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HYDROLOGICAL PROCESSES

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- Arid and semi-arid hydrology
- Erosion and sediment yield
- Solute transport in the unsaturated zone
- Groundwater

HYDROLOGICAL PROCESSES

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FLOOD MONITORING WORKSHOP ESRIN, FRASCATI, ITALY 26–27 JUNE 1995

INTRODUCTION

Great effort is currently being devoted by the European Space Agency (ESA) to the assessment of the potential of space-derived earth observation technologies and data products for use in the domain of major risk management.

As has been widely proven by a number of events during 1992–1995 in Europe, flooding is undoubtedly one of the major risks.

In almost all of those unfortunate circumstances, profitable use of the information derived from processing and analysing satellite data was made. It was of particular importance to ESA and ESRIN, the Agency data handling centre based in Italy, that the products and services 'band' on the ERS/1-2 satellites successfully contributed to the management of the incidents. This has been reported through various studies and projects in many European countries.

With the final objective of being able in the near future to offer more tailored and specialized services to the users of remote sensing, ESA and ESRIN decided, in 1995, to engage in a communication process whereby all parties interested in flood prevention, as well as in monitoring and relief actions, would be given the opportunity to exchange, for their mutual benefit, views, experience, requirements and, essentially, expertise.

This special issue of *Hydrological Processes* contains a selection of the most significant reports presented at the meeting held at the ESA/ESRIN premises in Frascati, Italy. It is intended to provide the reader with an overall assessment of the capability of remote sensing to contribute to flood risk management, including the advantages and limitations, as well as critical areas, for further improvement.

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February 1997

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FLOODNET: A TELENETWORK FOR ACQUISITION, PROCESSING AND DISSEMINATION OF EARTH OBSERVATION DATA FOR MONITORING AND EMERGENCY MANAGEMENT OF FLOODS

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ABSTRACT

The aim of FLOODNET is to provide a communications and data distribution facility specifically designed to meet the demanding temporal requirements of flood monitoring within the European Union (EU). Currently, remotely sensed data are not fully utilized for flood applications because potential users are not familiar with the procedure for acquiring the data and do not have a defined route for obtaining help in processing and interpreting the data. FLOODNET will identify the potential user groups within the EU and will, by demonstration, education and the use of telematics, increase the awareness of users to the capabilities of earth observation (EO) and the means by which they can acquire EO data. FLOODNET will act as a filter between users and satellite operation planners to help assign priorities for data acquisition against previously agreed criteria. The network will encourage a user community and will facilitate cross-sector information transfer, particularly between 'flood experts' and administrative decision makers. The requirement for two levels of flood mapping is identified: (1) a rapid, 'broad-brush' approach to assess the general flood situation and identify areas at greatest risk and in need of immediate assistance; (2) a detailed mapping approach, less critical in time, suitable for input to hydrological models or for flood risk evaluation. A likely networking technology is outlined, the basic functionality of a FLOODNET demonstrator is described and some of the economic benefits of the network are identified. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS flood; remote sensing; communications; data distribution; telematics; mapping; SAR; satellites; aircraft

BACKGROUND

The all-weather capability of high resolution satellite radar sensors for monitoring floodwater extent has been well demonstrated over the last few years when extensive flooding occurred in many EU countries (Wang *et al*., 1995). Much of the satellite data recording floodwater extent has been collected on an *ad hoc*, opportunistic basis and many potential end-users probably did not appreciate the capabilities of satellites prior to seeing images in the national press and other publications. Of those that did, many would not know how to acquire the data or to extract the necessary information from then. As more suitable radar sensors come on line within the next few years, to replace those currently available (J-ERS1, ERS-2, Radarsat) (Figure 1), together with the growing availability of sophisticated airborne sensors, a communications network that speeds and simplifies the collection and dissemination of EO data to the flood management community is badly needed. An urgent requirement exists for the development of such an EU-wide communications network, which will help with the coordination of requests for earth observation data for monitoring river and coastal floods. It will be necessary to determine how the data can be most efficiently processed, interpreted and disseminated to a wide range of hydrological and administrative organizations having different requirements. This paper is based on a proposal made to the EC Framework IV programme

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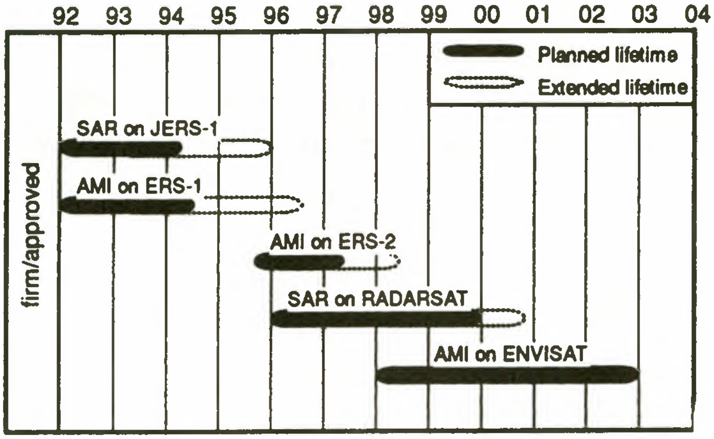

Figure 1. Planned and expected availability of satellite synthetic aperture radar (SAR) suitable for flood monitoring. JERS-1 is Japanese earth resources satellite, AMI is an active microwave instrument which includes a SAR mode and Envisat is the European polar platform contribution to the earth observation system programme

and it outlines the requirements for and stages of development of a FLOODNET communications system for the efficient monitoring of floods by remote sensing.

USER NEEDS AND APPLICATION AREAS

Each year, river and coastal flooding, world-wide, results in major loss of life and property. The United Nations (1994) report showed the results of disaster statistics collected world-wide during a 30-year period between 1963 and 1992, and found that floods killed more people than any other type of disaster (22% of all deaths) and caused the most damage (32% of the total bill). The UN study classified disasters according to their 'significance' within their country of origin. Thus, factors such as damage in relation to the gross national product (GNP), the number of people affected in relation to the total population and the number of deaths it caused were all taken into account. These statistics are illustrated in Figure 2, which suggests an actual increase in the number of 'significant' flood events during this period. An alternative, and more likely, explanation is that population increases have occurred in flood-prone areas such as Bangladesh and hence the number of flood events classed as 'significant' or 'disasters' has increased. Whatever the cause, the result has been a significant increase in losses both to property and life during this period. In order to halt, or even reverse this trend, it will be necessary to improve our understanding of the dynamics of river and coastal flooding to facilitate better management of these flood-prone regions. Satellite radar is the most suitable technology for acquiring this information, particularly over large river systems where the demands on temporal and spatial resolution of the satellite data are least severe.

A requirement for two levels of flood extent monitoring using satellite radar can be identified which would augment current flood forecasting and warning procedures established over many years using conventional hydrological information (Parker, 1987). The first is a broad-brush approach which would look at the general flood situation within a river catchment or coastal belt with the aim of identifying areas at greatest risk and in need of immediate assistance. This type of information would be of great value to central government offices in assigning priorities to the overall flood response. For major floods especially, where ground communications may be severed, there is a need for rapid overview information on floodwater extent in order to prioritize:

- downstream warning response;
- rescue/evacuation of residents and livestock;

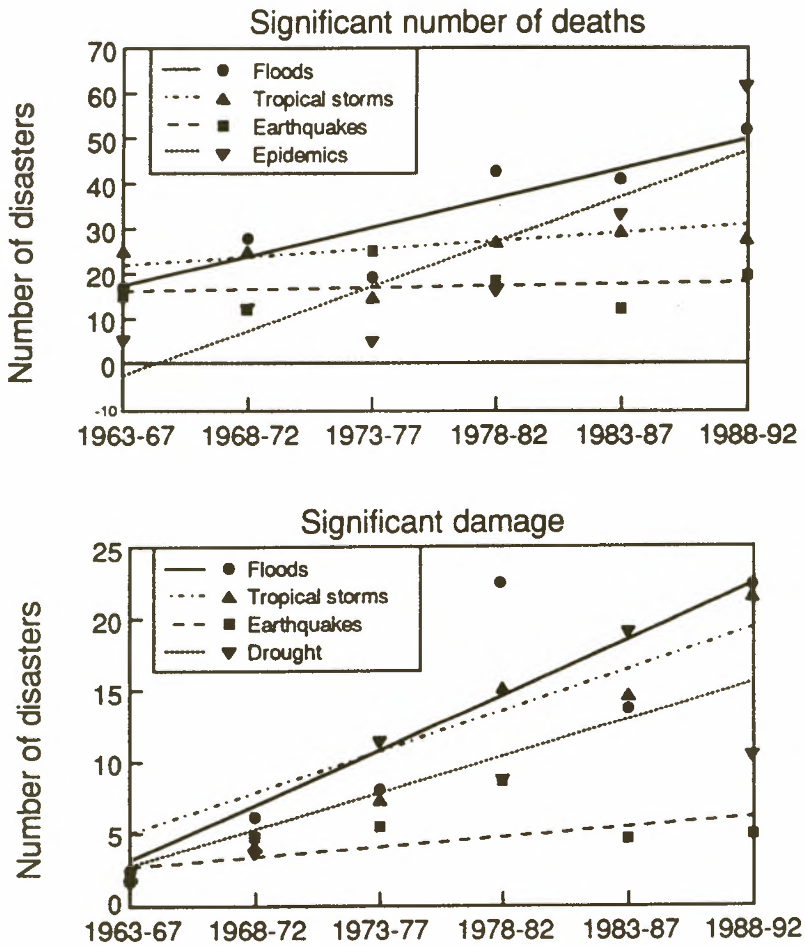

Figure 2. Major disasters around the world, 1963–1992 (United Nations, 1994). Trends of the most significant disaster types are shown by category. (a) Number of 'significant death' events, (b) number of 'significant damage' events (see text for details)

- supply of food/medical aid;
- strengthening/repair to flood defences;
- repair of communications; and
- repair of water supply, power and other infrastructure.

To be of real value, the first two applications would require data dissemination within a few hours of satellite acquisition, whilst dissemination within the 1–7 day period may still be of value for the remaining applications.

The second, less time-critical requirement, is for detailed flood extent maps, which are needed for:

- hazard assessment;
- input to hydrological/land use models; and
- evaluation of insurance risk/claims.

Data turnaround time is not really an issue for these applications and current satellite data delivery times of, typically, two weeks would generally be acceptable. However, both types of requirement are time critical

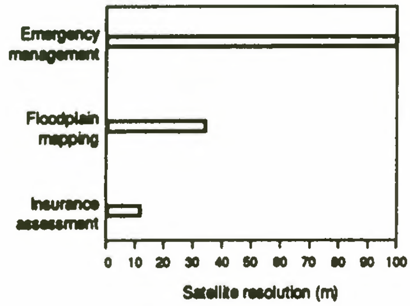

Figure 3. Maximum acceptable resolution range of satellite data for different flood requirements

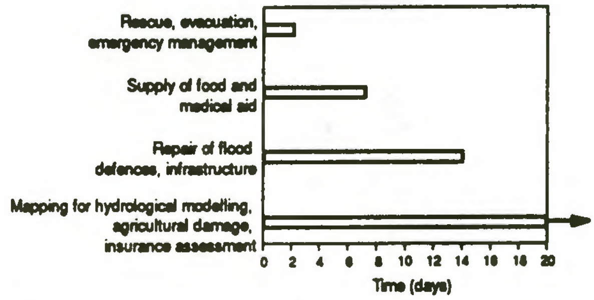

Figure 4. Typical turnaround time for acquisition, processing and dissemination of satellite data for flood requirements

in terms of data *acquisition*. More efficient remedial action can thus be expected if suitable flood extent information can be distributed to the key authorities during, or shortly after flooding. It has long been appreciated that such information cannot be readily determined from the ground because of inadequate manpower availability during flood crises, coupled with the effects of restricted access caused by floodwater (Blyth and Nash, 1980). However, remote sensing by satellite and aircraft is now able to supply a more efficient method of flood mapping. Figures 3 and 4 show minimum requirements in terms of satellite resolution and data delivery for different application areas. It is interesting to note the reciprocal demands of resolution and time. Where rapid response is paramount, it should be possible to extract useful information from relatively low resolution data. Conversely, where maximum resolution is required for detailed mapping, the time element is generally less critical. The issues of SAR resolution and data dissemination are discussed later in relation to specific application requirements.

In the longer term, detailed information of floodwater extent for floods of differing return period are required for the production of hazard assessment maps (Handmer, 1987; Penning-Rowsell and Fordham, 1994) and for input to various types of hydrological and land use models (Bates and Anderson, 1993). As a result of a number of major flood events within the EU in recent years, insurance companies are taking a critical look at the flood insurance sector and represent a major potential customer for the type of information that could be assembled within FLOODNET (Mitchell, 1995). A number of general studies defining the hydrological requirements for satellite data have been undertaken in the past, within which the requirements for flood mapping and monitoring have been included (e.g. Herschy *et al.*, 1985; Kuittinen, 1992). However, this type of study has tended to concentrate on the needs of engineering hydrologists and has not taken into account the requirements of administrative organizations, whose needs may be quite different. Clearly then, there are a wide range of users to be identified and user needs to be addressed before a satisfactory design for FLOODNET can be evolved. The user analysis phase of the project is very important as this will determine the basic structure of the network and consequently the design of its component parts.

FLOODNET will act as a filter between users and satellite operation planners (Figure 5) by applying criteria, previously agreed by users, to facilitate the prioritization of requests for satellite coverage of flood events. After applying the criteria, requests for data acquisition will be assigned a level of importance, perhaps on a scale of 1–5, before being forwarded to the satellite operators for consideration. This arrangement will be mutually beneficial as the satellite operators will be spared the task of assessing the importance of each request as it comes in, on the basis of little or no background information, whilst the users will be assured of receiving the highest priority for important flood events. As more potentially useful satellites come on-line in the future, the task of determining what data is available will become more onerous to the individual user. FLOODNET will simplify the process by acting as a clearing house for flood-related satellite data acquisition with links established world-wide with the main satellite operators. Such an arrangement will enable procedures to be established that are specific to the needs of the flood-monitoring community. Similarly, FLOODNET will encourage a more informed communication between the user

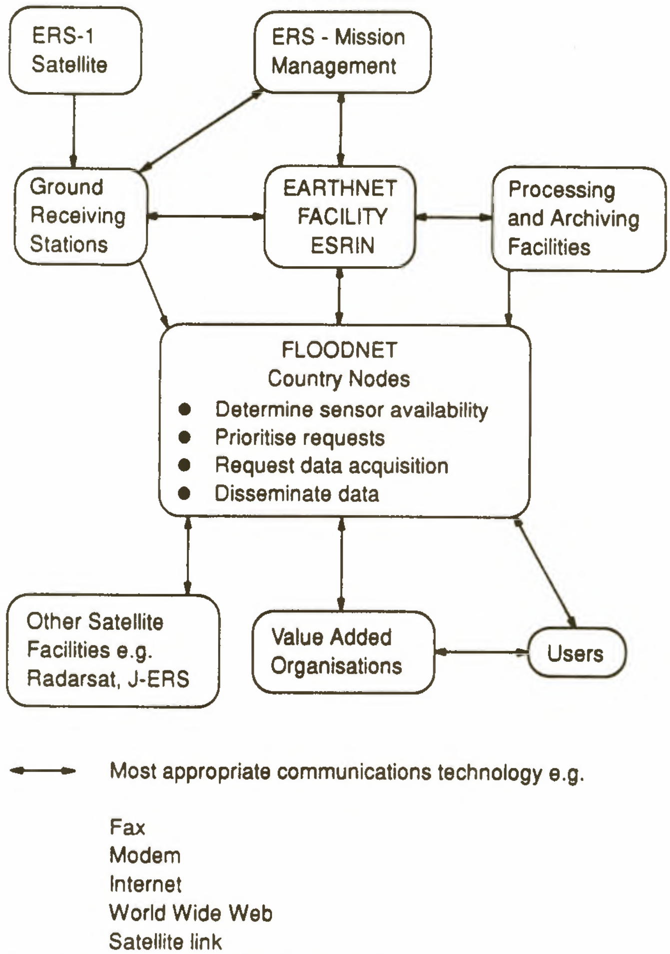

Figure 5. Main links of communication between FLOODNET and existing satellite data distribution networks. ESRIN is the European Space Research Institute at Frascati, Italy

community and companies that are able to provide value added services. Indeed, once user needs are fully defined, it is expected that many of the functions of FLOODNET would be carried out on a commercial basis.

Market situation and prospects

Large volumes of data have been collected on a European and global scale since the early 1970s. By the end of the century, the volumes of data available will increase by several orders of magnitude. Planned polar orbiting satellites will acquire up to 20 terabytes of earth observation (EO) data each week.

Currently, the use of data from space-based EO missions is rather limited, and mainly restricted to the research community or, to a limited extent, to government organizations. There is, however, a large potential for further exploitation of these data, which will be supported by better satellite instruments and better and faster data delivery with improved data distribution networks and services. This need for an improved ground segment and user-oriented data access is currently being addressed by the European Commission's Centre for Earth Observation (CEO), (European Commission, 1995). As a result of an improved interface between users and providers of data, services and information to the user community will be enlarged, which by itself will trigger a stronger EO industry and will consequently improve services for the end-users. The need on the user's side is expected to expand towards the need for information rather than data, which is fully taken into account by the current FLOODNET project.

Flood mapping using both aircraft and satellite data has been shown to be more cost effective than ground-based survey (Blyth and Nash, 1980; Biggin and Blyth, 1996) and the market potential for such information is high, provided the market can be persuaded to use this type of data. An important aspect of FLOODNET will be market stimulation which will result from contact with the user community during the user-linked phases and as a result of publicity through scientific and promotional publications and presentations at relevant national and international conferences. The market covers suppliers of satellite data and aircraft data, value added companies who offer specialist services in data handling and information extraction and end-users such as statutory authorities and insurance companies.

The success of FLOODNET relies on a thorough knowledge of the current and likely future capabilities and limitations of satellite and aircraft data for supplying flood information, and on the ability to design a data and communications network around users' needs and currently available systems.

Availability of satellite data

In the past, satellite observation of floods have been hampered by the presence of clouds and high resolution data have not been available in near-real time. Aerial photography has traditionally been used for flood mapping, but its availability has also been weather dependent and its high cost has resulted in limited application. The cloud-penetrating ability and high spatial resolution of synthetic aperture radar (SAR) sensors operating from satellite platforms make an attractive package for monitoring floodwater extent. Satellite radar only recently became available for operational civilian use with the launch of the European ERS-1 satellite in 1991 but its availability well into the next century is assured as a result of approved satellite programmes such as ERS-2, Radarsat and Envisat (Figure 1). Blyth (1994) describes the advantages and disadvantages of using satellite radar for monitoring fluvial and coastal flooding, whilst Dautrebande *et al.* (1994) describe the use of ERS-1 SAR for flood mapping applied to rural basin hydrology studies. Land/flood water boundaries cannot always be readily delineated by satellite radar because the ideal situation of smooth floodwater against rough land features (producing respectively dark and bright radar back-scattering responses) does not always apply. The back-scattering response from water can increase to a similar level as the surrounding land as a result of the effects of wind roughening the water surface or as a results of crops and other tall vegetation emerging from the floodwater. Current research is concentrated on quantifying these effects and on the development of algorithms that will help automate the selection of a land/flood water boundary.

Timing of satellite data dissemination

One of the earliest studies to determine satellite observational requirements for hydrological applications was undertaken for the European Space Agency by Herschy *et al.* (1985). Under the subheading of 'surface water', flooding was divided into two distinct categories: flood extent and floodplain mapping. A range of satellite observation frequencies was given to cover maximum, minimum and optimum frequencies of observation. For general floodplain mapping, this ranged from every year to every five years, whilst for flood extent mapping the range was 6 hours to 24 hours. Kuittinen (1992) carried out a similar exercise for the World Meteorological Organization and quoted the same requirements. Figure 4 identifies four broad categories of user requirement in terms of acceptable data dissemination times. Whilst these will vary considerably according to local conditions and river catchment size, they serve to illustrate the range of possible applications and turnaround times for SAR primary data and secondary data products.

Warning, evacuation, emergency management. For these applications, remote sensing from satellites is only likely to be feasible when the river basin is large enough for its response time to be similar to the satellite repeat period. The latter is currently around three days at best, but it may be possible to improve on this through use of the pointable Radarsat SAR antenna (Parashar *et al.*, 1993). For the UK situation, Parker and Neal (1990) noted that most British rivers were relatively short in length which reduced flood warning lead times to between 2–10 hours. It would thus be fortuitous if satellite data were available to capture such quick-response events. Berger (1991) described the requirements for a flood forecasting model of the River Meuse and concluded that to minimize damage in case of a flood, the lead time of the model should be at least 12 hours, but preferably 24 hours and its (water level) accuracy should be approximately 0·10 to 0·20 m. Satellite data of floodwater extent can only be acquired after the flood event, so it cannot be used directly as a means of damage minimization, but can be a valuable input to procedures designed to reduce damage in future flood events.

For larger UK basins such as the Thames, Severn or Ouse, overbank flooding may persist for two or more weeks and this is also typical of many other European rivers. On the world's largest rivers a satellite-based response time of 5–7 days may be acceptable for downstream warning purposes, but on most large rivers within the EU, information would have to be disseminated within 2 or 3 days at most to be of value (Figure 4) and would have to improve on, or augment the information available from conventional hydrological forecasting models. It is therefore unlikely that satellite data will be of much *operational* value on smaller European rivers until satellite repeat times are dramatically reduced. This is only likely to be possible if a number of suitable satellites are operational at any one time. However, for smaller rivers, it will still be possible to assemble an archive of floodwater extent for floods of differing magnitude, and this will represent a significant step forward from the current situation where many floodplains are poorly defined.

In the UK the Environment Agency (formerly the National Rivers Authority) is obliged under act of government to:

- carry out surveys of all main and ordinary rivers under Section 105, to provide information on land at risk of flooding
- increase the extent and accuracy of floodplain data, transferring these to a geographic information system when these become available
- produce updated maps showing floodplain areas
- make use of models, where appropriate, to supplement historic flooding data.

Few UK rivers have yet been mapped to this standard and it is clear that this cannot be achieved using ground-based observations alone. The incorporation of SAR information on floodwater extent will greatly aid this mapping process and will provide better understanding of the dynamics of river floods over a wide range of return period.

It is believed that satellite SAR will be of greater value for flood warning as a result of its sensitivity to soil moisture and texture. Badji and Dautrebande (1995) noted the ability of the ERS-1 SAR to delineate areas of poor internal drainage within a catchment and they describe a GIS system for floodplain management that combines soil maps, hydrographical network maps and *in situ* soil moisture measurements to identify areas of potentially high water retention which can be monitored using ERS-1 SAR. Fellah and Tholey (1995) describe how land use masks were derived from SPOT XS data to aid the analysis of segmented single and multi-temporal ERS-1 SAR data to derive a soil moisture index. These types of data can be used to identify areas at greatest risk from flooding and to provide warnings when certain soil moisture thresholds are exceeded. A knowledge of the spatial distribution of antecedent soil moisture within a river catchment is fundamental to successful rainfall–runoff modelling and to the resulting prediction of floods, and further work is required to incorporate remotely sensed data into such models.

Supply of food and medical aid. For the organization of remedial action, satellite observation within 3–7 days of a major flood may still be of value since the effects of scouring, sediment deposition and damage to infrastructure are likely to be persistent. Following the Mississippi flood of 1993, analysis of aerial photographs, satellite imagery and historical Missouri River floodplain maps revealed that more than 90% of the heavily affected areas were associated with breached levées situated in active, high-energy floodplain zones (USGS Report, 1994). The ideal situation would be to obtain satellite coverage of a given area within 1–3 days of the flood peak and then to be in a position to disseminate the data within a further 2 or 3 days at most. This would enable prioritization of aid to those areas in greatest need rather than to those areas that are most accessible. Aid agencies are not used to incorporating satellite data into their response procedures so pre-processing of the data and inclusion of relevant GIS layers (topography, main communications, habitation, etc.) would be required.

Repair of flood defences/infrastructure. Whilst structural repairs are of high priority following destructive floods, the speed at which repairs can be carried out varies enormously and consequently the need for overview information is also variable. Power and communication lines could be replaced typically within a few days, whilst transportation links and flood alleviation structures could take weeks or months to repair. Dissemination of satellite data within the normal turnaround time of about two weeks is likely to be adequate for the planning of most of these repairs, but earlier access to the data would obviously be advantageous. Whilst SAR images of floodwater extent may be of value, temporal composites showing structures before and after flooding would be more informative. Data would have to be disseminated in a form that was readily understandable and some interpretation of the SAR images together with GIS overlays would be required.

Mapping for hydrology, agriculture, insurance. This is the application area that places least temporal demand on the supply of satellite data, and it is consequently the area that has received greatest attention thus far. Satellite data have been widely used, in conjunction with GIS technology, for the assessment of flood risk and subsequently flood damage. The United Nations (1995) Economic and Social Commission for Asia and the Pacific (ESCAP) report on flood loss prevention and management made the following observations about the importance of establishing comprehensive flood databases:

> "In order to properly assess the magnitude of the flood problem, it is necessary to establish and maintain a representative and comprehensive flood data base ... The monitoring of actual flood situations is essential for floodplain mapping and the development of good floodplain management programmes to control future floodplain damage ... A flood damage data base which provides representative estimates of both urban and rural flood damages is an essential factor in the formulation of effective floodplain management plans. This data base facilitates the setting of priorities, of comparing options and for assessing the effectiveness of flood damage reduction programmes."

Hydrological models of flooding require calibration and satellite SAR offers a means of calculating peak flows when conventional gauging structures are overtopped. Brackenridge *et al.* (1994), reporting on the use of ERS-1 SAR to estimate discharges during the Mississippi Great Flood of 1993, made the following observations:

> "Flood stages determined from ERS-1 scenes lack close-interval sampling in time and are not as accurate as in situ recording gauges. However, the satellite data offer an important spatial perspective for particular moments. Instead of a continuous local record of rising or falling stage, a single ERS-1 SAR image is a time-instantaneous, spatially continuous portrait of flood stage along as much as 100 km of valley reach. Given favourable floodplain morphology for measuring flood stage, longitudinal profiles of the instantaneous flood surface can be constructed. Such satellite observational data can supplement the field-intensive reconstruction of river flood profiles using high water marks. Flood energy profiles are critical for accurately estimating the actual flood discharge, but, measuring high water marks is inaccurate because the marks are not necessarily time synchronous (Magilligan, 1988). In contrast, orbital SAR can observe the water profiles directly."

One area where SAR data analysis can be carried out in retrospect is in the assessment of flood damage to agriculture, which is of prime importance to the local economy. This can often be adequately assessed several weeks after flooding as a result of vegetation flattening and silt deposition which can produce changes detectable in visible, infrared and microwave responses (Sivaprasad and Bolus, 1994). Multi-sensor (e.g. ERS-1 SAR combined with Landsat TM or SPOT) classification of agricultural damage is likely to be more successful than the use of SAR data alone, provided that cloud-free visible/near infrared imagery is available. Smith *et al.* (1981) produced guidelines for assessing flood damage in rural South Africa and such procedures could be adapted to allow the incorporation of remotely sensed data. Penning-Rowsell and Chatterton (1977) produced more detailed computer models for assessing flood damage in both urban and rural areas and for the assessment of land enhancement resulting from proposed flood protection schemes. More recently, the strengths of GIS for combining land use and flood extent information have been demonstrated (Noyelle *et al.*, 1995) and this technology is likely to form the basis of future satellite-based mapping of floods and their associated effects.

For applications such as insurance assessment, the timing of data acquisition in relation to flood peak is important, but processing and dissemination of the data can be carried out at a later date. A SAR image captures the floodwater extent at one point in time and this information must be combined with conventional flood routing models to estimate the maximum flood extent over a given river reach (de Jonge *et al.*, 1996). In terms of insurance risk, the largest claims will come from urban areas but it is unlikely that satellite SAR can provide any useful measure of flood damage in urban areas other than through the delineation of floodwater extent. By combining floodwater extent with topographic information, water depth can be calculated and this is the most important measure for estimating flood damage in urban environments, provided the property type is known (Parker *et al.*, 1987). Additional calculations are best carried out from detailed ground survey.

Resolution of satellite data

Following a survey of European hydrologists, Herschy *et al.* (1985) found that the optimum resolution for floodplain mapping was 20 m, while that for flood extent mapping was 100 m (max. 10 m, min. 1 km). These were mean values covering a range of applications, but clearly, the effective resolution of ERS-1 of around 30 m (max. pixel resolution 12·5 m) should be capable of satisfying many of these requirements. Sensor resolution is a difficult thing to come to terms with and is often subjective, especially if satellite data is being compared with aerial photographs that have been used conventionally for flood mapping.

Figure 3 suggests that satellite data with ground resolution up to 100 m would be of value for rapid response requirements, especially for major floods on large rivers such as the Rhine. No evidence has been found to support this claim, but the need for rapid dissemination of the information is probably of greater importance in the first instance than the production of a high resolution product. If higher resolution data were available in near-real time, then this would presumably be preferred, but the cost of data would then become an important part of the equation. A more precise measure of floodwater extent (<30 m resolution) is required for the production of hazard assessment maps, for hydrological modelling applications and for the assessment of land use change, such as urbanization or deforestation, on hydrological response (Figure 3). The former can only be achieved with satellite radar because of the critical timing requirement, whilst the latter can make use of both satellite radar and other sensors that may be able to acquire data during cloud-free periods. For insurance assessment of risk and claims, the requirement is primarily to identify flood extent in relation to individual properties, which demands a spatial resolution of 5 m or less. Greig Fester (UK) are currently running flood simulation models on a 5 m grid, but their current knowledge of property location is only accurate to ± 100 m (Greig Fester, 1995).

For some mapping requirements, the resolution of satellite data will not be adequate and aircraft remote sensing will have to be employed. FLOODNET will help coordinate the acquisition of aircraft and satellite data by establishing links with the main operators of airborne remote sensing systems in Europe, both government and commercial. This will help ensure that the limited airborne facilities are most efficiently used and that duplication of effort and costs are minimized. Aircraft will always play an important role in flood mapping and monitoring in Europe and are likely to be of particular value in the following areas.

- high resolution surveys
- time-critical surveys
- limited area surveys
- multi-sensor surveys

Networking technology

There is a rapidly increasing number of thematic information servers being set up and maintained. Most of these are based on Internet and World-Wide-Web (WWW) networking technology and networking protocols. Popular browsers currently in use are Mosaic and Netscape. However, these user interfaces have limited capabilities for the dissemination of spatial information. In order to improve some of the shortcomings of these WWW-based systems, the Centre for Earth Observation is currently developing an improved version of a data and information exchange system. The system, called European-wide service exchange (EWSE) is currently in use and further improvements will be implemented throughout the CEO Design and Implementation Phase (1996–1998). EWSE is an integrated system whose purpose is to help customers and services to find one another and to promote and expand the application of EO data by attracting new users and services. EWSE will aim to provide a single reference point for all potential users of EO data and for all service/data suppliers (European Commission, 1994). Users will have a user friendly and intelligent inquiry system, while service providers will have an easy mechanism to advertise their products. It is expected that the experience gained from these system developments, together with relevant technical support within EWSE, would form an integral part of a FLOODNET programme.

A FLOODNET DEMONSTRATOR

Whilst the technical aspects of a FLOODNET demonstrator would have to be guided by the results of a user requirements study, one can define some basic functionality that is likely to be required.

The first indications that significant inundation may occur in a region generally come from the meteorological services and regional flood warning centres, the latter being normally run by the authorities responsible for rivers and coastal regions. These are the most likely candidates to initiate a flood warning to a central FLOODNET server (Figure 6) which could then interrogate European and other relevant satellite acquisition programmes to determine if the area under threat was scheduled to be imaged by suitable satellite sensors. If no suitable satellite coverage was planned, the central server could place requests for acquisition of data via the relevant space agency. A previously agreed methodology for assigning a priority rating for each acquisition request would have to be in place, together with agreements covering payment for the data. The users would benefit by having a pre-defined methodology for requesting satellite coverage at short notice and the space agencies would benefit from perhaps a five-level priority indicator of the importance of each request.

On the data distribution side, the network would enable satellite data to be delivered either directly to the user who would process it to his own specification, or via an intermediary who would undertake this work on his behalf. The intermediary could be a national remote sensing centre or other government organization, university or commercial company.

