Institute of Hydrology

[redacted]

Natural Environment Research Council

[redacted]

Commission of the European Communities

STORMS, FLOODS AND RADAR HYDROLOGY

Annual Report January to December 1993

Contract No. EV5V-CT92-0182

Institute of Hydrology
Maclean Building
Crowmarsh Gifford
Wallingford
Oxon OX10 8BB
UK

Tel: +44-(0)491-838800
Fax: +44-(0)491-832256
Telex: 849365 Hydrol G

Natural Environment Research Council

January 1994

Contents

Institution: Institute of Hydrology, United Kingdom

Project Leader: Robert J. Moore

Institutions cooperating: National Rivers Authority
Ministry of Agriculture, Fisheries and Food

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

The main objectives of the Institute of Hydrology programme are as follows:

(i) Use of a dense raingauge network and radar to quantify the rainfall field structure and to assess the accuracy of point and areal average rainfall estimates;

(ii) Exploration of high resolution rainfall estimation and forecasting methods that are physically-based and incorporate consideration of the vertical profile of radar reflectivity;

(iii) Development and assessment of distributed flood forecasting models based on the radar grid and utilising digital terrain, satellite land-use and soil survey data;

(iv) Assessment of Doppler/dual polarisation radar for hydrological use; and

(v) Use of radar data for design flood estimation and sub-grid rainfall parameterisation for large-scale hydroclimatological models used in flood-impact assessment of climate change.

METHODS AND MATERIALS

The Project will develop and use the HYREX (HYdrological Radar EXperiment) infrastructure centred on the Brue catchment in Somerset, South-west England. This will comprise a network of 52 recording raingauges over the 132 km^2 catchment gauged at Lovington and scanned by 3 radars: a new Doppler C-band radar at Cobbacombe Cross, a conventional C-band radar at Wardon Hill and an experimental Doppler dual-polarisation S-band radar at Chilbolton (Figure 1). A mobile vertical-pointing X-band radar will also be deployed by the University of Salford group within the catchment. Climate data from an Automatic Weather Station in the catchment will be complemented by more wide-ranging data on climate and upper air soundings from an existing network of synoptic observing stations. Additional data from the Thames basin, north-west England and south Wales will be used to support the distributed flood forecasting model and design/impact assessment components of the project.

RESULTS

1. HYREX Network Design and Implementation

A design for a dense network of recording raingauges over the 132 km^2 Brue catchment was formulated. This comprised 22 gauges at the centre of each 2 km radar grid square, two SW-NE lines of four squares each containing two gauges and two dense networks with 8 gauges per square in areas of low and high relief. The arrangement of the 8 gauge-within-a-square networks was chosen so that the mean of their values would provide the "best" estimate of the mean rainfall over the square: this resulted in a diamond-within-a-square configuration with sides .778 and 1.38 km respectively. This "design requirement" has been turned into an "operational design" following site visits and discussions with landowners. Installation began in September 1993 and in December was largely complete. The final "as constructed" design is shown in Figure 2. An Automatic Weather Station, sited in the 8-gauge low relief square, was installed on 2 September 1993 but problems with a distrometer have delayed its installation at the same site. Database management of the HYREX dataset is ongoing.

2. High resolution radar rainfall estimation and forecasting

A simple two-dimensional rainfall model based on the conservation of mass in a cloud column, originally developed at the University of Iowa, has formed the starting point of work on this topic. The model is being modified to accommodate UK data in the form of radar rainfall, Meteosat cloud top temperature, synoptic surface climate and upper air soundings. A Meteosat Receiver Station at IH has been enhanced to receive data over the UK, and has been collecting data since 21 August 1993. The raindrop size distribution parameter, originally constant, now varies as a function of rain rate. Also, in computing the beam height the earth's curvature is taken into account; changes to allow for conversion from radar rainfall in mmh^{-1} to kgm^{-3} have been made.

A major constraint in the use of the model is that UK radar data, at present, are only available for 4 elevations with the highest at 4°: this means that potentially the moistest parts of the troposphere are not sampled by the radar within a range of about 80 km. To improve matters the radar data have been interpolated onto a 3D grid, 5 km in the horizontal and 1 km in the vertical, using a 3D multiquadric interpolator over part of the range and a simple 1D vertical interpolator elsewhere. A 2D multiquadric scheme has been used to interpolate the Meteosat data onto the same regular 5 km grid over the 210 km radius scan range of the radar (Figure 3). Using a fixed vertical spacing for the radar data simplifies the calculation of vertically integrated liquid water content in the model. A 2D time-height form of multiquadric interpolation has been used to visualise the development over time of vertical profile measurements obtained from radiosondes (Figure 4).

