Use of remote sensing data in a GIS environment for water resources management

GERT A. SCHULTZ
Institute of Hydrology, Water Resources and Environmental Technology, Ruhr University Bochum, D-44780 Bochum, Germany

Abstract While in the field of hydrology remote sensing techniques are often applied and well accepted there is still a deficit in the use of remote sensing techniques in the field of planning, design and operation of water resources systems. It is the aim of this paper to overcome this deficit and encourage water managers to use remote sensing techniques more widely. In order to achieve this, several successful examples of applications of remote sensing to water management are presented, viz. in the fields of design of water supply reservoirs, reservoir sediment monitoring and control, flood forecasting and control, hydropower scheduling, irrigation scheduling and groundwater exploration for water supply purposes. It is shown that remote sensing data cannot be directly used for these purposes since the electromagnetic data observed by remote sensors have to be transformed into hydrological relevant information. Some techniques are presented, how this can be achieved.

INTRODUCTION

During the last two decades a considerable number of publications was produced, which show actual and potential application of remote sensing information to hydrology (Rango & Ritchie, 1996). This information may be used directly, e.g. as survey of areas covered by snow, detection of areas inundated by floods, precipitation measurements, water quality monitoring etc.. Remote sensing data are, however, particularly useful in the field of hydrological modelling, where such an information can be used for both, the estimation of hydrological model parameters and as input to hydrological models. It seems, that nowadays the use of remote sensing data in the field of hydrology is beyond doubt and some of the techniques developed are already operational, while others are still in the research stage. It is surprising that despite the fact that remote sensing gained wide acceptance in the field of hydrology in the closely related field of water resources management the use of remote sensing information is still underdeveloped. Therefore, the main focus of this paper is directed to the attempt to convince water managers of the usefulness of application of remote sensing data in water resources management. Since such attempts are usually most successful, if convincing examples of practical applications are given, the remainder of this paper consists in the presentation of several examples, in which it is shown, that remote sensing data can, in many cases, strongly support necessary activities in the field of water management.

EXAMPLES OF REMOTE SENSING APPLICATION TO PLANNING AND MANAGEMENT OF WATER RESOURCES SYSTEMS

Out of the examples presented below the first one shows an application of remote sensing in the field of planning and design of water resources systems, while the others deal mainly with the application of remote sensing data to the operation and management of water resources systems. Several different types of remote sensors and platforms are presented in these examples, viz. ground-based weather radar, echo-sounders used on a boat, and several types of satellites and sensors, viz. Meteosat, NOAA, Landsat.

Design of water supply reservoirs with insufficient data

In many regions of the world, particularly in developing countries, water managers are often faced with the problem to design a water resources system, e.g. a water supply reservoir for a city or an irrigation system, where no or almost no hydrometeorological information is available. Many failures of such water supply systems are due to the fact that they were designed with inadequate hydrological data. In such situations usually an observation system consisting of one or a few river gauges with equipment for velocity measurements is installed. The data collected during the design period form the basis for the estimation of the required reservoir storage capacity, in order to meet the demand. Such short time series (usually between one and three years) are highly inadequate for this purpose since reservoir design requires the estimation of the reliability of a reservoir to meet the demand. In order to quantify such statistical parameters it is necessary to have long time series of hydrological data available. The idea of the technique presented here consists in the trick to extend the short observed runoff data time series with the aid of remotely sensed data, in this case satellite data obtained from the European satellite Meteosat. In order to compute the required long time series of monthly runoff values at the site where the dam is to be erected, the following principle was developed: At the beginning of the design period of the water project (if no hydrological data are available) a hydrological network (at least one streamgauge) is installed which collects data in form of "ground truth" during a short period (planning period), e.g. between one and three years only. A mathematical model was developed which connects this ground truth to data obtained from satellite (Meteosat) imagery. The parameters of the nonlinear mathematical model are calibrated based on short-term simultaneous satellite and ground truth data. After this calibration procedure it is possible to reconstruct historical river flows with the aid of the mathematical model just based on satellite data, for the whole period of time for which satellite information is available (e.g. 20 years). Thus the very short time series of observed hydrological ground truth is extended considerably into the past. This way a long time series of monthly runoff values is generated exhibiting the same statistics (mean, variance, autocorrelation) as the short observed time series. With the aid of this extended runoff time series it is possible to estimate the expected future performance of the intended water project and thus the reliability of the planned reservoir to meet the demand. The principle of the technique is illustrated in Fig. 1. The model works in two consecutive steps:

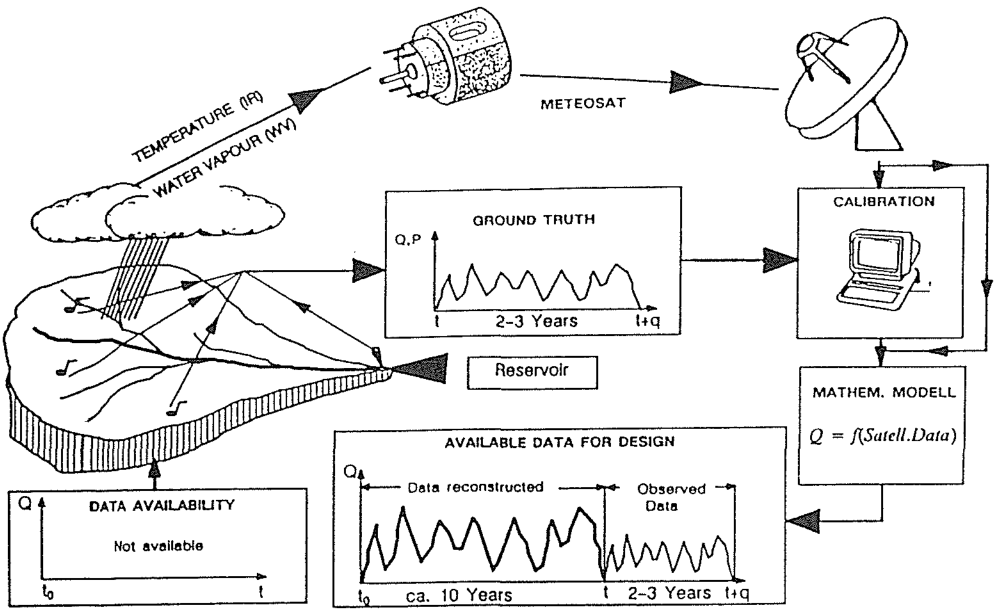


Fig. 1 Principle of generation of long runoff time series for the design of a water supply reservoir with the aid of satellite imagery (Meteosat).

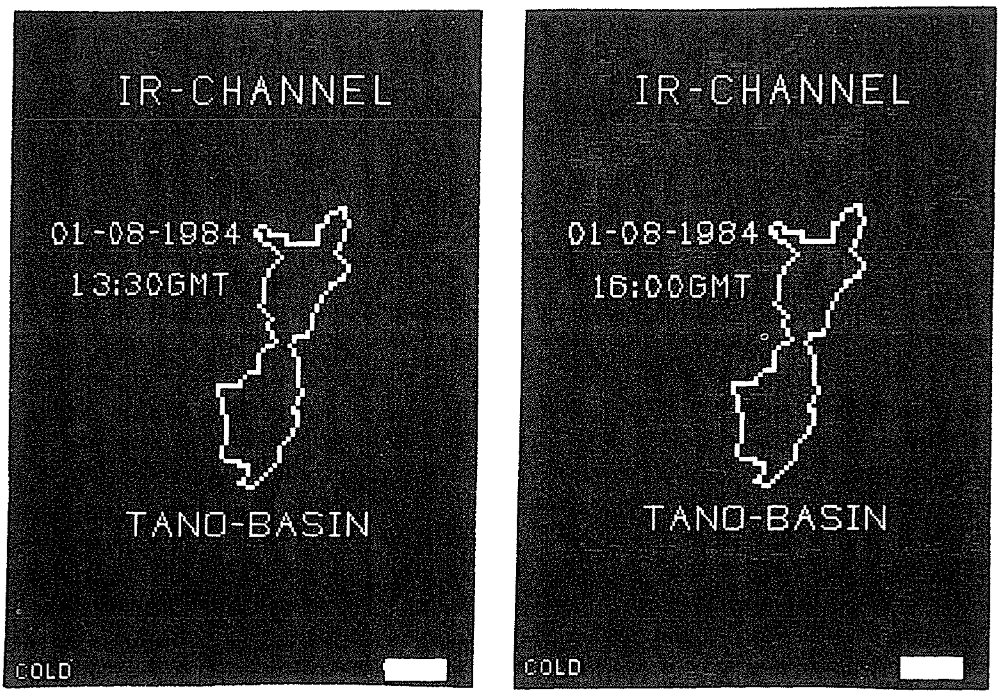


Fig. 2 Cloud development, Tano River basin, Ghana, West Africa. Two successive Meteosat IR images.

