SAR data have been used operationally. As well as *Example 6* below, the following examples can be quoted:

- Floodplain management in Wallonia, Belgium. This illustrated the successful integration of ERS and traditional data sources within a GIS.
- Flood mapping in the Mississippi Basin, USA during the disastrous and prolonged flooding of 1993. The data were used as part of the strategic decision-making process during the rescue operations.
- Provision of flood information in the Netherlands during the floods of January, 1995 in which the evacuation of 250 000 people was ordered.
- Flood mapping in the Unkel area of Germany in which ERS SAR data were used to supplement traditional methods for determining the extent of major flood events.
- Flood monitoring and assessment in Piedmonte, Italy during the major floods in November 1994. The all weather capability of SAR provided invaluable in this case, and the results were used for agricultural damage assessment as well as subsequent land use planning.

There are some limitations to this technique, which are mainly associated with factors which change the backscattering properties of the water surface. These include:
— wind or subsurface induced perturbations in the water surface;
— vegetation protruding through the water (*cf. Blyth's findings in ESA, 1995*);
— very high levels of sediment charge;
— buildings or other urban structures which may act as corner reflectors and obscure the effects of the flooded surface.

Although important, these limitations do not undermine the basic value of the technique. They represent considerations to be taken into account when interpreting data.

Example 6 provides a more detailed example of the application of ERS SAR data to flood monitoring. It shows the synergistic use of ERS-1 SAR data with Spot XS high-resolution optical data. The Spot data were used in this case to derive a DEM while the ERS SAR data provided a soil moisture index indicating areas likely to flood.

Discharge measurement

River discharge is generally determined by measuring the stage of a river at a point where the stage/discharge relationship is well defined. This usually means a controlled cross section such as a weir or flume, or in larger rivers a cross section calibrated using current meters. The relationships rely on there being a constant river cross section at the point of measurement. Two examples where this is does not apply are:

1. When the control structure has become 'drowned' during periods of flooding and thus the stage discharge relationship no longer applies;
2. When the river channel is unstable, such as in wide, shallow gravel rivers where braiding and shifting channels are common.

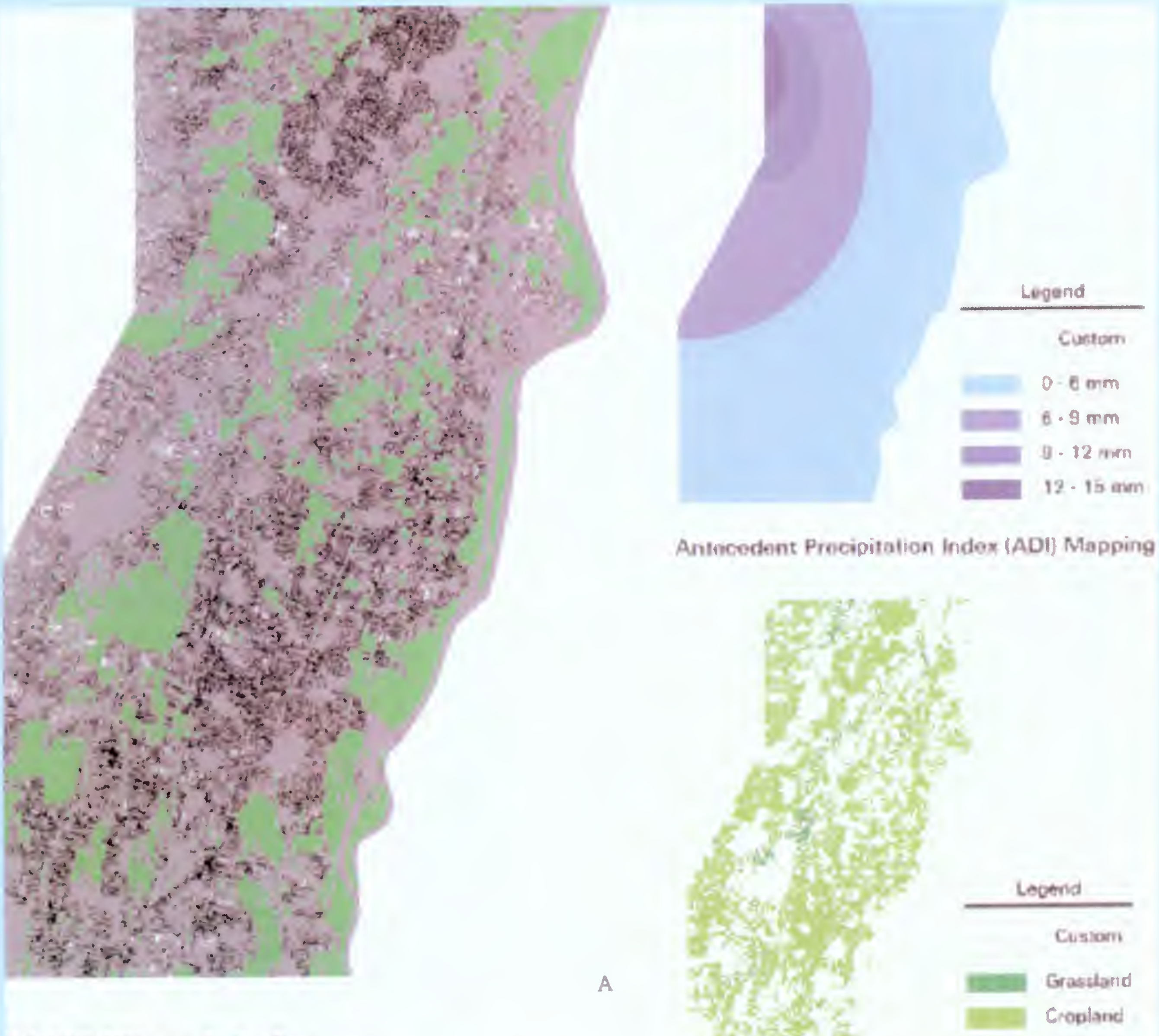
The contribution of ERS SAR to floodplain determination and flood monitoring has been illustrated above. *Example 7* illustrates the use of ERS-1 SAR to estimate discharge in a large gravel river.

Example 6: The use of ERS SAR data to estimate flood risk

Kader Fellah, Service Régional de Traitement dÍmage et de Télédétection (SERTIT)

A demonstration project to highlight the use of ERS-1 SAR data together with Spot images in flood risk evaluation and monitoring was carried out in the central Alsace region of France from 1992 until 1994. The region is prone to flood events from the Ill river, a principal tributary of the Rhine. The work had two aims, to enable assessment of flood risk through determination of soil moisture characteristics and also to evaluate the effects of flooding during events.

The main focus for the first case was to use the level of soil moisture and its space time variation derived from the SAR images with soil information and a Spot-based DEM to identify and classify land areas at risk from



S-1 SAR data : 17 April 1992.
e signal intensity is shown over the cropland
d grassland themes. Forestry theme is repesented
green and the other themes in light grey.

Antecedent Precipitation Index (ADI) Mapping

Landuse classification from SPOT synchronos da
Cropland and Grassland themes

Figure 4-13: A GIS approach for the ERS signal analysis, including ERS-1 SAR data, antecedent precipitation index and Spot landuse classification. *(Image from the Application Achievements of ERS-1 p.89).*

flooding. The analysis was based on the use of an environmental GIS. The processing and analysis of the SAR data were carried out by SERTIT and the results delivered to the Service des Eaux et des Millieux Aquatiques d'Alsace.

In addition to the DEM, Spot XS data were used to generate multi-date images which formed the basis of a five class land cover map. This classification was then used to produce various masks for the analysis of segmented single and multitemporal SAR data.