Sample data for a major convective storm complex that occurred over southern England and Wales in June 1993 is being assembled to support initial work on model development and assessment: this dataset is expected to be complete in January 1994.

3. A distributed flood forecasting model based on the radar grid

A practical methodology for distributed rainfall-runoff modelling using grid square radar data has been developed for use in real-time flood forecasting. Problems associated with

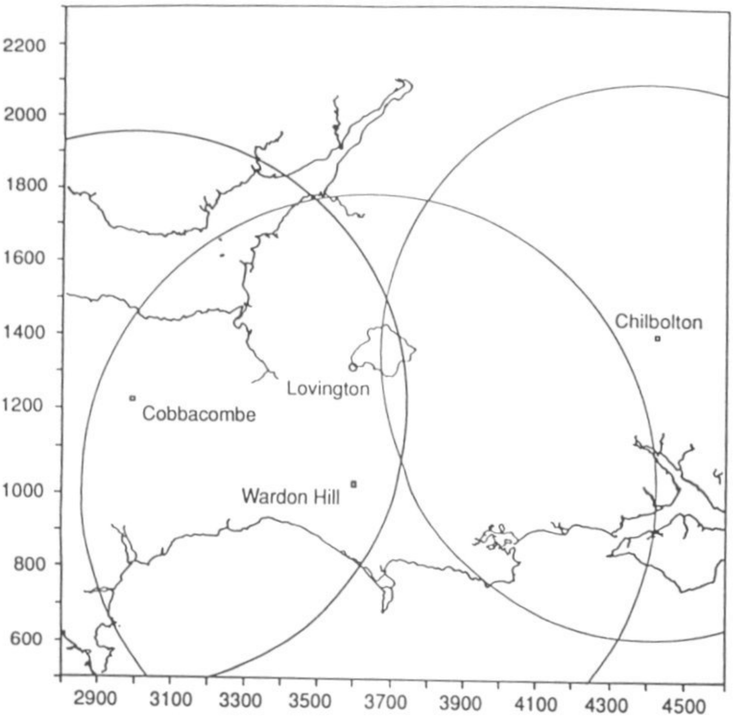


Figure 1 *The Brue catchment gauged at Lovington and the associated scanning radars (75 km radar circles indicated).*