The FLOODNET information server would probably be based on Internet/WWW technology. On the user interface side, the choice would be between a standard browser software (e.g. Mosaic, Netscape) or the improved EWSE interface currently being developed by the CEO Team at the Joint Research Centre, Ispra, Italy. The choice would depend on user needs which may opt either for a standard system (e.g. Netscape,

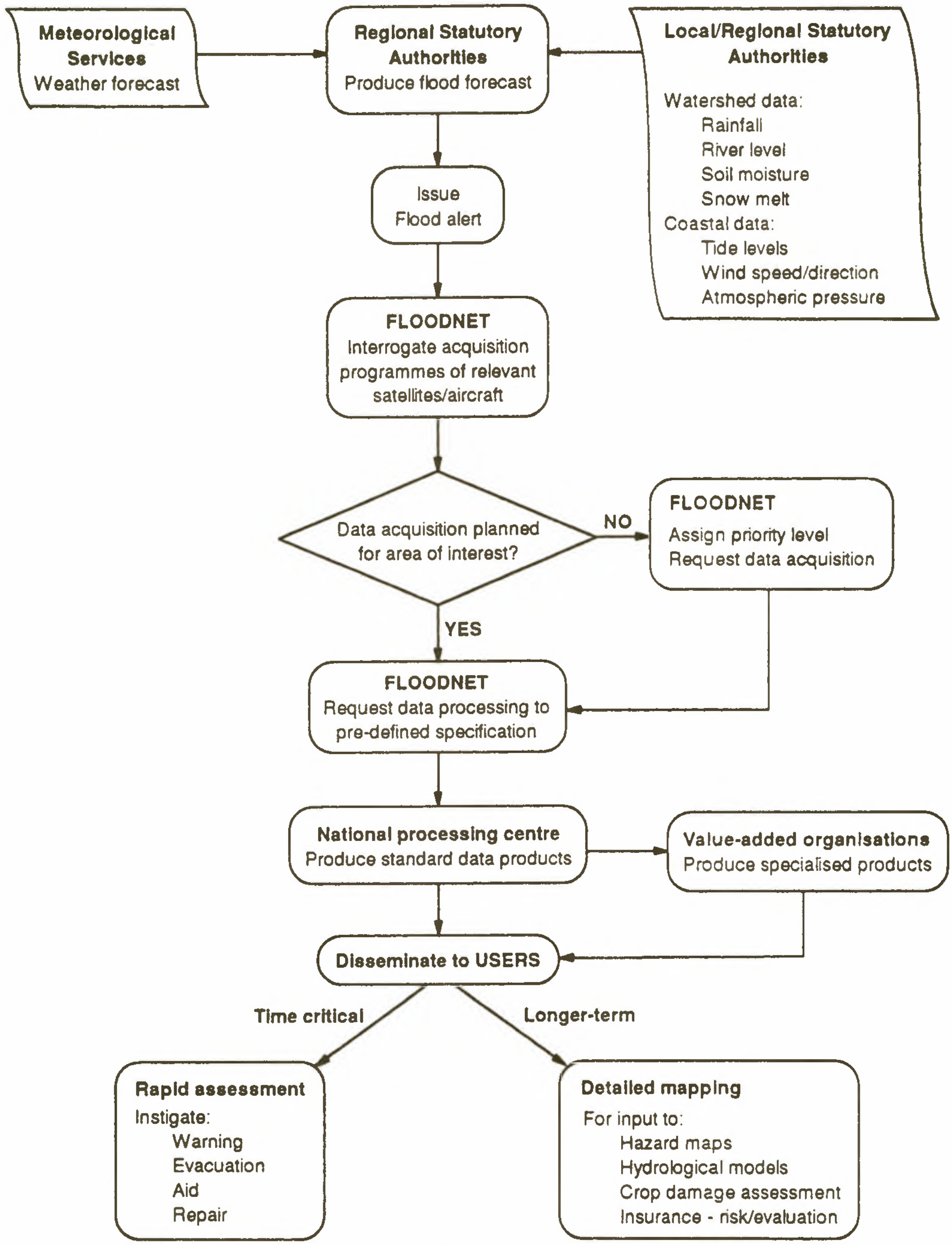

Figure 6. Conceptual design of a FLOODNET demonstrator

Mosaic) or a more advanced, but still new and less proven system (e.g. EWSE). For those users who have no access to Internet, there could be a two-options approach: either they could install an Internet connection (most likely with modem dial up) or they could receive the information via 'appropriate technology' means (e.g. via a fax server, e-mail, etc.). This basic type of communications system must be retained within FLOODNET to be sure of serving the widest user community. A special fax server could be installed for that purpose, which extracts information retrieved from the Internet-based (and well networked) system and distributes this in fax form to relevant flood early warning/emergency centres.

On the data providers side, the information server should be able to handle inputs from any sources of flooding within the EU and it should be capable of redistributing this information to other relevant sites across Europe. It must therefore be designed to send, conveniently, information, such as water level data, to a central information server and subsequently to have this information incorporated into a local database, following guidelines issued by the FLOODNET system developers.

The information server should also build up its own database, which may range from historical flood events, flood statistics, topographic data, background information and literature overviews on flood related subjects, to contact persons for different aspects (scientists, value added industry, emergency centres, hydrology institutes, etc.). This information database should, in the long term, become a valuable source of information for users within the EU for flood-related issues.

User needs

The design of the FLOODNET demonstrator must be determined by user needs. User needs would have to be determined by a comprehensive user analysis study which would draw on the results of previous relevant studies and would augment these with a literature search designed to identify the main user groups who may benefit from FLOODNET. Part of the literature study would aim to identify the main areas within the EU where flooding is considered to be of major economic significance. The results of this survey will help determine if there are any trends in user needs between countries which may affect the design of FLOODNET.

It is envisaged that, in the exploitation phase, FLOODNET will be accessed by a wide variety of users ranging from local councils, who may require detailed information on a small area, to national water authorities or insurance companies, who may require country-wide information. The networking facilities of these users are likely to be as equally diverse as their requirements for data and the functionality of the database will have to cope with this. The following examples cover the likely range of users.

Research departments. The current users of data equivalent to that provided on FLOODNET are mainly researchers in university or government departments who are aware of the capabilities of satellite SAR sensors for flood monitoring and have the necessary equipment to process the data themselves. They will have Internet and World-Wide-Web links which will enable them to interrogate FLOODNET readily at a very early stage. In addition, they will have the academic interest to provide high quality feedback on the capabilities or shortfalls of a pilot system. This type of user is likely to require direct access to single-look complex (SLC) or precision processed (PRI) SAR data which will subsequently be analysed for their own purposes. This type of user, although small in number, will quickly publicize their results which should encourage wider use of the network.

Water authorities. The next type of user most likely to make early use of FLOODNET will be the national water authorities who have statutory responsibilities to respond to the threat of floods. Their internal communications infrastructure will be well developed and they will have flood forecasting divisions who rely on telemetered rainfall and stream flow data to operate their flood forecasting models. Many will have experience of using airborne remote sensing for flood mapping and some, particularly those having coastal responsibilities, may operate more sophisticated airborne sensors, such as LIDAR and SAR, mainly for pollution monitoring. Consequently, the computing facilities in such establishments will generally be good and some will have staff who are familiar with remotely sensed data. Whilst some of these users may be able to handle SAR data internally and may wish to apply their own algorithms, the majority will not. This implies that the satellite data will have to undergo enhancement to a specified level (perhaps including geometric correction) before distribution to the user. These users will wish to transfer the satellite-derived flood extent information to some form of map base. Most will have access to GIS systems and these groups should have the capability to carry out the transformation themselves. Others will require a derived product comprising a flood extent boundary overlayed on a map base of variable scale.

Insurance and reinsurance companies. Insurance and reinsurance companies have very specific requirements for flood data, but, with the exception of a few very large organizations, they will not be interested in handling the remotely sensed data themselves. They will generally look for expert help for the derivation of flood statistics for each post code area (typically 10–20 houses). They would like to know when an area was last flooded and how often it is likely to flood in the future. The assessment of flood risk is of primary importance in deriving realistic insurance premiums and for reinsurance. Following a flood event they require an early indication of the number of properties affected, followed by evidence of which properties were flooded, together with an indication of the likely depth of floodwater. Such detailed information requires the use of sophisticated image processing and GIS techniques, coupled with extremely detailed topographic data. The organizations undertaking this work for the insurance companies are likely to require only the basic satellite or aircraft data to be delivered on Internet or WWW.

Local government. At this level, the requirements are likely to be quite different. Workers on the ground, involved in rescue or mitigation, require pictorial information of floodwater patterns and their highest priority is to acquire the information as quickly as possible. 'Quick and Dirty' methods are required to get this information into the hands of key workers and faxed images are likely to be the most efficient way of achieving this. Standard enhancement procedures would be applied to the images prior to their widespread distribution. To achieve this, it may be necessary for the data to be routed through an intermediary (perhaps a national remote sensing centre or similar commercial organisation).

The results of the user study will enable a functional specification of the demonstrator to be produced from which the demonstrator system can be built, installed and tested within a selected environment. Further development of the system based on the feedback from this selected group would enable it to be released to a wider selection of end users, and eventually developed into a European-wide operational telenetwork system. At this stage, it is envisaged that FLOODNET would have been developed to such a level that users would have rapid access not only to satellite and aircraft images of their area of interest, but also to other relevant data such as topographic information, current land use, population distribution, transport and infrastructure details and perhaps even rainfall distribution from ground-based radar.

Cost effectiveness

What may be an indicator of success for one user, e.g. time for delivery of a product, may not be the most important criteria for another user, who may require the most spatially detailed end-product.

Cost effectiveness and user friendliness will be gauged against current methods for obtaining flood information. Cost effectiveness over conventional techniques has already been demonstrated for some applications (Blyth and Nash, 1980; Biggin and Blyth, 1996) but user friendliness will very much depend on matching the method of communication and data transfer to the needs and capabilities of each user. Direct user feedback on server performance will be the most useful criteria.

This proposal is based on the assumption that the majority of users will have access to some type of telecommunications infrastructure, which at its simplest need only be a telephone line. The purpose of the proposal is for FLOODNET to be capable of supplying information in a form that is suited to the users facilities. No pre-determined infrastructure will therefore be required to access FLOODNET.

EXPLOITATION PLAN

Exploitation of FLOODNET can be expected in a number of sectors, but the main requirement probably lies within statutory government organizations. The incentive to monitor flooding by satellite or aircraft using

FLOODNET will be driven by their budgets. Losses from the single Mississippi flood event in July 1993 were estimated at around \$50 billion (NOAA, 1994), and the threat of widespread flooding on the lower Rhine in January 1995 cost the Dutch government millions of guilders in evacuation costs alone (Wang *et al.*, 1995). It is expected that the long-term monitoring of floods by remote sensing will improve our understanding of the dynamics of flooding, which will lead to better flood prediction in terms of spatial distribution. This, coupled with near-real time information on the development of a particular flood event should help reduce overall losses through more efficient planning of flood defence reinforcement, evacuation procedures and remedial measures. Monitoring of such large events can only be satisfactorily carried out by remote sensing and the time to act to develop a better method of acquiring and distributing the data is now, before further major losses occur.

The most obvious government (or quasi-government) users are the water or river authorities who, in the UK, have statutory responsibilities to map flood extent along their main river courses. This requirement is not overtly time critical as information can be built up over a number of years using satellite data to monitor the extent of flooding for floods of a given size or return period. This information is useful both as input to hydrological models, which can be used to estimate the volume and extent of likely future floods, and for planning purposes, e.g. to restrict future development within floodplains. Satellite data are already being used in pilot studies to produce this type of information using both near-real time (Bhanumurthy *et al.*, 1994) and archived satellite products (Tanis *et al.*, 1994; MacIntosh and Profeti, 1995). Any improved methodology that enabled the authorities to access satellite data more easily when they forecast a significant flood event would be of immediate value to them.

Another area where flood extent information may be of value is in the refinement of DEMs. Very few DEMs exist with a vertical resolution suitable for floodplain modelling. Floodwater extent may be used as a surrogate for topographic 'level' to improve the spatial and vertical detail within relatively coarse DEMs. Care must be taken in applying this approach, however, as a moving water surface is not truly level and some form of hydraulic model will be required to estimate the slope of the water surface, especially in the presence of constrictions such as bridges.

In addition to hydrologically linked government departments, there are many administrative departments at central and local government level that require information on flooding for decision support. Timely provision of overview information would be invaluable for central government decision makers when widespread flooding, such has been experienced in recent years in southern France and central Europe, occurs. The value of improved flood extent information in such situations is hard to estimate, but it will undoubtedly exceed the cost of installing the infrastructure to make use of the data. At the local level, there are fewer funds to support such infrastructure, but again, the potential saving to local authorities is likely to far outweigh the installation and running costs of a system linked to FLOODNET.

On the purely commercial side, insurance companies are currently showing great interest in the use of satellite data for carrying out country-wide monitoring programmes at the post code level of discrimination.

On the supply side, the suppliers of satellite data stand to gain from an increased requirement for flood-related satellite data within the EU and suppliers of value added services will benefit greatly from the demand for their products. At the exploitation phase of FLOODNET, there will still be plenty of scope for commercial operators to tailor the standard end-products further to suit the particular needs of customers. Also at the exploitation stage, the methodology of deriving the flood information could be further enhanced by introducing into the system additional hydrological information such as antecedent rainfall or soil moisture conditions, topographic and GIS information. Similar applications and customers apply to the use of aircraft data and of course the aircraft operators stand to gain from increased awareness of their products. Clearly then, there are many opportunities to exploit the concept of FLOODNET and the products that derive from it.

A user analysis will start with a literature review which will first search for studies already undertaken to determine needs for flood information, particularly via earth observation. This will be followed by a wider literature review to identify types of users who require flood information. The review will aim to cover all types of user and potential user, including those in administrative positions who make decisions relating to flooding and its effects. At this stage it is expected that use will be made of the European-wide user requirements study (undertaken by CEO) to help formulate a methodology to capture and synthesize user requirements for FLOODNET.

CONCLUSIONS AND WAYS FORWARD

FLOODNET addresses the problem of flooding at the European level, rather than the national level because of the economies of scale of satellite systems. Satellites image huge areas at once; approximately 100×100 km in the case of the ERS-1 SAR. Whole river catchments can be captured in a single image. By utilizing satellite data through a system such as FLOODNET, information on flood damage to property and crops can be assessed at the EU level and can thus be of great economic benefit to the union.

Biggin and Blyth (1996) have demonstrated that flood mapping using ERS-1 SAR is a more economic method than mapping using aerial photography from light aircraft, and Blyth and Nash (1980) demonstrated that flood mapping using aerial photography from light aircraft was more economic than mapping by conventional ground survey. Mapping by satellites is particularly well suited to the study of large areas. Airborne surveys using state of the art sensors offer a high resolution alternative method, which will be more suitable than satellite survey for some applications. FLOODNET will enable potential users of such data who have little knowledge of remote sensing techniques to choose the method most appropriate to their needs and provide a system by which they can acquire their data with the minimum of effort. Such a system will encourage more widespread use of satellite and aircraft data as the economic effectiveness is demonstrated.

Floodplains are now recognized as being very important to the hydrological response of river systems, and development within floodplains should be carefully monitored in the future. Recently, as a response to the exceptional flood events in Europe, there have been growing demands to re-introduce wetlands as a natural way of dampening the peaky effect of river levels in highly populated catchments. In order to aid decisions within central government that will have to be made on the future land use change within floodplains, a reliable, long-term monitoring method for evaluating the effect of such changes on flood extent and duration should be put in place at the earliest opportunity. FLOODNET represents a major step towards this end.

Feasibility study

For FLOODNET to move forward from the concept stage to something more tangible, a feasibility study is required which would aim to achieve the following.

1. Establish the need within the EU for FLOODNET.

2. Better define the main user-groups within the EU and their requirements for satellite and aircraft information in terms of:

   - typical flood warning times (together with ways of extending these)
   - data acquisition procedures (together with ways of improving these)
   - acceptable time frequency and spatial resolution range of observations

3. Identify preferred routes for data dissemination, product generation and analysis within the EU, such as:

   - multi-national nodes
   - country nodes — government
     — commercial
   - area nodes

4. Start to define a methodology for assigning priorities to requests for the acquisition of SAR data for flood events. For example:

- hydrological rarity of event (e.g. 1 in 20 year, 1 in 50 year recurrence)
- proximity of flood to urban area (number of people who could be affected)
- other measure of likely losses (e.g. through pre-defined GIS-based methodology which could cover such things as housing, industry, infrastructure, agriculture)
- slope of main stream (as indicator of flood persistence and urgency of satellite acquisition)

It is preferable that such a study is instigated at the earliest opportunity whilst memories of the recent European floods still persist and the interest to improve communications in preparation for future similar events is still strong.

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HYDROLOGICAL PROCESSES, VOL. 11, 1377–1392 (1997)

HYDROLOGICAL RUNOFF MODELLING BY THE USE OF REMOTE SENSING DATA WITH REFERENCE TO THE 1993–1994 AND 1995 FLOODS IN THE RIVER RHINE CATCHMENT

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ABSTRACT

In hydrological modelling of runoff processes, including water balance, various input data and parameters can be acquired or estimated by the use of remote sensing (RS) techniques.The acquisition and use of synoptic RS areal information rather than traditional point information is an important issue in hydrology. Hydrological models allow runoff/water balance in catchments to be calculated and flow routing within flow channels to be done. For runoff and water balance computations land use, soil moisture, detection of snow and ice, digital terrain models (DTM), as well as hydrometeorological information and discharge are important. For flow routing, water level information, geometric–topographic information such as cross-sections for normal and flood conditions, coefficient of roughness and velocity of flow and its cross-sectional distribution are required. In addition, water level information (lower and upper level) is needed for shipping and for design purposes.

In the German part of the River Rhine catchment, several focus areas in the December 1993–January 1994 and January 1995 floods were covered with RS data [ERS-1 and airborne SAR, both C-band VV, passive microwave (18·7, 36·5, 89 GHz), TIR, UV, aerial photographs (b/w PAN, b/w NIR)], giving a good opportunity for a comparison of methods. Evaluation is still continuing. The importance of soil saturation for flood generation and, therefore, for flood monitoring, was shown on this occasion. The use of ERS SAR data for soil moisture estimation is currently being investigated by the Federal Institute of Hydrology. Also, the need for emergency schemes for data acquisition and easy, quick and affordable RS data dissemination was demonstrated. The assimilation of RS data with GIS information such as DTMs, including relevant topographic features like dams, which is omitted in currently available raster digital elevation models, is promising. RS altimetry techniques can be a step towards high resolution DTMs for hydrological purposes. Ground truth reference data are still needed. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS hydrological modelling; flood monitoring; remote sensing; digital terrain models; C-band SAR; soil moisture; River Rhine

DATA REQUIREMENTS IN HYDROLOGICAL MODELLING

Hydrological modelling of the quantitative aspects of the water cycle (Figure 1) is done by using point information and areal information of various input data and parameters. Areal information is often only derived by simplistic generalizations of point data, e.g. Thiessen polygons for precipitation input (e.g. Maidment, 1992).

Hydrological models are far from being uniformly structured, and comprise a range from purely hydraulic to purely stochastic concepts, largely depending on the scope of application and on available data. Therefore, input variables and parameters differ from model to model.

Only some general elements that have to be quantified shall be mentioned here.

hydrometeorological situation (e.g. precipitation depth or intensity, radiation, air temperature, wind speed)

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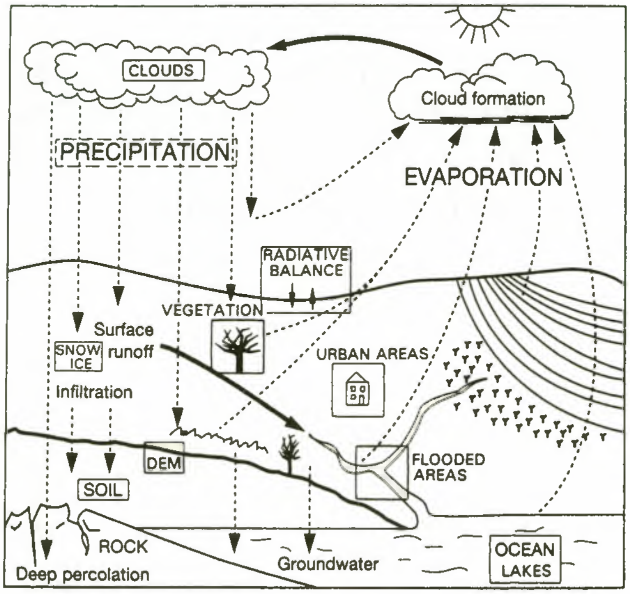

Figure 1. The hydrological cycle. Bordering shows components and parameters accessible to remote sensing techniques (based on WMO, 1994, altered)

catchment (e.g. land use, infiltration capacity, maximum soil moisture content, actual soil moisture content, slope/aspect, elevation)

flow channel (e.g. slope, longitudinal profile, geometry of cross-section, coefficient of roughness, potential flood areas)

water level and discharge at gauging stations, sometimes between gauging stations

Depending on the application and structure of the model, only a selection of these variables and data are used (cf. for example Schultz, 1994a,b) as shown in Table I.

Table I. Data requirements in hydrological modelling according to application

Application	Data requirements
Water balance	Hydrometerological situation, catchment data, discharge
Catchment runoff	Hydrometerological situation, catchment data, flow channel data, water level/discharge
Flood/flow routing hydraulic models	Flow channel data, water level/discharge

The big floods of recent years, in Germany especially in December 1993–January 1994 and January 1995 in the lower River Rhine catchment, have renewed interest in high quality flood forecasting, monitoring and assessment.

Flood monitoring and assessment in meso-scale catchments is performed mainly by deterministic rainfall–runoff models and hydraulic or stochastic flow routing models, also combined within the same model (e.g. Todini and Partners, 1994). Besides hydrometeorological, catchment and channel geometry data, the instantaneous water level or discharge data at predefined gauging stations, or the water levels along a river reach, are needed. For hydraulic computations, the geometry of the water surface (longitudinal and within cross-sections) is needed; the peak water level of a flood being a very important feature. This level usually should be the water level at the channel line, whereas traditionally the levels are only measured at the river banks. Owing to geometry, e.g. meandering, differences in height occur. For the River Rhine these differences may be up to 30 or even 50 cm.

For shipping, and for design purposes in water resources, water level information is equally important. Inland navigation in Germany has to be provided with characteristic values of low water level (level not reached on average 20 days a year), and of high water level, distinguishing two categories of upper levels: the first, at which no shipping is allowed near the banks, the second, at which no shipping is permitted at all. For water resources, water levels for specific return intervals for the design of dam heights and information for riverside residents have to be calculated. Also, for the assessment of changes by planned new structures in the water courses, water levels are required by 2-D and 3-D hydraulic models.

TRADITIONAL AND REMOTE SENSING DATA ACQUISITION FOR HYDROLOGICAL MODELLING A. D FLOOD MONITORING

Traditionally, the information used in hydrological modelling are ground-based observations, except for some specific atmospheric observations. In Germany, the traditional way of data acquisition for hydrology is to use the ground-based hydrometeorological data of the German Weather Service or the authorities' own stations, combined with water level information from specific gauging stations. Catchment data are taken from topographic maps, while conventional data are often gained by specific survey, if gathered at all.

With remote sensing (RS) techniques, the required input data or parameters are either provided indirectly or directly, giving the opportunity to use area-based large-scale synoptic information.

General information on this is cited in a variety of monographs and papers (e.g. Colwell, 1983; Schneider, 1984; Lillesand and Kiefer, 1987; Cracknell, 1988; International Symposium on Remote Sensing and Water Resources, 1990; Engman and Gurney, 1991; Lindenberger, 1993; Rango, 1994; Schultz, 1994a,b). They show the following features to be detectable by RS, shown in Figure 1: cloud cover, precipitation, radiative balance, extent of snow and ice, and their properties, soil units, land use and digital elevation model (DEM), and geomorphological or morphometrical features.

So far, the most widely used application of RS has been the indirect generation of catchment data, needed for traditional hydrological models either as, for example, land use, soil units/properties and geomorphological or morphometrical features. In combination with ancillary data and geographical information systems (GIS), these data are used for calculation of, for example, infiltration capacity of soils, subcatchment slope and length of flood routing reach in models such as HEC-1 of the US Army Corps of Engineers' Hydrologic Engineering Center (e.g. Suwanwerakamtorn, 1995). A delineation of homogeneous subareas might equally be done (Allewijn, 1986).

In addition, general approaches are directed towards hazard assessment, mitigation and remediation, especially in the field of mass-movement, like soil erosion, landslides, mud flows, etc. (Claure *et al.*, 1994) or geomorphological morphometrically derived flash flood potential (Ashmawy, 1994). Furthermore, the use of land use classification in soil erosion quantification using the universal soil loss equation (USLE) and other morphometric features (e.g. Jürgens, 1992) and comparison with drainage density (Gonzalez Loyarte *et al.*, 1990) is a proven RS application, which is beyond the scope of this paper. For water balance models and soil–vegetation–atmosphere models average land surface parameters can be estimated, yielding canopy resistance, albedo, leaf area index (LAI) and fractional vegetation cover (e.g. Huang *et al.*, 1995). Concerning land use, the definition of classes and classification accuracy, including spectral and geometric resolution, are issues to be considered. Kite (1995), for example determined 10% relative differences comparing Landsat multispectral scanner (MSS) and National Oceanic and Atmospheric Administration (NOAA) advanced very high resolution radiometer (AVHRR) derived land cover with 80 m and 1 km geometric resolution, respectively. As to perennial snow and ice, the error rose up to 60%.

The direct integration of RS data in hydrological models is still restricted. Peck *et al.* (1981) stated that at that time in the configuration of hydrological models the use of RS data was restricted to defining impervious area, special land cover categories, e.g. water surface and riparian vegetation, and the use of areal extent of snow cover and water equivalent of snow cover to update and calibrate the National Weather Service river forecast system (NWSRFS) snowmelt model. With modifications in the models and the advent of distributed and semi-distributed models (cf. Singh, 1995), these restrictions seem to be partly overcome, yielding the possible detection of direct hydrological variables such as rainfall, cloud cover, snow/ice cover and melting, soil moisture content, extent of water bodies and flooded areas.

With respect to precipitation, time-series of weather radar data may provide climatological information on seasonal and diurnal precipitation patterns for programmes like the global energy and water experiment continental scale international project (GCIP) (Baeck and Smith, 1995). Although rainfall cannot be estimated from weather radar and satellite cloud cover without any ground truth reference data. The rainfall intensity–radar reflectivity relationship and other systematic problems still introduce errors, and the shorter the aggregation interval, the more the validity of estimation and forecast is reduced (cf. Cluckie and Collier, 1991; Deshons, 1994; Schultz, 1994a; Goodchild *et al.*, 1994). The snow and ice cover and their properties might be estimated by RS techniques quite well (cf. Kite, 1995; Rango, 1994), while the melting process itself might be characterized by modelling like snow cover depletion curves, also based on land use information itself (cf. Maza *et al.*, 1990; Maidment, 1992; Donald *et al.*, 1995). With appropriate soil stability models, landslide hazard can be inferred from snow cover (Merry and Wu, 1994). Soil moisture, being an important feature for the runoff generation process, is traditionally measured only at specific points, if it is measured at all. RS techniques may provide areal information (see later section in this paper). During flood events, the extent of water bodies is of general interest for appropriate emergency management. Real time information on flooded areas, water level and forecasts on future rise or recession may guide appropriate protection or mitigation measures, including evacuation, which took place in 1993–1994 in the Netherlands (Pohl *et al.*, 1995). Besides this prominent use, governmental bodies in Germany need channel banks and water levels for specific return intervals for classification and delineation of submersible areas with restrictions in use. Moll and Overmars (1990) derived river axes and river width from Landsat thematic mapper (TM) imagery for the use within a 1-D flood routing model.

In hydrology, rather than the extent of the flood, the water level and volume of the flood are needed for running and calibrating hydrological and hydraulic models, and for calculating return intervals of water levels.

In the federal waterways, which comprise all major river reaches, the peak level is marked by pegs every 500 m at the most, rarely using crest-stage recorders (cf. Herschy, 1985). Yet the water level gathered by survey of the pegs after the flood's recession is not representative in every case. Because of difficulties of access, local hydraulic conditions and positioning of the pegs possibly several times during a flood, the location of the pegs is not always on the river banks nor are they regularly spaced. Even ancillary data such as deposited material or wetted surfaces of walls might be taken as references, adding additional insecurity to the data. In addition, the survey of the pegs might take place after a longer period of time, deterioriating the quality even more. Therefore, the water level information gathered has to be carefuly revised and selected, and sometimes is available only after a year or more.

Remote sensing (RS) techniques, e.g. aerial photographs, imaging radar or altimeter (either laser or radar) are very promising tools for determination of water level and the extent of flooded areas. As predominantly cloudy skies are expected during big floods, cloud-penetrating synthetic aperture radar (SAR) and microwave radiometer seem to be most promising for this application (e.g. Giacomelli *et al.*, 1995). In the case of SAR imagery acquisition during flooding, the extent of the flooded area might be derived directly from the imagery as low back-scattering because specular reflection of water bodies occurs (Badji and Dautrebande, 1995; Bonansea, 1995; Kannen, 1995; MacIntosh and Profeti, 1995; Noyelle *et al.*, 1995; Oberstadler, 1995; Tholey *et al.*, 1995). In good weather conditions, RS techniques like Landsat imagery or even panchromatic (PAN) metric camera data can be used for the delineation of flooded areas during the flooding (e.g. Miller, 1986). Also, the extent of the flooding can be extracted from sediment deposition or wet soil detected by RS (Deutsch and Ruggles, 1974; Lillesand and Kiefer, 1987; Bonansea, 1995).

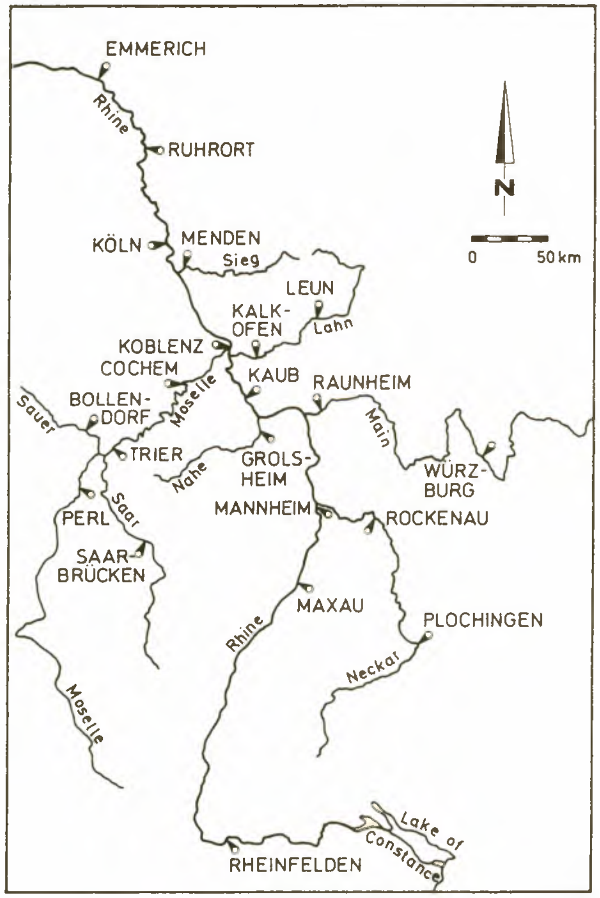

Figure 2. The River Rhine catchment up to the Emmerich gauging station, with important gauging stations

EXPERIENCES WITH SAR AND OTHER REMOTE SENSING TECHNIQUES IN THE RIVER RHINE CATCHMENT IN GERMANY DURING THE 1993–1994 AND 1995 FLOODS

Within a time period of only one year, the middle and northern part of the River Rhine catchment (total area about 185 000 km^2) suffered from two extraordinary flood events, in December 1993–January 1994 and January 1995. Estimated damage in Germany alone was 1.3 billion German mark (DM) and 500 million DM, respectively (Ebel and Engel, 1994, 1995). During these floods, SAR and other RS data were acquired, offering valuable information about the potential benefit of RS data. Even if hydrographs and the return periods were not the same within the catchment (Figures 2 and 3), the hydrological situation was similar: In a period of 10 days up to 18 December 1993, mean long-term monthly precipitation depth filled the soil and rendered the surface nearly impervious. By the end of the month, precipitation depth had risen to 300%, or even 375% of the long-term mean, and in January 1994 by an additional 200%. The saturated soils caused runoff coefficients up to 50–70%. In January 1995, the sealing of the surface was caused by snowmelt and frozen soil in the higher regions (Engel, 1995). A comparison of the hydrographs of the Cologne gauging station relative to the peak discharge is shown in Figure 4. In January 1995, a steep increase at the beginning was followed by only slowly rising levels; whereas in 1993, just like the flood in 1925, the discharge continually rose at a high rate. Following the December 1993 peak, a secondary peak occurred in January 1994, shortly afterwards.