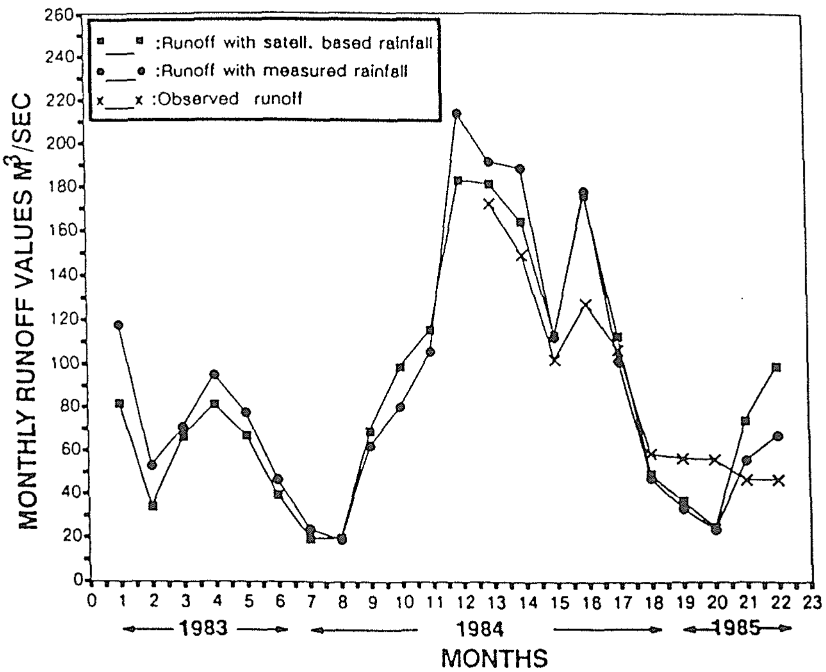


Fig. 3 Monthly runoff, Tano River basin (16 000 km^2), Ghana, West Africa: observed, computed from observed rainfall and from Meteosat IR data.

(a) estimation of monthly precipitation values with the aid of Meteosat infrared data and
(b) transformation of the monthly rainfall volumes into the corresponding runoff values with the aid of the calibrated model.

The model was applied to the Tano River basin (16 000 km^2) in Ghana, West Africa. Figure 2 shows two consecutive infrared Meteosat images of the region of the Tano River in Ghana. The spatial resolution of Meteosat is 5 km $\times$ 5 km, the temporal resolution is 30 minutes. The relatively coarse spatial resolution allows the application of this technique only for larger drainage basins, i.e. larger than *ca.* 5000 km^2. The high temporal resolution of Meteosat provides 48 images per day in three spectral channels. A sensitivity analysis carried out at the authors institute showed that it is sufficient to use only one spectral channel, i.e. infrared (IR), and to select only two images per day. Furthermore for the comparatively large drainage basin of the Tano River it was sufficient to use a coarser spatial resolution of the Meteosat data, i.e. the Meteosat level B2 data, which are represented by only every 6th pixel in a row and every 6th row. This way it was possible to reduce the tremendous amount of available Meteosat data by a factor of 2500 without any significant loss of accuracy. A detailed description of the model and its sensitivity analysis is given in Papadakis (1994). An example of the model performance is given in Fig. 3, which shows the monthly runoff of the Tano River in three different curves. One represents the observed runoff, the second shows the runoff which was computed with the rainfall runoff model based on observed rainfall data (ground

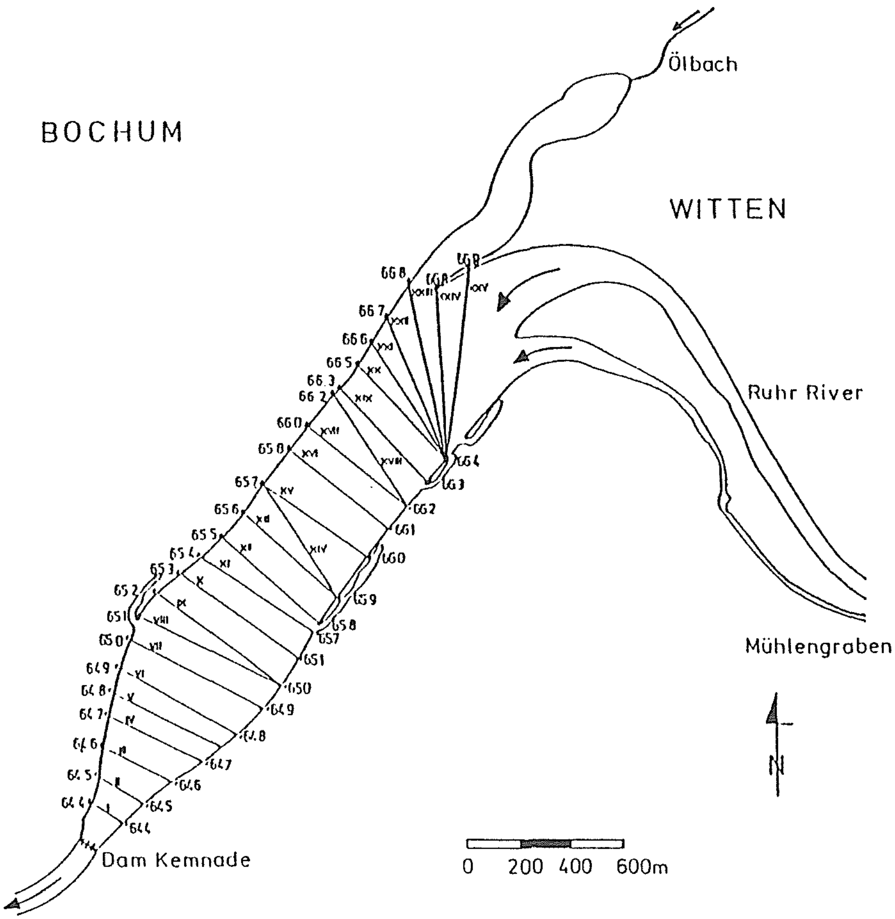


Fig. 4 Lake Kemnade with cross-sections.

truth) and the third curve represents monthly runoff values calculated based on remote sensing information (Meteosat, IR data). As can be seen from Fig. 3 the agreement between the three curves is relatively good, which means that it is certainly sufficient in a statistical sense for the design problem under consideration.