The SAR data used in the multitemporal analysis were acquired during periods corresponding to different soil hydration levels. The processed SAR data were then used to determine a soil moisture index. Further data were derived from the GIS and SAR/Spot data including the depth of underground water and the soil moisture capacity in both normal and flood conditions. Figure 4-13 illustrates the Antecedent Precipitation Index used to calibrate the ERS-1 image and the appropriate Spot-based land classification map. This work led to a strong correlation between the ERS SAR backscattering coefficient and the soil moisture at a regional scale. The study also emphasised the importance of scale in the SAR backscatter/soil moisture relationship.

As well as the identification of areas at risk from flooding and a quantification of the level of risk, the data can be used during a flood event to evaluate rapidly the level and extent of inundation. This potential has been tested in the Camargue region. Figure 4-14 shows the Spot optical and ERS-1 SAR radar imagery integration, Figure 4-15 an ERS-1 image of the Camargue flood on 1 November 1993 and Figure 4-16 flooded areas derived from ERS-1 images of both 16 October and 1 November 1993. The study shows that ERS-1 multitemporal analysis, combined with Spot XS data affords flood monitoring and therefore furnishes information relative to flood extent, flood persistence, flood impact and therefore flood damage.

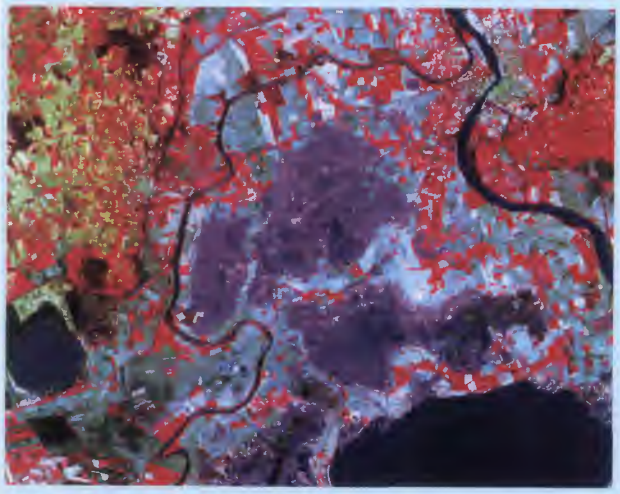


Figure 4-14: Spot optical and ERS-1 SAR radar imagery integration for the Camargue

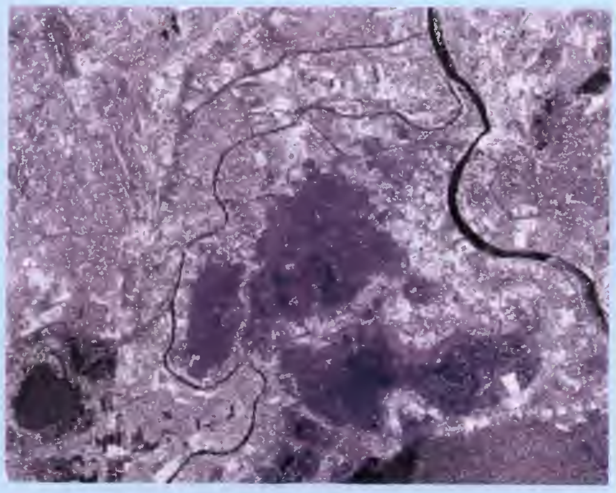


Figure 4-16: Flooded areas derived from ERS-1 images of 16.10 and 1.11.1993.

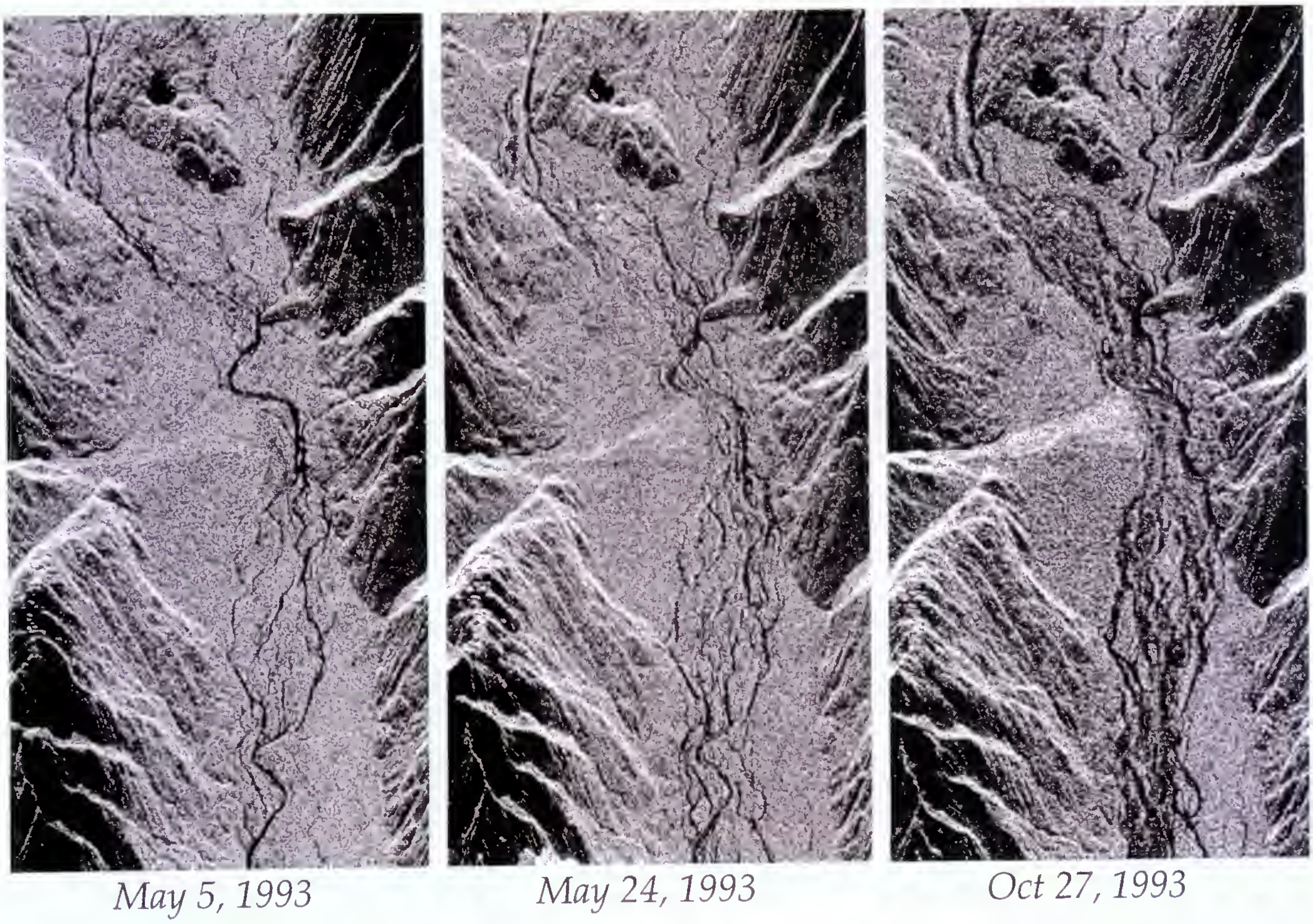
Figure 4-15: ERS-1 image of the Camargue flood, 1.11.93 © CNES 1993, ESA 1993. Processing SERTIT 1994

Example 7: Estimating discharge in braided rivers from space using SAR

Larry Smith, Cornell University

The water surface on an unconfined braided floodplain increases or decreases in response to total river discharge. This is confirmed from 1994 field measurements on the braided Iskut River in British Colombia, which show that braid channel width increases much faster than either depth or velocity when river discharge increases. These effects are integrated over a two dimensional area when total water surface area of a braided reach is measured and correlated with the total discharge through the reach. The surface area contributed by transient channels (which is also highly dependent upon discharge) is thereby included in the water surface area estimate.