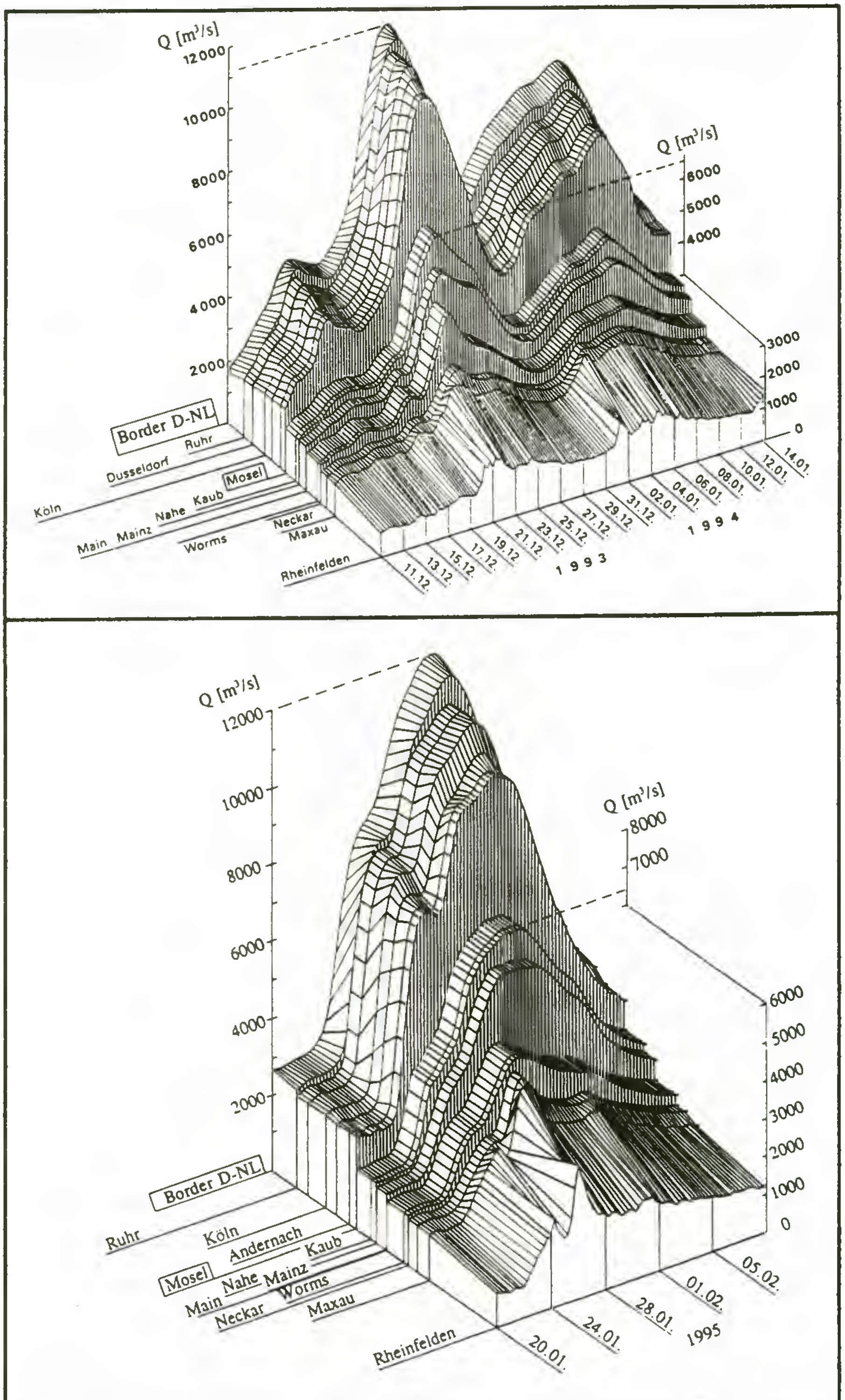

Figure 3. Stereographic representation of flood hydrographs of December 1993–January 1994 and January 1995 in the River Rhine catchment

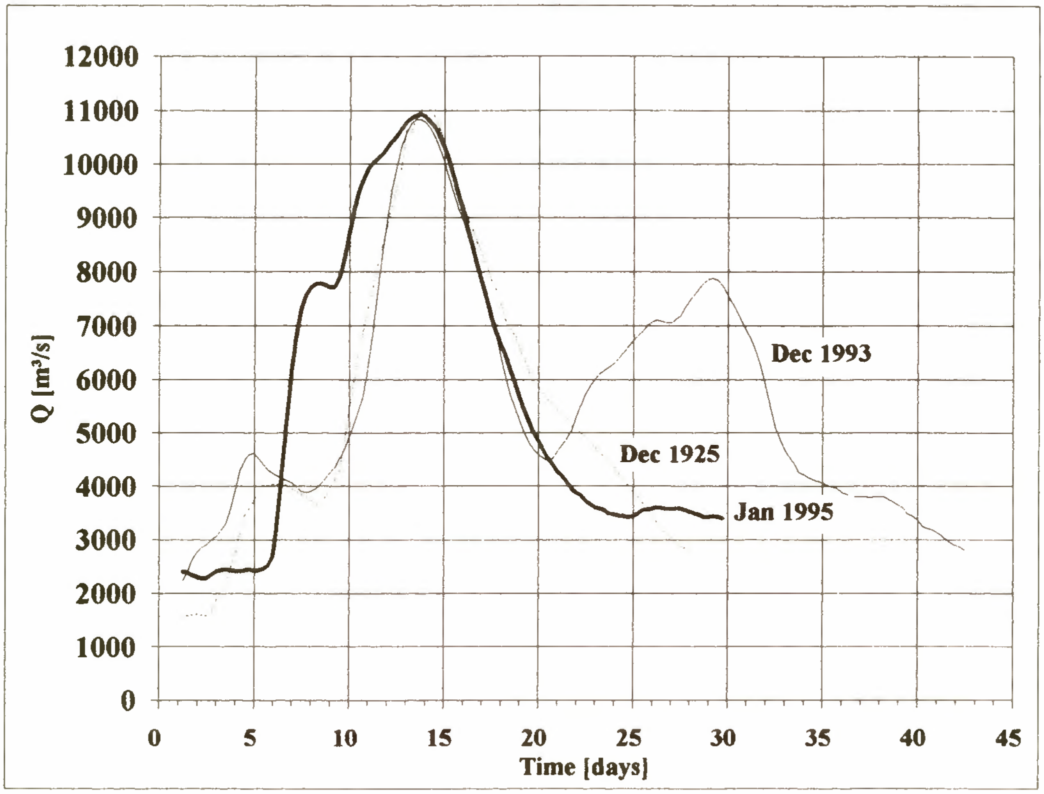

Figure 4. Flood hydrographs at Cologne (Köln) gauging station December 1925, December 1993 and January 1995

During the 1993–1994 flood, an ERS-1 SAR scene covering the Cologne/Bonn area was acquired nearly at the peak time on this river reach, on 25 December 1993. Unfortunately, in January 1995 no ERS-1 SAR imagery of this area could be evaluated, preventing direct comparison. Only an ERS-1 SAR scene covering the lower River Rhine catchment in the Netherlands was acquired, on 30 January 1995 (orbit 18531/frame 2565; cf. Pohl *et al.*, 1995). Instead, airborne sensors, including a SAR device with the same wavelength and polarization as on the ERS-1, extensively covered areas of key interest within the River Rhine catchment. The key areas were, among others, the mouth of the River Main at the River Rhine, west of Frankfurt am Main, and the mouth of the River Sieg at the River Rhine between the cities of Bonn and Cologne (Köln), where severe flooding took place, with critical water levels in the city of Cologne (Engel, 1995). Table II lists the main imagery acquired and being evaluated under coordination of the Federal Institute of Hydrology.

Table II. RS imagery acquired during the 1993–1994 and 1995 floods within the River Rhine catchment and evaluated under the coordination of the Federal Institute of Hydrology, Koblenz. For explanations of abbreviations see text

Acquisition date	RS data type	Platform
25 December 1993	C-band VV SAR	ERS-1 (orbit 12778/frame 2583)
30 January 1995	Multifrequency microwave radiometer, TIR-, UV-scanner	Navy aircraft
28–30 January 1995	C-band VV SAR	DLR aircraft
27 January–1 February 1995	b/w-PAN, b/w-NIR aerial photographs	Airforce aircraft

The navy platform, a Do 228 aircraft, was designed for oil-spill detection (Smid *et al.*, 1991; Grüner and Schreiber, 1995). It carried a scanning microwave radiometer (MWR) (frequencies 18·7, 36·5 and 89 GHz, corresponding wavelengths of 1·6, 0·82, and 0·33 cm, respectively), thermal infrared (TIR) and ultraviolet (UV) line scanners (wavelengths 8·5–14 μm, and 320–380 nm, respectively), and a laser fluorosensor (LFS) and a side-looking airborne radar (SLAR), the data of those were not transmitted. The DLR platform (DLR: German Aerospace Research Establishment), a Do 228 aircraft, carried a C-Band VV polarized SAR device with on-board recording and quality check. The air force platform, a Tornado aircraft, carried camera devices with various lens systems and viewing angles, using black and white (b/w) PAN and b/w near-infrared (NIR) film.

All the data obtained are currently being investigated for their use in flood monitoring and general hydrological purposes under the coordination of the Federal Institute of Hydrology. Considering the status of the investigations, only preliminary results can be presented here.

The ERS-1 SAR imagery of the December 1993–January 1994 flood was investigated to delineate flooding, by two commercial companies in a research project funded by DARA (German Space Agency) and assisted by the Federal Institute of Hydrology (Oberstadler, 1995; Dreiser and Mertens, 1996; Oberstadler *et al.*, 1996). The results show the potential of ERS SAR C-band data in identifying flood areas, especially using multitemporal approaches like that for the 1994 flood on the River Saale in Thuringia (Kannen, 1995). Some problems arise with undulating topography owing to shading, which leads to misclassifications. The misinterpretation occurs with visual interpretation of the imagery as well as with the use of automatic classification algorithms like the sophisticated EBIS (evidence-based interpretation of satellite images) classification algorithm, which is supported by *a priori* class information (Lohmann, 1991; Oberstadler, 1995). An attempt to overcome these problems was made by combination with geographical information system (GIS) data, e.g. land use and elevation, and excluding particularly the shaded areas. Dreiser and Mertens (1996) used a DEM inferred from contour lines and dam lines to generate comparable trapezoidal-shaped units of 30 m by 100 m (breadth by length) parallel to the river banks for statistical evaluation of pixel subgroups. Thus, comparable statistical values of flood-prone areas could be extracted. They concluded, for their Bonn study area, that because of the relatively coarse geometrical pixel resolution and speckle feature of the SAR data, the comparison of statistical results of ERS SAR data with DEM gives information on flooded areas. Nevertheless, flooded areas in the hinterland not shown in official maps were successfully detected, although a cross-check by DEM interpretation or questioning of local residents is recommended.

For the January 1995 flood, as already mentioned, ERS-1 SAR data of the same area were not available. Instead, airborne C-band SAR of the DLR with the same VV polarization, may be considered comparable. For the first key area, the mouth of the River Main at the River Rhine, airborne SAR imagery taken on 30 January 1995, clearly shows predominant features, like a railway bridge crossing the River Rhine, in combination with regions of low back scattering (Figure 5). In a density-sliced colour-coded representation, potentially flooded areas are shown in dark blue colours (Figure 6). Areas directly bordering the rivers are clearly identifiable as flooded, proved by video images taken shortly afterwards. Some vegetated regions at the slope of the Taunus Mountains, just to the north, are misclassified. Using *a priori* information in EBIS classification or ancillary GIS data might be of help in this situation.

The passive MWR at 89 GHz (0·33 cm wavelength, 4·5 m resolution) was able to detect flooding at the immediate mouth covered by the imagery, with good delineation of prominent features such as rows of trees and a railway bridge (Figure 7). The other MWR bands with coarser resolutions of 22 m (18·7 GHz and 1·6 cm wavelength) and 11 m (36·5 GHz and 0·82 cm wavelength) add no further information nor do they show sufficient spatial detection capabilities. In addition, the TIR imagery shows clearly the colder water of the River Main entering the River Rhine or flooding residential areas at the north-eastern river bank, shown to the right in Figure 7. The UV channel shows some features that cannot be interpreted directly (Figure 7). Again here, additional GIS information, like distribution of residential dwellings, can support the interpretation and subsequent quantification of flooding extents and losses.

Figure 5. Mouth of the River Main at the River Rhine, airborne C-band VV SAR, DLR platform, 30 January 1995 (courtesy Mr Horn, DLR Institut für Hochfrequenztechnik)

For the mouth of the River Sieg into the River Rhine, the second key area, the C-band VV airborne SAR clearly shows inundation of meadows on 30 January 1995 (Figure 8, coded in blue), and was also affected in the 1993–1994 flood (Dreiser and Mertens, 1996).

The b/w NIR photographs, taken from the airforce camera device, clearly show inundated areas shortly afterwards on 1 February 1995 (Figure 9). The image resolution is very good, but because of panoramic image geometry, stereometric measurements are not possible, inevitably leading to visual interpretation and manual transfer of flooding limits into maps.

A difficulty arises with the interpretation of the flood extents and water levels at different times during a flood. Because of acquisition restrictions, not all of the interesting areas could be covered, either each day or at the same time on a certain day, for all areas. So comparisons for a specific time are to be supported by a model providing stage information. Although, for design purposes, only maximum water levels are needed which, owing to flood propagation in a big watershed like the River Rhine Basin, do not occur at the same time at all river reaches. For these purposes, flood extent delineation at peak flood conditions at the reaches considered are sufficient. The information may be gathered from imagery acquired near to the experienced flood peak time, the time inferred either by residents' records or estimated propagation time from a reference gauge or a flood routing model, respectively. In Germany, by statistical comparison of discharges at reference gauges for which rating curves exist, the return intervals of the water levels for specific river reaches are calculated. By this procedure, the so-called equal water levels (GLW), i.e. water levels for discharges of specific return intervals, are computed. They are subsequently used in updating official maps with flood prone areas where construction is prohibited or restricted. For flood routing models, stage–discharge relationships, either as classical rating curves or as hydraulic or mass balance equations, are used in the assessment of water level data at a specific time. Water level data other than stage data at gauges are used mainly for calibration purposes (cf. Wilke, 1995; Busch *et al.*, 1996). Given a real time availability of flood extents and water levels provided by RS, which is not the case today, updating of forecasts would be possible, but requires suitable accuracy of the values (cf. Peck *et al.*, 1981).

SOIL MOISTURE ESTIMATION USING ERS SAR

The flood events of 1993–1994 and 1995 showed the importance of soil moisture for runoff generation. Even if quantitive estimation is desirable, qualitative classification such as water-logged or not, in combination with the variable source area concept for runoff generation promises to give good results in combination with areal estimates of soil moisture regions derived from RS data. Several approaches might be followed in soil moisture estimation (cf. Rango, 1994). SAR with direct dependency on dielectricity of soil water content is promising, although problems exist (Altese *et al.*, 1996; Ragab, 1995; Ulaby *et al.*, 1982, 1986). Chanzy *et al.* (1990) found linear correlation of back-scattering with volumetric soil moisture for bare soil on C-band SAR at 23° incidence angle; the results of Cognard *et al.* (1995) point in the same direction for vegetated surfaces, with less sensitivity. Therefore, the Federal Institute of Hydrology is currently investigating the possibilities of ERS SAR to estimate soil moisture at a lowland catchment on the lower River Elbe, at 11°25′E and 53°5′N. Preliminary results are shown in Figure 10, representing the 14 September 1995 GEC data from ERS-1 (orbit 21782, frame 2529). Differences in back-scattering within the study area, stretching about 15 km W–E occur, according to the surface texture being dependent on land use (arable land versus meadows). The use of GIS land use information again seems to be helpful in distinguishing different soil moisture states within homogeneous land use classes.

CONCLUSIONS AND FURTHER CONSIDERATIONS

As far as preliminary evaluations of the flood-related RS data of the 1993–1994 and 1995 floods in the River Rhine catchment exist, some general conclusions can be drawn. They are supported by research for other regions (e.g. Bonansea, 1995; Janssen, 1995; MacIntosh and Profeti, 1995).

1. C-band VV SAR might be used in the evaluation of flooded areas. The use of additional polarizations could enhance the information.

2. The relatively coarse resolution of ERS SAR (about 25 m × 22 m original pixel size), plus the inherent speckle feature, indicates that evaluations should preferably be at larger spatial scales.

3. The dissemination of RS data in real time will be an invaluable tool for flood monitoring.

4. The acquisition of data should be planned in advance in alerting schemes, enabling quick response to regional data necessities. This was not realized in 1993–1994 and only partly in 1995. Uncomplicated and quick distribution of imagery at affordable costs should be accomplished for end-users and value-added companies.

5. Products that can be related directly to GIS databases of the users are useful for quick assessment of flood extent, imminent risks or damages, and mitigation strategies.

6. Due to the inherent system repetition rate, normally 35 days for ERS-1 and ERS-2 (during tandem operation until mid-1996 a lag of 1 day between ERS-1 and ERS-2), steady coverage in peak flood times is not always guaranteed, although neighbouring orbits partially cover the same areas (like the Cologne/Bonn area during the 1993–1994 flood). Therefore, flood peaks might be missed by the satellite. As a consequence, continual monitoring and flood warning or flood damage assessment, rather than real-time flood monitoring during peak conditions seem to be most appropriate long-term applications. A flood warning issued because of soil saturation recognized by satellite radar in advance might be combined with weather radar and precipitation forecasts, perhaps themselves assisted by RS, to release airborne RS campaigns.

7. The combination of high precision digital elevation data promises to enable the transfer from information on extent of flooding gathered by RS to water level data needed by hydrology. Water level is also needed

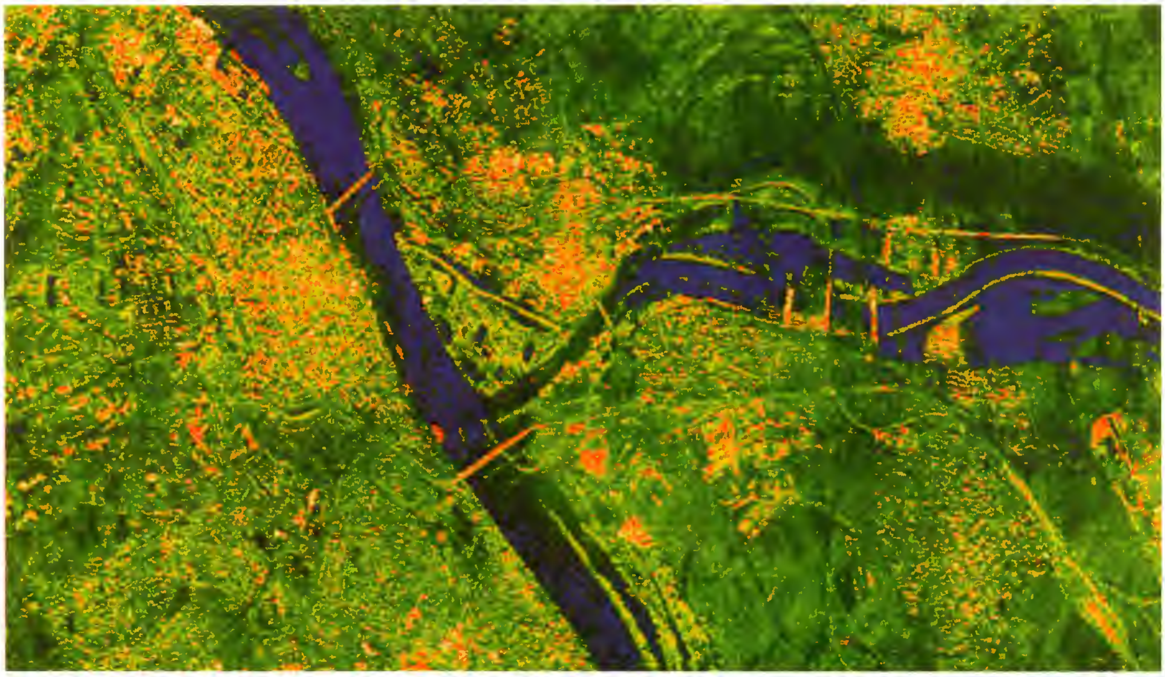

Figure 6. Mouth of the River Main at the River Rhine, airborne C-band VV SAR, colour-coded, DLR platform, 30 January 1995 (courtesy Mr Horn, DLR Institut für Hochfrequenztechnik)

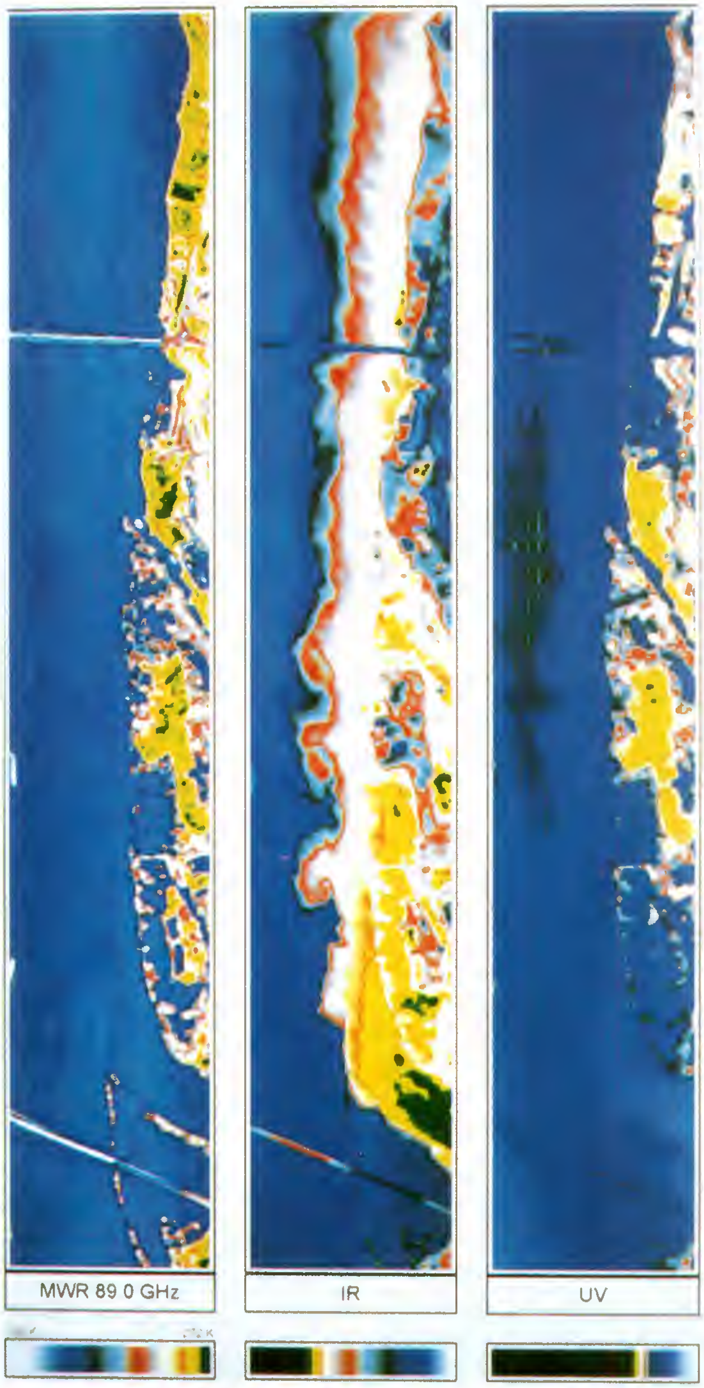

Figure 7. Mouth of the River Main (at bottom right) at the River Rhine, MWR (89 GHz), TIR, UV, navy platform, 30 January 1995 (courtesy Mr Grüner, DLR Institut für Hochfrequenztechnik)

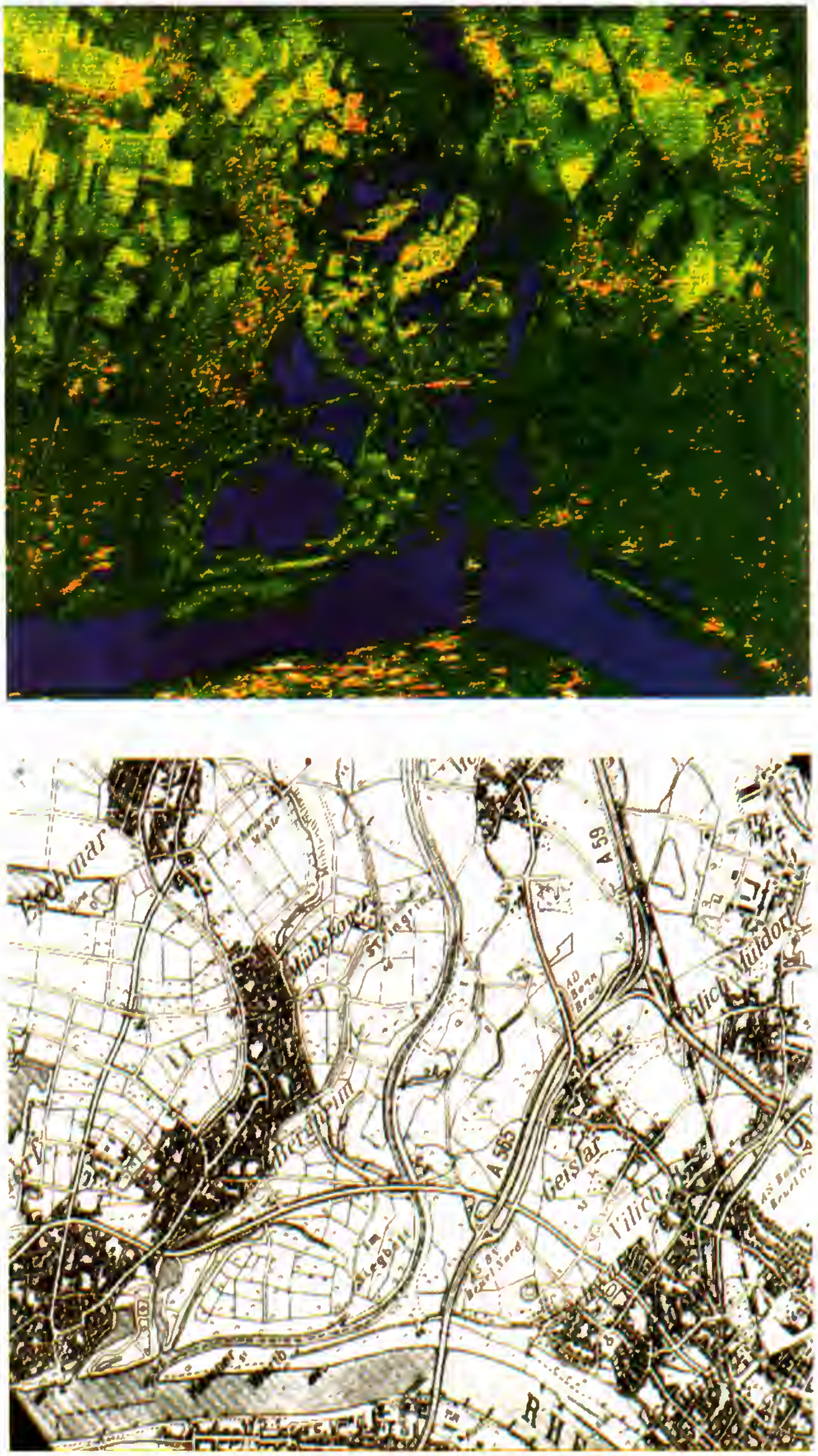

Figure 8. Mouth of the River Sieg at the River Rhine, airborne C-band VV SAR, colour-coded, DLR platform, 30 January 1995 (courtesy Mr Horn, DLR Institut für Hochfrequenztechnik)

Figure 9. Mouth of the River Sieg at the River Rhine, b/w near-infrared film, air force platform, 1 February 1995

Figure 10. Test site for soil moisture estimation (11°25′E, 53°5′N) of the Federal Institute of Hydrology, ERS-1 C-band VV SAR, GEC product, 14 September 1995 (orbit 21782/frame 2529) (courtesy ESA)

by hydrologists for forecasting purposes and by decision makers in order to take appropriate measures in real time flood emergency. The latter, in Germany, use water levels either at gauges or at arbitrary points as reference for their decisions. Although some difficulties exist, or most importance for flood assessment are permanent artificial or ephemeral natural dams, which have decisive effects on flooding or no flooding. When the critical water levels of respective dams are reached, the floodplain or even the hinterland will be flooded directly. Gaps in dams, e.g. for access to landing bridges, and failure of dams may lead to direct flooding behind known flood protection structures. Furthermore, indirect flooding by groundwater or tributaries impeded to seep or flow into the main river by above normal high water levels is common.

Accurate representation of topography can support considerably the prediction of possible flooding either in real time or at post-flood assessment. Although currently available DEMs are normally raster based, with best grid resolutions of about 30 m (e.g. Defense Mapping Agency 90 m by 60 m; US Geological Survey 30 m by 30 m only partially for the US; Germany 20 m by 30 m up to 50 m by 50 m) (Maidment, 1992; Petzold, 1995), the error (discrepancy from true value) and accuracy [discrepancy from a modelled or an assumed value, as defined by Goodchild *et al.* (1994)] of the topographic data often do not meet hydrological data needs. This holds true especially for linear topographic features like dams, stream banks or ridge lines in the floodplain, which are not represented in these raster DEMs, mainly because of their coarse grid resolution. The integration of linear data or other relevant topographic data (e.g. location of culverts) with raster DEM data yields digital terrain models (DTM) describing the landscape features relevant for flooding and hydrological purposes (Maidment, 1992). The use of already available GIS vector data sets for integration seems to be one of the possible ways towards solving this task. In Germany, assimilation of digital ATKIS (official topographic and cartographic information system; Grünreich, 1992) data, including linear dam features, is taken into consideration. Up to now, the dams are not manageable within ATKIS as 3-D features, including height of the structures, but only as 2-D features with location and width (Petzold, 1995). So, the interpolation of a high-resolution raster DEM meeting the user's needs, e.g. 1 m by 1 m, from a currently available DEM with additional relevant topographic line and point data seems, for larger areas to be covered, to be the only method at this time. Nevertheless, information compression should be applied whenever possible, as the raster DEMs size increases exponentially with grid resolution without necessarily increasing the representation of topography. This might be demonstrated by the example of a floodplain with a gentle uniform slope, which might be better represented by the parallel lines of a river bank and crest with their respective heights, than with a lot of points perpendicularly between these lines: the height of the points may be easily interpolated if needed. Eklundh and Martensson (1995) state that data quantity does not guarantee high precision, the choice of input data sampling (i.e. distance and distribution of supporting points, either gained by survey or taken from other sources, e.g. contour lines) and interpolation methods are most important for the generation of the best representation of topography, which is the primary goal.

The conversion to the data format finally needed is a question that should be considered at this point. Sometimes, hydrological models, when finally applied for flow/flood routing, need critical points of the floodplain at cross-sections already existing rather than grid point elevation. So, specific interpolation for the required points, e.g. cross-sections, may give the most significant information for the final purpose through retaining optimal compression, rather than simple interpolation of an arbitrary grid from which relevant information has to be extracted and transformed in a second step.

Another point of interest is the small ephemeral natural dams of deposited material, which sometimes are found in the floodplains, e.g. on the River Weser in Germany. For less significant events it is these that determine whether parts of the floodplain are flooded or not. Because of their non-durability and size, unlike artificial dams, they probably are not contained in any official cartographic database. They might be detected and mapped using high resolution RS altimetry. For this purpose scanning laser devices promise to give reasonable results (Bates and Anderson, 1995; Lohr and Eibert, 1995; TopScan, 1995). Interferometric SAR application (INSAR) from ERS-1 data, with deviations of, for example, 3 up to 4 m at the southern German test site Freiburg i.Br., would probably not meet necessary error limits. This might be different for differential INSAR, showing very good change detection of about 1 cm (Hartl, 1991; Hartl and Xia, 1993).

8. Hydrological models normally still require input data other than RS data (e.g. Maidment, 1992; Rango, 1994; Schultz, 1994a). Only a few models are able to use RS data directly as data input, most only use RS indirectly (cf. for example, Suwanwerakamtorn, 1995). Schultz (1994a), for example, presents a model deriving monthly runoff from Meteosat IR data. The adaptation of current models and development of new models to meet available RS data input is still a task for the future. Alternatively, the data and products delivered by RS techniques need to be redefined in order to meet the needs of current sophisticated hydrological models. Most models need water level and discharge information rather than delineation of flooded areas, which can be derived directly from RS data. Although, the water surface topography generated by RS techniques can be used as input and validation data for appropriate hydraulic models. Laser techniques, in particular, are considered appropriate for this purpose (cf. Bates and Anderson, 1995; Lohr and Eibert, 1995). Estimation of runoff with the breadth of the water course detected by RS is possible, but requires appropriate area–discharge relationships or sophisticated hydraulic modelling (Moll and Overmars, 1990; Smith, 1995a; Smith *et al.*, 1995).

9. A cost benefit analysis of RS data acquired and evaluated (coordinated by the Federal Institute of Hydrology in 1993–1994 and 1995) cannot be undertaken yet, given the open status of the data evaluation. Although it can be stated that as long as no appropriate models exist that can use RS low-level data as a direct input for the desired scope of application, e.g. flood prediction within a certain catchment, the products derived from RS data must be designed to fit the needs of the currently used hydrological models. Because running operational models is better than running no model at all, the research on appropriate methods to derive these products has to be intensified, along with the development of appropriate models with integration of RS data and the adaptation of present day models to RS data.

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USE OF ERS-1 DATA FOR THE EXTRACTION OF FLOODED AREAS

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ABSTRACT

The aim of this study, undertaken by Geoimage, was the setting up of a fast and precise location method of flooded areas over two sites in southern France. The use of satellite imagery seemed to be the appropriate tool for this study.

Two types of flood had to be distinguished: (i) an oceanic flood, of long duration characteristic, and of low intensity on the Rhône Valley, (ii) a torrential flood, of short duration characteristic, but of high intensity, on the Var Valley. As we distributed of ERS-1 images over both sites, during the floods, we could test our methodology. A multitemporal approach using ERS-1 images in PRI mode, acquired before, during and after the flood, was set up. In the case of oceanic flood, the radar images characteristic answers, enabled us to extract and identify areas under water at each date of acquisition of the images. Therefore, if we distribute images at each step of the flood, its evolution can be precisely reconstituted (in terms of time and surface). In the case of torrential flood, it is more difficult to localize the flood with precision. This can be explained by the change of water surface, which has a large swell in this case. Radars are sensitive to these changes in the turbidity, an interaction occurs and thus the results were 'turned off'. Nevertheless, simulation studies from other satellite data make possible the location of more or less strong hydrological risk accident areas.

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KEY WORDS oceanic flood; torrential flood; radar images; multi-temporal approach

INTRODUCTION

Following the numerous torrential floods that have affected the southern 'départements' in France since 1992, the Environment Ministry has reinforced its legislative policy concerning the prevention of natural risks, and in particular of flooding. It has also initiated a programme of knowledge and cartography of the risk in relation to the rise in water and to the urban rain flow in the thirty 'départements' of the Mediterranean arc that are most affected (Delmeire *et al.*, 1995).

The previously established means, which were based on a historical, geomorphological and hydraulic approach, served to set up the first prevention and protection measures over the most vulnerable areas. But this type of study is not exhaustive and must be limited to certain areas because of the high cost involved. Faced with this problem, the Geoimage company aims to provide a solution by using remote sensing. The studies that Geoimage carries out in this field are aimed at evaluating the rapidity and trustworthiness of the flooding cartography with the help of satellite data.

Geoimage has a particular interest in the data resulting from synthetic aperture radar (SAR). In fact, the acquisition of data from conventional satellites (passive sensor) is seriously limited by the presence of clouds during periods of flooding. However, SAR, which is an active sensor, allows the acquisition of images by day or night, and whatever the cloud cover may be. Moreover, the sensitivity to determine areas under water is a most important advantage with regard to the cartography of flooded areas.

In our study, we used the radar images from the European ERS-1 satellite because it offers an interesting geographical cover of the Rhône and Var valleys (South of France) and the available acquisition dates over these two zones corresponded to the dates of the floods we wanted to map.