Reservoir sediment monitoring and control

Dams built to store water for various purposes (e.g. water supply, irrigation, hydropower) usually undergo sediment processes, i.e. erosion or silting up. It is very important to know the state of sedimentation within a reservoir in order to either prevent deterioration of the reservoir due to erosion or to restore the reservoir capacity in case of silting up (e.g. by excavation of sediments). Both processes, erosion and silting up, are unfavourable for the use of the reservoir: erosion since it endangers the structure of the dam itself, siltation since it reduces the available storage capacity considerably. Since a reservoir is a three dimensional body the required knowledge of the reservoir state can be gained only with the aid of monitoring techniques showing a high resolution in space. Under such conditions remote sensing techniques are very useful, in this case multifrequency echo sounding taken from a boat in a multi-temporal fashion, which allows detection of changes of the sediment conditions. In the example presented here, both, erosion and silting up of a reservoir occurs. Figure 4 shows the reservoir Lake Kemnade in the Ruhr River valley in Germany. Twenty-five cross-sections can be seen, which are observed periodically by echo sounder from a boat. Figure 5 shows a cross-section in the upper region of the lake eight years after construction. We observe siltation in the centre and the right hand part of the cross-section, while there is some minor erosion in the left part of the section. While in the upper region and centre part of the lake siltation is dominant, near the dam and close to the weir erosion is the dominant process. The cross-sections are taken with two frequencies of the echo sounder, i.e. 100 kHz and 15 kHz. While the latter indicates the fixed river bed, the former gives information on the upper edge of the sediment layer. The cross-sections obtained by the remote sensing technique give information on where in the lake sediment changes occur, and an integration over all cross-sections of the lake allows an estimation of the total change in sediment volume within the reservoir. Since in this lake siltation is dominant — like in most developing countries — the problem arises that storage capacity is decreasing over the years yielding the reservoir useless after some decades. In order to avoid this the relevant river authority dredges sediments out of the reservoir every couple of years. The location and quantity of sediments to be dug out can be taken from the cross-sections of the lake monitored with the aid of the echo sounder.

Flood forecasting and control

In recent years we observe increasing damages and losses of lives due to severe floods on all continents of the Earth. This shows that the problem of flood elevation still needs increasing attention. Flood warning on the basis of flood forecasts is one way to reduce problems, another — and better — way is reduction of floods with the aid of flood protection reservoirs. For both purposes, flood warning and the operation of flood protection reservoirs, it is necessary to have real time flood forecasts available. The usefulness of these forecasts is the higher, the sooner they are available. In order to gain lead-time of the forecast it is advisable to compute forecast flood hydrographs on the basis of rainfall observed in real time. Since the variability of rainfall in time and space is very high it is advisable to monitor rainfall with the aid of remote sensing devices having a high resolution in time and space. For this purpose ground-based weather radar operating on the basis of active microwave information is most useful. Figure 6 shows schematically the acquisition of rainfall information by radar and its transformation into real time flood forecasts, which in turn may be used for the computation of an optimum real time reservoir operation strategy. Figure 7 shows two consecutive isohyet maps of the Günz River drainage basin in Germany observed by ground-based weather radar. This information has a high resolution in time and space which can be used in order to