Multitemporal ERS-1 imagery (Figure 4-17) and simultaneous ground measurements of discharge reveal a strong correlation between discharge and total water surface area for the Iskut, Taku and Tanana Rivers in North West British Colombia and Alaska. The satellite derived area discharge rating curves (Figure 4-18) show the relationships between changes in discharge and resultant changes in inundation area over km scale reaches of braided floodplains. The relationships display little temporal or spatial variability, unlike the at-a-station width / discharge relationships obtained in the field for individual braid channels. Differences in rating curve slope for the three rivers examined indicate differences in each river's propensity for widening, which appears to be a function of longitudinal river slope, grain size and braid intensity.


May 5, 1993

May 24, 1993

Oct 27, 1993

Figure 4-17: Multitemporal ERS-1 imagery

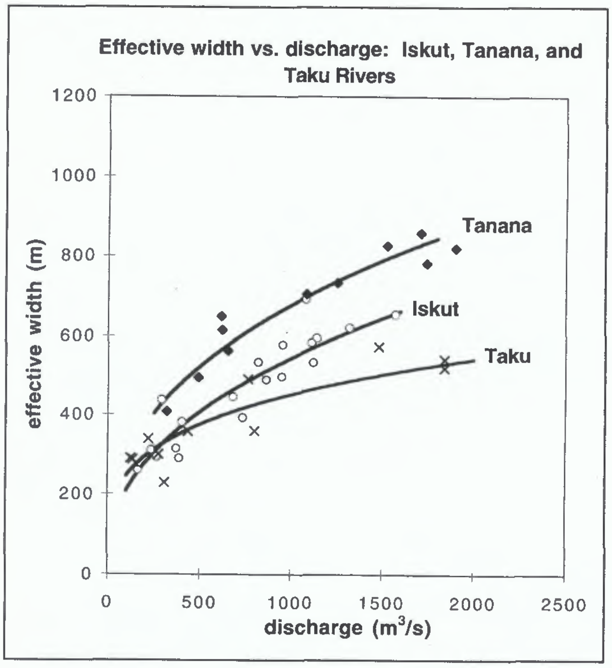


Figure 4-18: Satellite-derived area-discharge rating curves

Modelling and forecasting

Having extracted the required hydrological variables from the instrument data, the next stage is to use them for hydrological applications. The data have been applied in a number of ways, but perhaps the most suitable mechanism in the long term is in conjunction with distributed hydrological models, because it is with such models that the need for spatially distributed input variables is most apparent.

Such models need representative values of key variables such as soil moisture for initialisation. During the development of such models, the use of spatial measurements to validate spatial forecasts is also essential.

One of the hydrological modelling areas in which the use of ERS data is closest to operational status is in the provision of snow cover information as a basis for discharge prediction. The use of ERS-1 SAR to support such models is illustrated in *Example 8.*

Example 8: The use of ERS-1 SAR data in a hydrological model to forecast snowmelt runoff

Helmut Rott and Thomas Nägler, University of Innsbruck

Runoff from melting snow and glaciers provides significant parts of the water supply in high as mid-latitudes and in many of the world´s mountain regions. Hydrological models of various degrees of complexity are applied for monitoring and forecasting snowmelt runoff in order to optimise the management of the water resources and to study climatic impacts on snowmelt. Conventional snowmelt runoff models are based on point measurements of snow depth or water equivalent. More advanced runoff models are utilising spatially distributed information as provided by satellite remote sensing.

A method has been developed to map the extent of melting snow areas by means of the ERS SAR. Snow extent is required as input for distributed runoff models. As an example for the application of ERS-SAR, results of calculations of daily runoff during a period of snow and glacier melt are shown for a drainage basin in the Austrian Alps, the basin Rofenache which extends over an area of 98 km and is partly covered by glaciers. The basin, illustrated in Figure 4-19 was divided into several elevation zones (Figure 4-20), the snowmelt volume for each zone was calculated from the snow extent mapped by means of ERS-1 SAR and from meteorological data (Figure 4-21). Due to the regular repeat observations and its sensitivity to snow properties, SAR is a valuable tool for operational hydrology. Figure 4-22 shows a comparison of measured daily runoff with results of calculations using ERS-1 SAR derived snow cover maps.

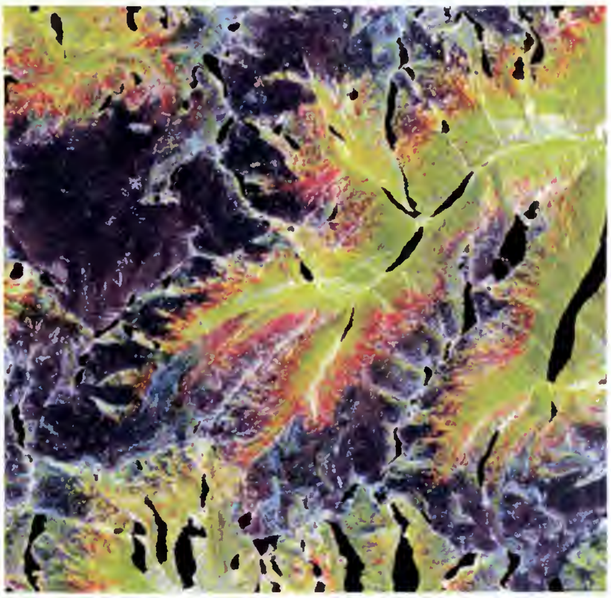


Figure 4-19: Composite of geocoded, terrain corrected ERS-1 SAR images from ascending and descending orbits acquired on 27 April 1992 (blue), 1 June 1992 (green) and 6 July 1992 (red). showing the basin Rofenache and surrounding areas. The snow cover on 6 July appears in magenta the change of snow covered area between 1 June and 6 July appear in red. The black area represents areas of layover.

Figure 4-21:Snowcover map of the basin Rofenache on 1 June 1992, derived from ERS-1 SAR data.

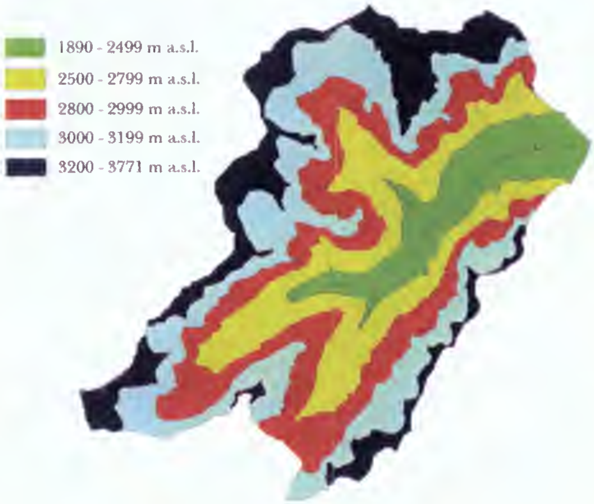


Figure 4-20: Elevation zones of the basin Rofenache.