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The aim of this study was to test and compare the cartography of the flooded zones from SAR images for both types of existing flooding: the oceanic floods, which are slow and long lasting, stretching over extensive areas; and the torrential floods, which are of high intensity but short duration. The selected test zones are the Rhône Valley during the floods of October 1993 and January 1994, which show the characteristics of an oceanic flood, and the Var Valley during the flood of 5 November 1994, which presents the characteristics of a torrential flood.

METHODOLOGY

Flood inundation mapping is based on the fact that water will normally appear black in a SAR image, i.e. minimum radar echo. This principle has provided the guidelines for mapping of inundated areas. Flood inundation monitoring will call on change detection based on temporal differences in radar back-scatter. Differencing and ratioing are well-known techniques for change detection (Singh, 1989). In differencing, changes in radar back-scatter are measured by subtracting the intensity values pixel per pixel between two dates (Badji *et al.*, 1994). Here, we used a multitemporal approach to set out the flooded areas (Corves, 1994), i.e. use several images of the same area at different dates. One of the dates used must be after, and the closest possible to, the maximum of the flood. It is possible then, with the help of the characteristic response of the zones under water in the SAR images and by using one or two other images (which were acquired before or after the flooding), to map the land under water at the time of the acquisition of the image, showing the rise of the waters. The response of the zones under water in the radar image will differentiate the cartography of an oceanic flood from a torrential flood. In fact, in the oceanic flood the zones under water will be characterized by a low-intensity response (dark pixels in the image), because in this type of flood the water, being calm and flat, plays the role of a mirror. On the other hand, during a torrential flood the turbulence of the water will generate a response of high intensity in the radar image (light pixels in the image).

The images that we used are ERS-1 images in PRI mode. Before combining these images to extract the flooded areas we carried out some pre-processing, the purpose of which was to:

(i) recode the images on eight bits to allow a processing with the Geoimage digital mapping workshop;

(ii) filter the images in order to diminish the noise caused by the speckles using a Lee's filter with a 7×7 window size;

(iii) modify the histograms in order to increase the contrast of the zones under water; and

(iv) make the multitemporal images perfectly overlapping.

Such pre-processings helps to create a coloured composition from two or three images.

STUDY AREAS

The Rhône Valley — October 1993 and January 1994

The important floods which happened along the Rhône Valley in October 1993 and in January 1994 triggered many reactions related to the need to have quick information at one's disposal to be able to understand the extent of the phenomenon. Geoimage was contacted at the time by various organizations that wanted to find answers to precise and urgent needs, as well as to evaluate to what extent remote sensing was a trustworthy means of mapping the flooded areas which could also be integrated as a standard tool in the study of such a phenomenon.

The Environment Ministry, through the DGE and the DGAD, wished to have rapid mapping of the flooded zones in order to have at their disposal a document, which could be opposed to the SNCF, presenting the crossing of the flooded areas and the planned line of the Mediterranean High Speed Train. The Compagnie Nationale de Rhône also wanted to have a map of the flooded areas over the whole of the Rhône Valley, between Lyons and the sea, and a map of the land use, to be able to evaluate the impact of the flooding in economic terms.

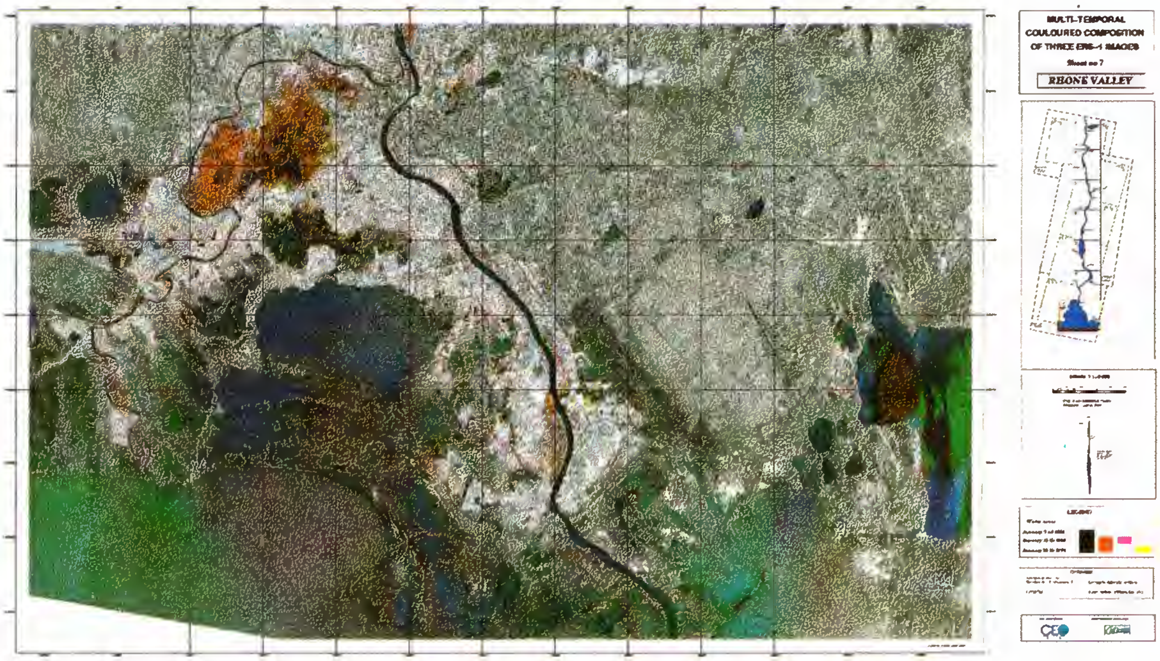

Figure 1. Coloured composition of three ERS-1 images

Figure 2. Space map and flooded areas

Figure 3. Flood risk simulation in the Var River (southern France)

Other more local requests also involved the same problem. The coverage of such an important zone, even from satellite images could represent a very high cost for each of theses organizations, although a lesser one compared with the cost if the work had been carried out through traditional methods. For this reason, and as far as these various requests involved the same study area and concerned the same problem study, Geoimage suggested bringing the problems together on a common database and as part of a common processing.

The database consists of:

1. A 1:50 000 space map covering seven segments of the zone under study;
2. A map of the land use according to the same cartographic gridding; and
3. A map of the flooded areas at the two previously mentioned times.

For the January 1994 flood, we used three ERS-1 images. The first was acquired on 3 January 1994, four days before the rise in water. This image enabled us to locate the areas permanently under water. The two other images were acquired during the flooding on 12 and 15 January. For the October 1993 flood, we used two images. One was acquired on 16 October, during the flooding, and the other on 16 November 1993.

First, we produced a coloured composition on three dates over the Camargue (lower part of the Rhône Valley, Figure 1). The date–channel associations are as follows: 3 January = red channel; 12 January = green channel; and 15 January = blue channel. Since we are dealing with an oceanic type flood we must point out that in an image the zones under water will appear dark. From this statement we can draw the following analysis. We can observe the rivers and water stretches in black water. These water surfaces form the areas that are always under water and therefore never flooded. The magenta represents the areas under water on 12 January 1993. Therefore, these areas correspond to the beginning of the flood in January. They are essentially located along the waterways and are probably caused by their overflowing. The red represents the areas that were flooded on 12 and 15 January. We can see a large red spot located on the north-west part of the pond situated in the middle of the image. It is located in the region of marshy areas which are, therefore, more prone to flooding. We can also observe areas that were flooded at the two dates all along the Rhône Valley. They are the result of a water surplus from the Rhône. The yellow areas correspond to the areas that were only flooded on 15 January. We can locate them, for instance, round the big spot located at the north-west of the pond.

Three hypotheses can be surmised concerning the presence of the water: either it rained again between 12 and 15 January, or water coming from the previously flooded Rhône Valley came down and spread over already flooded zones thus increasing the affected area, or both phenomena occurred simultaneously.

We then produced a document to superimpose the results. This space map was obtained through LANDSAT TM images from July 1993, which were satisfactory for mapping the vegetation, and from 10 m SPOT P images from February 1993, to determine the built up areas and the infrastructures. On this space map we superimposed, in orange, the zones that were flooded on 12 and 15 January 1994, and, in yellow hatching, the zones under water on 16 October 1993. These data come from two coloured compositions which we produced from the ERS-1 images (Figure 1).

Var Valley — November 1994

The area of the Alpes-Maritimes on which Geoimage had an important database from remote sensing was selected because of the topographical and hydrological characteristics, which are favourable to torrential-type flooding.

At the beginning of 1994, a rise in water level of the most important river of the Var 'département' took place. We tried to map this water rise. To do this, we acquired two ERS-1 images; one from 6 November 1994, i.e. the day after the beginning of the water rise; the other before the water rise, dating from 20 October 1994. In this type of water rise, however, mapping of the flooded areas seems to be more difficult than the mapping of an oceanic flood. In fact, in the case of the Var Valley, the rise was quickly limited by the relief and did not spread very much. Therefore, because of ERS-1 resolution, the floods generated by this type of water rise are not easily noticeable. Moreover, the lower part of the Var Valley is located in an urban periphery and, therefore, the strong spectral response of the buildings in the image affects the distinction from water.

The date–channel associations are as follows: 6 November 1994 = red channel; 20 October 1994 = green channel; and 20 October 1994 = blue channel. Since we are dealing with a torrential-type water rise, we must point out that in the image the areas of water rise will appear light. From this statement we can draw the following analysis. The areas of water rise appear in red in the image. But, as we remarked previously, it is difficult to distinguish the areas under water that are located outside the river bed. Normally, the Var River only occupies part of its bed. However, Geoimage has started a study in collaboration with the Environment Ministry to establish a map of the flood risk. To do this, a database of flood risk has been constructed from: (i) a digital elevation model (DEM) produced from SPOT stereoscopic couples; and (ii) the land use.

Taking the DEM into account it is possible to describe the relief by determining the slopes, the drainage basins and the hydrographical network. All these parameters will then enable us to model the potential local or cumulated flow into the hydrographical network. From this model, we can get a realistic simulation of a flood.

This simulation takes into account: the DEM; the hydrographical network; and the water heights in the network, which are determined from the real and weighed flow by real pluviometrical data.

The use of real data enables us to calibrate the model.

In Figure 3 we can see the simulation for the Var river in the case of the centennial flood (mouth flow: 2165 m^3/s).

CONCLUSIONS

The mapping of the torrential-type floods from SAR images does not give obvious results in the case of our study on the Var Valley. This is because the small surface of the areas under water and the difficulty in differentiating the response of the water from the land above water. The simulation can be of help in the mapping of such floods. However, in Camargue, where the flooding phenomenon is spread over several weeks (oceanic-type flood), even over several months, the radar datum offers a quick and precise mapping tool of the zone that is affected by the flood. In order to explore further the possibilities of radar images to map the flooded areas within oceanic- or torrential-type water rise, the CNES and the Compagnie Nationale du Rhône carried out a research programme, led by Geoimage, on how to determine 'flood reoccurrence' zones from radar or optical images. In fact, if the radar images allow the discarding of the cloud cover problem, they are still affected by constraints of periodicity of acquisition. During the October 1993 floods, the ERS-1 satellite was in image acquisition phase over the same geographical zone every 35 days. In the case of a torrential water rise, this made it nearly impossible to have images at a date sufficiently close to the maximum flooding in order to map the limits accurately. Therefore, it was necessary to try and set out, in a direct way, the submersion of a given area during the maximum flooding but which was not submerged at the date of the acquisition of the satellite image. Such a reoccurrence phenomenon was already set out from optical (SPOT XS) images during an important water rise in 1989 in the Sidi Bou Said region of Tunisia. The aim of the methodological study led by Geoimage was to try and set out this same phenomenon on radar data that are acquired before and after the water rise.

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FLOOD MANAGEMENT THROUGH LANDSAT TM AND ERS SAR DATA: A CASE STUDY

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ABSTRACT

This paper deals with the experimental activity carried out in the field of flood monitoring at the Civil Engineering Department of Florence University (Italy) in cooperation with EOSAT (USA) and Eurimage (Italy). The aim of the study is to research the possibilities of satellite data utilization to aid in modelling of the hydrological behaviour of a river basin and monitoring flood emergencies. The area selected for the study is the Fucecchio Marsh (Tuscany, Italy), in which flooding events are very frequent. This paper describes the results of the study, with particular reference to the use of Landsat TM data to estimate soil water content, and the use of ERS SAR data to analyse flash flood events. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS flood management; remote sensing

INTRODUCTION

The present paper describes some applications of satellite data to flood prevention and flood damage survey developed at the Civil Engineering Department of Florence University, Hydraulic Section, in cooperation with EOSAT (USA) and Eurimage (Italy).

The area selected for study is the Fucecchio Marsh (*Padule di Fucecchio*) located in the Arno River Basin, Tuscany, Italy. The Fucecchio Marsh is one of the most important wetlands in Italy, and the prevention of flash flood events represents one of the major tasks related to its preservation. Prevention activity is based on the prediction of the terrain's response to storm events by means of a distributed hydrological model of the marsh. Landsat thematic mapper (TM) data have been used in this part of the research to estimate the water content of the upper soil layer for use as input in flash flood event simulations.

The second part of the paper concerns the post-flood relief activity. In Italy, damage evaluation is performed mainly through ground surveys. The purpose of the research has been to demonstrate to the local administrative authorities the utility and convenience of using ERS SAR data to monitor the extent of flooded areas, even when a limited territory such as the Fucecchio Marsh is affected. The research has been executed at pre-operational level, in cooperation with the Pistoia Province (Tuscany, Italy), which has jurisdiction over the marsh and thus represents a potential user of ERS SAR-derived products.

FLOOD PREVENTION

Structural works are not sufficient to avoid the danger of floods in river basins characterized by fast response to storm events, such as the Arno River Basin. Real time monitoring systems are thus necessary to improve flood danger forecasting and give the necessary advance notice to competent authorities. In this context, the

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application of satellite data to flood prevention concerns the modelling of hydrological processes in a river basin.

Real time monitoring systems are based upon a distributed hydrological model of the river basin that describes the hydrological processes taking place when a storm event occurs. Once the hydrological processes have been modelled with sufficient accuracy, it is possible to use rainfall measurements acquired on the ground and sent in real time to the processing centre to evaluate the risk of flooding (Becchi *et al.*, 1994). To achieve the necessary accuracy, distributed models require knowledge of hydrological parameters with high resolution in space and/or time over the study area. Remote sensing represents the most promising solution to this need (Schultz, 1988).

This first part of the paper summarizes the results achieved using Lansat thematic mapper (TM) images to estimate the water content of the soils' upper layer in the Fucecchio Marsh area. This parameter is used as the initial condition in the simulations. It is also one of the most difficult quantities to measure *in situ*. For this reason, an estimation of soil moisture with the high spatial resolution required by distributed models was impossible before the advent of remote sensing.

The Landsat TM detects and records the solar energy reflected from the earth's surface with a ground resolution of 30 m × 30 m in six wavelength intervals belonging to the visible and infrared regions of the electromagnetic spectrum. The surface reflectivity is correlated to the characteristics of vegetation and soil over the surface itself, the latter including the soil water content. Numerous authors have investigated the factors influencing the spectral reflectance curves of soils in the visible and infrared bands in order to develop methods of estimating soil moisture from TM images (particularly Idso *et al.*, 1975a,b; Skidmore *et al.*, 1975; Kauth and Thomas, 1976; Reginato *et al.*, 1977; Peterson *et al.*, 1979, 1980; Stoner *et al.*, 1980; Crist and Cicone, 1984a, b; Baumgardner *et al.*, 1985; Musik and Pellettier, 1986, 1988; Pranzini and Della Rocca, 1986; Van den Bergh and Bouman, 1986; Maselli *et al.*, 1990). In the visible and infrared spectrum, soil water absorption causes a decrease of soil reflectivity in several wavelength intervals (Baumgardner *et al.*, 1985), the main two being located in the mid-infrared and centred at 1·45 and 1·95 μm. The best regions for mapping water content are those adjacent to these bands, i.e. 1·50–1·73 and 2·08–2·32 μm, corresponding respectively to band 5 and band 7 of Landsat TM. In these bands, the spectral reflectance of the surface is strongly influenced by water content, but other factors, such as vegetation cover and the quantity and quality of soil components, are important as well. For this reason, many authors have proposed indexing methodologies to enhance the contribution related to water content in Landsat TM bands; for example, the contrast (ratio) between TM band 5 and 7 (see above and Alessandro *et al.*, 1990).

In this study, a spectral decomposition technique was used to extract the soil contribution from Lansat TM data, using the decorrelating properties of the principal component analysis. The index thus obtained has been tested using the water content of the terrain obtained from a model of the marsh's upper soils layer. A similar analysis was performed using the ratio of band 5/7. The results show that the decorrelated index has a better correlation to the model's estimates of soil moisture.

Three Landsat TM images, acquired in 1991 (27 January, 7 August, 26 October) have been used. These dates were selected to compare the indices obtained from images acquired under different conditions of vegetation cover and soil water content.

The first aim of the work has been the development of an index that makes use of the decorrelating properties of the principal component analysis of TM bands, to minimize the dependence on vegetation cover. The preliminary results of this technique are reported in Maselli *et al.* (1990). The methodology is based on the creation of a bivariate data set from a TM image, in which the first variable is exclusively dependent on vegetation cover and the other contains information both on vegetation and soil conditions. The principal component analysis allows definition of a new couple of reference axes. The first component axis is oriented on the maximum variability direction, and is therefore directly correlated to the response of the vegetation. The second principal component axis is oriented in the direction of the residual variability, i.e. to the soil spectral response. Over homogeneous soils, the variability of spectral response is related to soil water content; the second principal component is therefore a proper soil water index. This interpretation of the results of principal component analysis is a result of the peculiar characteristics of the data set. In this study, the two variables have been chosen as follows. (1) The first variable must be strongly influenced by soil water content and vegetation cover. These characteristics are satisfied by both the middle-infrared TM bands (5 and 7). Band 5 has been chosen because of its greater dynamic range. (2) The second variable must be almost exclusively correlated to the vegetation characteristics. A vegetation index satisfies this condition better than a single TM band. The vegetation indexes generally emphasize the presence of vegetation contrasting the spectral response of surfaces in the red and infrared wavelengths. These indices are not suitable for the present study owing to the sensitivity of infrared bands to soil water content. The contrast between the response in the blue : green (band 1 : band 2) wavelength has been used instead. An example of the 5 : 7 ratio and decorrelated soil moisture indices, obtained from the 27 January 1991 image, is shown in Figure 1.

To obtain an estimate of soil water content at the three acquisition dates, a simplified hydrological model of the Fucecchio Marsh was built (Profeti, 1996). The reference model is the distributed water balance model developed at the Civil Engineering Department of Florence University (Becchi and Federici, 1987; Becchi *et al.*, 1989, 1991, 1994). Landsat TM data carries information on the soil water content of the uppermost layer of soil. Therefore, the model takes into account only the hydrological processes that influence the water content in the soil's sub-horizons A00 and A1. In the Fucecchio Marsh area the relevant processes are infiltration, evapotranspiration, capillary absorption and variations of the water table height. The model is based on a cell grid corresponding to that of Landsat TM (30 m × 30 m), and uses cumulative daily rainfall (mm) and point measurements of soil moisture, when available ('natural soil water content' in percentage, obtained from geotechnical analysis of undisturbed samples of the upper soil layer), as input. The hydrological parameters of soils have been obtained from a detailed pedological study of the area (Magaldi *et al.*, 1988), while data on soil use were obtained by photointerpretation of aerial photographs of the study area acquired in 1989. The output is a daily average water content of soils (mm).

Finally, the correlation between the index values and model estimates of soil water content has been sought for each soil class of the marsh and simultaneously for the three dates. This is justified by the fact that the index value is independent of the vegetation cover, and also of the seasonal variations in illumination conditions. In fact, ratios such as the band 1 : band 2 ratio used in the decorrelation process are scarcely influenced by illumination conditions (Lillesand and Kiefer, 1994). Also, the principal component analysis has been performed using the correlation matrix, and thus compensating for the seasonal variations in the dynamic range of band 5. Therefore, their value is related only to the soil's characteristics; over the same soil, the variations are correlated only to the amount of water in the soil itself. The same considerations are applicable also to the band 5 : band 7 ratio, and the same procedure has been applied to this index map and the corresponding soil water content maps.

Then, a linear and a semi-logarithmic regression have been tested on the couples of indices values and model values for each soil class of the marsh. The semi-logarithmic regression did not describe properly the two distributions of values (average correlation coefficient $<0{\cdot}5$). Both were better described by a linear correlation, i.e. (index value) $= a$ (model value) $+ b$.

The decorrelated index had the best correlation with the model values over the majority of the 15 soil classes present in the study area (see Table I). The average correlation coefficient obtained between soil moisture values and decorrelated index values was 0·727, and the correlation coefficients were above 0·65 for 11 soil classes of 15. The 5 : 7 band ratio gave an average correlation coefficient of 0·639, and the correlation coefficients of the single soil classes were above 0·65 in nine classes on 15.

Table I. Correlation coefficients of the linear regression between index values and model values for each soil class (USDA, 1975) of the Fucecchio Marsh (Magaldi *et al.*, 1989)

Index	TX1	TX2	TX3	AX1	AX2	AX3	AX4	AX5	TH1	TH2	TH3	TH4	TH5	P	Q	Average
5:7	0·373	0·657	0·629	0·931	0·543	0·971	0·599	0·595	0·765	0·646	0·952	0·763	0·348	0·852	−0·048	0·639
Decorr.	0·580	0·722	0·692	0·900	0·597	0·970	0·659	0·655	0·842	0·710	0·935	0·840	0·382	0·938	0·485	0·727

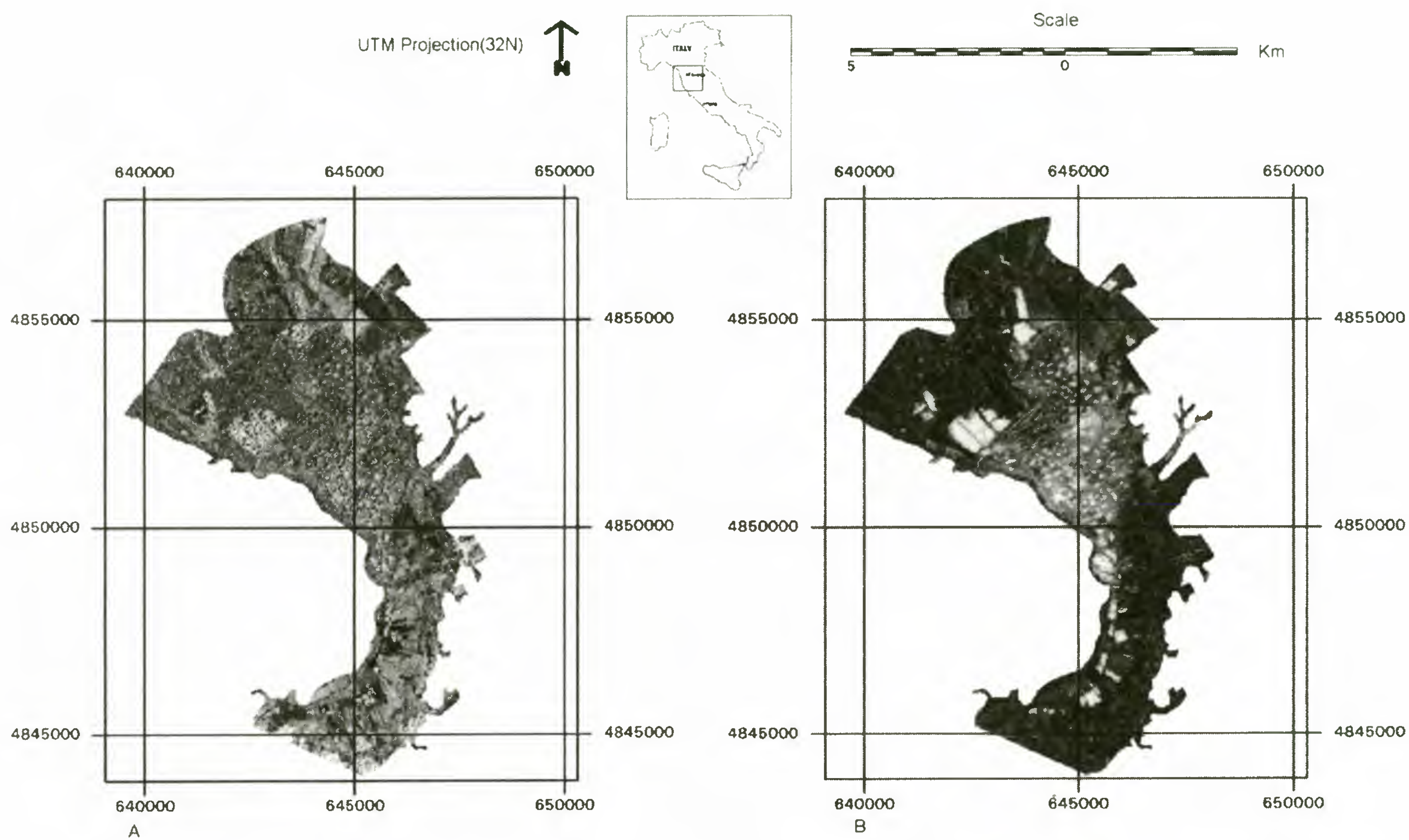

Figure 1. TM band 5; band 7 index (a) and decorrelated soil moisture index (b) obtained from the Landsat TM image of the Fucecchio Marsh acquired on 27 January 1991. Lighter tones correspond to a greater water content

The best results (correlation coefficients $>0{\cdot}9$) have been obtained for three soil classes characterized by low vegetation cover during the year. The worst result (correlation coefficient $<0{\cdot}5$) have been obtained for a soil partially covered by wood vegetation. This suggests that the decorrelation procedure is not able to separate completely the vegetation and soil contributions. In general, the decorrelated index performs well over a homogeneous surface when it is possible to obtain at least one image in which the soil is bare.

Once a correlation between the soil water content and the values of the index has been established, it may be used to obtain a fast estimation of the amount of soil moisture from other TM images of the study area. Such a 'training procedure' requires a detailed pedological knowledge of the study area. It should also use numerous images acquired during a year, under different soil moisture and vegetation cover conditions. In this way, both index and model values will have the greatest variability range, thus leading to a more accurate correlation of values. It must also be underlined that the training procedure must be repeated on each river basin, because the coefficients of the linear regressions vary according to the specific soil and vegetation characteristics.

FLOOD MONITORING

Landsat TM data may also be used to inventory flooded terrain. However, the frequent presence of clouds over the damaged areas after an event limits their usefulness. Clouds interfere with the visible and infrared radiation, and thus prevent this type of sensor from obtaining an image of the earth's surface. Therefore, when maps of flooded areas are needed shortly after the event, imaging radar systems are used.

In the present work, two images acquired by the SAR (synthetic aperture radar) mounted on board the satellites ERS-1 and -2 were used. ERS's SAR generates signals in the microwave range of the electromagnetic spectrum, transmits them towards the surface and receives the returned signal after its interaction with the target. The signal belongs to the C band of the microwave spectrum, at an average wavelength of 5·3 cm, and the sensor operates in VV polarization. As clouds are composed of droplets with a typical diameter much smaller than the microwave wavelength, the SAR signal is scarcely affected by the presence of clouds. For this reason, images acquired by the sensor are very useful when bad weather conditions affect the area to be sensed, as during or immediately after a flooding event. Also, flooded areas are easily recognizable in SAR images. In fact, the strength of the returned signals from the surface is influenced by a number of ground parameters, including the average surface roughness of the sample area. Horizontal smooth surfaces, such as inland water bodies, reflect nearly all incident waves away from the radar. The weak return signal is represented with a dark tonality on radar imagery, and it is easily distinguishable from the higher response of vegetation and land. Some difficulties may be found only when the flooded terrain is covered by a dense wood of tall trees, or when strong winds ripple the water surface.

For the above reasons, the use of ERS SAR has immediately been recognized by the scientific community as a powerful tool to monitor flooded areas (for example, see Wang *et al.*, 1995; Oberstadler *et al.*, 1996). However, except for experimental work performed after the Alessandria Flood in 1994 (Bonansea, 1995), in Italy, flood mapping is still performed with traditional methods. The purpose of this part of the research was to demonstrate the utility and convenience of the use of SAR data in flood mapping, even when a local event occurs. This section describes a feasibility study on the use of satellite data for flood survey and relief at the local scale, emphasizing the user's requirements, the results obtained in the SAR data processing and the cost/benefit analysis of this kind of service.

The Environmental Office of Pistoia Province helped in the compilation of a requirements list that a SAR-derived map has to fulfil, and in estimating the costs of traditional ground surveys, to be compared with the costs of satellite-based mapping. The time of study was during a period of heavy rainfall and consequent flooding in October/November 1992. Two SAR images were obtained for this period, one before the flooding occurred (16 October 1992), the other four days after the flood (4 November 1992) (Figure 2). A flood extent map (Figure 3) was obtained from the two images using a supervised classification procedure (Lillesand and Kiefer, 1994).

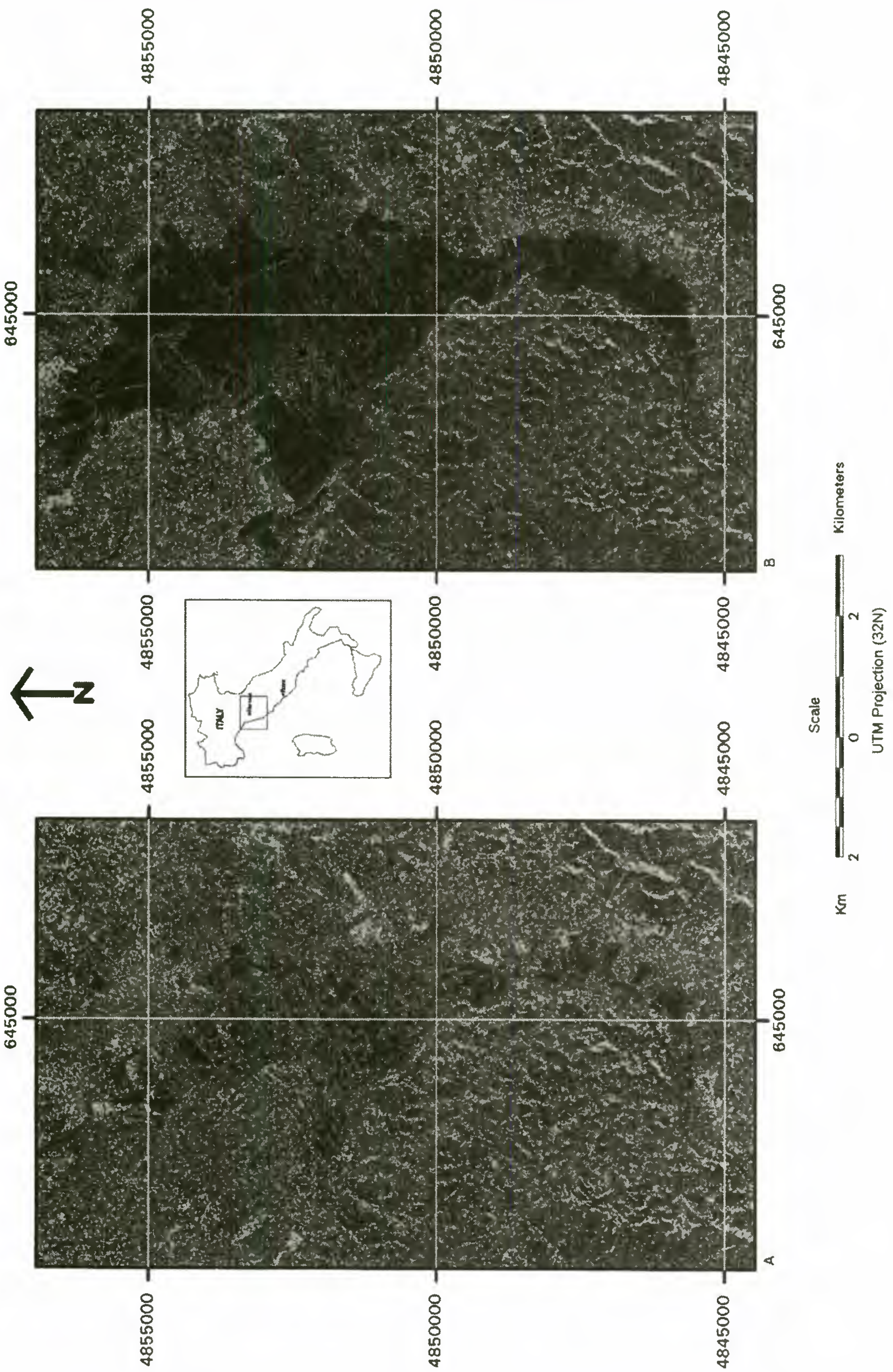

Figure 2. ERS SAR images of the Fucecchio Marsh acquired on (a) 16 October 1992 and (b) 4 November 1992, respectively before and after the flood event of 30–31 October 1992

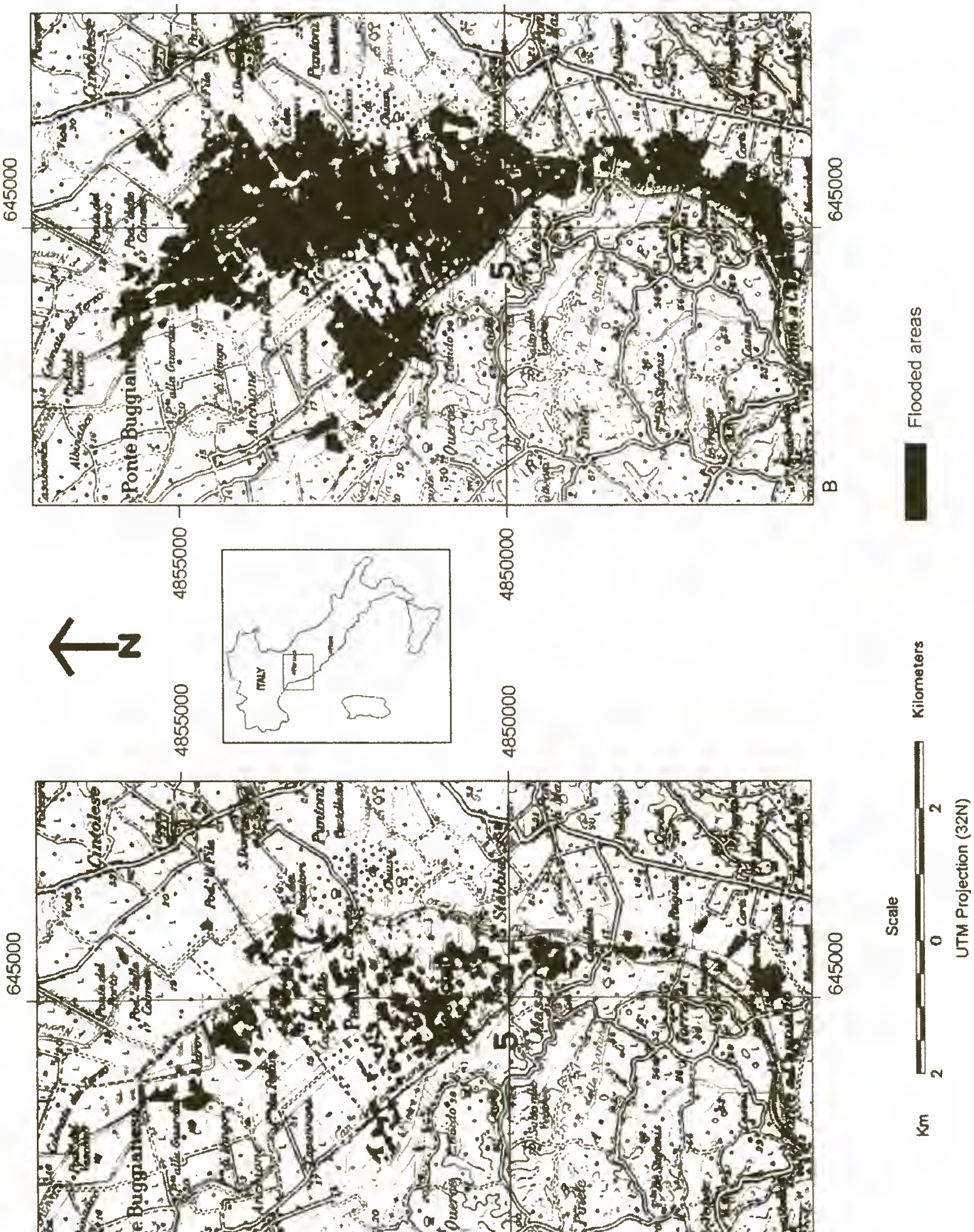

Figure 3. Map of flooded areas obtained from the ERS SAR images of (a) 16 October 1992 and (b) 4 November 1992

The map of flooded areas obtained by processing ERS SAR data has been analysed on the basis of the user's specifics on map scale and error on boundary positioning. Regarding the former, if a graphic tolerance of 0·5 mm is assumed, the resulting restitution scale of SAR images and derived products is 1 : 25 000. This scale has been declared acceptable by the users. At the 1 : 25 000 scale, the maximum error on the boundary position specified by the users is 2 mm on the map, equivalent to 50 metres, or 4 pixels. The average error on the map was 32 m (2·56 pixels) with a maximum error of 43 m (3·44 pixels). This prerequisite has therefore been fulfilled.