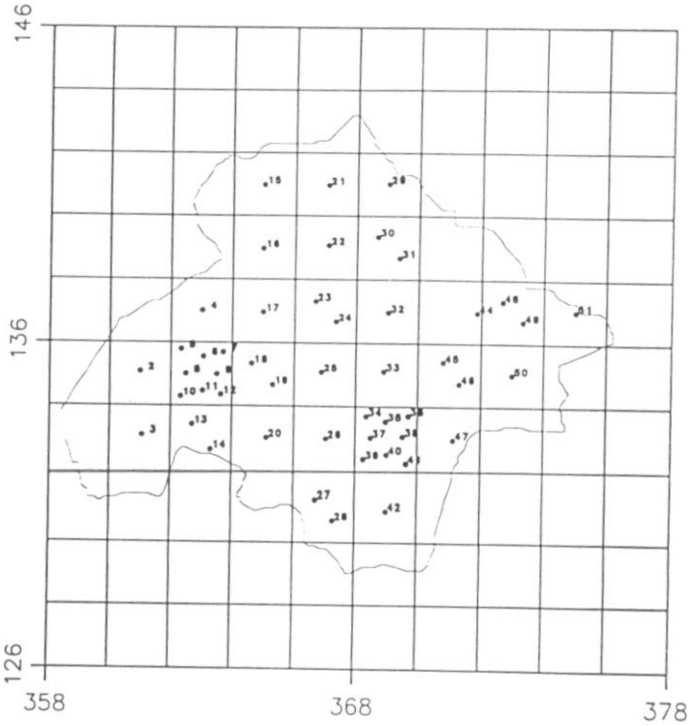


Figure 2 *The HYREX raingauge network within the Brue catchment*

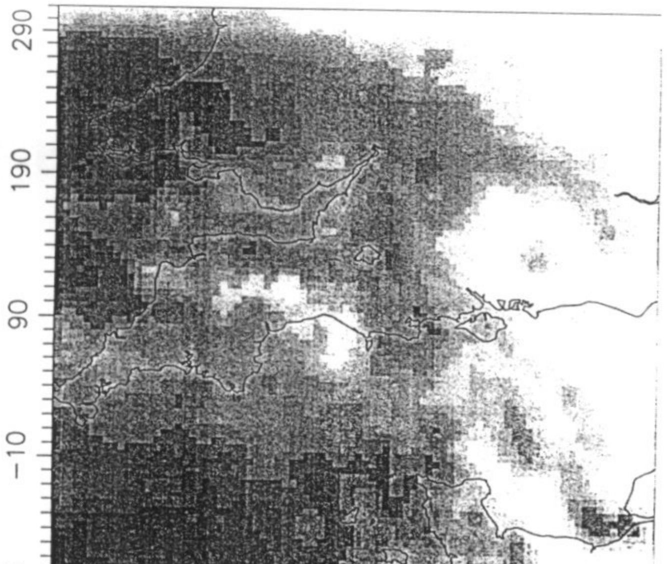


Figure 3 *Regular-gridded Meteosat cloud top temperature data over the Brue catchment and southern England and Wales, 12:02 13 November 1993.*

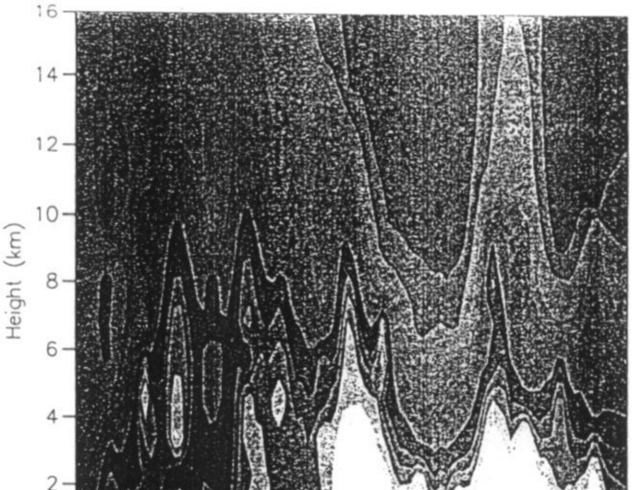


Figure 4 *Interpolated time-height radiosonde data: relative humidity at Herstmonceux, 23:00 to 17:00 12 June 1993.*

overparameterisation have been circumvented through the use of a Digital Terrain Model (DTM) together with simple linkage functions involving a small number of regional parameters suitable for automatic optimisation. A kinematic routing function is derived from the DTM via an extension of the classical isochrone concept; transfer of the DTM flow path information to the grid model allows flow velocities to be estimated as part of the overall model calibration process yielding optimised isochrones and improved forecasts. Runoff production from a grid square is represented, either in lumped or probability distributed form, using a slope-dependent storage capacity, a topographic index or an integrated air capacity soil survey value. An assessment of these model variants, using catchments in the Thames basin, South Wales and north-west England, indicates that the slope-dependent probability distributed storage capacity formulation, in conjunction with the DTM isochrone-derived kinematic routing model, provides the best overall performance. Incorporation of an impervious fraction, using Landsat-derived urban areas, also proves useful. Results suggest that when radar data are of good quality, model performance is improved by replacing data from a single raingauge by 2 km grid-square radar data. However, for the hillier catchments performance may be worsened at times when there is beam overshooting or low level enhancement of rainfall below the radar beam (Figure 5). Model extrapolation (without recalibration), using paired and nested catchments, proved only moderately successful with both good and bad results depending on catchment.