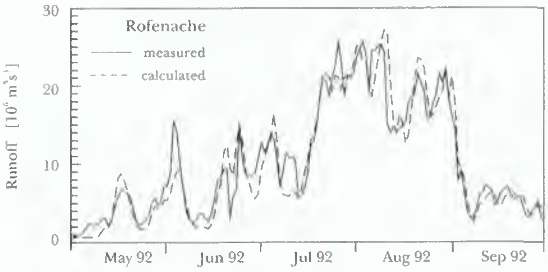


Figure 4-22: Comparison of measured daily runoff with results of calculations using ERS-1 SAR derived snow cover maps.

5. ERS Mission Performance

5.1 ERS Performance

One of the most notable qualities of ERS is its extremely good calibration and stability. This makes a range of techniques possible, including multitemporal comparisons. The opportunity to make spatial measurements of surface moisture variability using SAR could not be realised were it not possible to rely on the stability of the sensor over time. Similarly, the continuity provided by the succession of ERS-1 by ERS-2 with a near identical instrument complement is vital in ensuring long term provision of data, essential for operational applications.

The performance of the ERS mission is examined below with emphasis on the SAR but the performance of the other instruments should also be noted. The tracking of the ERS Radar Altimeter over the Earth's oceans has been very stable and robust since early commissioning. Optimisation of the onboard tracking loop parameters during the early part of the mission has allowed good tracking to be achieved over sea ice and land ice as well. This is demonstrated by the subsequent production of an elevation map of Antarctica based on ERS-1 Radar Altimeter data.

The objectives of the ATSR mission were to provide long-term and highly accurate records of sea surface temperature for use in climatology studies. High radiometric accuracy, on board calibration targets, mechanical cooling capabilities and the dual view approach all contribute to the accuracy and stability of the ATSR mission.

The performance of the ERS SAR instruments is considered from two perspectives: radiometric performance and phase performance. In each case, accuracy, stability and continuity are examined.

Radiometric performance

As a type of pulsed radar, the ERS SAR can be characterised by the ratio of the peak power of its transmitted pulse to the minimum discernible signal of its receiver. Issues associated with the radar´s power transmission and reception capabilities, such as its signal-to-noise ratio, are referred to as its radiometric characteristics. These characteristics are important because they determine the ability of the SAR to distinguish objects and to quantify variations in continuously varying surface characteristics such as soil moisture.

Central to the radiometric accuracy of the measurements made using the ERS SARs is the calibration process. The performance of the end to end system relies on the following components:

- consistently high on-board performance (not only of the instrument itself, but also of supporting elements such as thermal stability);
- accurate on-ground performance measurements;
- precise data processing;
- provision of SAR data related information to the user community.

The calibration of the ERS SARs is achieved at two levels:
- internal calibration which forms part of the instrument operations;
- external calibration using ground targets (deployed in the flat reclaimed lands of Flevoland and Zeeland, Netherlands)

To illustrate the radiometric accuracy of the instrument, the conclusions of the ESA report on radiometric calibration (*Laur et al, 1993*) were as follows:
- they confirm the high radiometric stability of the ERS-1 SAR since the start of the mission;
- by including Analogue-to-Digital Converter non-linearity corrections, there is a reduction by half of the radiometric calibration parameters such as the radiometric accuracy or radiometric stability, ie values of calibration constants previously given within maximum bounds of ±0.8 dB were reduced to ±0.4 dB;
- the radiometric stability measured over two years was about 0.2 dB, well within specifications.

In concluding the study, it was noted that one of the original recommendations for the ERS missions, formulated in 1982, stated that:
'calibration to a level of ±1 dB would be a major achievement' (EARSEL, 1982).

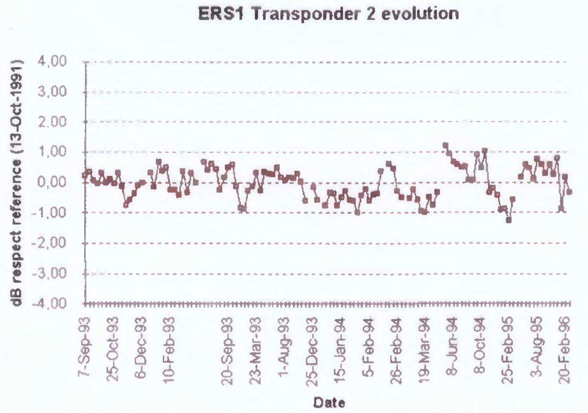


Figure 5-1: Changes in response from ESA transponder 2 at Flevoland for the ERS-1 SAR

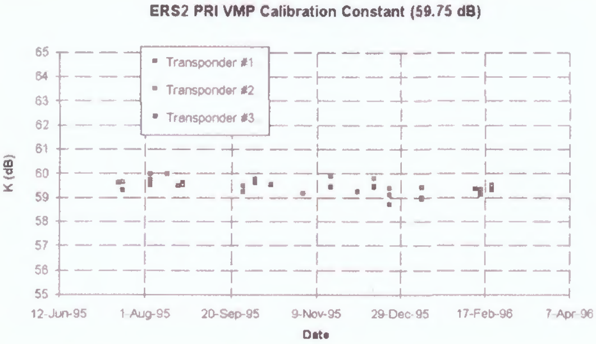


Figure 5-2: Changes in the ERS-2 calibration coefficient over time based on the use of the Verification Mode Processor (VMP)

The fact that calibration to less than half this value has been achieved and stability to an even lower level is testament to the success of the mission.

The radiometric stability of the ERS SAR systems is one of the key issues to ensure that the scientific community can take full advantage of ERS SAR data. This stability is continuously monitored, providing the information needed by users to allow absolute calibration of the ERS SAR imagery. Without this calibration it would not be possible to compare SAR image ERS data with data acquired by other sensors effectively and the extraction of geophysical information related to the surfaces imaged from the SAR images would be compromised.

Both ERS SARs have shown a very high stability through their missions. Radiometric stability is defined as the standard deviation of the radar cross section measured on the transponders deployed at the ERS calibration site of Flevoland (or Zeeland for the 3-day cycles) in The Netherlands.

The stability of the ERS-1 SAR system is 0.5 dB, as shown in Figure 5-1. For the ERS-2 SAR system the stability shown by the transponder measurements is similar. Figure 5-2 shows the variation of the calibration constant value through time.

A number of other parameters indicate the good performance of the ERS SAR system. These are the low noise levels present in the receiver, the calibration pulse and the replica pulse.

Many of the examples given in Chapter 4 illustrate the successful applications which can be undertaken as a result of the radiometric performance of the SAR instrument.

Phase performance

As well as its radiometric or power performance, good instrument phase characteristics are essential for successful applications. This takes into account both the frequency characteristics of the instrument itself and the orbit and attitude performance of the satellite as a whole.

Output frequency is important in determining the nature of the response from the surface. As a result, accurate generation of the output frequency and accurate detection of the return frequency is needed for interpreting imagery effectively. Particularly important is the frequency stability over time. This is fundamental, not only to basic interpretation, but also to complex applications such as interferometry which require an accurate knowledge of phase relationships.

The other component of the good phase performance is to ensure accurate observation geometry, and in particular the incidence angle. On the ERS satellites, such variables are measured and controlled to a very high level of accuracy.

The applications which can be achieved as a result of the phase performance are illustrated by *Example 9*, an interferometric application for detecting very small changes in ground level. In this case, ground movements of only a few cm are measured and have been interpreted as the effects of frost heave in a clay soil.

Example 9: Measuring surface deformations with interferometric SAR

Erik van Halsema, TNO

In the Netherlands, ESA supported research is being carried out toward the application of SAR interferometry to monitor land subsidence which is caused by, among others, natural gas extraction. Deformations of this kind in the Netherlands are generally less than 6 mm per year. SAR interferometry offers an attractive price combined with high accuracy and a large areal coverage. At present costly yearly levelling campaigns are being carried out to monitor the subsidence.