Finally, the costs of satellite and ground survey aimed at the delimitation of the flooded areas were compared. For this purpose only the delimitation of the flooded areas has been taken into account. In fact, the production of maps from ERS SAR images does not eliminate the necessity of ground surveys, in which data on flood dynamic and structural damages is sought. Such investigations must be carried out anyway, and therefore their costs must be calculated separately. The analysis of costs has been used on the time employed in performing the survey and producing the flood extent maps.

Flood extent mapping through ERS SAR data: one day/person for georeferenced data, two for non-georeferenced data (including georeferencing), for one or more SAR images.

Flood extent mapping by ground survey: ground surveys of this kind cover an average of 3–4 km^2/day, employing two operators. Restitution (on paper support) is then performed at an average of 20 km^2/day at the 1 : 25 000 scale.

To compare the two cases, it has first been assumed that a SAR image contains the whole affected area. Then the kind of SAR product is selected. Working at the local scale it is often faster and more convenient to buy non-georeferenced data and correct them using the standard ground control points method (Lillesand and Kiefer, 1994) than buying corrected data. Thus, the present cost of a SAR non-georeferenced (PRI) image has been converted in the equivalent number of days/person, and added to the number of days/person necessary to process a single image. Calculating the number of km^2 covered by traditional ground surveys in a corresponding number of days/person, gives the result that, at present, the use of SAR data is less expensive than a ground survey when the extension of the flooded area is greater than 20 km^2. It must be noticed that a SAR image covers about 100 km × 100 km, and allows simultaneous mapping of concurring flash flood events, which, if examined singularly, are too small to be mapped conventionally. For example, in the event studied the Fucecchio Marsh was flooded over an area of 16 km^2. Two neighbouring zones were flooded in the same event, reaching a total flooded surface of 53 km^2.

It should also be noted that in the event studied the post-flood SAR image was acquired on the study area when the flooded terrain was still covered by water. If the SAR image is acquired when part of the flooded surfaces are not still covered by water, it is necessary to identify them using a different, more complex processing procedure. Higher knowledge of the characteristics of the study area is therefore required, and the accuracy of the results may not be anticipated. At present, this problem is avoided by the high acquisition frequency (an average of three images/month) of SAR data by ESR-1 and ESR-2. However, the main concern of the potential users of this service related to the availability of images in the future, when only ESR-2 will be operational.

DAMAGE ASSESSMENT

This stage is perhaps one of the most important aspects of flood monitoring. The need to know the amount and type of damage sustained, and what is needed to relieve the immediate consequences, is uppermost. Swift evaluation of the situation would therefore allow more time to be allocated to relief of the flood instead of assessment. ERS SAR imagery can provide such information as found by this research.

The flood extent map can be used in combination with the pedological map (Figure 4a), the land use map (Figure 4b) and other thematic data, such as the digital terrain model or the channel network vector layer, to provide more detailed information on the flood statistics. These data are necessary both to estimate the

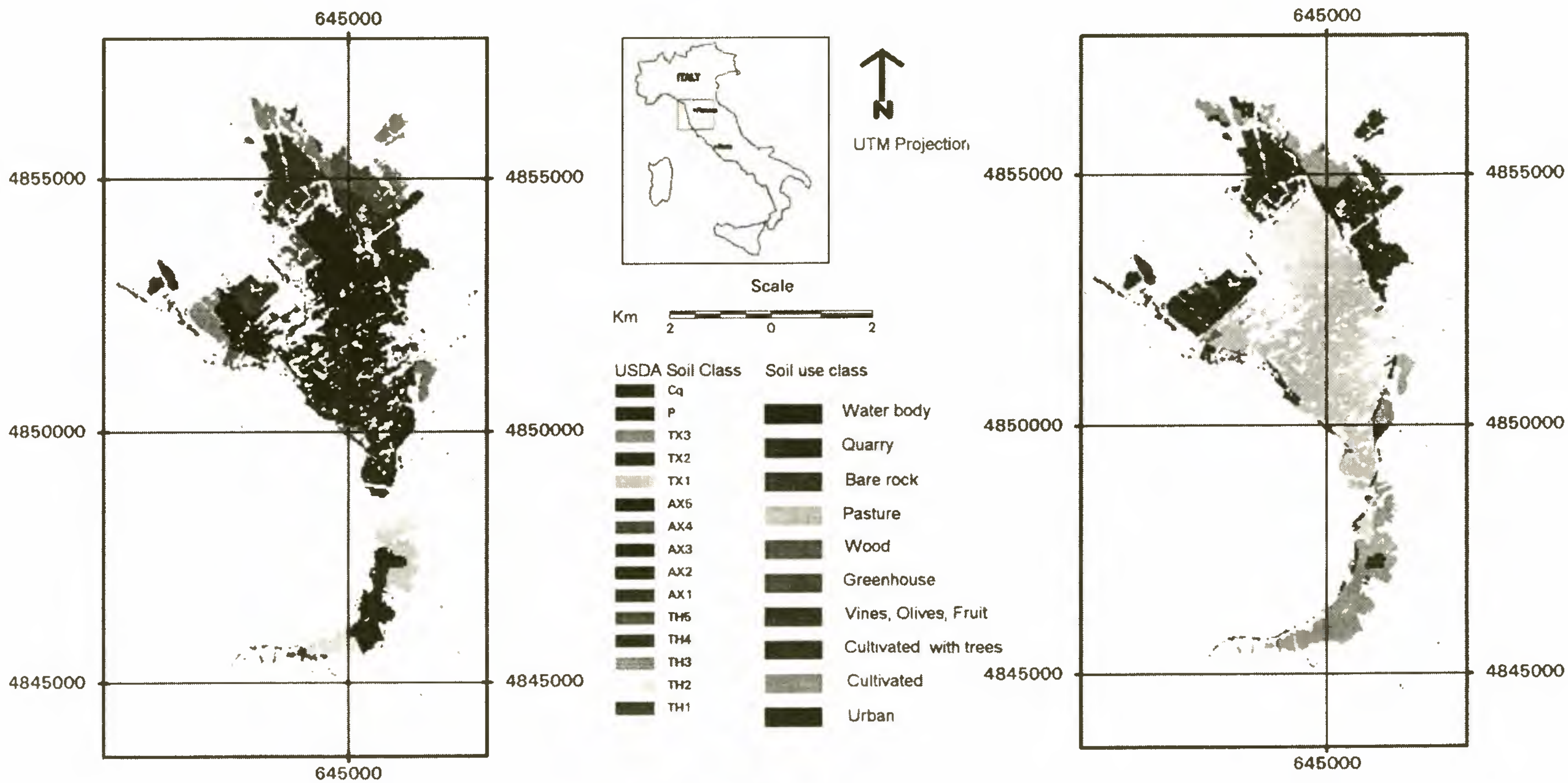

Figure 4. Combination of SAR-derived maps of flooded areas (event of 30–31 October 1992) with thematic data. (a) Pedology (USDA classification). (b) land use

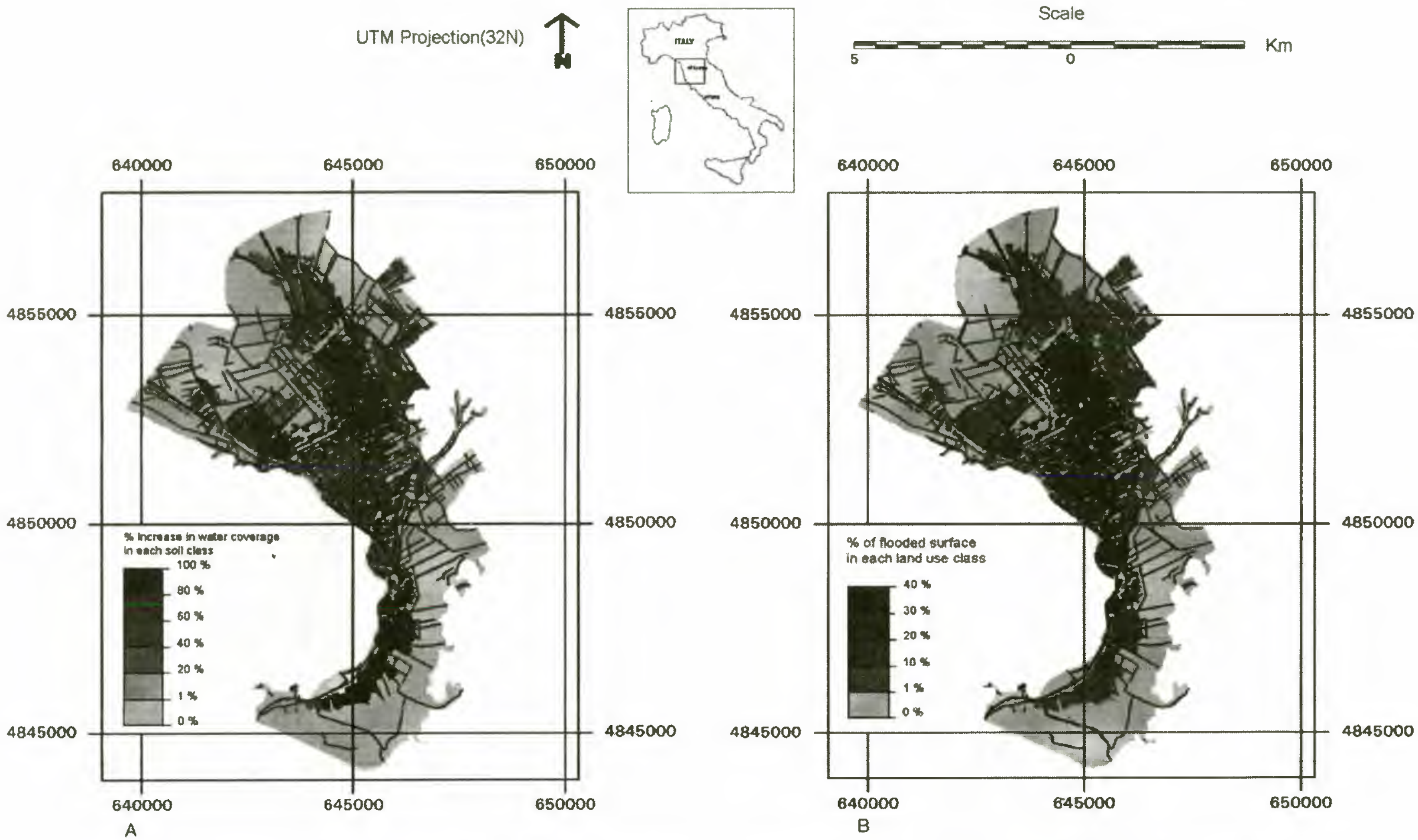

Figure 5. Maps used for (a) flood risk and (b) damage assessment in the Fucecchio Marsh event of 30–31 October 1992. See text for explanation

damages and to analyse the event. The use of the data mentioned before allows one to estimate average flood height and volume for each individual soil type and land use class, which in turn allows one to estimate crop or structure damage. The analysis of an event requires data on flood path and life, which can be evaluated if there is a sequence of images covering the flood event. In this section, an example of information that can be provided to the competent authorities is given in the form of raster maps that are used to evaluate flood risk and assess flood damage.

The flood extent map was first combined with a digitized pedological map of the area. The proportion of flooded area of each individual soil type to total study area, total flooded area, and total area of respective soil type, was then obtained. From this, areas of high flood risk were determined. The area shown to be most at risk produced an 85% increase in water coverage and the area least at risk only a 1% increase. It was shown that the high risk areas were those occurring towards the outlet of the Padule, as would be expected. The final flood risk map (Figure 5a) contains, in order, the areas of soils that show a greater increase in water coverage at the time of the flood, and not the soils that have a greater percentage of their area under water, since it is more important to know which areas would be the most affected. A vector layer of the channel network has been overlain on to this map to demonstrate that the areas most at risk are also near a denser assembly of channels.

The same processes were carried out with a digitized land use map, obtaining the raster map of the flooded surface's percentage in each land use class (Figure 5b). This map was then cross-correlated to the Province's archives of agricultural and urban inventories to assess the damage to crops and structures involved in the flood. The analysis of damage is easily performed using a geographical information system containing the necessary environmental data (soil use maps, pedological maps, agricultural and urban inventories, etc.). In this context, the costs of map production using traditional methods and ESR SAR data are as follows.

Risk and damage assessment using ERS SAR data: risk/damage assessment maps such as the ones described above may be produced in 1 day/person.

Risk and damage assessment by ground survey: the time of digitizing the flood extent maps (20 km^2/day at the 1 : 25 000 scale) must be added to the survey and restitution time mentioned in the previous paragraph.

The use of SAR-derived products is therefore more convenient than the traditional methods, and the convenience increases with increasing areas. It must also be pointed out that the fast processing time of SAR-derived products allows one to obtain damage evaluation maps immediately after the emergency, increasing their usefulness.

CONCLUSIONS

Remote sensing data is a powerful tool for the provision of information for flood control purposes. Their application to flood prevention relates mainly to the estimation of hydrological parameters and variables to build distributed hydrological models. The first part of this paper described an example of the use of Landsat TM data to estimate soil water content. The study was carried out in cooperation with EOSAT (USA). The results show the potentiality of using TM data, provided that pedological data is available in the calibration stage.

Remote sensing also provides useful data for flood monitoring. The second part of this paper described the cost/benefit analysis of using ERS SAR data to map flooding events and evaluate damage at the local scale, carried out in cooperation with Eurimage (Italy).

The results described in this paper demonstrate that optical and microwave satellite data are extremely valuable, both for theoretical research on flood prevention and for practical applications to flood analysis.

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THE CONTRIBUTION OF SPACEBORNE SAR AND OPTICAL DATA IN MONITORING FLOOD EVENTS: EXAMPLES IN NORTHERN AND SOUTHERN FRANCE

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ABSTRACT

This paper demonstrates the utility of satellite remote sensing data in water management, and particularly, for flood monitoring and impact analysis. Satellite-derived data can provide timely geographical data from which water body extent in normal and flood regimes can be ascertained. Combined with exogenous and historical data, within a GIS, these can provide information useful for flood prevention decision making. The recent French Alsation, Camargue and Vaison la Romaine floods are taken to illustrate the utility of satellite remote sensing. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS remote sensing; GIS; flood monitoring; impact analysis; soil moisture

INTRODUCTION

Flood event studies necessitate multidisciplinary approaches to enable the understanding of the phenomena, their monitoring and the forecasting of such events in order to aid in land planning decision making. Within an observational or management system of natural hazards, geographically related information is of primordial importance, allowing the localization, measurement and spatial representation of the studied phenomena. Among all the tools that are available to build up geographical data, satellite imagery is a valuable source of information. This paper presents application examples of the use of satellite imagery in the detection, monitoring and analysis of exceptional hydrological events like flood events.

These application examples were performed at the Service Régional de Traitement d'Image et de Télédétection (SERTIT) which is an organization under public body law piloted jointly by the Centre National d'Etudes Spatiales (CNES), the Direction Régionale de la Recherche et de la Technologie, the Conseil Régional d'Alsace and the Université Louis Pasteur of Strasbourg. As a director of projects, SERTIT performs studies in the following domains: regional scale land cover/land use and agro-environmental mapping, monitoring of ecologically important zones, urban planning through remote sensing, infrastructural impact studies and flood impact assessment.

Particularly involved in the evaluation of research in the field of water management, various water management related programmes using multiscalar approaches were realized at SERTIT. In this paper, three of these will be used to illustrate the use and the contribution of remote sensing data within a geographical information system (GIS) in detecting, monitoring, preventing and making provision for flood events. The case studies used are related to different flood events that have occurred during the last five years in north-eastern and southern France.

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The Camargue flood event of October–November 1993, for which a remote sensing approach using both radar and optical data was adopted which illustrates their potentialities and synergy in flood impact assessment (Fraipont *et al.*, 1994).

The Alsace and the Ill River flood of February 1990, for which a remote sensing approach using optical data was adopted, leading to an agro-environmental impact study analysis (Tholey and Fraipont, 1991; Clandillon *et al.*, 1993).

The Vaison la Romaine region and the Ouveze River flood of September 1992, for which a cartographic approach using remote sensing-derived information was adopted, leading to the modelling and study of hydrological parameters (Flageollet *et al.*, 1993, 1994).

FLOOD EVENTS AS SEEN THROUGH REMOTE SENSING

Remote sensing earth observation techniques provide frequent and pertinent information at different scales about our environment; in the analysis of flood impacts this above-mentioned frequency is often useful, allowing access to data relating to normal and flood hydrological regimes. High resolution optical and radar systems provide information at a regional scale; they deliver high spatial resolution digital images that can be processed to extract geographically located information represented on maps and/or integrated into a GIS for further flood-related analysis. Whereas optical systems like Landsat TM or SPOT are passive systems and can only operate effectively during daytime and in good weather conditions (i.e. no clouds), SAR systems like ERS are active ones and can deliver all-weather, day and night coverage. Landsat TM multispectral data has a square pixel of 30 m, SPOT in multispectral XS mode has a 20 m square pixel resolution and 10 m in panchromatic P mode; ERS has a spatial resolution <30 m with a 12.5 m square pixel size. Owing to bad weather conditions, SAR is often the only available tool in the observation of flooded regions at a good temporal frequency, i.e. nearly daily. In addition, SAR has a particular sensibility to soil moisture content which allows for mapping of water bodies by computer-aided photo-interpretation or by automatic digital image processing techniques.

WHAT FLOOD-RELATED INFORMATION CAN BE PRODUCED?

With high resolution remote sensing data, different kinds of flood-related information can be produced; on the one hand while exclusively using ERS SAR data (or optical data if available), or on the other hand, within a GIS by merging remote sensing-derived flood-related information with other spatial information.

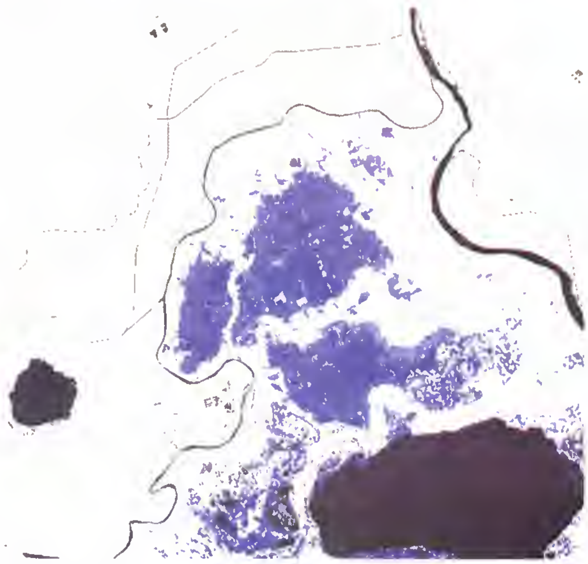
Using unique remote sensing data

One image of the flood zone can lead to the mapping of all water bodies present at the time of data acquisition, including both permanent water bodies and flooded areas. Therefore, to separate these, historical optical or SAR data or existing maps are required to provide land cover information under normal hydrological conditions in order to ascertain the hydrological network. Thus, historical images of flood and non-flood periods, giving a multitemporal image, permit the distinction between permanent water bodies and flooded areas, which leads to flood extent mapping. In the same way, several flood period images facilitate the monitoring of the flood's evolution, both its rise and dissipation. For example, in the Camargue flood event application, presented in Figure 1, an ERS-1 image taken on 1 November 1993 during the flood was processed to extract all water-covered areas at this date and was then compared with a co-registered SPOT XS image of March 1993 showing permanent water areas, this led to mapping of the flood extent. At its maximum this flood, which lasted more than two weeks, covered 12 000 ha, or approximately one-sixth of the Camargue Region.

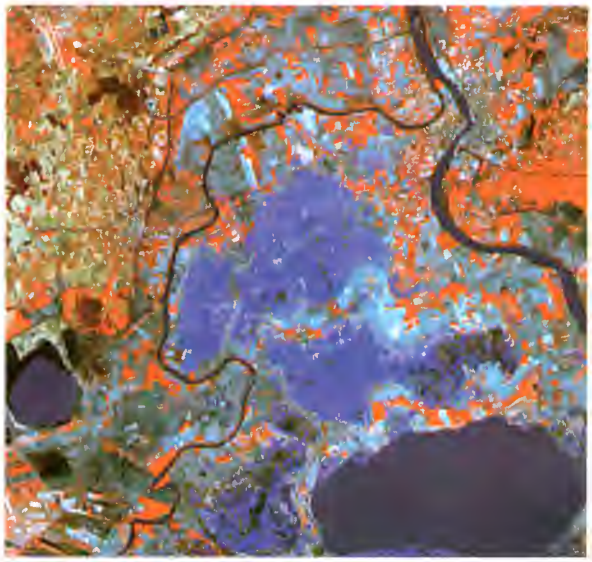
Figure 1. The Camargue Flood Event of October–November 1993

ERS-1 image 1 November 1993

SPOT XS image March 1993



Permanent water flooded areas

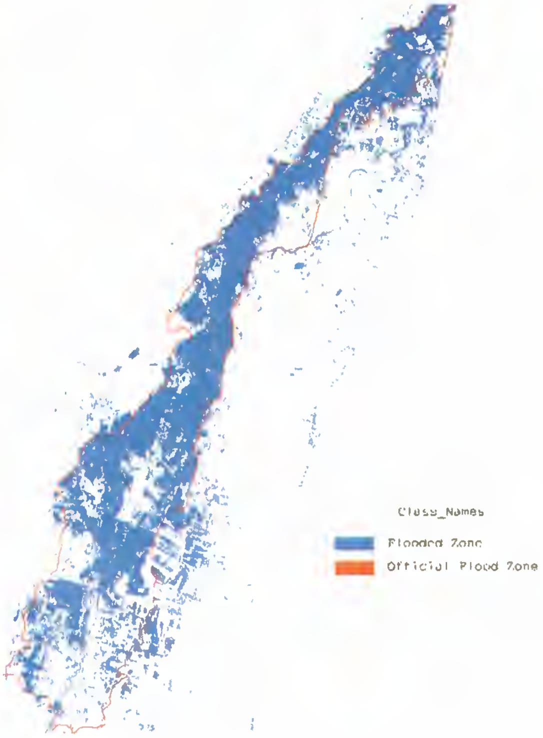


Flood-affected land cover

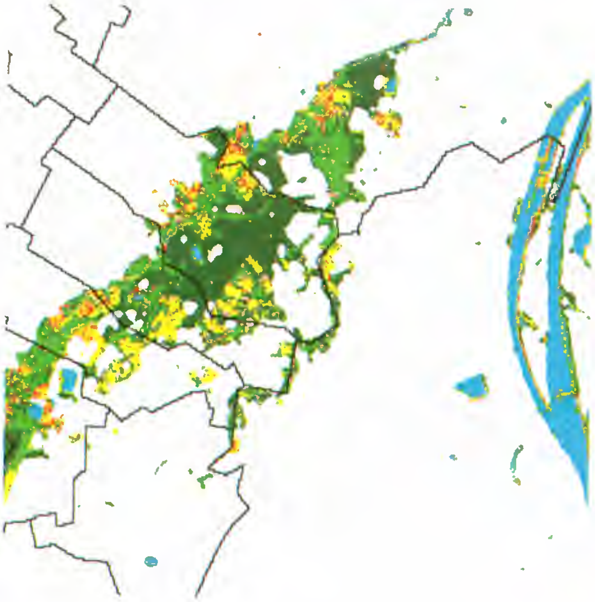
Derived from ERS and SPOT images

Figure 2. The Alsation Flood Event of February 1990

SPOT XS image of February 1990



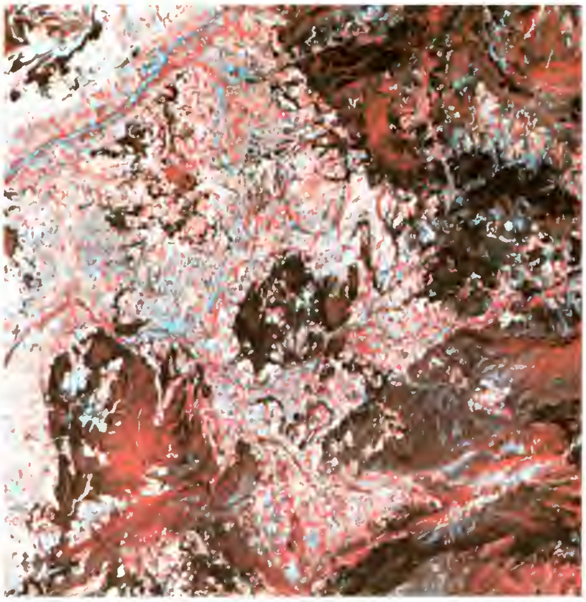
Comparison between the administrative flood zone and the 1990 flood extent



Flood affected land cover and communal limits

Legend

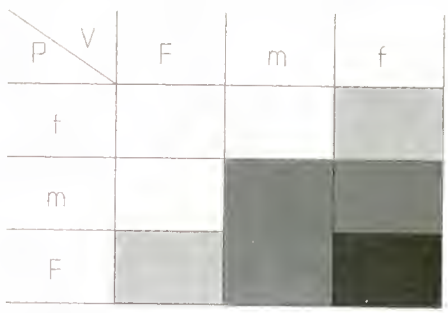
Figure 3. The Vaison la Romaine flood event of September 1992



SPOT XS image of July 1992

Illumination model derived from the digital elevation model

3-D perspective view of the potential runoff index, south-east direction



Legend

V: vegetation density, P: slope, F: high, m: medium, f: low

Remote sensing flood-derived information within a GIS

Complementary qualitative and quantitative flood-related impact studies can be carried out with ERS–SAR (or optical) flood extent-derived information after the integration of these data into a GIS with other thematic spatial information.

With cartographic data such as administrative boundaries like communal limits, the flood affected (or non-affected) communes can be listed with an estimation for each of them of their flood zone area; the perceived flood extent can be compared with the administrative flood zone boundaries for its control and updating if needed. With up to date thematic information layers, which could have been derived from remote sensing images or from any other source of geographical information, the land cover of flooded and non-flooded areas can be extracted and analysed class by class. Figure 2 shows examples of the work that has been done on the one in 100-year, Alsation Ill River flood of February 1990. Flood-related information has been produced by combing the flood map extent derived from an available SPOT XS image, cloud-free over the river, with SERTIT's Alsation thematic database for agro-environmental applications (related to CAP implementation). In the officially declared flood zone, a sensitive protected biotope, 7600 of the 13 000 hectares were detected as being affected by either direct fluvial flooding or the rise of the water table to or above ground level.

FLOOD ZONE MANAGEMENT WITHIN A GIS

GIS functionalities and their database management systems allow us to store, retrieve, manipulate and combine multiscale, multitemporal and multithematic data layers that have been recorded over a certain region. These different coverages can be exploited to prevent flood events and to forecast such events; first, by observing and taking lessons from the past, and, secondly, by trying to understand such phenomena in order to model them and hence simulate such potential hydrological events.

Thus, multi-year historical data on flood events and their respective maximum flood extent mapping can point out the recorded historical flood-prone areas of a certain region, i.e. the areas that have already been affected by flooding during the past and/or the areas that are frequently flooded, which gives a flood risk evaluation assessment of the region of interest based on the historical frequency of flooding.

In another context, within a real time forecasting perspective and in the building of prediction models for river flooding, remote sensing-derived information can be useful in the definition of a region's morphological and biophysical characteristics. Morphological parameters, like altitude, slopes, orientation, basins and sub-basins, can be extracted from digital elevation models (DEMs) constructed with optic or radar remote sensing data, whereas biophysical parameters describing the land cover of a region, like hydrography, vegetation cover or urban areas, are more likely to be derived from optical imagery. Then, via GIS modelling and the utilization of these multithematic information layers available within the system, information pertinent to hydrological models can be estimated and the identification of risk areas and their flood hazard designation can be performed. For example, the runoff characteristics of different surfaces can be described depending on the slopes and the vegetation cover of the region of interest; land slide risks can be evaluated depending on slopes, land cover, soil types and rainfall. Figure 3 illustrates different thematic information layers that have been derived from remote sensing data and, in particular, the potential runoff index per basin and sub-basin that has been estimated for the Vaison la Romaine Region and the Ouveze Basin. These parameters, associated with runoff paths and pluviometric data, are presently being exploited in hydrological and hydraulic models in order to understand the causes of this catastrophic flash flood event that occurred on 22 September 1992 (Risser, 1995) destroying everything in its path. More than 200 mm of precipitation fell over the Ouveze watershed basin within a few hours. Land use and river management practices along the river amplified the problem leading to an exceptionally large river flow.

REMOTE SENSING AND SOIL MOISTURE OBSERVATION

As demonstrated before, remote sensing techniques can offer valuable and accurate information for observing and managing flooded or flood-prone regions. In a flood detection alert system contact, soil moisture surveys can also be useful to decision makers and can be made with the help of earth observations techniques. The future satellite SPOT 4, for example, which will have a middle infrared band (MIR) will present a certain capacity in detecting wetlands and constitute a qualitative soil moisture detection tool (Clandillon *et al.*, 1995), whereas, in a quantitative approach, ERS systems offer a valuable and complementary information source to the mid-infrared optical data in measuring, at a regional scale, soil moisture evaluation as proven by theoretical (Evans, 1995; Fellah, 1995) and experimental studies, conducted over the Alsace Region, showing a strong correlation between radar's back-scattering coefficient and soil moisture content linked to rainfall events (Fellah *et al.*, 1994).

CONCLUSION

Remote sensing optical and radar data can provide a wide range of flood-related information that can be exploited at different levels in water crisis management. At a flood prevention level, flood hazard or flood-prone areas can be determined with a flood risk coefficient estimation; at a flood prediction level, some hydrological model parameters can be evaluated and soil moisture evaluation can be followed; at a flood monitoring and management level, a flood can be detected and its evolution followed; and, finally, at a flood impact assessment level, damage analysis can be undertaken with the use of already existing maps of the studied area.

All this hydrological information is needed and can be generated at different time frequencies and at different spatial scales, depending on the final end-user application fields. As reported to the Committee on Earth Sciences (Evans, 1995), the routine measurement and estimation of these hydrological parameters, including flood-related parameters and soil moisture-related parameters, could be useful in four general areas ranging from global-scale earth observation application fields to local or regional scales (Table I).

Table I. Spatial and temporal information scales of interest for hydrological applications

Hydrological applications	Spatial scale of interest	Temporal scale of interest
Climate model	10–100 km	1–4 weeks
Weather forecasting	30 km	1 day
Water management	100 m–1 km	3–7 days
Agricultural	100 m–1 km	3–7 days

Of all the agencies implicated in water crisis management, this water related information should particularly interest end-users like state services and local/regional planning authorities or services, in charge of planning, environment, natural resources or agriculture; civil protection authorities; and, obviously, insurance companies and the building industries.