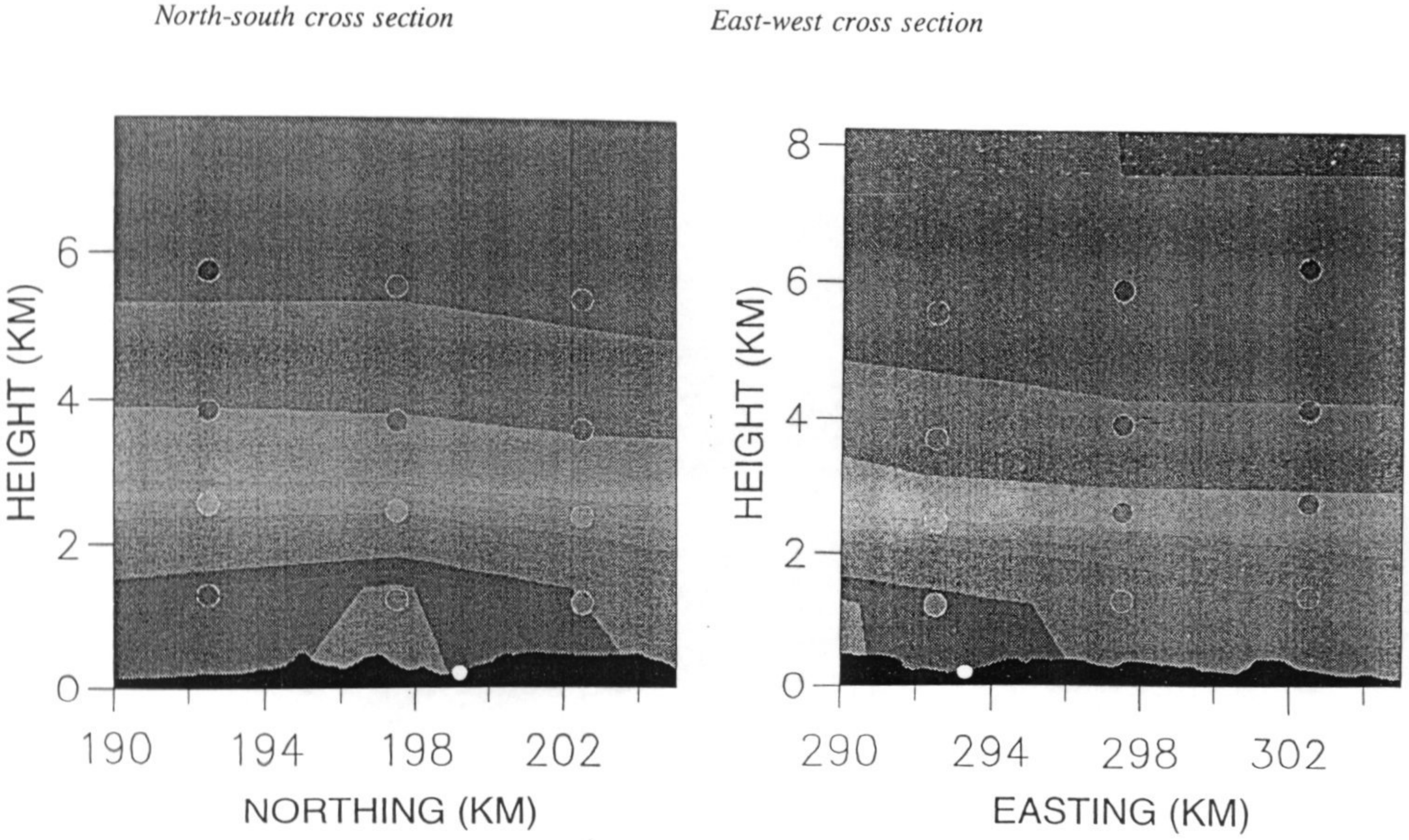


Figure 5 *Vertical sections through the Welsh DTM and the rainfall field derived from multiple beam data from Dyfed radar centred on the Tyn-y-Waun raingauge (marked as a small intensity-shaded circle) in the Rhondda at Trehafod catchment: 09:30 10 January 1993.*

4. Sub-grid rainfall parameterisation for large-scale hydroclimatological models

A major problem with global climate and continental-scale hydroclimatological models is the choice of parameterisation of rainfall variability at the sub-grid scale. If a lumped parameterisation is assumed this suppresses locally more extreme rainfall intensities and results in less flood runoff being generated within the grid. Radar data, together with satellite data, may be used to suggest appropriate parameterisations of rainfall at the sub-grid scale. In this project 2 km radar data from the London Weather Radar have been analysed at a variety of aggregation levels, in both space and time, focusing on the form of the probability distribution function (pdf) of rainfall at each level. The following distributions have been considered: exponential, lognormal, gamma, generalised Pareto and normal. The results suggest that a generalised Pareto distribution is most appropriate across a range of scales (2,4,8,10,20 km in space; 0,.25,.5,1,2,6,12,24 hours in time), with parameters α and β in the pdf

$$f(x) = \frac{1}{\alpha}\left[1 - \frac{\beta x}{\alpha}\right]^{\frac{1}{\beta}-1}$$

increasing with increasing time and space scales.

CONCLUSIONS AND ADDITIONAL REMARKS

(i) An inaugural meeting of the CEC Radar Hydrology Group was convened at Wallingford in March 1994.

(ii) The first year of the project has seen the design and implementation of the HYREX raingauge network over the Brue catchment and initiation of the data collection phase.

(iii) A model and database infrastructure has been built up to support work on high resolution rainfall forecasting using a physically-based model. The first model results should be obtained in the first quarter of 1994. A Special Interest meeting of the Radar Hydrology group in Barcelona provided an opportunity to exchange views on this topic with other CEC partners.

(iv) Work on a distributed rainfall-runoff model based on the radar grid and a DTM, has seen new model variants developed, and assessed using data from three radars. Good results are obtained when radar performance is unaffected by beam overshooting or low level enhancement of rainfall below the radar beam.