In SAR interferometry use is made of the detected phase of the radar signal. Phase differences are calculated between two or three carefully aligned radar images. This way phase difference images are created which are often referred to as 'interferograms'. The phase differences in these interferograms present a very accurate measure (mm accuracy) of path length differences between the footprint on the Earth´s surface and the position of the antenna during both acquisitions. The interesting point is here, that these small differences in path length can be directly related to interesting geophysical measures as terrain *topography and Earth surface* deformations such as land subsidence or frost heave.

An example of the potential of SAR interferometry to measure small surface deformations is given in Figure 5-3. Shown is an interferogram from the province of Zeeland in the Netherlands during the second ice phase in January-March 1994.

The interferogram shows systematic phase effects that are clearly related to the land use and/or the soil type. It seems very likely that these systematic phase effects in the Zeeland are due to a change of temperature from frost to thaw *in the time interval* between the two ERS-1 passes. During the first pass the temperature was below zero and during the second pass above. Of all the interferogram studied, those with the largest differences in phase between the fields consist of one image during the frost period and the other during the thaw period. It is thought that the phase differences are caused by heave of the ground through freezing of the water contained in the clay. This is also suggested by the differences in phase between sandy grounds and urban areas, which have little or no water content, and the clay grounds.

The phase differences between different agricultural areas may have to do with difference in clay content (i.e. water content) and/or differences in structure, caused by agricultural activities. The magnitude of the effects range from several mm up to 1 cm. Figure 5-3 shows that the technique indeed is able to measure very small surface effects.

Further research is currently being carried out toward the potential and limitations of the SAR interferometry technique to measure small deformations which occur over large periods in time. Also the effect of atmospheric and ionospheric conditions is taken into account.

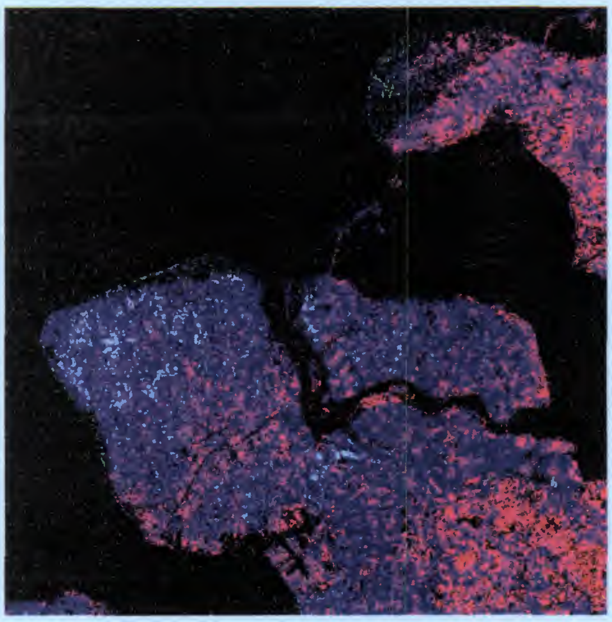


Figure 5-3: Frozen soil example (Erik van Halsema, TNO Physics and Electronics Laboratory)

5.2 ERS Achievements

Table 5-1 summarises the performance of ERS SAR in the different areas needed for high-quality applications.

The successful performance of the ERS sensors is thus the combined result of a number of factors:

- the instruments have been reliable, giving high levels of availability;
- the platforms have performed beyond expectations in areas such as power availability and thermal control, giving a stable environment in which the instruments can operate;
- the orbital control and determination has been very precise, ensuring that the geometry of observation is stable and accurate;
- the instruments have performed beyond expectation in terms of their individual stability and accuracy;
- extensive calibration, both on board and ground based, has accompanied the missions and ensures that what variations there are can be accounted for.

The fact that instrument and platform induced variability has been minimised means that the data can be applied to geophysical measurements with confidence. In particular, the use of the data to determine not only boundaries and objects, but spatially continuous variables such as soil moisture is an illustration of the ERS achievement.

	Accuracy	**Stability**	**Continuity**
Radiometric performance	High output power (4.8 kW) and sensitive detection allow high signal to noise ratio. This provides high sensitivity to surface phenomena.	Factor such as good thermal control and small ageing effects lead to low output variability. This is essential for time series applications.	Identical instruments on ERS-1 and 2 leads to similar characteristics. Reductions in ERS-2 SAR output calibrated
Phase performance (frequency)	Performance of AMI frequency generator and detector allows frequency to be known accurately.	Low variability of output frequency essential for precision applications such as interferometry where phase relationships are important.	Common characteristics of ERS-1 and ERS-2 have allowed the two satellites to be used in a 'Tandem' mission for interferometric applications
Phase performance (orbit and attitude performance)	The use of laser retroreflectors in addition to Doppler tracking provide very accurate orbit determination. Other valuable factors include yaw steer and good attitude control.	Since launch, the ERS-1 orbit has been maintained within 1 km of deadband. For the Tandem mission, this was improved to 200 m with variations less than 60 m in most cases.	Accurate orbital control and monitoring allows effective combined use of data from ERS-1 and 2.

Table 5-1. Summary of ERS SAR performance characteristics

6. Outlook

6.1 Expectations for the ERS missions

The original objectives for the ERS satellites emphasised oceanographic and cryospheric applications. It was also recognised that the sensors would be able to provide valuable information on characteristics of the land surface. This initial expectation, based on a secondary use of the data, has clearly been considerably exceeded as has been demonstrated in a hydrological context, a particularly challenging application area.

The accuracy, stability and continuity achieved by the ERS satellites, particularly with the SAR, have presented a unique opportunity to develop operational applications of remote sensing data in hydrology.

6.2 Future SAR missions

One of the main criticisms of remote sensing for hydrology has been that the satellites either do not observe a given location often enough, or if they do, that this is achieved at the expense of an adequate resolution. To some extent, these problems are imposed by the technology which limits the combination of resolution and coverage available.

One way to achieve the desired combination of resolution and coverage is to use data from more than one satellite. The benefits achieved from the tandem operation of ERS-1 and ERS-2 have already illustrated the value of this approach. With the recent launch of Radarsat and the unexpectedly long lifetime of ERS-1, there are currently 3 C-Band SARs in orbit, all of which can be used for hydrological monitoring. As launch costs are reduced, and the technology for active microwave sensors develops, opportunities for increasing the number of such instruments will increase. Recent interest in radar remote sensing satellites in the USA and China are further evidence of this.

The future availability of multi-frequency and multi-polarisation SARs will also help to overcome some of the difficulties in geophysical conversion, bringing an increase in the number of operational capabilities. Techniques to handle data of this type are already being researched using airborne data and data from the Shuttle Imaging Radar (SIR) series.

The trend towards increasing numbers of instruments, and an increased variety of sensor options is very valuable. What should not be lost with this specialisation is the possibility to use data from multiple missions effectively. If it is possible to develop applications requiring frequent revisit times using data from more than one mission because the measurements made are sufficiently compatible, both the users and the data providers will benefit.

6.3 Future enabling methods

This document has emphasised the need to develop hydrological models which can make use of the spatially distributed and measurable variables provided by remote sensing. The importance of these models is considered further below, but there is also a need for an approach which can effectively extrapolate the measurements of the satellite in space (to the layers below the measured surface value) and in time (to cover the time period between images).

Such an approach can allow data to be used for applications which require observations more frequently than the sensor can provide. For example soil moisture forecasts currently provided by national meteorological agencies for agricultural applications are based on raingauge data and evapotranspiration estimates. These methods typically operate on a grid of about 40-50 km and the addition of spatial information at higher resolutions would be a valuable enhancement.