These agencies require information in order to observe and monitor flood events. This information can aid damage estimation and compensation. Satellite remote sensing or conventional survey methods can fulfil these requirements. Conventional techniques, which include ground and aerial surveys, imply many man hours and are therefore more expensive and time consuming, often making the process unviable. Access to the areas may be difficult, especially during flood events as a result of weather conditions. These traditional methods become difficult to manage at large scales and may encounter problems owing to flight restrictions and national boundaries. Data acquisition, digitization and management can be cumbersome and expensive as these methods generate vast amounts of data. As a comparison, a SPOT scene covers the same area as 100 standard 1:30 000 aerial photos.

The advantages of remote sensing include the provision of a global view, no matter what the region or weather (radar), which is easily updated on further scene capture. The data is digital and immediately exploitable, integrating into infrastructural, land use and administrative geographical information systems. It has the potential of observing events, obtaining objective information and producing good cartography, generally to a 1:25000 scale. If the observation scale needs to be increased over certain areas of interest conventional survey methods would prove complementary.

Finally, oceanic climate flood events, which are often repeated and of variable amplitude, are more likely to be observed through remote sensing techniques and can be followed daily in terms of detecting their extent and monitoring their evolution. Flash floods, on the other hand, being abrupt exceptional events, are more difficult to observe in real time by satellite remote sensing but their flood damage remains observable. These real time, post-event or historical observations can be used to aid hydrological models in their development, calibration, updating and evaluation, thereby helping in the understanding and prevention of these phenomena through their simulation.

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ASSESSMENT OF THE MAPPING CAPABILITIES OF ERS-1 SAR DATA FOR FLOOD MAPPING: A CASE STUDY IN GERMANY

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ABSTRACT

GAF examined, under contract to DARA (German Space Agency), the applicability of ERS-1 SAR data for flood mapping under operational conditions. The flood event investigated was the flooding in the Rhine valley in winter 1993–1994.

In order to carry out an examination close to the end-user needs, the specific user requests concerning information about flood events were identified. The mapping accuracy in view of the flood extent and the flood level, the production of flood maps as well as the demonstration of the runoff turned out to be the most interesting points. The specific user information needs were considered in the project objectives to define the applicability as well as the deficits of ERS-1 data concerning an operational use for flood mapping. After a detailed analysis of the time aspects of the traditional mapping method and a satellite data analysis, a visual interpretation as well as an automatic classification were applied, including various filter steps to derive the flood boundary. As a result, the visual interpretation proved to be the more accurate method. Crucial domains for both the visual interpretation and the automatic classification turned out to be settlements, forests and bushes as well as regions with layover and foreshortening effects. The comparison between the flood level derived from satellite data and the flood level registered by the water authority boards brought a height difference which ranged between 0·5 and 2·0 m. The relatively coarse resolution and problems with correct interpretation of the flood line proved to be the reason for this difference. In general the results are convenient, but in relation to field measurements of the water level they are too inaccurate. A cost and benefit analysis as well as a proposal for an operational GIS system using ERS-1 SAR data are still under investigation. © 1997 John Wiley & Sons, Ltd.

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KEY WORDS ERS-1 SAR; flood mapping; visual image analysis; automatic classification; water level measurement

INTRODUCTION

In recent years severe flood events have afflicted the Rhine valley causing a lot of damage to houses and infrastructure. To prevent further floods, exact measurements of the water amount and the flood extent are necessary in order to be able to calculate the dimensions of dikes and embankment constructions, to identify retention areas and to delineate flood endangered areas.

In Germany, the supervision of the main waterways is in the domain of the water authority boards, which are responsible for flood mapping. Consequently, the registration, mapping and control of flood events are their responsibility. The actual methods used to acquire flood data are to send out field workers who strike plugs every 500 m at the highest water level. Afterwards the plugs are measured, and hence the geographical reference is achieved by striking the plugs in the profile. However, an exact local reference of each plug is not provided. This method is very precise and produces data sets with height precisions ranging from 5 to 20 cm. Decimetre accuracies are essential for further hydrological calculations. Despite the high accuracy of the ranging, the water authority boards are thinking about new possibilities to derive the flood level. This is because the method is time-consuming and staff-intensive, and so expensive, and because data processing takes a relatively long time. Another problem is that pedestrians often vandalize the plugs so that gaps in the

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database appear. Finally, the highest water level is only marked in the main river course; areas where the water has flown behind the dike are neglected.

ERS-1 SAR data cannot provide data sets with decimetre accuracy. Nevertheless, they are appropriate for overcoming some of the difficulties the navigation staff have to cope with: they can be obtained relatively quickly, enabling an immediate view of the actual flood situation. The geographical reference is available and the data are easy to combine with digital information such as digital maps. Moreover, the great advantage of ERS-1 SAR is the ability to acquire data without restrictions from weather conditions.

The objective of this study, therefore, was to examine the mapping accuracy of ERS-1 SAR data in comparison with the results of the water authority boards. The satellite data were investigated in view of an operational use for flood mapping, taking into account the restrictions of data acquisition, satellite parameters, time aspects of data processing and analysis, as well as the financial components.

DATABASE AND SITES

SAR systems are sideways-looking systems which operate in the microwave portion of the electromagnetic spectrum. The spectrum is separated into different bands, each defining a special wavelength. The ERS-1 SAR is a C-band SAR system, which means that it transmits and records wavelengths of about 5·2–7·14 cm (Ulaby *et al.*, 1981).

The SAR antenna directs microwave energy to the terrain in a fan-shaped beam and records the radar returns scattered back from targets on the earth. Because of the sideways-looking operation mode, the geometry of the terrain features is distorted. Terrain slopes towards the radar will be foreshortened and slopes away from the radar will be elongated. Areas with foreshortening effects show high back-scatter values, and regions with radar shadow show very dark values, covering any information from the actual land use.

There are different SAR products available which are distinct from each other in their resolution and the degree of geometric correction. The most common are fast delivery products (resolution 100 m × 100 m, not terrain corrected), SAR precision images (resolution 30 m × 30 m, not terrain corrected) and SAR ground terrain corrected (GTC) (resolution 30 m × 30 m, terrain corrected) images. For this project SAR–GTC products were chosen because geometric distortions were corrected and therefore combination with auxiliary data sets (e.g. topographic maps, land use data, etc.) is possible. The specific parameters of the SAR–GTC products are shown in Table I.

The inundation of the Rhine Valley in December/January 1993–1994 was recorded on three multi-temporal ERS-1 SAR images. Fortunately, just at the end of December the three-day orbit of the ERS-1 mission started, therefore the following images could be collected: 25 December 1993, 31 December 1993 and

Table I. Specification of ERS-1 SAR–GTC products (ESA, 1993)

Product	ERS-1 SAR–GTC
Scene area	100 km × 100 km
Scene size	9000–12 000 pixels per line 9000–12 000 lines
Pixel size	12·5 m × 12·5 m
Resolution	about 30 m × 30 m
Product location accuracy	better than 50 m
Projection	UTM
Ellipsoid	WGS 1984
Number of looks	3

Product specification: system-corrected, precisely located and rectified on to a map projection, corrected for terrain distortions by use of a digital elevation model

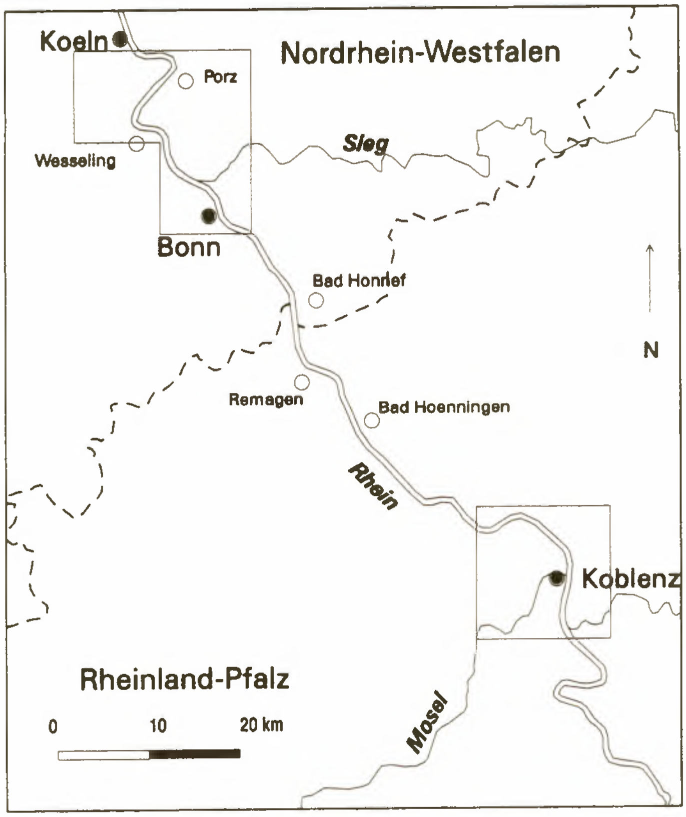

Figure 1. Location of the Koblenz, Porz and Bonn, test sites

3 January 1994. The acquisition time was 10:25 am. As reference for a normal water level one scene from 10 June 1992 was used.

Each scene maps an area of about 100 km × 100 km between Duisburg (Nordrhein-Westfalen) and Koblenz (Rheinland-Pfalz). Three river sections were chosen as project test sites, each of them covering an area representing the size of one map sheet, 1 : 25 000. In accordance with the water authority boards, the test sites had to meet special requirements: they include river shores that are not protected by dikes or have steep river banks. They also cover regions where the water had flown behind the dike. The river sections between Porz and Bonn, as well as around Koblenz, seemed to be suitable for the investigation. The location of the test sites is shown in Figure 1.

As additional data sets the corresponding map sheets, digital and analogue, as well as aerial photography data, which unfortunately only exist for parts of the Koblenz test site, proved to be helpful for data interpretation. The flood level measured, the river profiles and the foreland profiles and registrations of the water level per hour for the Koblenz, Bonn and Cologne gauges were made available by the water authority boards.

Time aspect of ERS-1 SAR data acquisition

Because floods are a wave phenomenon, different flood levels are present on a satellite image. Therefore, the date and time of data collection is of great importance for an investigation based on satellite data. Examining the exact time shift between the highest flood level and the acquisition date of the ERS-1 data, it is obvious that the acquisition of the satellite data has some delay in regard to the flood peak. With regard to Koblenz, the delay is about two days after the peak passed. For Bonn it is 1·5 days and for Cologne only

Table II. Acquisition dates of the water level measurements and the resulting water height

Water gauge	Acquisition date of the traditional measurement		Acquisition date of ERS-1 SAR		Water height (cm) measured by the water authority boards	Water height (cm) at the time of the ERS-1 pass	Height difference (cm) between the acquisition dates
	Date	Time	Date	Time			
Koblenz	23.12.93	9:30	25.12.93	10:25	949	840	109
Bonn	23.12.93	18–22:00	25.12.93	10:25	1013	950	63
Cologne	24.12.93	0–6:00	25.12.93	10:25	1063	1017	46

3 hours because the wave was steady for some hours. The acquisition dates and the resulting decrease of the flood level are presented in Table II. Figure 2 indicates the wave propagation during the time of data collection and demonstrates at what situation the ERS-1 scenes map the flooding. The second flood peak in January is of interest, however, it is not evident in the extent of inundated surfaces on the related SAR imagery. Corresponding to the chronological order of the images, there is a steady decrease in the flood extent.

In general, the time aspect for data collection and production of ERS-1 SAR data is an important factor. Normally, ERS-1 requests should be made at least four weeks before the date of acquisition. Then, data processing takes another two weeks, so approximately six weeks have to be assumed for data collection and processing. In urgent cases, ESA (European Space Agency) and the affiliated PAFs are eager to register ERS-1 data and therefore collect data in a shorter amount of time. If the satellite station is alert, low resolution products (Quicklooks) are available four hours after the acquisition. These images were

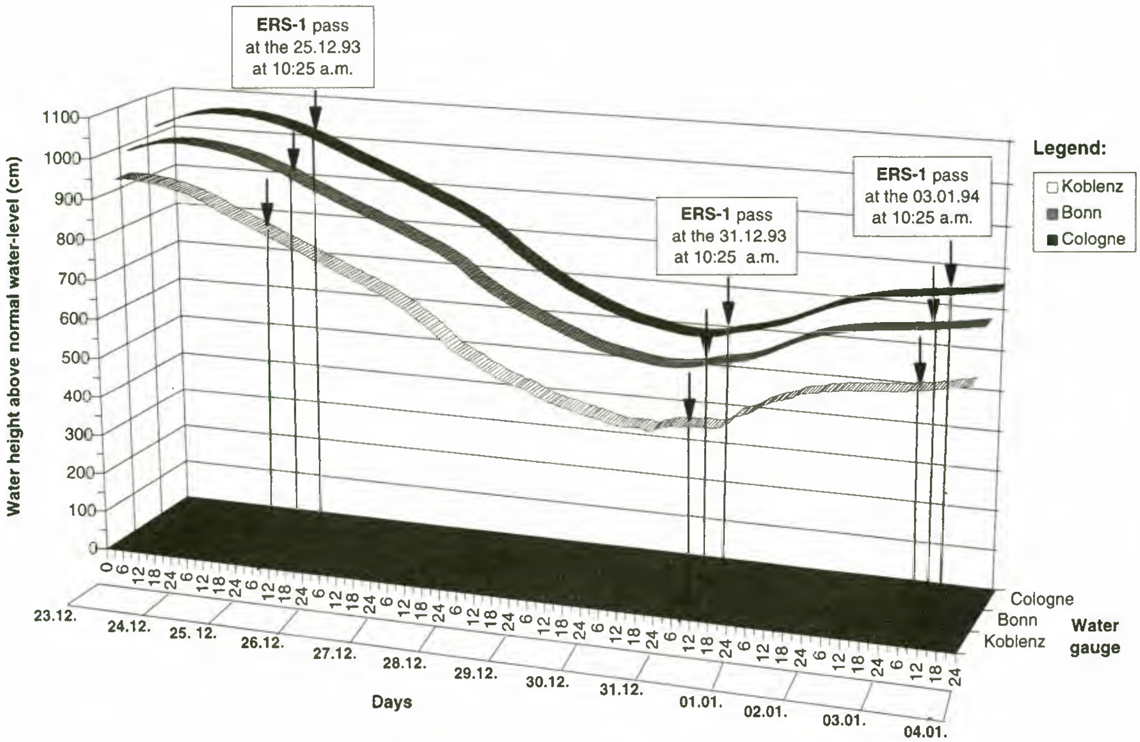

Figure 2. Measurement of the water level per hour for the water gauges at Koblenz, Bonn and Cologne from 23 December 1993 until 4 January 1994. The ERS-1 pass is marked in each curve to indicate which flood situation was registered by the satellite

successfully used for the December 1993 flooding over Cologne/Bonn, giving an overview in just a few hours. Full resolution products can be delivered within 10 minutes to the archiving and processing centres. The constraint is, however, that the transmission is planned once a day for each station near midday. Requests in the early afternoon therefore have to wait nearly 24 hours to receive the data. Only for very special events is it possible to plan another transmission.

METHODOLOGY

Identification of the data users

Close contact with data users was of special importance for the project. User information needs had been ascertained by questioning in order to compare the user requests with data based on ERS-1 SAR data. In general, the users of flood information can be divided into two groups: those interested in information about the water volume (i.e. national and federal institutes) and those interested in the flood level and flood extent (i.e. the water authority boards, the federal institute for hydrology, emergency organizations, headquarters for flood defence, insurance and re-insurance companies, as well as planning authorities).

There are various products required by the users which can be established by ERS-1 SAR data: a quick view of the flooding, maps with flood extent delineation, a demonstration of the runoff, a measurement of the flood level and evidence for surfaces that are inundated owing to a rise of the groundwater table. Because insurance companies separate their customers in relation to postal code districts, the flood extent per postal code district is interesting.

In combination with auxiliary data, the flooded land use classes can be calculated using a Landsat TM classification. In combination with a digital elevation model the water volume can be derived and the data can be used for model validation.

Data analysis

The software used was the ERDAS IMAGINE Package and ARC/INFO. A data scaling from 16-bit to 8-bit, applying a linear histogram stretch, made the data handling easier without affecting the information content of the data.

Visual interpretation

The first step in the examination was a visual interpretation of the aerial photographs of Koblenz, on which the flood line can be clearly identified. Additionally, the photographs were used as reference for the satellite data interpretation, helping to verify flooded areas. Furthermore, the satellite data were interpreted directly on the screen, producing different flood lines, which document the decrease of water. The interpretation was carried out on a colour composite because the inundated area appears in bright colours. The interpretation of a single ERS-1 scene, however, is rather difficult, because the human eye has only a restricted differentiation ability for grey values. Additionally, some back-scatter values of flooded surfaces are not very characteristic at all and can only be detected using different dates.

For the interpretation a combination of one scene (i.e. GTC of 25 December 1993), a difference image of the scene under investigation and the imagery of 3 January 1994, and a reference imagery from June was used. This data combination proved to be the best data base for a visual interpretation. A reference scene is not urgently necessary for the interpretation, but in the case of interpretation difficulties it was helpful to be able to compare the grey values of the supposedly inundated areas with the grey values of the non-flooded situation.

Automatic classification and filtering

Besides the visual interpretation an automatic classification was carried out. The aim was to find a quick and operational method for flood mapping whereby an automatic classification seemed to be a suitable attempt. The classifier used is a new evidence-based classification algorithm called EBIS (evidence-based interpretation of satellite images) (Lohmann, 1991). The EBIS classification was recently implemented as a new version in the ERDAS Imagine software package and is suitable for classifying radar data.

EBIS supports three parametric models to describe the statistical properties of an object class: the Gaussian distribution, the multinomial distribution and the Gibb's random fields. The model used to classify the ERS-1 SAR data was the multinomial distribution because it was assumed to describe SAR data best. The methodology to assign a pixel to an object class is based on the concept of evidential reasoning according to the 'Dempster–Shafer theory'. Belief functions are used to decide whether a pixel can be assigned to a specific object class.

The classification has two phases: a parametric phase and a classification phase. During the parametric phase (in the context of multinomial distribution) the percentage of occurrence of each grey value in some domain is described for each defined object class. This is done by either using a co-occurrence matrix or a local histogram. These matrices describe in which specific neighbourhood relations a group of pixels occurs. In the classification phase, the histogram of the pixel under observation, including a window of 5×5, 7×7 or 9×9 pixels surrounding this pixel, will be compared with the specific histograms of the different object classes. The percentage of occurrence of grey values in an object class is taken as evidence for the classification hypothesis. If a pixel's features match the histogram of the object class well, this constitutes evidence in favour of the corresponding classification hypothesis, if not, the hypothesis is refuted.

An advantage of EBIS is that each object class can be represented by a number of descriptors (= regions). Each descriptor is based on exactly one feature space.

The best classification results were achieved by classifying two images, the GTC of 25 December 1993 and the GTC of 3 January 1994. Classification tests with only one acquisition date or with all three dates in combination produced poorer results. Solely water classes against non-water classes were classified using about 10 different training classes. As parameters, the local histogram and multinomial distribution were applied.

After classification, various spatial filtering steps were used. Boundary operations helped to homogenize the edge of the water class and to extend the outer water boundary, because normally the class boundaries are poorly represented with EBIS. A density filter was used to select and afterwards eliminate single pixels that were spread in the agricultural fields. With a filter designed to extract groups of pixels, gaps inside the water class were closed. All steps were carefully observed to prevent negative effects.

Measurement of the flood level

In the case of flooding, the mapping teams of the water authority boards always try to seize the peak wave. Since the wave is normally steady for some hours, it can be assumed that the data sets of the water authority boards really do represent the highest flood level. For the satellite data, on the other hand, the time shift between the highest water level and the acquisition date has to be considered.

To derive the flood level from the ERS-1 images, the visually delineated flood boundary, which was more accurate than the classification result, was plotted on transparencies in combination with the foreland profiles. This plot was superimposed over the corresponding map sheets, 1 : 5000. By means of the contour lines of the map sheet, the corresponding water stage could be registered manually (this was done every 500 m in correspondence with the location of the river profiles) and stored in a database. The derivation of the water level was done only for the Porz test site, which means a distance of 19 km.

RESULTS AND DISCUSSION

Unfortunately no data verified by field checks could be made available to assess the results of radar interpretation. Therefore, the aerial photographs of Koblenz served as a standard for comparison. The visual image interpretation showed good results in comparison with the photographic interpretation. The flood

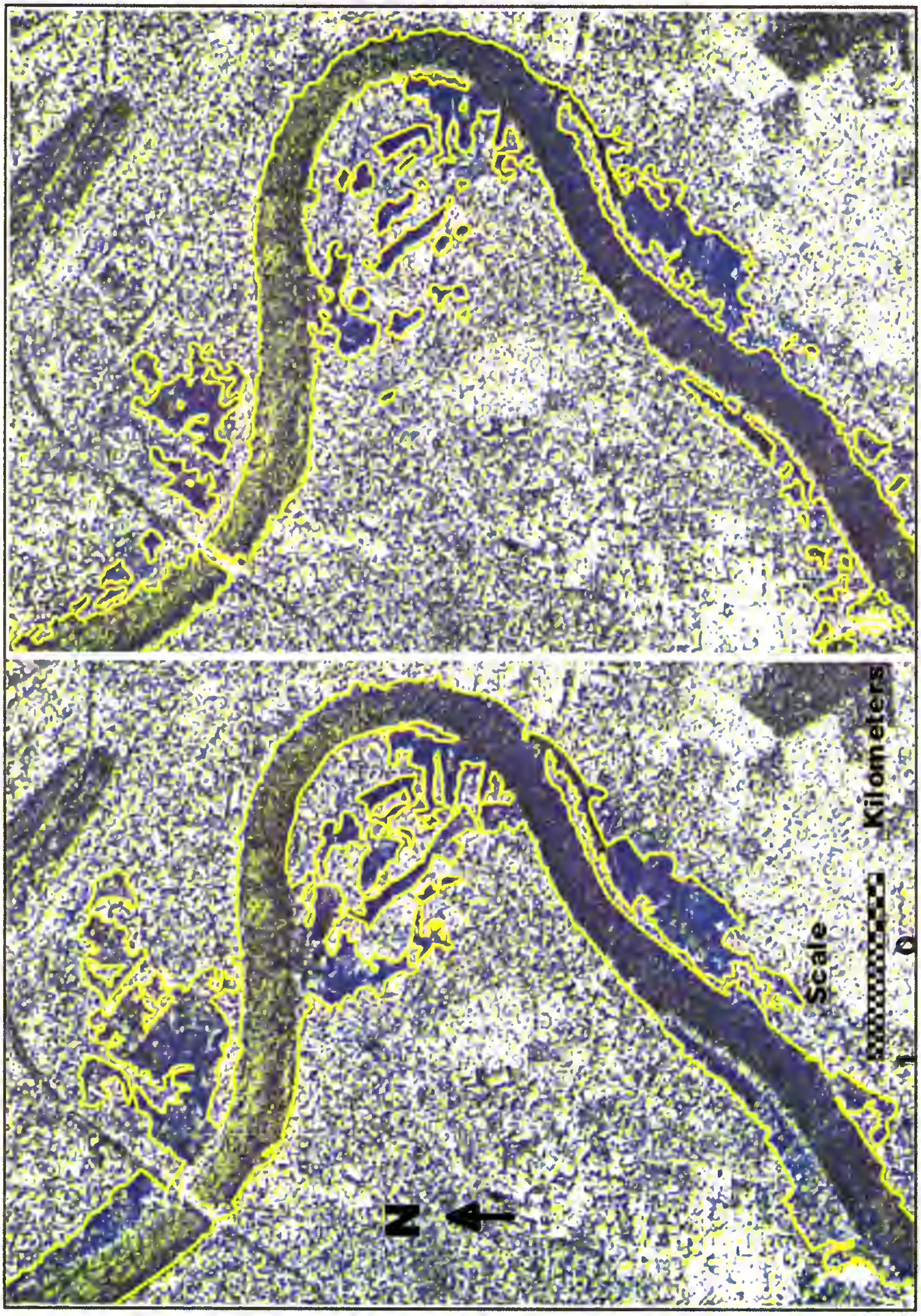

Figure 6. Comparison of the visual interpretation of the ERS-1 SAR data with the EBIS classification result for parts of the Porz test site (river section around Porz)

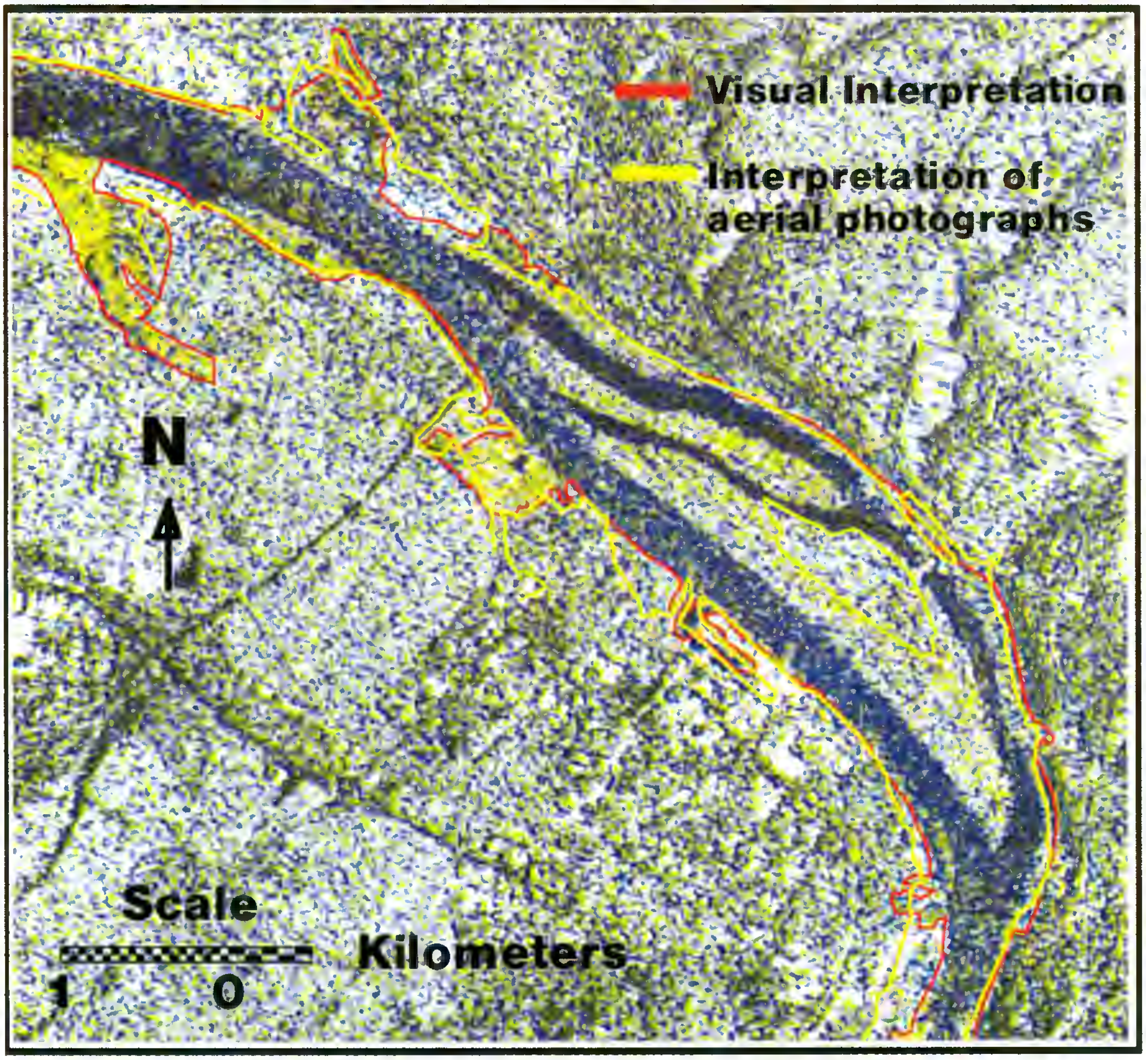

Figure 3. Visual interpretation of the aerial photography data and the satellite data for parts of the Koblenz test site (the section is located north of Koblenz)

lines were fitting quite well, as shown in Figure 3. However, there are some problematical regions, where it is complicated to find the virtual flood line. Problems arose, for example, where steep areas produced radar shadows and foreshortening effects which hide any land use information. Furthermore, forests, which show similar back-scatter values to inundated areas, are difficult to differentiate from flooded surfaces. In this case the information from the corresponding map sheets proved to be useful for the determination. A correct separation between flooded and non-flooded settlements also caused problems. In many cases the high back-scatter of the buildings overlaid the back-scatter of inundated areas, and often, the roads are too small to be distinguished. Another critical point is the amount of trees in cities. Especially in one-family housing areas, the number of trees is normally very high, which means that flooded surfaces will be covered by the trees and therefore cannot be detected. Wrong delineations also happen when embankment constructions or port installations produce high reflections which dominate the back-scatter of the surrounding areas. In some cases, the reflection was so strong that the interpreted flood line ran inside the normal river bed.

On the whole, the visual interpretation of ERS-1 SAR data seems to be an appropriate method to get a quick view of the flood situation and to derive the boundary of the flooded arable land and, with some restrictions, of settlements. But the more accurate method is the interpretation of the aerial photographs.

Concerning the classification, the results were encouraging and demonstrated that EBIS is useful for classifying radar data (Figure 4). The program is easy to use and produces acceptable results relatively

Figure 4. EBIS classification result for the Porz test site

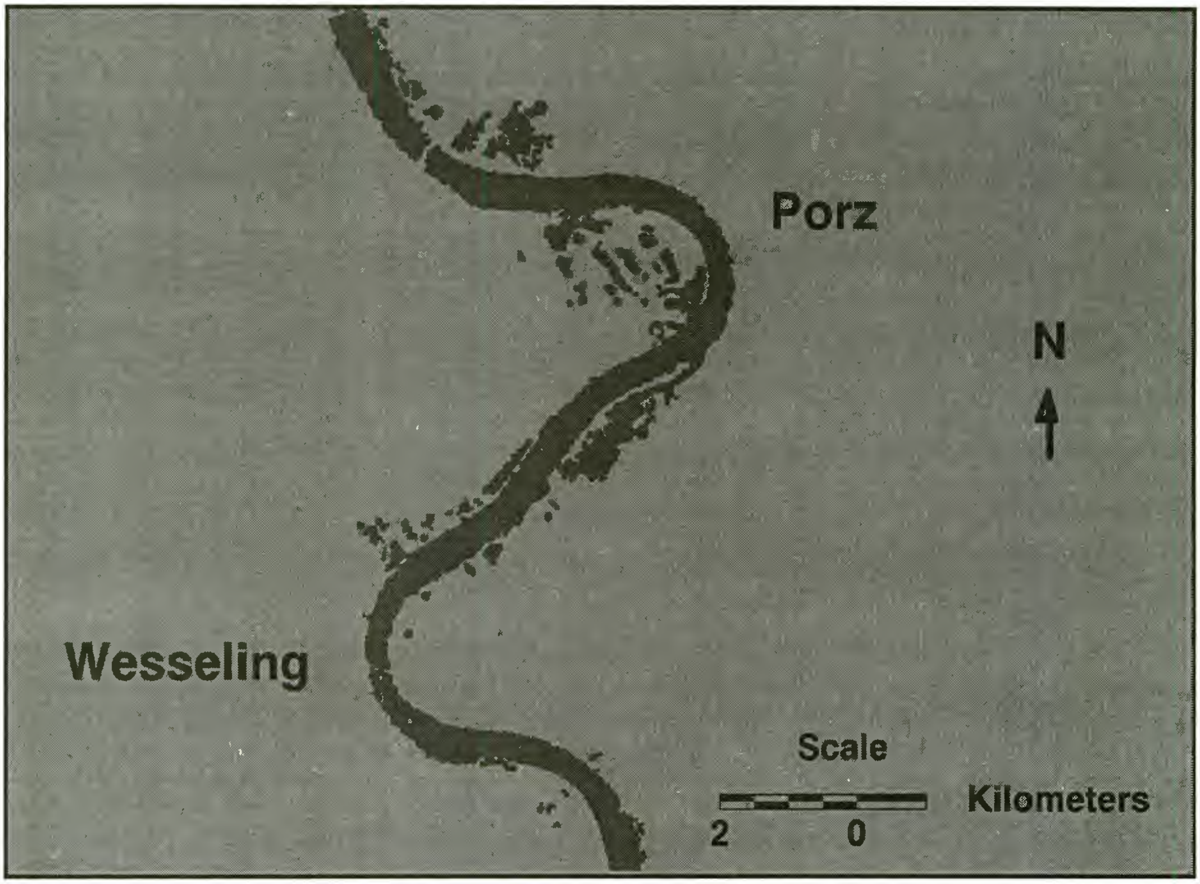

Figure 5. Result of the filtering process for the Porz test site

quickly. Owing to a lack of a standard of comparison, the visual interpretation of the flooded area was used to judge the results. A valuation of the quality of the classification could therefore only refer to the mapping of the visual, obviously flooded areas and not to the virtual flooded areas. Various water misclassifications occurred in the arable land, which had to be reduced afterwards by filtering or manual editing. The misclassifications arose because forested areas or bushes, as well as wet arable land, had similar signatures as inundated surfaces. In general, the flooded area is relatively inhomogeneous, encompassing a variety of grey tones. Layover zones were also falsely classified because of their low back-scatter, which resembles the back-scatter values of water. Moreover, a correct delineation was not found for the areas that had been problematic for the visual analysis, such as settlements.

The outcome of the filtering process was a real improvement (Figure 5). A large number of the flooded surfaces that were classified as arable land could be adjoined to the water class. As expected this process also increased the amount of wrong water pixels in the arable land. These pixels were eliminated manually according to the topographic map sheet.