(v) Radar data have been used to investigate how rainfall variability within a large-scale model grid varies with space and time scale, and can suggest appropriate parameterisations of rainfall to use in global climate and hydroclimatological models to obtain improved runoff estimates.

REFERENCES

Austin, R.M., Hotchkiss, D.S. & Moore, R.J. (1993) Improvements in flood warning using radar-derived rainfall forecasts as input to rainfall-runoff models. Annales Geophysicae, Part

II Oceans, Atmosphere, Hydrology and Nonlinear Geophysics, Supplement II to Volume 11, C243, European Geophysical Society, Springer International.

Bell, V.A. and Moore, R.J. (1994) A distributed flood forecasting model using weather radar and digital terrain data. European Geophysical Society, XIX General Assembly, Grenoble, 25-29 April 1994, HS1 Open Session on Hydrology, to be presented.

Institute of Hydrology (1993) Siting of 8 raingauges in a square. HYREX Internal Report, 5pp.

Moore, R.J. (1993) Integrated systems for the hydrometeorological forecasting of floods. EUROPROTECH Conference: Science and Technology for the Reduction of Natural Risks, 6-8 May 1993, CSIM, Udine, Italy, 17pp.

Moore, R.J. (1993) Real-time flood forecasting systems: perspectives and prospects. British - Hungarian Workshop on Flood Defence, 6-10 September 1993, VITUKI, Budapest, 121-166.

Moore, R.J. (1994) Applications of Weather Radar Data to Hydrology and Water Resources, WMO/TD - No.?, Technical Report of Rapporteurs, World Meteorological Organization Regional Association VI (Europe) Working Group on Hydrology, 26pp, in press.

Moore, R.J., Austin, R.M. & Carrington, D.S. (1993) Evaluation of FRONTIERS and Local Radar Rainfall Forecasts for use in Flood Forecasting Models. R&D Note 225, Research Contractor: Institute of Hydrology, National Rivers Authority, 156pp.

Moore, R.J, Bell, V.A, Roberts, G. and Morris, D. (1994) Development of distributed flood forecasting models using weather radar and digital terrain data. National Rivers Authority R&D Note 252, Research Contractor: Institute of Hydrology, draft, 106pp.

Walsh, P.D., Moore, R.J. & Rodda, J.C. (1993) Use of weather radar data for hydrological forecasting. First European Conference on Applications of Meteorology, 27 September - 1 October 1993, University of Oxford, UK, 4pp.

Institution: University of Lancaster, United Kingdom

Project Leader: Professor Peter Young

Institutions cooperating:

Title of project: **STORMS, FLOODS AND RADAR HYDROLOGY**

MAIN OBJECTIVES

The major areas for investigation are:

1. Selection of a number of severe convective storm events from current and very recent years. Storms from a variety of radar sites will be selected in order to study the effects of contrasting topography and urban areas on convective storm development.
2. Investigation of the factors determining the relation between short-term raingauge and the associated radar data. These factors will include both the spatial and temporal characteristics of the storm cells as derived by a storm tracking procedure.
3. Comparison of the initiation and development of storm cells with descriptive, microphysical and meteorological models of convective storms. The aim is to develop a model to forecast the effects of topography and urban areas on the development of precipitation cells in convective storm events.
4. Development of an adaptive and predictive radar correction scheme suitable for use as the input to a distributed hydrological model.

METHODS AND MATERIALS

Preliminary work has involved the study of a number of severe convective storms covered by the Hameldon Hill radar site situated in northern England. The knowledge in the research group of the area covered by the radar, and experience of using data from this site, has been invaluable during this research programme. The factors being investigated, that may influence radar performance when a cell passes over a raingauge, include the direction of cell movement and also the position of a gauge relative to a storm cell and its motion. To determine cell movement, a method of tracking storm cells for the duration of their lifetime is being developed, both for short-term forecasting and identification of the aforementioned performance factors. In order to achieve objective results the cell tracking system is fully automatic. Preliminary results indicate that it will result in much more consistent sequences than the manual system it replaces.

Initial processing of a storm event creates a dataset of all the cells identified in each radar image, along with cell characteristic data, including maximum precipitation rate and cell area.

Subsequent processing of these data results in the creation of another dataset which indicates how cells in one frame are physically associated with cells in the next frame. While this second dataset is being created, the system keeps a running estimate of the velocity and other cell characteristics of each cell, such as how rapidly the cell area is expanding and the rate of change of total precipitation from the cell. This running estimate can be used instantaneously to achieve very short-term forecasting. When used in conjunction with details of a cell's behavior due to geographical and meteorological conditions, it provides information required for longer term forecasts.