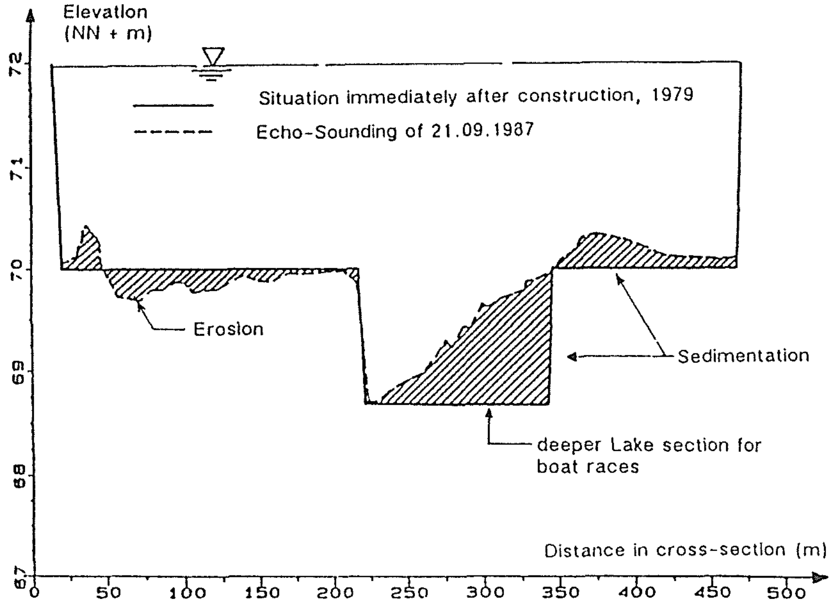


Fig. 5 Reservoir cross-section with sediments (Lake Kemnade, Ruhr River, Germany).

compute a forecast flood hydrograph in real time with the aid of a distributed system rainfall runoff model (Schultz, 1994). In order to gain lead-time it is not sufficient to base such forecasts only on observed rainfall, but rather on observed and forecasted rainfall. This implies the use of a real time quantitative precipitation forecasting technique. With the aid of observed (by radar) and forecasted rainfall it is possible to compute real time forecast flood hydrographs. Figure 8 shows such flood forecasts for different probabilities of nonexceedance in comparison to the (later) observed flood hydrograph. Although such forecasts are by no means perfect they are still useful for the computation of the optimum reservoir operating strategy of flood protection reservoirs as shown in Fig. 6. A method which is useful for the optimization of reservoir operation in real time is Dynamic Programming. Figure 9 shows the optimum operation of a flood for the two parallel reservoirs of the Breg and Brigach rivers with a dangerous double peak which occurred in February 1970. The computations are based on Dynamic Programming (Schultz, 1994).

FURTHER APPLICATIONS OF REMOTE SENSING TO WATER MANAGEMENT

Hydropower scheduling

In many regions of the world river runoff occurring in spring and summer originates from snowmelt in mountainous regions. Thus the hydropower production during Spring and Summer depends to a great extent on the quantity of snow which fell in the mountains during winter and early spring. If therefore the quantity of snow and its water equivalent is known early during the year it is possible to make forecasts of the expected runoff in the following months. If the reservoirs feeding the hydropower plants are large enough, it is possible to optimize hydropower production by scheduling the releases from the reservoirs to the power plants accordingly. This technique has been used already very early, i.e. in the late seventies and early eighties in Norway (Østrem *et al.*, 1981). Since most of the high mountain basins in Norway are not forested variations in the snow cover can easily be monitored with the aid of satellite data (e.g. NOAA). During the main snowmelt