Example 10 provides an example of this type of approach, currently under development, which is intended specifically for use with ERS SAR data.

Example 10: Method for vertical and time extrapolation of ERS SAR soil moisture information

R. Ragab & Ken Blyth, UK Institute of Hydrology

A study has been carried out to develop and evaluate a system to estimate soil moisture content in the root zone using data from ERS-1 to measure moisture content in the top 10cm of the soil profile.

The system consists of an initialisation phase, which provides surface and root zone moisture contents at a point in time, and a dynamic phase in which their variability with time is simulated using a soil water balance model.

For the initialisation phase, the initial value of surface moisture is intended to be derived from ERS SAR, though field measured values can also be used. The surface value for a given day is used to derive the initial value of the root zone moisture for the same day. Empirical relationships with strong coefficients of determination are used to achieve this and examples of such relationships for sand and clay soils are given in Figures 6-1 and 6-2.

The dynamic model simulates the changes in soil moisture over a period of time from the initial measurements and derived values through to the next update of the surface moisture measurements. To achieve this simulation requires that the soil be defined in terms of its moisture contents at field capacity and wilting point and also its diffusivity. In addition to these parameters, measurements or estimates of daily rainfall and evaporation are required. The approach as a whole is shown diagrammatically in Figure 6-3.

Until the number of soil moisture and ERS SAR backscatter pairs is sufficient to provide a statistically significant relationship, the model is being tested using measured values. With continued effort, the model will serve as a basis for extending the applicability of ERS and possibly other SAR measurements both in space to the subsoil and in time to the periods between overpasses.

To illustrate the nature of the output achieved without updating, Figure 6-4 shows the results for Cricklade (clay soil). These were achieved by starting the model at field capacity at the start of the year (a well founded assumption) and running it for a two year period. The effects of introducing the ERS SAR data will be to allow the point data to be updated more regularly and to allow the effects of spatial distributions to be taken into account more effectively.

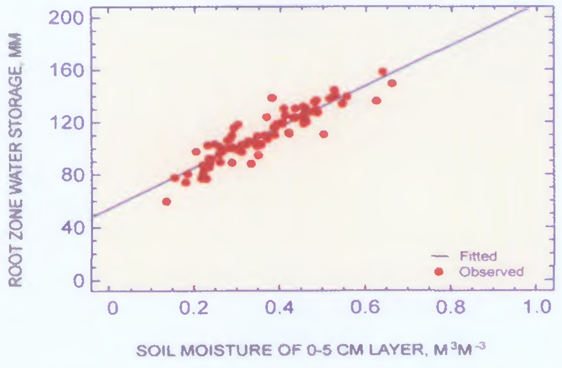


Figure 6-1: The relationships between root zone (0-50 cm) water storage and soil moisture content of the 0-5 cm layer at Chieveley (sandy soil).

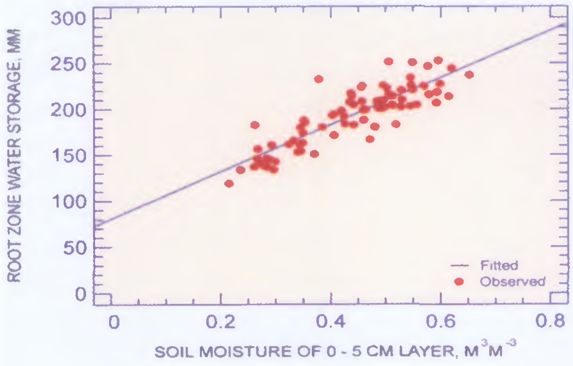


Figure 6-2: The relationships between root zone (0-50 cm) water storage and soil moisture content of the 0-5 cm layer at Cricklade (clay soil).

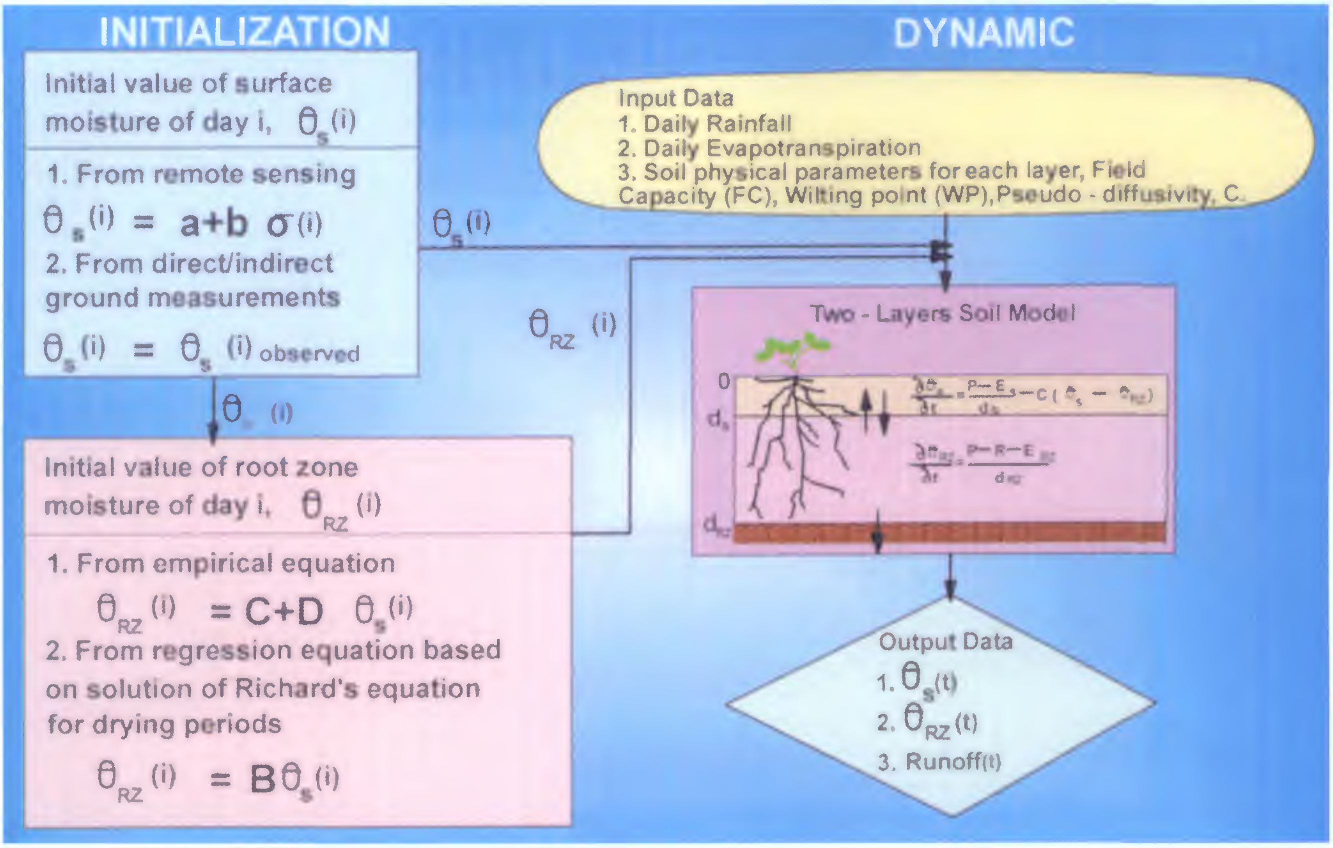


Figure 6-3: A continuous operational system to estimate the root zone soil moisture from intermittent remotely sensed surface moisture.