The identified cell characteristics and cell movement analysis are being compared to the behaviour of precipitation cells generated in a three dimensional physical cloud model, in order to clarify the influence of surface properties such as slope, aspect, roughness and thermal properties. The results of this analysis will be used to create a model of cell and storm behaviour to be used in the longer term forecasting procedures mentioned above.

RESULTS TO DATE (JANUARY TO DECEMBER 1992)

Cell tracking

It has been found than the raw data made available to us contains varying amounts of unwanted interference such as shadowing, clutter and bright band. Techniques are being developed that reduce such unwanted noise, both by initial preprocessing and during the later cell tracking procedures. Cell centres are initially identified by locating local maxima within a radar image (Figure 1). Each cell's extent is determined by identifying those pixels surrounding each maxima where the pixel precipitation is greater than a specified percentage of the local maxima (Figure 2). Cell characteristics can then be collected for each identified cell area within each radar image of interest. These characteristics include:

1. coordinates of the cell centre, both weighted and geometric;
2. maximum rainfall rate within the cell;
3. coordinates of cell maxima ;
4. cell area;
5. total precipitation of the cell.

The above characteristics are then used to associate active cells in adjacent radar frames. A running dataset (initially empty) is used to project the cells within a frame forward in time and predict their possible effect on the subsequent frame. A genetic algorithm then determines the optimum combination of cell associations, deaths and births, as well as cell decomposition and recombination. This optimum combination is stored and the running dataset is updated with the new associations, which then provide cell projections when processing data from the next frame. The lines in Figure 3 represent the lifetimes of identified cells as a series of cell associations. Some cells can be seen to split and combine (frames 31-34), whilst other areas of interest stand out due to an 'explosion' in the number of cells and their subsequent recombination (frames 48 - 49).