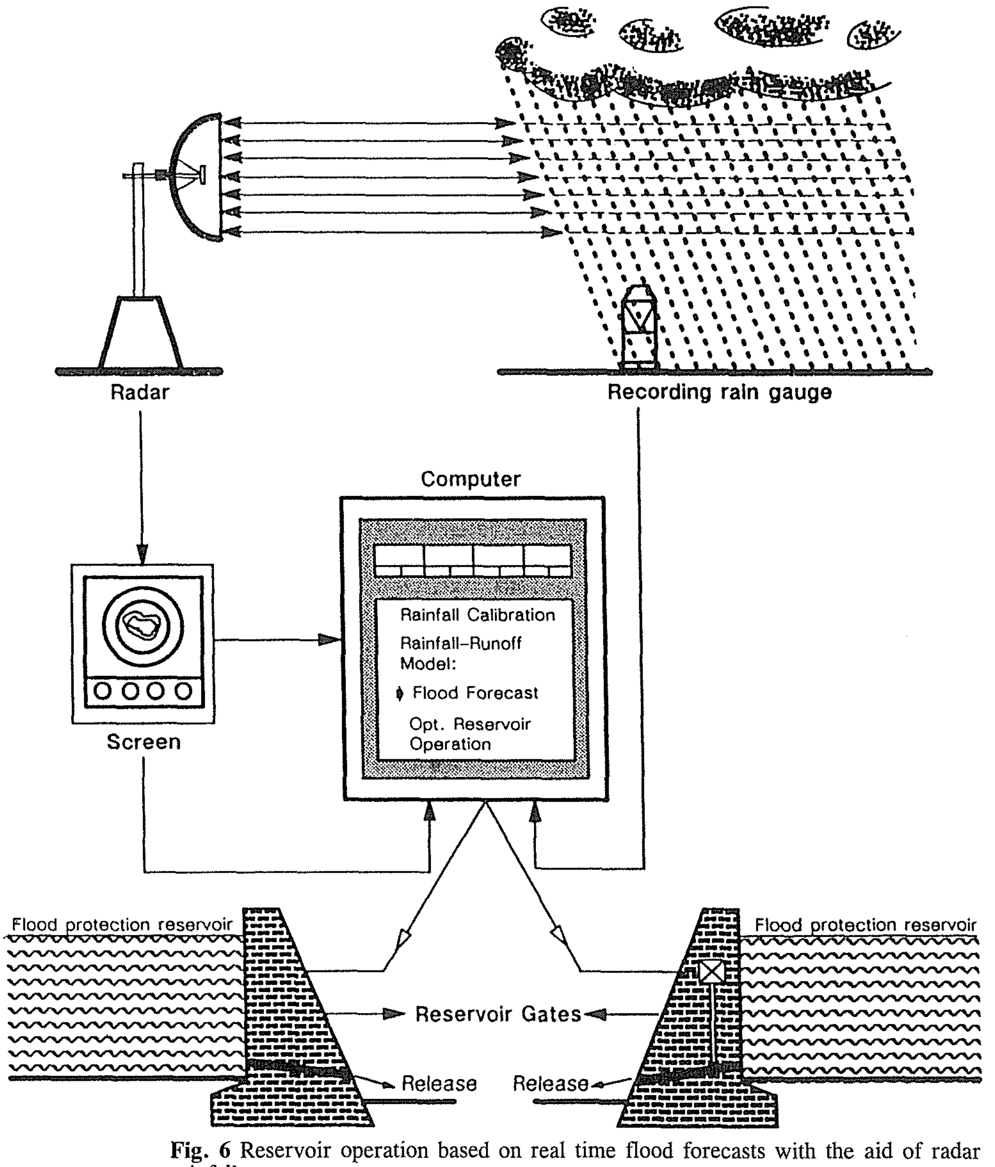


Fig. 6 Reservoir operation based on real time flood forecasts with the aid of radar rainfall measurements.

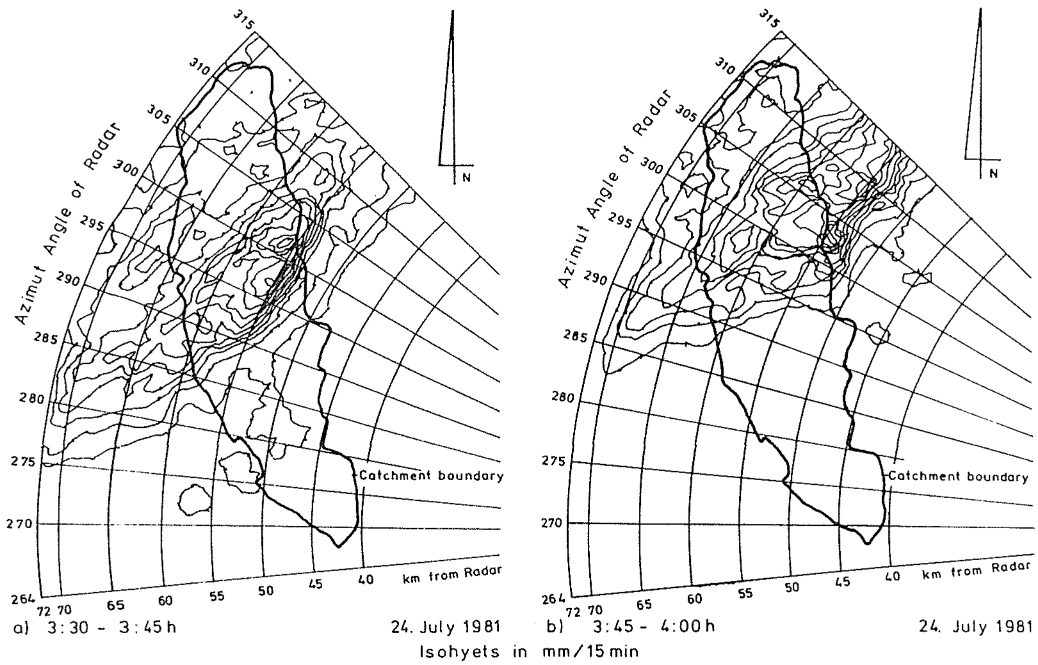


Fig. 7 Isohyets for the River Günz drainage basin, Germany, obtained from two consecutive radar measurements.

period, May to July, a forecast of expected river flows to be used in the power plants is of high interest for proper management of the plants. They use a known relationship between remaining snow cover and the meltwater flows during the following months based on some empirical relationship. Besides the knowledge of the snow cover also knowledge of the corresponding water equivalent is necessary. This can be obtained with the aid of remote sensing of snow covered areas by aeroplanes equipped with Gamma-ray sensors.