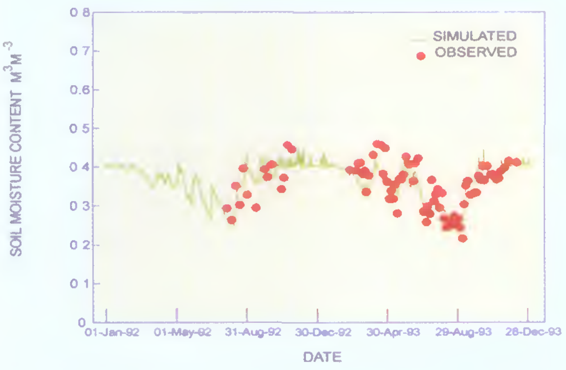


Figure 6-4: Simulated and observed soil moisture content of the root zone (0-50 cm) at Cricklade (clay soil)

6.4 Future hydrological models

The justifications for the development of spatially distributed, physically based hydrological models include:

- the need for a technique which can operate in situations where historical data are insufficient to use established empirical methods;
- the need, in some cases, to take account of spatial variability in the model, such as for the dispersion of pollutants within the catchment;
- the need for a technique to forecast the effects of changes within a catchment, such as the construction of a reservoir or other land use changes.

One of the benefits of recent work at larger regional and global scales linked to Earth system science in scientific hydrology has been the opportunity to continue the development of physically based distributed modelling. This in turn represents an opportunity for the application of EO data in hydrology as a whole, since it is only by using these models that the impact of the spatially variable measurements can be maximised.

In addition to the above, these models are also justified as a basis for testing the current state of process knowledge. For many years this field of modelling was limited by a number of factors:

- a lack of both spatial surface and subsurface data to initialise and validate the models;
- a lack of confidence in the ability to produce 'representative' variables from actual measurements;
- the consequent need to parameterise the models, removing some of the physical meaning and measurability of the input data;
- the computational power required to run the model with the necessary level of catchment subdivision;
- the competition from more established empirical techniques.

The computational problems are not now as great and this limitation is much reduced. In addition the availability of commercial GIS facilities, which are now widely used in operational environments allows data to be stored and prepared much more effectively. The fact that Earth system science has raised the profile of scientific hydrology also provides an opportunity to develop these models free from the competition that they often face in shorter-term engineering applications. This is important because the model complexity makes their development and validation a long-term task.

Further development requires a high level of cooperation between modellers and remote sensing researchers. This is because neither the model nor the EO instrument offers a perfectly representative picture of reality, but the need is for the EO data to be able to provide the data which fulfil models' representativeness requirements. These requirements will change as modelling capabilities continue to improve.

6.5 The current situation and view to operational use

The recent developments in hydrological science, which have emphasised the regional and global water cycle, have served to clarify the distinction between two key areas of hydrology, namely:

- engineering hydrology and water resources management;
- scientific hydrology.

Although there is considerable interaction and exchange of techniques between these subdivisions, the distinction is important because the priorities and information requirements are very different. This means that the obstacles to the use of remote sensing data are different in each group as are the approaches necessary to overcome these. Table 6-1 summarises the characteristics of the two groups:

It is clear from Table 6-1 that progress depends on both technological developments and the selection of methods to encourage the transfer to operations. There is also a case to suggest that the more operational users can be encouraged to use the data, the more rapidly understanding of the potential of the data will develop. This 'virtuous cycle' has been noted for a number of applications where the user's existing knowledge of in-situ conditions helps to extract the maximum information content from the data.

6.6 The transfer to operations process

The operationalisation of ERS data is not merely a technological issue. To be used, the data and information must form an integral part of the current

Aspect	**Operational hydrology**	**Scientific hydrology**
Key organisations	Water authorities, water companies, civil engineering companies, insurance companies, hydrological research institutes	Hydrological research institutes, universities, international programmes (incl. climatology and meteorology)
Priorities	Supply of water flood control and other water related problems Regulations / commercial returns	Understanding the hydrological system at all scales. Input to regulatory frameworks Developing techniques for transfer to the 'engineering' community
Spatial scales	Local scale up to large catchment / regional	All scales
Timescales of interest	From immediate operations and emergency planning to long-term design/analysis	Short timescales for plot studies through to 100 years or more for climatology
Remote sensing interest	Interest in solving existing problems. These include management and planning of supply and flood schemes, insurance assessment	Large scale monitoring and analysis for climatology and integrated studies (eg HAPEX/FIFE)
Obstacles to the use of remote sensing data	Lack of awareness and perceived complexity of using remote sensing data Cost effectiveness: remote sensing must compete with pragmatic in-situ techniques Existing operational methodologies not optimal for use of remote sensing data Increasing competition in water industry makes implementation of novel techniques more difficult to justify in the short term	Lack of an all weather, day/night monitoring instrument with daily coverage and moderate resolution Commercial emphasis leads to versatile instrument designs which can compromise continuity of observation Need to integrate remote sensing further into core science, overcoming need for initial time investment
Opportunities for future use of remote sensing	Future issues such as climate change, increases in domestic demand and pressure on land may lead to greater emphasis on water issues. Regulatory changes	Increasing use of physically based/distributed models will provide the necessary framework for the use of EO data
Key drivers to improve EO effectiveness	Need for reliable and cost-effective information to enhance existing techniques and provide a basis for their evolution Future instrument developments Need for software to support user interaction with key data sources, such as SAR	Need for sensor continuity and accuracy over time. The balance between general monitoring and specific campaigns which support parameterisation of models is important

Table 6-1: Current hydrological perspectives

or future strategy of operational organisations. As such, factors including cost, availability, reliability, compatibility and ease of use must be added to geophysical accuracy. Strategies to encourage the increased use of data by hydrological users are also important.

The process of transfer from research to operations has been analysed within the ESA context and is described in Table 6-2 *(Hannigan & Howes, 1994).*

The main headings of this table can be used to analyse the hydrological applications described earlier in this document and presented in Table 6-3. A key factor is the development of the user interest in the data and the information the data can provide. In the first two columns, the emphasis is clearly on the providers of the data to push it forward, since it is usually the case that remote sensing is new to users and their methodologies are not adapted to use it directly. The third column represents a stage where user interest is sufficient to warrant involvement with pilot services which require a degree of commitment on the user's part. By the last two columns, the user is convinced of the value of the data for their activities and is involved in defining optimum process and methods of supply. By the last column, the user is sufficiently familiar with the use of the data to be able to develop requirements for new sensors and sources.

The maximum extent of many projects is currently the 'Pilot Project' stage (as defined above). The key factor which is currently being addressed is the repeatability of the capability. This is particularly evident for the measurement of continuous fields such as soil moisture. In cases of delimitation (such as flood monitoring and snow cover), the applications have progressed further, although some difficulties remain in ensuring the accuracies of the boundary determinations.

Increasing development towards operations →				
Research and technology development	Demonstration	Pilot services	Pre-operational services	Operational service
Establish confidence in technology and data Validate sensor, retrieval algorithms and geophysical values Develop underlying tools to handle basic data Respond to market requirements as well as technology needs	Demonstrate that information content is applicable and of potential interest to users or 'proxy' users Demonstrate feasibility of technology when tailored to a specific user interest	Prove to user that repeat monitoring capability can be sustained Quantify benefits and costs for user Evaluate potential use and requirements with user	Data/service supply adjusted to user requirements Integrate information into user business Support user in qualifying business plans	Reliable and continuous services under contractual control of user Generate requirements for R&D to achieve more competitive market position (new data sources, improved techniques, improved means of supply).