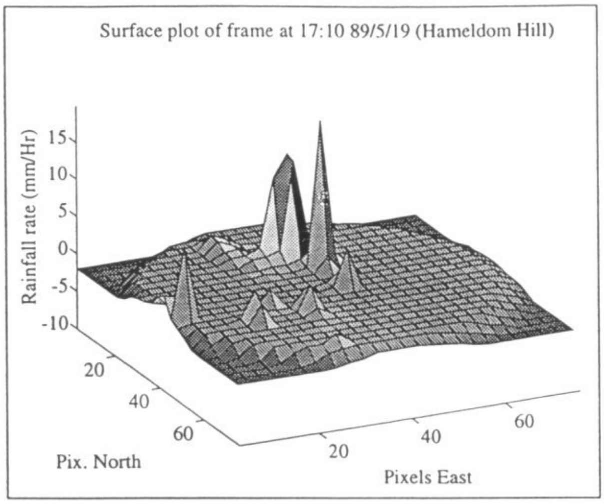


Figure 1

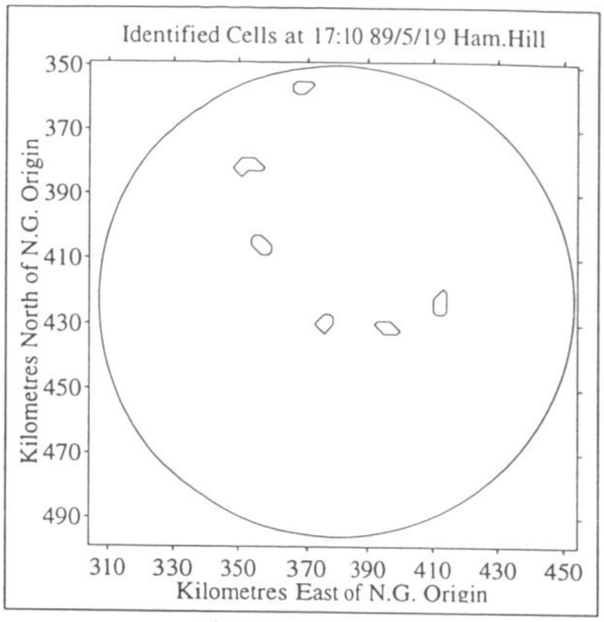


Figure 2

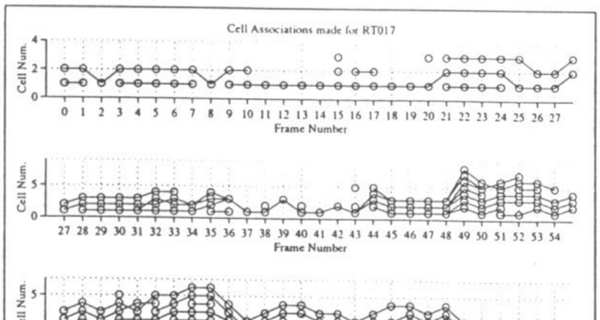


Figure 3

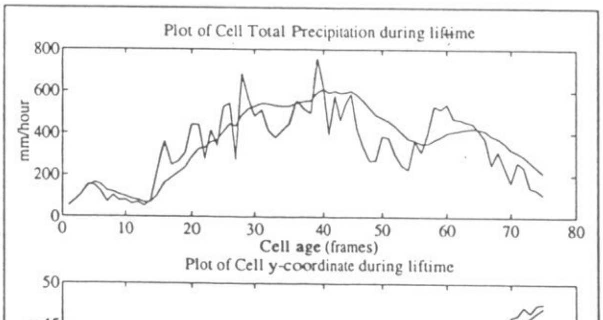


Figure 4

Short-term forecasting

Once the history of a cell has been determined, cell characteristics gathered earlier in the tracking process can be plotted with respect to an individual cell's lifetime. Figure 4 shows how the total cell precipitation and the y-coordinate of the cell centre vary throughout the lifetime of the longest lived cell in Figure 3. Also shown in Figure 4 is an estimate of the smoothed variations in the variables obtained by an optimal recursive Kalman filter. The derivative of this could be used to forecast the short term (half hour) value of a cell characteristic. Recent research has been concentrated on implementing this filter within the real-time cell tracking method, using procedures similar to those developed in another weather radar project being carried out by the Lancaster group. Also, a recursive, fixed interval smoothing version of the Kalman filter is being used for off-line analysis of the results obtained from different data sets.

Physical cloud model

Development of a physical cloud model has resulted in the simulation of a number of events based on real convective storms that occurred in the south Pennines during May 1989. Analysis of the simulations has revealed that cell creation was triggered by three basic mechanisms:

- forced lifting at windward slopes, assisted by an additional increase in surface temperature due to, for example, the presence of urban areas.
- cool air descending on the leeward side of a ridge pushing under warmer, more buoyant air. This mechanism is enhanced by the presence of incoming warm air possibly caused by a sea breeze.
- convergent surface winds, again triggered by the sea breeze effect, but also due to larger scale synoptic flow.

Cell movement is normally governed by the direction of steering level winds when cells are initiated by forced lifting. However, when triggered by the other mechanisms, the cells tend to remain stationary for some time before moving away in the direction of the steering level winds.

CONCLUSIONS AND ADDITIONAL REMARKS

1. An automatic cell tracking system has been developed that is capable of tracking precipitation cells as they mature, decompose or recombine. Short-term cell forecasting appears to be possible with the use of simple algorithms.
2. A recursive Kalman filter is being used to provide the cell tracking system with an on-line forecasting capability; a fixed interval version of the filter is being used for the off-line analysis of the results.
3. A three-dimensional, physical, cloud-based model has been developed, which suggests that there is an underlying pattern to the formation and propagation of precipitation cells. This pattern is related to the topography and land use of the area in addition to

the current synoptic situation.

REFERENCES

Thielen, J. & McIlveen, J.F.R. (in press) Topographical Influence on Severe Convective Storms. 2nd Int. Symposium on Hydrological Applications of Weather Radar, University of Hannover, 4-10 September 1992.

Collinge, V.K., Archibald, E.J., Brown, K.R. & Lord, M.E. (1990) Radar Observations of the Halifax Storm, 19 May 1989. Weather, 45, 345-365.

Thielen, J. (in press) Influence of the Central Pennines, England, on the Initiation and Development of Convective Storms. Rutherford Appleton Laboratory, Internal report.

Institution: Telford Institute of Environmental Systems, University of Salford, United Kingdom

Project Leader: Prof. I.D. Cluckie

Institutions cooperating: North West Water plc., NRA North West Region, Yorkshire Water Services

---

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

(i) Deploy a mobile X-band Vertical Pointing Radar (VPR) system at selected sites in the UK and possibly Germany in cooperation with EC partners;

(ii) Analysis of vertical reflectivity data, with particular attention paid to bright-band characteristics and dynamics;

(iii) Relate VPR measurements of rainfall to conventional scanning radar estimates (C-band or X-band as available);

(iv) Deploy the mobile system in areas subjected to orographic enhancement to obtain information on the rainfall structure and mechanism;

(v) Develop techniques which make use of information about the vertical reflectivity profile to correct for errors in scanning radar data.