Irrigation scheduling

The allocation of water to the various farmers within a irrigation scheme is usually regulated by certain fixed rules. These rules may allocate certain quantities to certain farmers or allocate water proportional to the irrigated area. Such rigid rules may be sub-optimal since they cannot be adapted to actual and real time water demand of the crops according to their present state. It is better to allocate water either to match crop water requirements or to maximize effectiveness (Menenti *et al.*, 1996). In order to allocate water to match crop water requirements it is necessary to know the actual water demand of the crop in real time. As long as the water supply meets the demand usually no problems occur. If, however, crop water stress occurs the water allocation is certainly not optimal. In order to improve the situation in real time it is necessary to detect crop water stress. In order to do this crop water stress indices have to be defined and the major unknown parameters in such an index should be detectable with the aid of remote sensing data. Menenti gives information on the definition of such a Crop Water Stress Index which can be detected with the aid of thermal infrared measurements. The evapotranspiration of crops under stress is different from crops under normal conditions and this difference can be detected with the aid of e.g. thermal infrared data. These may be obtained with the aid of ground-based platforms, aeroplanes or satellites. More detailed information of this techniques is given in Menenti *et al.* (1996).

Groundwater exploration for water supply purposes

Direct groundwater exploration or observations with the aid of remote sensing techniques is not feasible due to the fact that most remote sensing techniques — with the exception of airborne geophysics and radar — have no penetrating capabilities beyond the uppermost layer, i.e. less than 1 m. Therefore, the use of remote sensing

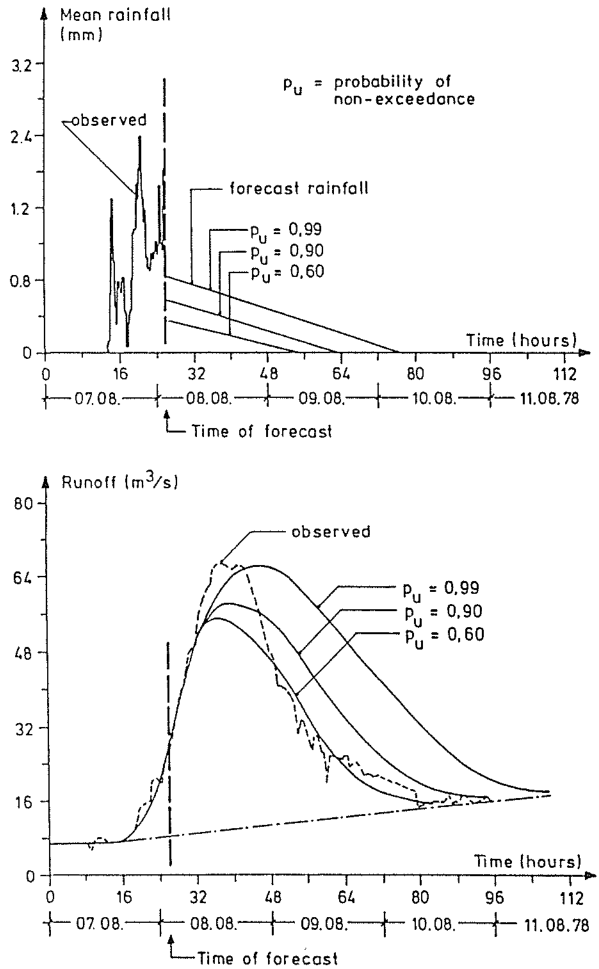
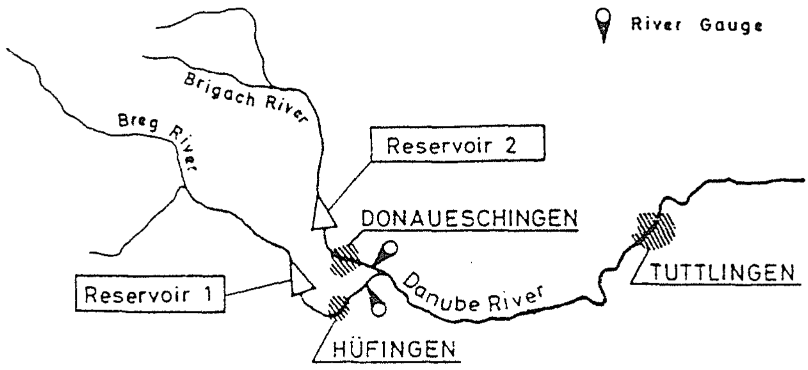


Fig. 8 Flood forecast based on radar rainfall measurement and rainfall forecast.



System Sketch, Danube River with Tributaries, Reservoirs and Cities to be Protected