Table 6-2: From research to operations: objectives and criteria

Application	**Research and technology development**	**Demonstration**	**Pilot services**	**Pre-operational services**	**Operational service**
Flood monitoring / floodplain delimitation (SAR)	▨	▨	▨	▨	Technique well developed and in use. Refinement necessary
Determination of land use cover types (SAR)	▨	▨	▨	▨	Technique used operationally for agricultural monitoring
Snowmelt based forecasting (SAR)	▨	▨	▨	▨	Technique well developed, need to integrate with user operations
Soil moisture determination (SAR)	▨	▨	Need to demonstrate repeatability and overcome unwanted effects. Soil moisture could be used as input to models or directly		
Wetland and lake level monitoring (ATSR / Radar Altimeter)	▨	▨	Technique established using some ERS data with AVHRR and Topex/Poseidon		
Soil moisture determination (Scattero.)	▨	Research on techniques continuing			

Table 6-3: From research to operations: Examples of hydrological applications

7. Recommendations

7.1 Introduction

Developing hydrological applications of data from ERS and their successors depends on two areas of progress:

- development of techniques for improving the accuracy, reliability and repeatability of the hydrological information extracted from the satellite data;
- provision of long-term stable datasets;
- creation of the most appropriate operational environment for increasing the use of the data by the hydrological community.

Although some hydrological applications are relatively straightforward 'look and see', many are more complex and require further development before fully operational application can begin. This can be achieved in two ways.

The first of these is the use of empirical relationships to develop applications. This type of approach is made possible by the long term continuity from ERS-1 through ERS-2 and onwards towards ENVISAT. The second approach is more difficult to achieve, but in the longer term may prove to be more satisfactory, namely the theoretical modelling of the instrument's interaction with the surface.

The operational environment also has two aspects. Firstly the technical side where the development of hydrological techniques to take account of remote sensing data is the key. Secondly is the commercial side, where the approach to demonstrations and pilot projects, the structure of the market and the mechanisms for providing support to users are important.

7.2 Development of empirical relationships

Many hydrological variables are immensely complex and scale dependent as has been illustrated for soil moisture. The land surface in which the soil moisture exists is also highly heterogeneous. As a result of these complexities, many hydrological techniques have a strong empirical element. This is particularly evident in engineering hydrology.

The uncertainties associated with hydrological variables are reflected in the observations made from remote sensors. This suggests that until the theoretical links can be better understood and modelled, an empirical approach to the interpretation of ERS data would be valuable.

The use of empirical techniques requires the following characteristics:

- continuity: enough observations to establish a satisfactory relationship across the range of variabilities;
- consistency between sensors, since more than one is required to provide the necessary record length;
- consistency within each sensor both in terms of random variations and drift;
- information to control for the errors which do occur.

Recommendation 1

The opportunities provided by the ERS missions for the development of empirical relationships should be exploited. Empirical techniques can be very effective and are familiar to most hydrologists. As the applications proceed, theoretical methods will develop and allow more sophisticated applications.

A number of research groups, some illustrated above, have developed empirical relationships for limited areas, along with methods for controlling the unwanted sources of variability. This type of work should be furthered because stable relationships have not yet been reached and are definitely needed for fully operational applications.

If possible, a wider study which tries to maximise the number of reliable backscatter vs soil moisture pairs should be undertaken using the extensive archives of ERS data which are currently available.

The use of this approach implies the need for support in the following areas:

- archiving of suitable SAR datasets;
- continuation of existing field measurements;
- development of techniques and approaches to classification.

7.3 Analysis and modelling of surface interactions

Continued development in the theory of interaction between instruments and surfaces, together with associated analysis and modelling techniques offers another potential route for development of hydrological applications.

This area applies not only to determination of spatial fields such as such as soil moisture, but also to the more accurate determination of discrete features such as flooded areas. A number of constraints still exist even with these techniques and theoretical analysis would help to overcome them.

The use of airborne sensors and ground-based studies have an important contribution to make.

Recommendation 2

In the longer term, the optimum approach to the extraction of hydrological variables from ERS data will be the use of physically based modelling techniques. Research in this area is already well developed using experience with ground and aircraft based sensors, but much remains to be done. This work should therefore be continued.

The difficulties associated with this type of work should not obscure the long-term importance of the work.

7.4 Hydrological model development

Modelling the sensor interaction with the surface is not the only area of modelling which needs to be explored. Equally important is to develop the hydrological techniques which will use these new types of data.

ERS data provide measurements of hydrological variables in a form which is incompatible with many existing operational hydrological techniques. The hydrological techniques which can use the data are not generally operational, mainly because of problems in supplying suitably representative variables.

Recommendation 3

ERS offers new opportunities to hydrologists, but if hydrological users are to make widespread use of ERS data, they must adopt new techniques. Although the availability of remote sensing data is not the only reason for adopting new techniques, it is a major one.

Consequently, it is recommended that support be given to the development of hydrological models which will allow remote sensing data to be used effectively for hydrological applications.

This work requires a mix of skills with close interaction between hydrologists, modellers and remote sensing experts.

7.5 Transfer to operations

The process of transition from research to operations has been described above. The actual process may vary for different applications and users, but some common elements exist:

- the basic understanding of SAR data for hydrological applications has improved considerably in recent years, but research into land interactions is still required;
- simple methods for end users to obtain a 'best estimate' with limited effort are required to overcome initial barriers to use;
- a simple nomenclature for describing SAR data to end users is required, taking into account the different balance between spatial and radiometric resolutions required for different applications;
- many potential end users now have access to advanced GIS facilities. Compatibility with these is important to enable the use of SAR data.

Recommendation 4

What this area must achieve is a low entry threshold to use of remote sensing data for potential users. This involves a number of aspects:

- the cost to users of trying out the techniques must not be too high, especially when monitoring with frequent revisit is required;
- end users cannot be expected to become remote sensing expertsthe complex issues must be made

transparent and expressed in terms of limitations to the user. Software packages to assist the end user are also required, and in some cases already exist;
- support to users must be readily available;
- irrespective of the market orientation of the services provided, they must be reliable and accurate.

It is important that the time taken for any new technique to be assimilated into operational procedures is recognised. Many hydrological practices are either safety critical or element of water supply and so procedures can only be altered with caution.

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9. Abbreviations & Acronyms

ADC	Analogue-to-Digital Conversion
AMI	Active Microwave Instrumentation
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High-Resolution Radiometer
DARA	German Space Agency
DEM	Digital Elevation Model
DMSP	Defence Meteorological Satellite Programme
ENL	Effective Number of Looks
ERS	European Remote sensing Satellite
ESRIN	European Space Research INstitute
FIFE	First ISLSCP Field Experiment
GCM	General Circulation Model
GIS	Geograpic Information System
HAPEX	Hydrology-Atmosphere Pilot EXperiment
HH	Horizontal/Horizontal (SAR polarisation)
IR	InfraRed
IRR	InfraRed Radiometer (ATSR component)
ISLSCPMWR	International Satellite Land Climatology Project Microwave Radiometer (ATSR component)
PRI	Precision Image (ESA ERS SAR product type)
SAR	Synthetic Aperture Radar
SERTIT	Service Régional de Traitement d'Image et de Télédétection
SHE	Système Hydrologique Européen
SIR	Shuttle Imaging Radar (radar series flown on US Space Shuttle missions)
SLC	Single-Look Complex (ESA ERS SAR product type)
Spot	Satellite pour l'observation de la Terre
SSM/I	Special Sensor Microwave/Imager
TM	Thematic Mapper
UV	UltraViolet
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin Scan Radiometer
VV	Vertical/Vertical
XS	Spot multispectral data

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