Comparison of the visual interpretation with the filtered classification result showed that most of the obviously inundated areas were included in the algorithm (Figure 6). Forests and one-family housing areas, however, as well as steep areas, had also been classified as water.

To demonstrate the flood decrease, the food boundaries for all different dates were combined, and this is shown in Figure 7. Areas that were affected the longest are obvious, as well as 'flooded islands', which must be flooded owing to a rise of the groundwater table.

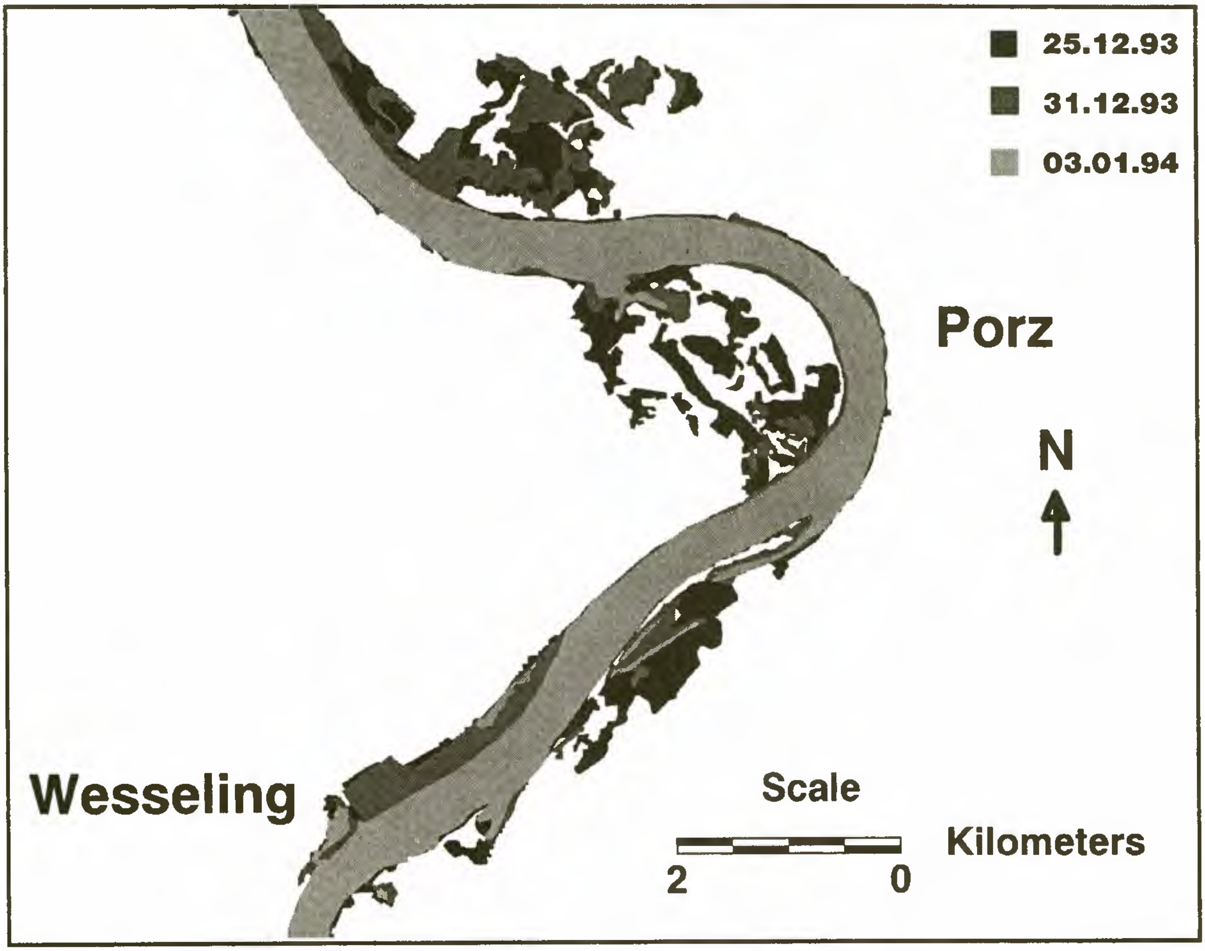

Figure 7. Demonstration of the flood decrease for the Porz test site

Measurement of the water height

The results of the water level measurement with ERS-1 SAR data are presented in Figure 8. Severe irregularities are obvious which can be related to the following effects: extremely low values refer to river sections, where corner reflectors near the bank (produced by embankment constructions or port installations) dominate the reflection. If this was the case, the flood line sometimes even lay inside the river bed. Another point is that, if the water is held by the dike, there was no possibility to define the water level because the slope of the dike made measurements impossible. In this case the next higher contour line was assumed to represent the water level approximately. Very high water levels can normally be related to measurements in settlements. As mentioned above, it is hard to achieve an exact demarcation of the flooded area inside cities owing to the problems referred to earlier. This is compounded by the fact that there are often no contour lines inside the settlements. A correct definition of the water height is therefore complicated and often has to be assumed.

With regard to the trend of the values, a general discrepancy of about 50 cm to 2·0 m is evident. This measurement has to be made relative owing to the time shift between the two measurements, which was about 54 cm for the Porz test site. Taking this into account the results showed only a discrepancy of about 10–50 cm (Figure 9).

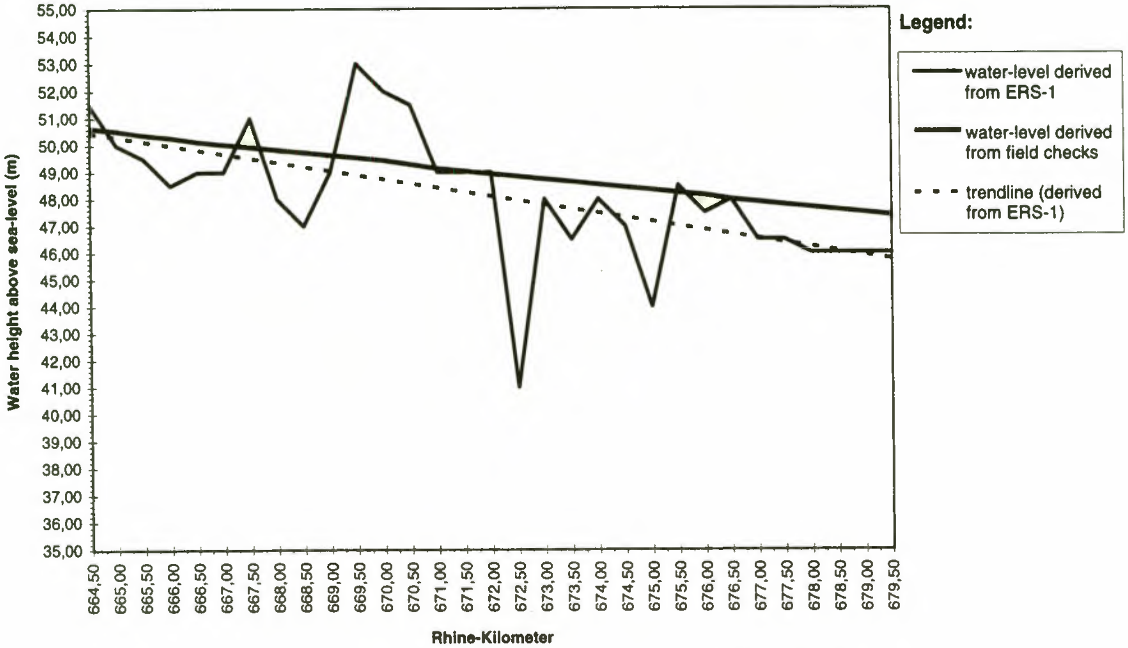

Figure 8. Measurement of the flood level with ERS-1 SAR data for the left river bank in comparison with the traditional measurement results

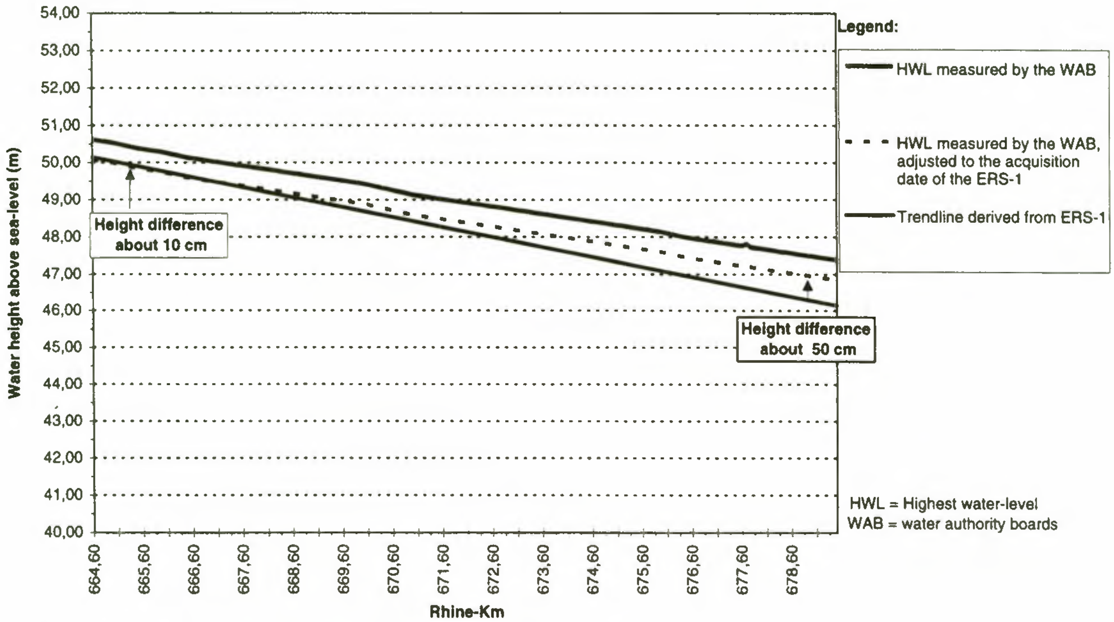

Figure 9. Comparison of the flood level measurement using ERS-1 SAR data with the traditional measurements for the left river bank. The ranging of the water authority boards has been adjusted to the water decrease owing to the time delay of the ERS-1 acquisition date

CONCLUSIONS

Comparing the results of the investigation with the end-user demands, the following conclusions can be drawn.

1. The actual time frame of ERS-1 cannot really ensure the recording of flood events. Therefore, at present, an operational use is not imaginable.

2. Mapping of the flood extent with high accuracy is possible for arable land. In settlements, forested or steep areas, no definitive delineation is possible.

3. To be able to calculate the highest water level with ERS-1 SAR data, the interval between the recording of two scenes has to be reduced. This is because a SAR image always covers an area of 100 km × 100 km, mapping different water levels on one image.

4. ERS-1 SAR data are too coarse to map the flood level with satisfactory accuracy in Germany. However, in regions where SAR is the only available tool the results are very useful.

5. Flood maps are useful and enable the establishment of a flood database. Moreover, they indicate areas flooded as a result of a rise in the groundwater table.

6. The representation of the flood decrease delineates areas that were affected by floods longest.

7. Flood maps with superimposed postal codes are helpful for insurance and re-insurance companies.

These points indicate which SAR specifications are necessary in order to be able to use SAR data for flood mapping in Germany. In fact, there are efforts from ESA and related processing facilities to establish data processing in a shorter amount of time. ESA/ESRIN is funded by the earth watching service, which produces images quickly after disasters. Additionally, there are some attempts to make data sets available for authorities in the case of emergencies such as flood events. In general it is difficult to introduce satellite data to such authorities, because, in most cases, satellite data cannot fulfil the accuracy demands necessary for basic planning levels. On a larger scale, however, and with regard to rivers being unsupervised, SAR data are sometimes the only available tool in the hand of civil protection authorities and decision makers. In these cases the achievable accuracy is sufficient.

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SATELLITE REMOTE SENSING OF RIVER INUNDATION AREA, STAGE, AND DISCHARGE: A REVIEW

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ABSTRACT

The growing availability of multi-temporal satellite data has increased opportunities for monitoring large rivers from space. A variety of passive and active sensors operating in the visible and microwave range are currently operating, or planned, which can estimate inundation area and delineate flood boundaries. Radar altimeters show great promise for directly measuring stage variation in large rivers. It also appears to be possible to obtain estimates of river discharge from space, using ground measurements and satellite data to construct empirical curves that relate water surface area to discharge. Extrapolation of these curves to ungauged sites may be possible for the special case of braided rivers.

Where clouds, trees and floating vegetation do not obscure the water surface, high-resolution visible/infrared sensors provide good delineation of inundated areas. Synthetic aperture radar (SAR) sensors can penetrate clouds and can also detect standing water through emergent aquatic plants and forest canopies. However, multiple frequencies and polarizations are required for optimal discrimination of various inundated vegetation cover types. Existing single-polarization, fixed-frequency SARs are not sufficient for mapping inundation area in all riverine environments. In the absence of a space-borne multi-parameter SAR, a synergistic approach using single-frequency, fixed-polarization SAR and visible/infrared data will provide the best results over densely vegetated river floodplains. © 1997 John Wiley & Sons, Ltd.

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(No. of Figures: 3 No. of Tables: 0 No. of Refs: 103)

KEY WORDS remote sensing; river inundation; review; synthetic aperture radar, Landsat, floods

INTRODUCTION

Satellite-derived flood inundation maps produced in near-real time are invaluable to state or national agencies for disaster monitoring and relief efforts. New facilities are being developed that will utilize Internet/World Wide Web technology to disseminate satellite data rapidly during flood events (Biasutti and Lombardi, 1995; Blyth 1995). Precise mapping of the maximum flood extent is also required for detecting deficiencies in existing flood control measures and for arbitrating damage claims later.

Remote sensing has proved useful in ecological, hydrological and geomorphological river studies. Its value in remote regions has been demonstrated in the Amazon Basin (Sipple *et al.*, 1992; Koblinsky *et al.*, 1993; Hess *et al.*, 1995), where seasonal to interannual variations in stage and floodplain inundation area are needed for assessing biogeochemical processes such as methane flux and main stem–floodplain exchange (Asselmann and Crutzen, 1989; Richey *et al.*, 1989; Richey *et al.*, 1991). Smith *et al.* (1995a,b) describe a method for using ERS (European Space Agency) high-resolution SAR (synthetic aperture radar) satellite imagery to estimate discharge in remote, braided, glacial rivers that may be sensitive to changing regional or global climate. ERS–SAR data have also been proposed as a source for validation of numerical hydraulic flow models, which predict floodwave surface profiles and inundation patterns (Bates and Anderson, 1995).

Swamp and other habitat types in the large and ecologically diverse Okavango Delta of Botswana have been mapped using Landsat MSS (Ringrose *et al.*, 1988) and TM (Watson, 1991) imagery. A similar study established the morphometry and connectivity of the thousands of channels, lakes and ponds that constitute the Mackenzie Delta in Canada's Northwest Territories (Mouchot *et al.*, 1991); the derived information is useful for watercraft navigation, fisheries and wildlife habitat monitoring. Intermittently flooded areas that

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are potential breeding grounds for mosquitoes that carry the dangerous Rift Valley Fever virus have been mapped in Kenya using Landsat TM and airborne polarimeter data (Pope *et al.*, 1992). Floodplain boundaries and land surface types can be delineated with Landsat (Rango *et al.*, 1975; Hollyday, 1976; Sollers *et al.*, 1978); Nagarajan *et al.* (1993) used Landsat images and aerial photographs over the Rapti River in India to identify areas vulnerable to channel migration and floods.

The sensors used in these and other river studies may be classified into two types: (1) passive, in which the sensor receives energy naturally reflected by or emitted from the earth's surface; and (2) active, in which the sensor provides its own illumination and records the amount of incident energy returned from the imaged surface. Passive sensors include all of the visible and infrared instruments such as the Landsat Thematic Mapper (TM) and Multi-Spectral Scanner (MSS), the Advanced Very High Resolution Radiometer (AVHRR), the Satellite Pour l'Observation de la Terre (SPOT) and the anticipated Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Moderate-Resolution Imaging Spectroradiometer (MODIS) and Landsat-7 sensors. Passive microwave radiometers such as the Special Sensor Microwave/Imager (SSM/I) measure the amount of microwave energy naturally emitted from the Earth's surface. However, the poor spatial resolution of spaceborne microwave radiometers (*ca.* 27 km at 37 GHz) limits their use to very large areas. This problem has been mitigated through use of spectral mixing models, which extract subpixel proportions of spectrally distinct end members (Sipple *et al.*, 1992; Hamilton *et al.*, 1996).

The active sensors described in this review consist of imaging radars and radar altimeters. Radars can penetrate clouds, darkness and, at the longer wavelengths, tree canopies. Cloud penetration is particularly important for monitoring flood events, as they commonly occur during periods of extended rainfall. However, interpretation of synthetic aperture radar (SAR) imagery is less straightforward than for the visible/infrared range. In addition, the presence of wind-induced waves or emergent vegetation can roughen the surface of open water bodies, making them difficult to discriminate from other, non-flooded land surface types.

The aim of this paper is to review briefly efforts to use active and passive remote sensing to estimate water surface area, stage and discharge. Methods for mapping surface area are by far the best developed. More recently, improvements in satellite orbital precision and the increasing availability of multi-temporal satellite data have enabled the estimation of river stage and discharge from space. While these techniques are largely in their infancy and not yet used operationally, three general approaches have emerged: (1) direct measurement of water surface level from radar altimeter waveform data; (2) determination of water surface elevations at their point of contact with the land surface using high-resolution satellite imagery and topographic data; and (3) correlation of satellite-derived water surface areas with ground measurements of stage or discharge. It should be noted that river flow velocity cannot be directly measured from space. Satellite estimates of discharge therefore require the use of ground-based empirical relationships between discharge and inundation area or stage.

Studies that have used passive (visible, infrared and microwave range) and active (microwave) sensors to delineate inundation area are reviewed in the first section, and efforts to estimate river stage and discharge from space are reviewed in the second section.

REMOTE SENSING OF INUNDATION AREA WITH PASSIVE AND ACTIVE SENSORS

Visible/infrared Remote Sensing of Inundation Area

Much of the pioneering work on the remote sensing of floods was accomplished using the Multi-Spectral Scanner (MSS) sensor on ERTS-1 (the first Earth Resources Technology Satellite, later renamed Landsat-1), launched on 23 July 1972. With a spatial resolution of about 80 m, MSS data were used to map the extent of flooding in Iowa (Hallberg *et al.*, 1973; Rango and Salomonson, 1974), Arizona (Morrison and Cooley, 1973), Virginia (Rango and Salomonson, 1974) and along the Mississippi River (Deutsch *et al.*, 1973; Deutsch and Ruggles, 1974; Rango and Anderson, 1974; McGinnis and Rango, 1975; Deutsch, 1976; Morrison and White, 1976). Maximum flood boundaries derived from the MSS imagery were shown to agree well with those derived from aerial photography (Hallberg *et al.*, 1973; Morrison and Cooley, 1973) and US Army Corps of Engineers and US Geological Survey flood hazard maps (Rango and Anderson, 1974). In one case, the MSS-derived flood hazard map performed best, near a major tributary where backwater flooding occurred (Rango and Anderson, 1974). In all studies, MSS band 7 (0·8–1·1 μm) was most useful for discriminating water from dry soil or vegetated surfaces owing to the strong absorption of water in the near-infrared range. This was further confirmed by comparing panchromatic and colour infrared aerial photographs over inundated areas (Hallberg *et al.*, 1973; Moore and North, 1974), and by analysing MSS band 5 (0·6–0·7 μm), band 7 and field spectral radiometer data along shoreline water–wet soil–dry soil transitions (Gupta and Banerji, 1985). Errors in MSS-derived flooded areas have been estimated to be less than 5% (Rango and Salomonson, 1974); a similar error estimate has been reported for lakes (Gupta and Banerji, 1985). Chidley and Drayton (1986) suggested that the SPOT system can detect water bodies smaller than 0·5 ha. France and Hedges (1986) found minimum detectable lake areas of 0·6 ha for TM and 2·4 ha for MSS. However, only a 64% accuracy was reported for MSS classifications of flooded land in Bangladesh, where the 80 m spatial resolution failed to resolve adequately the raised dike system that separates rice paddies and serves as infrastructure for transport and dwellings (Imhoff *et al.*, 1987). Even larger errors can occur in flooded forests, because trees are highly reflective in the visible and near-infrared range (Hallberg *et al.*, 1973; Moore and North, 1974). Floating emergent macrophytes are also a problem in many riverine environments, particularly in tropical systems such as the Amazon (Melack *et al.*, 1994; Hess, 1995). Vila da Silva and Kux (1992) noted a significant underestimation of inundation area over such aquatic habitats when using Landsat TM.

Perhaps the greatest problem with visible/infrared sensors is their inability to image the Earth's surface during cloudy conditions (Rango and Salomonson, 1977; Lowry *et al.*, 1981; Van den Brink, 1986; Blyth and Biggin, 1993; Rasid and Pramanik, 1993; Melack *et al.*, 1994). For the purpose of determining maximum flood extent, this difficulty is somewhat mitigated by the fact that residually wet soils and stressed vegetation can be mapped even after flood stage recession (Rango and Anderson, 1974; Deutsch, 1976). This effect can last from one to two weeks (Hallberg *et al.*, 1973; Rango and Salomonson, 1974; Morrison and White, 1976; Salomonson, 1983).

Other studies have continued the methodology first developed with MSS, using TM and SPOT data (France and Hedges, 1986; Jensen *et al.*, 1986; Watson, 1991; Blasco *et al.*, 1992; Pope *et al.*, 1992; Vila da Silva and Kux, 1992). There has also been some success studying very large rivers or floods with the coarser resolution (*ca.* 1 km) US National Ocean and Atmospheric Administration Very High Resolution Radiometer (VHRR) (McGinnis and Rango, 1975; Dey *et al.*, 1977), the Advanced Very High Resolution Radiometer (AVHRR) (Ali *et al.*, 1989; Barton and Bathols, 1989; Gale and Bainbridge, 1990; Rasid and Pramanik, 1993) and the Nimbus-7 Coastal Zone Color Scanner (CZCS) (Wiesnet and Deutsch, 1987). However, since the 1970s there has been little change in the way visible/infrared satellite data are used to map open water bodies. The approach is relatively straightforward and now considered operational where trees and vegetation do not obscure the water surface and clear skies prevail to permit data acquisition.

Passive Microwave Remote Sensing of Inundation Area

Natural thermal emission of microwaves from the Earth's surface may be measured by passive microwave radiometers such as the Scanning Multichannel Microwave Radiometer (SMMR) which flew on board the Nimbus-7 satellite from 1978 to 1987, and the Special Sensor Microwave/Imager (SSM/I) currently operating on a DMSP (Defense Meteorological Satellite Program) platform. Brightness temperatures (K) measured at the sensor are proportional to the product of the effective surface temperature and the emissivity of the emitting medium (Choudhury, 1989). At the 37 GHz frequency, atmospheric water vapour content and temperature influence the received brightness temperatures. To mitigate these effects, the difference between the vertically and horizontally polarized brightness temperatures (ΔT) is often used instead of the actual brightness temperatures. Large values of ΔT are found over surfaces that emit a strongly polarized microwave signal (such as open water). Depolarization by scattering from vegetation or

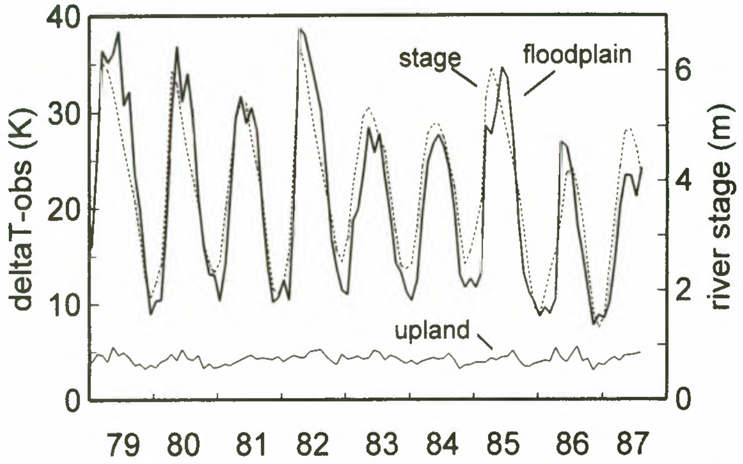

Figure 1. Time trends from 1979 to 1987 of the SMMR 37 GHz polarization difference observed at the satellite (ΔT-obs) over a seasonally inundated Pantanal floodplain (bold solid line) and a nearby upland area (solid line). Polarization difference values are averaged from four SMMR grid cells (floodplain) and sixteen grid cells (upland). Monthly mean stage from the Paraguay River (dashed line) is also shown. The strong correlation between the 37 GHz polarization difference and observed river stage indicate that seasonal differences in ΔT are driven largely by inundation cycles. (From Hamilton *et al.*, 1996)

surface roughness causes values of ΔT to decrease (Schmugge *et al.*, 1986; Choudhury, 1989). Scattering from precipitating clouds can also exert a depolarizing effect, reducing ΔT (Hamilton *et al.*, 1995). A theoretical basis for the use of ΔT over land surfaces is provided by Choudhury (1989). In general, the polarization difference ΔT decreases with increasing vegetation density and surface roughness, and increases over wet or inundated soils.

In South America, monthly SMMR-derived values of ΔT were used to determine seasonal inundation patterns for 15 rivers and wetlands in the Amazon, La Plata, Orinoco and Sáo Francisco river systems (Giddings and Choudhury, 1989; Choudhury, 1991). Distinct differences in the timing of seasonal flow cycles can be seen in the ΔT time-series from a selection of basins, with more subtle differences found among rivers of the same system. These studies were limited to the continental scale by the *ca.* 27 km resolution of SMMR at 37 GHz. An improved 37 GHz resolution of 14 km will be provided by the Multi-Frequency Imaging Microwave Radiometer (MIMR), scheduled for launch on the EOS-PM platform in the year 2000. At present, subpixel estimates of inundation area may be extracted from 37 GHz SMMR data, using empirically derived values of ΔT for open water, seasonally flooded land and non-flooded land as end-member inputs to a linear spectral mixing model (Sipple *et al.*, 1994; Hamilton *et al.*, 1996). In Figure 1, SMMR 37 GHz polarization differences for a seasonally inundated floodplain from the Pantanal wetland of South America are presented with monthly mean ground measurements of discharge in the Paraguay River. Polarization differences for a nearby, non-inundated upland area are also shown. A screening procedure was used to eliminate SMMR images that were affected by heavy rains. Values of ΔT over the inundated floodplain correspond closely with ground measurements of stage in the Paraguay River, the major outlet of the Pantanal. Polarization differences over non-inundated upland show little or no change over time, demonstrating that fluctuations in inundation area are responsible for the corresponding changes in microwave emission from the flooded land surface.

Radar (active microwave) Remote Sensing of Inundation Area

Spaceborne radars can image the Earth's surface in all weather conditions, day or night. As described earlier, the inability of visible/infrared sensors to penetrate clouds poses a severe problem for regular monitoring of river conditions. For example, in the Amazon basin, a search of Landsat data archives from 1972–1985 found just 1–3 useful images per year, most occurring between July and October (Melack *et al.*, 1994). Rasid and Pramanik (1993) cited pervasive cloud cover as the single greatest limitation to their study of flooding in Bangladesh using AVHRR imagery. Van den Brink (1986) reported the same difficulty in Kenya.

An early attempt to map flood inundation extent with active microwaves used a side-looking airborne radar (SLAR) at the X- and L-bands (Lowry *et al.*, 1981). X-band SLAR imagery, acquired in the late 1970s was also used to map floodplain lakes along the Amazon River, Brazil (Sipple *et al.*, 1992). At the First ERS Thematic Working Group Meeting on Flood Monitoring (ESA/ESRIN, 1995), numerous investigators presented flood inundation maps derived from C-band ERS-1 synthetic aperture radar (SAR) images. A general observation was that for smooth open water bodies without vegetation, especially trees, radar returns are normally low due to specular reflection from the water surface. This characteristic permits flood boundaries to be determined with a good level of accuracy under many conditions. However, turbulence, wind, emergent vegetation and trees can all cause significant increases in radar back-scatter, making inundation extent difficult or impossible to determine.

When a micro-scale element (at the scale of the radar wavelength) of an imaged surface is subjected to an incident microwave, the ratio of incident energy reflected away from the surface to the energy refracted downwards into the media is proportional to the dielectric constant and the incidence angle at which the microwave intersects the imaged surface. The complex dielectric constant of a material is proportional to the strength of its dipole moment in the presence of a time-varying external electric field, while the incidence angle (at the micro-scale) is determined by the surface roughness. Over a larger area (such as a pixel), the angular radiation pattern reflected by the surface is also affected by the local slope, which exerts a net directionality to the radiation pattern. For smooth water bodies, surface roughness and the local slope are both nearly flat. Consequently, most incident microwave energy impacts the surface obliquely and is specularly reflected away from the satellite, yielding low radar returns. Wind reduces this effect by roughening the water surface, increasing radar back-scattering to the satellite. Since water bodies are perfectly saturated, dielectric contrast effects are less important than surface roughness effects. This is not the case for unsaturated soils, where the presence of liquid water causes increased radar back-scatter owing to an increased complex dielectric constant of the soil–water mixture. When the soil becomes saturated and water is ponded, specular reflection is enabled (in the absence of wind or emergent vegetation) and back-scatter to the satellite is dramatically reduced.

Where vegetation or trees are present, a wavelength-dependent increase in radar back-scatter is commonly observed. Surface roughness elements of the order of the radar wavelength exert maximum scattering effect. For example, X-band (2·4–3·8 cm) and C-band (3·8–7·5 cm) signals are effectively scattered by the leaves, twigs and branches within a forest canopy. L-band (15·0–30·0 cm) and P-band (30·0–100·0 cm) display greater canopy penetration but interact strongly with trunks and large branches. Radar impulses are transmitted and received in plane-polarized form by the radar antenna. Polarizations may be transmitted and received horizontally (HH), vertically (VV) or cross-polarized (HV or VH). Radars with multiple frequencies and polarizations provide much more information about the imaged surface than single-polarization, fixed-frequency radars. L-band radar back-scatter is commonly increased over flooded forests through a double-bounce mechanism between the water surface and inundated tree trunks or branches (Hoffer *et al.*, 1985; Harris and Digby-Argus, 1986; Richards *et al.*, 1987; Hess *et al.*, 1990; Hess and Melack, 1994). An HV phase difference of 153° was found in airborne polarimeter data over a forested swamp (Durden *et al.*, 1989), agreeing closely with a phase difference of 152° modelled for the site (a pure double-bounce return is defined as having a 180° phase difference between the vertical and horizontal polarizations). The magnitude of the back-scatter increase is significantly affected by vegetation type (Krohn *et al.*, 1983; Evans *et al.*, 1986; Harris and Digby-Argus, 1986; Pope *et al.*, 1994) and may be suppressed altogether by a dense undergrowth between the tree canopy and water surface (Waite *et al.*, 1981). Airborne multi-polarization radar studies have generally indicated that flooding beneath forest canopies is best detected with co-polarizations rather than cross-polarizations (Wedler and Kessler, 1981; Hoffer *et al.*, 1985; Evans *et al.*, 1986; Pope *et al.*, 1992; Hess *et al.*, 1995), although Wu and Sader (1987) favour use of a co- and cross-polarization ratio.

From L-HH Shuttle Imaging Radar B (SIR-B) SAR data collected over the Altamaha River in Georgia, Hess and Melack (1994) confirmed the observation of Hoffer *et al.* (1985) that L-band enhancement is affected by radar incidence angle. Flooded pine forest could be discriminated from dry forest at incidence angles of 18° and 45° from vertical, but not 58°. Horizontally polarized (HH) C-, L-, and P-band NASA/JPL AIRSAR data were also acquired over this site, and illustrate superbly the features that can be observed in wetlands and flooded forests with different frequencies. Increased returns at C-band over marshes were interpreted as double-bounce reflections between emergent plant stalks and a smooth water surface. These stalk dimensions were too small to increase returns at L- and P-band, so marshes appeared dark at these longer wavelengths. The converse was true in flooded bottomland forests, where L- and P-bands penetrated the upper canopy but experienced double-bounce reflections between the water surface and inundated tree trunks. C-band was attenuated by the leaves and twigs of the forest canopy, except in areas defoliated by caterpillar damage and permanent inundation by beaver ponds (Hess and Melack, 1994). Comprehensive reviews of the interaction of various radars with a wide range of flooded vegetation types are provided by Hess *et al.* (1990) and Melack *et al.* (1994).

Recent efforts have used fully polarimetric SAR data to classify various inundated land surface types. Amplitudes at multiple frequencies and polarizations vary with vegetation structure and species. Multi-parameter SAR can thus be used to detect flooding in vegetated riverine environments to an extent not possible with single-frequency, fixed-polarization radars. Pope *et al.* (1994) presented four biophysical indices that can be used to discriminate thickets and areas of forest regrowth, marshes, swamp forests and upland forests. Hess *et al.* (1994, 1995) used a decision-tree model to classify polarimetric SIR-C (Shuttle Imaging Radar C) acquired over the Negro and Amazon rivers near Manaus, Brazil in April and October, 1994. Both C- and L-bands were used to distinguish open water, floating macrophytes and flooded forest from upland forest and clearings. While the total area of open water did not change significantly between data acquisitions, the extent of flooded forest was nearly 50% less in October. It is clear that multi-parameter SAR offers a distinct advantage over single-frequency, fixed-polarization SAR where diverse vegetation cover is found.

REMOTE SENSING OF RIVER STAGE AND DISCHARGE

In the previous section studies that used passive or active sensors to measure river inundation area or flood extent were reviewed. In this section, a small group of studies that attempted to use satellite data to estimate river stage or discharge are discussed. Such efforts will likely become more common in the future as satellite orbital errors decrease and high-resolution multi-temporal data become more plentiful. Data availability has already increased with the launch of the ERS-1, ERS-2, JERS-1 and RADARSAT spaceborne SARs, which are not limited by weather conditions or darkness. Even more data are anticipated from future high-resolution SARs (JERS-2, ENVISAT-1, RADARSAT-2) and visible/infrared sensors (Landsat-7, ASTER, SPOT 5 and 6).