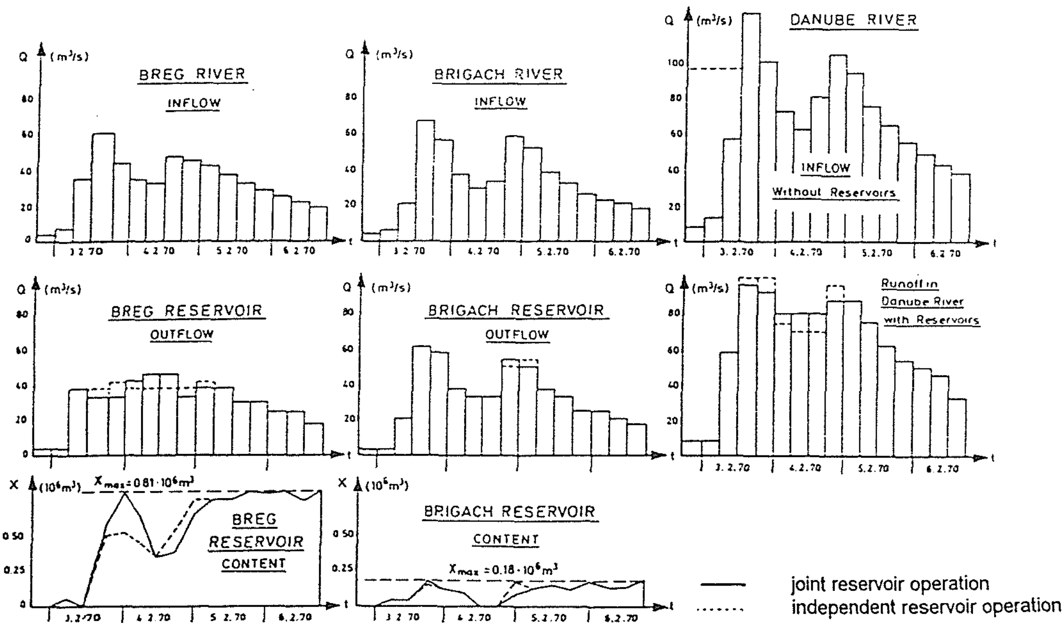


Fig. 9 Optimal release policy for two parallel reservoirs. Flood of February 1970.

techniques in groundwater exploration is limited to being a powerful additional tool to the standard geophysical methods. Therefore, the general application of remote sensing in hydrogeology lies in the domain of image interpretation, i.e. qualitative information, which is, however, very useful and may enable the groundwater explorer to reduce the very expensive conventional techniques considerably (Meijerink, 1996). This qualitative or indirect information, which can be obtained from remote sensing sources is e.g. (a) likely areas for the existence of groundwater, (b) indicators of the existence of groundwater, (c) indicators of regions of groundwater recharge and discharge and (d) areas where wells might be drilled. These indicators are usually based on geologic and geomorphologic structures or on multi-temporal observations of surface water and on transpiring vegetation. Landsat visible and infrared data are preferred for these purposes, but also other sensors including microwave sensors are used. In the thermal infrared band temperature changes in multi-temporal imagery may provide information on groundwater, e.g. areas containing groundwater being warmer than the environment in certain seasons of the year. Shallow groundwater can be inferred by soil moisture measurements and by changes in vegetation types and patterns. Groundwater recharge and discharge areas within drainage basins can be inferred from soils, vegetation and shallow or perched groundwater. Lineaments detected by Landsat or SPOT imagery are straight to slightly curving lines formed in many different types of landscape. Many linear features, which are not continuous may be extended or joint in image analysis. It is assumed that lineaments mark the location of joints and faults, which again are indicators of potential groundwater resources. Also soil type and changes in vegetation types and patterns in the area may give certain indications of the potential availability of groundwater. It should be stated, however, that in the field of groundwater exploration remote sensing information can only add to the conventional exploration techniques, but certainly cannot replace them.

CONCLUSIONS AND RECOMMENDATIONS

From current research activities as well as from experience in the field of remote sensing applications to water management the following conclusions and recommendations can be given:

(a) The current use of remote sensing information in the field of planning, design and operation of water resources systems still falls far below its potential.

(b) This deficit is certainly partially due to insufficient information on the remote sensing potential in the field of water management. In order to show the usefulness of such techniques and to encourage water managers to use them six examples of successful application of remote sensing to water management problems were given.

(c) Also for general information on water resources systems (e.g. landuse in a drainage basin, vegetation, construction activities) remote sensing data are most useful and if a multi-temporal approach is carried out changes in the area, for which e.g. a water authority is responsible, can be detected and documented for further use. Furthermore, monitoring of water quality can be achieved with the aid of remote sensing techniques — at least to a certain extent.

(d) From the examples given above it can be seen, that remote sensing data can almost never be used directly. The electromagnetic information obtained by spectral sensors has always to be transformed into other information, which is relevant in the field of hydrology. This transformed information can be used for water management purposes.

(e) Very often remote sensing information is most useful in combination with other information as shown in the section on groundwater exploration, flood control and hydropower scheduling.

(f) The activities of the space agencies (e.g. NASA, NASDA, ESA) are geared towards providing better remote sensing systems in the future. These future systems will have more spectral channels, higher resolution in time and space and provide better multi-temporal information. It can also be expected that ground-based weather radar systems covering large regions will be available in the near future at least in Western Europe, Northern America and Japan. These new remote sensing systems will provide water managers with more and better data services than presently available and thus give the water managers better opportunities to apply remote sensing information for the solution of their problems in the field of planning, design and operation of water resources systems.

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