Radar Altimetry of Water Surface Elevation

Radar altimetry has emerged as a promising method for directly measuring stage variations in large rivers. Radar altimeters emit a short, nadir-directed radar pulse to the Earth's surface. The two-way return time is used to calculate the range between the satellite and the target. Because the pulse is in the form of a curved wave front, a time-varying waveform is returned to the satellite. An on-board tracker, which assumes a gradually changing surface (i.e. ice sheets and water bodies), is used to estimate when the return echo will arrive. Interactions with the surface cause the waveform to be distorted. If the tracker receives a rapidly changing echo, the tracker may not 'lock' properly and range estimates are lost. For this reason, radar altimeters generally do not work well over land. However, where a lock on the land power return is maintained, it is possible to identify peaks in the waveform data that result from specular returns over large rivers (Guzkowska *et al.*, 1990). These spikes progress through the waveform as the satellite passes over the

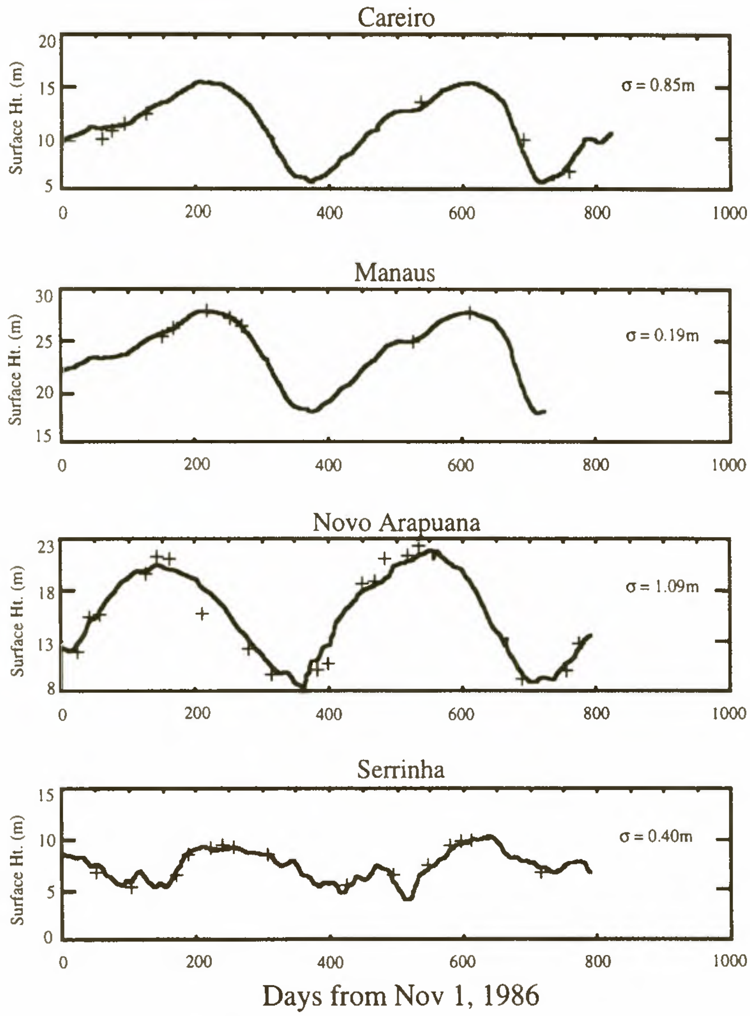

Figure 2. Comparisons in river stage at four sites in the Amazon basin, as estimated from river gauges (solid line) and Geosat altimeter waveforms (pluses). Standard deviations of the differences between the altimeter and river stage data are also shown. Period of observation is from November 1986 to November 1988. (Adapted from Koblinsky *et al.*, 1993)

river. Koblinsky *et al.* (1993) used this approach with Geosat waveform data to estimate river stage at four sites along the Amazon. The derived water surface levels are presented with the corresponding ground measurements in Figure 2. Altimeter ranges were calculated by manually selecting specular returns from the waveform data. An average root mean square error of 0·7 m was found between the ground and altimeter estimates of water surface level. Uncertainties in the ground stage measurements (*ca.* 10 cm or more) and the radial component of the satellite orbit (estimated at 50 cm) were major contributors to this error.

Birkett (1994) obtained lake level changes using a similar analysis of Geosat altimeter waveforms. Her results suggest that radar altimetry can be used to measure relative water level changes in lakes within 10 cm. For very large lakes, waveform analysis is not required to obtain good estimates of water level: Morris and Gill (1994) used average height estimates from the Geosat altimeter to estimate levels in the five Great Lakes of the United States, with an average root mean square error of 11·1 cm. Average heights are a standard altimeter product and represent the average water level over the altimeter footprint, which typically has a radius of several kilometres.

Errors in orbital precision pose the greatest problem to using satellite altimetry to measure stage in rivers or lakes. The Geosat orbital error has been estimated at about 50 cm (Koblinsky *et al.*, 1993), although it has been subsequently reduced through recomputation of some of the 17-day exact repeat mission (ERM) orbits (Morris and Gill, 1994). However, this problem is steadily diminishing as satellite tracking systems improve. The radial component of the ERS-1 orbit is determined to within 15 cm; the equivalent error is only 3 cm for TOPEX/Poseidon (Le Traon *et al.*, 1995). ERS-1 orbital errors have been reduced even further by using TOPEX/Poseidon data to minimize the variation in measured sea surface heights at points where the two satellite tracks cross (Le Traon *et al.*, 1995). As altimeters with small orbital errors (such as TOPEX/Poseidon) become more common, radar altimetry over inland water surfaces may become routine for those sites where a lock on the land surface can be maintained.

Water–surface Elevations from Satellite Imagery and Topographic Data

River stage can be estimated at the land–water contact, using high-resolution satellite imagery in combination with topographic maps or a digital elevation model (DEM). Requirements for this approach are high image and topographic resolution and an unobscured water edge boundary along an area of gently sloping relief. Gupta and Banerji (1985) used topographic maps and Landsat MSS data to obtain water surface elevations for a large reservoir in India. Land–water contact elevations were chosen along two low-gradient, inundated stream channels near their confluences with the reservoir. The derived water surface elevations agreed closely with values estimated from measurements surveyed on the ground.

Miller (1986) used Landsat MSS and 1 : 50 000 topographic maps to obtain spot water surface elevations over the Belize River in Central America. Flood volumes subsequently estimated by assuming mean inundation depths of 1·5–3·0 m were in general agreement with volumes calculated from hydrograph analysis. However, significant parts of the land–water boundary were obscured by vegetation, limiting the spot elevations to areas near permanent lagoons. Brakenridge *et al.* (1994) used ERS-1 SAR images and 1 : 24 000 US Geological Survey topographic maps to pick water edge elevations at gently sloping alluvial fans along the Mississippi River during the ‘Great Flood’ of 1993. Instantaneous flood stages differed by as much as 2·4 m at opposite sides of the Mississippi River, illustrating the value of this approach for estimating flood profiles and monitoring flood wave dynamics.

Correlation of Inundated Area with Ground Measurements of Stage or Discharge

A third method for estimating river stage or discharge from space is by correlating ground measurements of these variables with satellite-derived estimates of inundation area. Until recently, the major obstacle to this approach has been the requirement of a large number of satellite images to construct empirical rating curves relating inundation area to stage or discharge. Kruus *et al.* (1981) compared total inundation areas from seven Landsat MSS scenes over the St John River in New Brunswick, Canada with simultaneous measurements of river stage. They found a general increase of stage with inundation area, but at some times an increase in stage was associated with a decrease in inundation area. Usachev (1983) used a similar approach to determine the relationship between inundation area and ground measurements of stage and discharge in the Ob River of Siberia. In all of the Ob River analyses, increasing stage or discharge was associated with increasing inundation area. The correlation was quasi-linear and quite similar for three study sections at Mogochin, Kolpashevo and Kargasok. Xia *et al.* (1983) presented a strongly linear correlation between water surface area and ground measurements of water level for Dongting Lake, China’s second largest freshwater body.

Until additional empirical rating curves relating inundation area to ground measurements of stage or discharge are made, it is difficult to assess their potential for extrapolation to other rivers of similar morphology. However, it seems likely that such curves will vary significantly between rivers and therefore must be constructed for each site. An exception may be the special case of braided rivers, which display an extreme spatial sensitivity of water surface area to changing discharge, and also share some common morphological properties. Smith *et al.* (1995) used multi-temporal ERS-1 SAR data and simultaneous

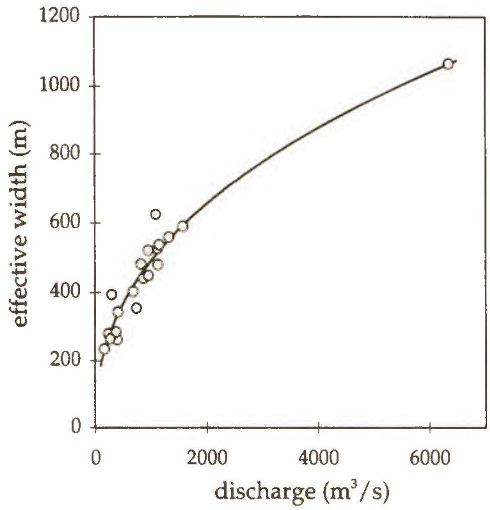

Figure 3. Relationship between satellite-derived effective width and river discharge for a large braided river in Canada. Effective width is the total water surface area contained within a 10 km × 3 km river reach, divided by the reach length. Each point is determined from a single ERS-1 SAR image and a ground measurement of discharge. The outlier is an extreme flood event; maximum annual flows do not normally exceed 2000 m^3/s. (From Smith *et al.*, 1995)

ground measurements of discharge to derive a stable, power-law correlation between satellite-derived water surface area and discharge for a large braided river in Canada (Figure 3). Subsequent work (Smith *et al.*, 1996) found similar curves for two other braided rivers in Alaska and Canada. A theoretical power-law correlation between water surface area and discharge was also found (Smith *et al.*, 1996), using a cellular model of stream braiding (Murray and Paola, 1994). Moderate differences in the satellite-derived rating curves relating water surface area to discharge are explained primarily by the intensity of braiding, with braid channel morphology and valley slope exerting smaller effects. In the absence of ground data, it appears that this method can be used to estimate relative discharge in order to determine the shape and timing of seasonal hydrographs in braided rivers. Absolute discharge can be estimated within a factor of two, with more accurate estimates requiring one or more ground measurements of discharge acquired simultaneously with a satellite image acquisition. More work is needed to determine if known morphological controls, such as total sinuosity, valley slope, bank material and stability, and braid channel hydraulic geometry, can be used to parameterize empirically derived rating curves for extrapolation to other ungauged braided rivers.

CONCLUSIONS

High-resolution visible/infrared sensors such as Landsat provide good delineation of flood extent where clouds, trees or floating vegetation do not obscure the water surface. Passive microwave radiometers show promise for acquiring estimates of inundation area over very large rivers or wetlands, but sensor resolution is coarse and the land–water boundary cannot be located accurately. Spaceborne synthetic aperture radars (SARs) are not limited by weather conditions or darkness. Single polarization, C-band SARs are effective for mapping smooth, open water bodies. However, emergent vegetation, trees, wind or flow turbulence can all increase radar back-scatter returns, making delineation of inundated areas problematic. L-band SARs can penetrate forest canopies and often display increased returns over flooded forest produced by a double-bounce mechanism between inundated tree trunks and the water surface. Multi-frequency polarimetric SAR provides much more information and can be used to classify different types of inundated terrain to an extent not possible with single-frequency SARs and visible/infrared sensors. However, there are no current plans to launch a multi-frequency, fully polarimetric SAR on a satellite platform. As a consequence, a synergistic remote sensing approach utilizing both visible/infrared and SAR data may be the only effective way to monitor inundation area in vegetated riverine environments. Visible/infrared data will provide good discrimination of flood extent in open areas, identify places where vegetation is a problem and help with interpretation of SAR data. SARs will provide excellent temporal coverage and, in certain situations, will be able to determine the flood extent through emergent plants and forest canopies.

As satellite orbital precision and data availability improve, promising methods for estimating river stage and discharge should continue to develop. Radar altimetry shows potential for measuring stage in large rivers to within 10 cm. Orbital laser altimeters such as GLAS (Geoscience Laser Altimeter System), planned for launch in 2003, should also permit monitoring of stage variation in large rivers. Landsat and ERS-1 SAR data have been combined with topography to obtain water surface elevations at the point of contact between water and land. This approach can also be used to determine lateral asymmetries in river stage and estimate the flood profile. Satellite-derived estimates of water surface area have been correlated with ground measurements of stage or discharge to obtain rating curves that can subsequently be used to estimate these flow variables from satellite data alone. Transfer of such empirical rating curves to estimate discharge in ungauged basins appears feasible in the special case of braided rivers, which are spatially sensitive to changing discharge and commonly share some morphological similarities between sites.

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CHARACTERIZATION OF FLOOD INUNDATED AREAS AND DELINEATION OF POOR DRAINAGE SOIL USING ERS-1 SAR IMAGERY

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ABSTRACT

Recent years have been marked by a continuous availability of spatial SAR data since the launch of the European remote sensing satellite (ERS-1) in 1991. Consequently, remote sensing techniques now offer an opportunity to map flood inundation fields caused by river overflow or waterlogging in environments characterized by frequent cloud cover. Indeed, inundation fields can clearly be seen on ERS-1 SAR images taken during flooding periods. However, such an identification can be constrained by the similarity in behaviour between water surfaces and other features of the landscape such as extended asphalt areas, permanent water bodies and less illuminated slopes. For consistent flood inundation extent mapping a more robust approach is required. This is provided by a conceptual flood inundation index that is physically sound in relation to radar imaging. Moreover, this index has proved to be useful for highlighting soils located within inundation fields and having significantly different internal drainage. The results achieved in the framework of the research must be seen in the context of intensive use of remote sensing data to support decision methods for sustainable management of land and water resources. Such decision support methods could be provided by river hydraulic models aimed at assessing environmental effects of inundation floods and at early flood warning systems.

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KEY WORDS Flood inundation; ERS-1 SAR; remote sensing

INTRODUCTION

Agriculture, in its broadest sense, and tourism are important economic activities in Wallonia (southern Belgium). Much of these two economic activity types, plus some city services, are located in the neighbourhood of floodplains. They are, therefore, frequently subjected to the threats of heavy flooding during winter periods as a result of rainfall leading to river overflow.

For proper protection and remedial measures with respect to flood inundation calamities, local authorities are aware of the usefulness of a decision support method. This must necessarily include a suitable system for regional monitoring of high risk areas. To this end, a very promising data source is earth observation satellite information.

The region of concern occupies the whole southern part of Belgium and is frequently subjected to cloud cover. This makes weather-independent satellite imagery a prerequisite link for the design of any decision support method in relation to flood monitoring during winter periods. Moreover, decisive events that favour the rapid design and implementation of a proper method for regional monitoring of high risk areas are

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the recent great floods that occurred in northern Europe during the winter periods of 1993 and 1995. These floods did not spare Belgium despite its forecasting and prevention/control methods, which have long been developed, tested and implemented.

RESEARCH EMPHASIS AND SPECIFIC OBJECTIVES

Research emphasis

The research is focused on the evaluation of broad environmental information, particularly satellite information, and its transformation into an appropriate database for end-users such as river hydraulics modellers or public services in relation to sustainable land and water resources management.

Specific objective

The specific objective of the research is to provide a proper methodology for mapping flood inundation fields caused by river overflow during the winter period in an environment, such as that of Wallonia, characterized by frequent cloud cover in the context of consistent flood monitoring.

STUDY SITE AND DATA REQUIREMENTS

General considerations for site selection

The availability of data has determined the selection of the study site. Indeed, the research was carried out taking advantage of the availability of two types of information with respect to the problem studied:

radar satellite information that may be acquired at day or night in all weather conditions. This type of information is provided by the ERS-1 satellite;

conventional cartographic data (topography, soil) and on-field investigation data (stream water level measurements, information from previous research activities).

The strategy adopted during the research has consisted of evaluating the different types of information through a methodology that takes into account their complementarity.

For the above reasons, a subcatchment including a segment of the Lesse River between the cities of Wanlin and Houyet and the Biran water course has been selected. The Biran is a tributary of the Lesse River. The site has been subjected to previous hydrological research activities (Mokadem *et al.*, 1988; Dewez, 1993), and was thus selected for basic investigation with regards to mapping of fields. The River Lesse is a tributary of the main river flowing through Wallonia, the Meuse.

Basic database

The data set required for carrying out the research is given in Table I.

Table I. Available database and its usefulness to the problem of flood inundation mapping

Basic data	Related issues
Radar data (ERS-1 SAR–GEC) frame 2601 (08/12/92) (Figure 1b) frame 2601 (12/01/93) (Figure 1a)	Mapping inundation fields Analysis of radiometric variation within
Traditional cartographic data Topography Soil	support to inundation field mapping (by of potential inundation zones)
Field investigation, results from previous research	Conceptual support to flood inundation mapping

METHODS AND MAIN RESULTS

General considerations

The research has been carried out keeping in mind the need for consistent estimating and monitoring, at a regional scale, of hydrological variables such as flood inundation extent.

The methodological tools designed and implemented are mainly related to:

identification of inundation fields on ERS-1 SAR images taken during the flooding period;

detection of change in soil surface conditions by colour composite technique, as a means of qualitative mapping in inundation fields; and

detection of change in soil surface conditions from a conceptual index application, as a means of quantitative inundation field mapping and radiometric variation study within inundated zones in relation to soil hydrodynamic characteristic.

All SAR images used in the framework were first speckle reduced. For the speckle reduction, it was found that for rural environments, where large homogeneous textural areas exist, a median filter provides satisfactory means. For a spatial resolution similar to that of ERS-1 SAR images (12.5 m $\times$ 12.5 m) an optimum is achieved by applying the median filter once in a 7 $\times$ 7 moving window or twice in a 5 $\times$ 5 moving window.

Approach to inundation field mapping

Inundation fields identification on flood period SAR image. Inundated areas are clearly seen on SAR images (Henderson, 1987), and thus on ERS-1 SAR data (Figure 1a). The one SAR image-based assessment and mapping of flood extent resulting from river overflow relies on the fact that the generally smooth surface of inundation water in the absence of marked wind gives a nearly specular reflection. Specular reflection in terms of radar back-scattering always results in a low intensity signal, leading to low back-scattering coefficient values. The pixels characterized by specular reflection will appear in a dark grey tone. Inundation-free areas, because of a rather high back-scattering coefficient value, will appear in a bright grey tone. However, in areas characterized by well-marked relief, SAR images can show shadows, located at foothills, which will also appear in a dark grey tone resulting in possible confusion with inundation water surfaces. Moreover, extended asphalt areas and permanent inland water bodies during still wind will have similar behaviour to inundation fields. Confusion is possible from observation of the ERS-1 SAR image of the study site taken during the normal period (Figure 1b). That is to say that, unless we apply change detection techniques to SAR imagery of the same ascending or descending phase nature, it will be rather difficult to distinguish between inundation fields and other landscape features showing similar radar back-scattering characteristics.

Inundation field mapping from temporal SAR data analysis. The miscellaneous constraints that may be encountered when a single SAR image of the flooding period is considered could be relieved by applying change detection techniques to a temporal set of SAR data (Singh, 1989). The temporal SAR data must be made of an image taken during the normal, off-flooding, period and an image acquired during the flooding. Two change detection techniques can be investigated in the framework of this project: colour composite and conceptual index application.

Colour composite technique. The colour composite technique applied to radar imagery relies upon the following basic principles: (i) Any temporal change of soil surface condition can be expressed in terms of surface 'roughness' (r) or 'smoothness' (s); and (ii) the change in surface condition is translated in terms of the back-scattering signal intensity. A rough surface will have a high radar back-scatter coefficient value and will therefore tend to be bright. On the other hand, a smooth surface will tend to be dark because of a low back-scatter coefficient value resulting from a rather specular reflection response or to strong signal attenuation. The changes in surface conditions will result in changes of colours from basic [red (R), green (G), blue (B)] to a resultant combination (yellow, cyan, magenta). If a colour resulting from the combination

(a) (b)

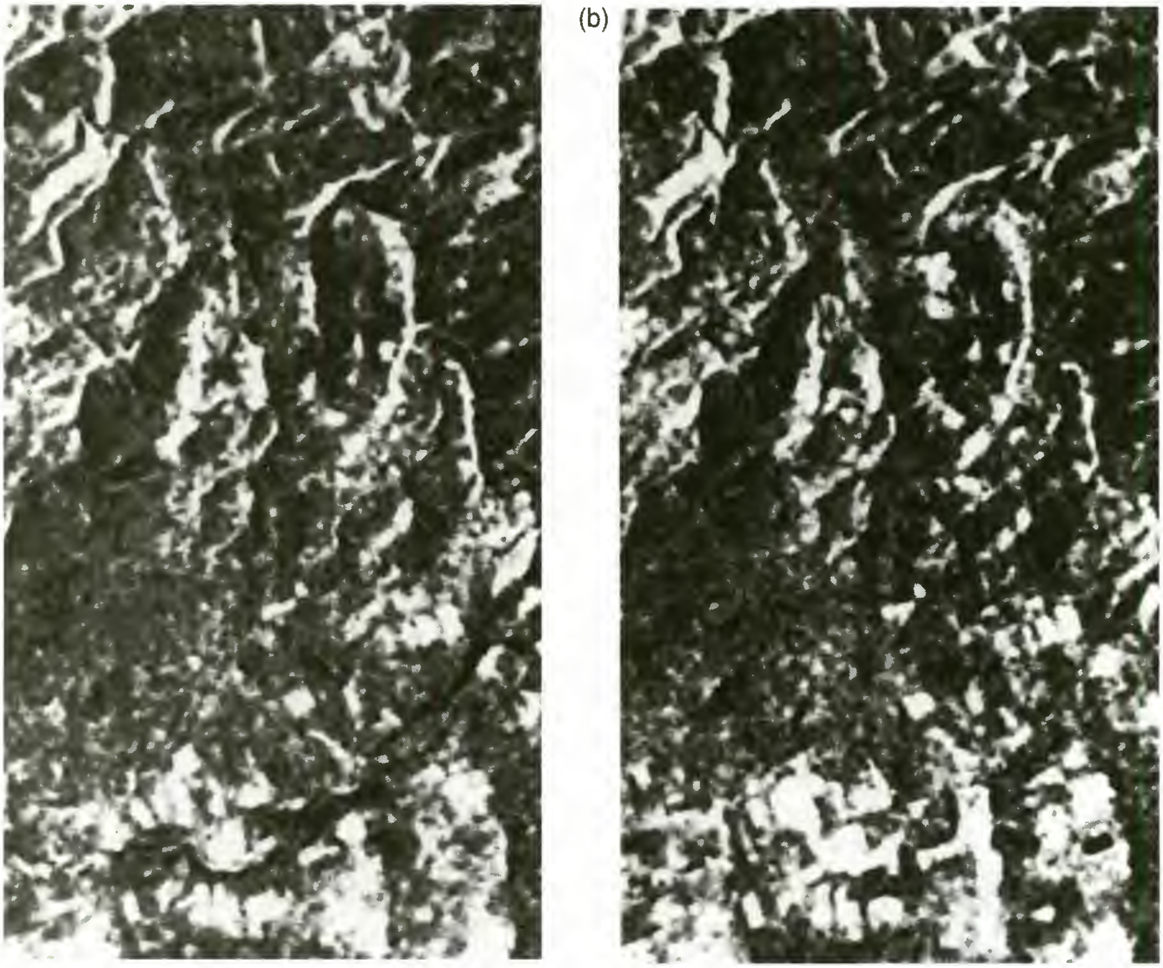

Figure 1. ERS-1 SAR image of the study site taken on (a) 12 January 1993 during flooding, and (b) on 8 December 1992 at a normal (off-flooding) period

of the basic colours is noticed, this must be interpreted as a conservation of surface condition. This means, for example, that an inundated-free surface at date 1 (red) has remained inundation-free at date 2 (green) if the resulting colour is yellow.

In summary, the presence of a basic colour on the derived image means a change in surface condition. If a colour resulting from the combination of the basic colours is noticed, this must be interpreted as a conservation of surface condition.

In cases such as the assessment and extent mapping of flood inundation areas along rivers, and when a simple cartographic image has to be generated, the visual image enhancement is of most importance. As a consequence, the change detection technique based on interpretation of a colour composite image is the correct technique to apply.

Conceptual index definition and application. The colour composite technique approach to inundation extent mapping cannot be integrated straightforwardly to conventional cartographic data for geographic information system design. This specific constraint is relieved by applying change detection index analysis, namely the normalized difference index. The basic principle of the conceptual index is the strong dependence of the radar back-scatter intensity on surface dielectric properties. It has been noticed that, with other determining parameters being constant, radar back-scatter intensity will increase as soil moisture increases. It will then reach a maximum in the neighbourhood of saturation and decrease as the soil gets covered by inundation water (Badji *et al.*, 1994).

The conceptual index used in the specific framework of the research is expressed as the normalized difference of the radar back-scatter intensity function. The function considered calls on the linear relationship that exists between radar back-scatter intensity $< I >$ and image digit number (DN) squared. Therefore, the expression of the conceptual flood inundation index (ICN) is as follows:

$$ICN = K\,.\,(DN_{\mathrm{n}}^2 - DN_{\mathrm{i}}^2 + e)/(DN_{\mathrm{n}}^2 + DN_{\mathrm{i}}^2 + e)$$

where e is a small positive constant introduced to prevent the denominator from becoming zero, K is a constant (set equal to 100) aimed at enhancing the dynamic range of index values, and DN_{n} the radar digit number of the norma image (off-inundation) and DN_{i} the radar digit number of the inundation image.

The image derived form the index calculation presents maximum values at inundated pixels. These pixels appear white in the grey scale. For convenience the derived image has been reversed to show inundation fields in black (Figure 2).

Delineation of poor internal drainage soil

Basic concept. With regards to the radiometric variation with inundation fields, it is generally accepted that, with all other factors remaining invariant, the higher the near-soil surface moisture content, the higher the radar back-scatter intensity. A wetland, owing to the rather poor internal drainage of its soil, will tend to remain moist for a longer time period compared with a soil with favourable drainage characteristics. A wetland will therefore present a higher radar back-scatter coefficient value during off-inundation periods. During inundations, because of the specular reflection nature of the smooth water surface the resulting radar back-scattering will have a rather low intensity. Thus, by applying the change detection principle, soils that significantly differ by means of their internal drainage characteristics will be highlighted.

Soil map information. The fact that a soil series has been adopted as the basic classification unit in Belgium has made the soil map a precious means for mapping floodplains and depressions. Soil series, as indicated in Table II, are characterized by texture, internal drainage class and profile development. Therefore, the Belgian soil legend clearly differentiates soils of valleys and depressions because of their lack of profile development, thus providing a means to delineate these entities.

Table II. Classification of soils in Belgium based on their texture and internal drainage status. A soil is generally characterized by three letters; for example, Afp, where A designates the textural class, f the drainage class and p the profile development status

Internal drainage class	U-E-A-L	Z-S-P
a: excessive drainage	–	very dry soils
b: favourable drainage	without gley	dry soils
c: moderate drainage	slightly gleyed	moderately dry soils
d: imperfect drainage	moderately gleyed	moderately humid soils
h: rather poor drainage without a reduction horizon	strongly gleyed (temporary water table)	humid soils
i: poor drainage without a reduction horizon	very strongly gleyed (temporary water table)	very humid soils
e: rather poor drainage with a reduction horizon	strongly gleyed with a reduction horizon (permanent water table)	humid soils
f: poor drainage with a reduction horizon	very strongly gleyed with a (permanent water table)	very humid soils
g: very poor drainage	a full reduction horizon	extremely wet

Textural class legend: Z: sand; S: loamy sand and clayey sand; P: slightly loamy sand; L: sandy loam; A: loam; E: clayey material and U: heavy clay

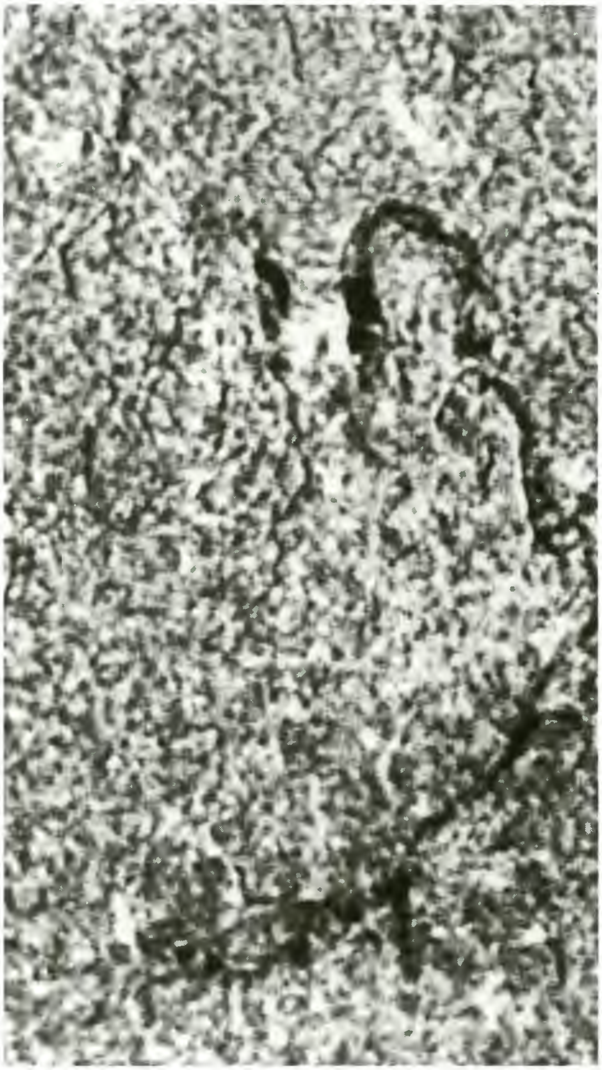

Figure 2. Inundation fields map from conceptual index application. The inundated zones are indicated in black

The flood inundation map from index analysis is controlled through result superimposition with the floodplain and depressions derived from the soil map (Figures 3a and b). A floodplain or a depression is generally characterized by a less developed soil profile (index p as third letter in soil series classification).

Radiometric variation with inundation and soil drainage characteristics. Slope conditions determine the overland runoff velocity. Thus, topography is the leading factor for external drainage conditions. In fact, overland runoff velocity increases with increasing slope. However, water will accumulate in depressions and valleys leading to hydromorphic conditions except in the case where deep percolation ensures rapid drainage. The rate of deep percolation is determined by the soil internal drainage condition.

The principles of Belgian soil classification have provided the means to validate the basic concept for delineating poor drainage soil with radar imagery, namely ERS SAR. The concept is implemented through a normalized difference index which was used to characterize radiometric variation within inundation fields as shown in Figure 4. The soils are grouped into three classes according to their internal drainage characteristics: very poor, moderately poor, poor.

(a)

(b)

Figure 3. (a) Potential inundation zones (floodplain) map of the study site obtained from the Belgian soil map. (b) Inundation field map control by superimposition of index application results and digital floodplain

Figure 4. Radiometric variation within flood inundation field and soil internal drainage characteristics (white: very poor; grey: moderately very poor; black: poor)

CONCLUSIONS AND PROSPECTS

Conclusions

Microwave response is dependent upon surface roughness, soil moisture, texture and geometry, and vegetation cover, as well as characteristics such as wavelength, polarization and incident angle. Therefore, one could reasonably expect this response to have a complex non-linear pattern. Consequently, temporal SAR data analysis applying the principle of the normalized difference index appears to be the most appropriate technique for unambiguous flood extent mapping along river valleys and for delineation of floodplain poor internal drainage soil. Indeed, the inundation field, although clearly seen on ERS-1 SAR images taken during the flooding period, can be constrained by similarity in behaviour between water surfaces and other features of the landscape. Thus, a consistent flood inundation extent mapping and monitoring will generally not be feasible considering an image taken during the inundation period alone. A more robust approach is provided by a conceptual flood inundation index which is physically sound in

Figure 5. An example of flood inundation map updates in Wallonia obtained by superimposition of inundation fields from ERS-1 SAR data and the scanned topographic map

relation to radar imaging. Applied to a properly selected temporal radar data set, this index has proved to be consistent in mapping inundation fields resulting from river overflow or waterlogging under an environment frequently dominated by cloud cover. Moreover, this index could be used to highlight soils located within inundation fields and having significantly different internal drainage characteristics. Data obtained from the index calculation can be directly integrated into other geographically related data sets such as optical satellite images, for further detailed analysis of land use affected by inundations.

Prospects

The vulnerability of an area to inundation, resulting from river overflow or waterlogging, can be expressed in terms of the frequency and duration of flooding. Thus, vulnerability to inundation can be related to area location within floodplains and depressions. The concept of area vulnerability to inundation is, nowadays, basic to land planning in Belgium. Therefore it could be reasonably expected, that the results achieved here would be validated in the framework of inundation map updates in Wallonia, as shown in Figure 5. Indeed, the information on flood extent derived from radar imagery analysis is actually used in the Walloon Ministry for Equipment and Transport to update inundated area maps along the Sambre, Meuse and Lesse river valleys. This was done in the framework of a programme aimed at providing local government with the *ad hoc* information for land use planning. Updating of the inundated area maps was achieved by overlaying the results of flood extent assessment from SAR images on digital topographic maps provided by the ministry.

The main goal of the programme was to allow combination of SAR data with a GIS for early identification of potential areas of water retention, which in turn will allow land planners to identify regions at risk of flooding and to allocate appropriate resources for damage prevention and control.

Finally, the results achieved here could also be evaluated within the framework of activities aimed at sustainable management of lowland areas located in Sahelian African and of some subtropical river catchments.

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