METHODS AND MATERIALS

The project involves deploying a static VPR device, housed on the roof of the Telford Building at Salford University, and two trailer-mounted systems. The radar system is compact with low power requirements. Its main components are illustrated in Figure 1 and Table 1 provides a summary of the technical and operational features of the VPR. The high temporal and spatial resolution of the device enables storm characteristics to be studied in great detail from near ground level up to 12km altitude.

The static VPR at Salford measures the height-time variation of precipitation as it moves over the radar site, and therefore represents a *point* sample only. Deployed in conjunction with the Salford-based radar, the mobile systems enable the *spatial* variability of the vertical reflectivity profile and orographic effects to be studied. This research will take the form of selected transect experiments, initially in the North West of England, with the radars static and strategically positioned in order to monitor the passage and possible enhancement of a frontal rain system across the region.

Figure 1 *Schematic of the VPR system hardware components*

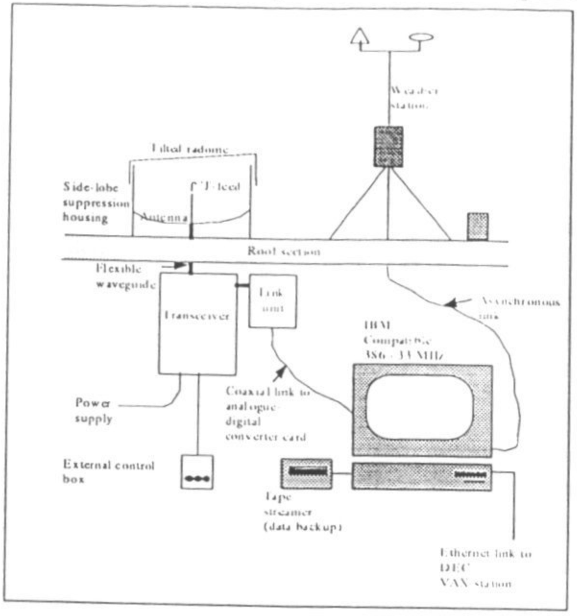


Table 1 *Overview of the VPR technical specification and operational characteristics*

General	
Radar type	Racal Marine Navigation Transmitter
Frequency	9380-9440 MHz
Wavelength	approx. 3cm (X-band)
Antenna	
Type	Parabolic reflector
Diameter	1.2m
Elevation	Zenith pointing
Beam	
Elevation	Azimuth (vertically pointing)
Beamwidth	1.8° (between half-power [3 dB] points)
Power	
Mean power supplied to antenna	12 dBW
Peak power " " "	44 dBW (25 kW)
Relative gain of antenna	38 dB
Radiative	
Pulse recurrence frequency	1300^a/ 650^b Hz
Pulse width	0.05^a/ 0.25^a/ 1.0^b ms
Polarisation	Linear
Observation	
Observation height range	from approx. 100m to 12000m (nominal)
Maximum vertical resolution	7.5 m
Maximum temporal resolution	2 seconds (256 pulses averaged over this period)

Each radar system is complemented by a ground-based transportable weather station which provides a full range of meteorological parameters (wind speed and direction, wet and dry bulb temperatures, humidity, barometric pressure, raingauge rainfall amounts). The information provided by the weather stations, along with radiosonde data, will be incorporated into case studies of the bright-band and orographic enhancement as well as the broader analysis of storm systems observed by the VPR and the recently commissioned Salford C-band scanning radar.

RESULTS

(i) Mobile VPR

The first of the mobile radar systems was deployed at Audenshaw (approx. 11 km east of Salford) for a ten-week period during the late summer. The aim of this initial two-point experiment was to collect and compare rainfall event data at the two locations, with a particular interest in the *bright-band*. The bright-band is a feature observed in radar reflectivity data and represents the layer in the atmosphere where falling ice crystals or snowflakes melt to form raindrops. The bright-band is associated with high reflectivities (created by the differing backscattering characteristics of dry ice and partly melted ice) and its presence in a scanning radar beam can adversely affect precipitation estimates by causing an overestimate of rain at the ground, particularly at close ranges to the radar. The bright-band may go undetected in scanning radar images due to the resolution of the data and/or variations in the width of the bright-band. The VPR yields valuable information on the dynamics of bright-band height, width and intensity which will be incorporated into current correction procedures for scanning radar data (section (v)).

One of the mobile systems will be involved in research in the south of England in conjunction with the HYREX (Hydrological Radar Experiment) study programme. Initially, the VPR will be sited close to the Chilbolton weather radar in Berkshire and the vertical profile data will be related to the scanning data to investigate X-band attenuation. Numerical modelling of the bright-band will also comprise a major part of the research to be undertaken.

(ii) Vertical profiles and bright-band climatology

The Salford VPR has been operating near-continuously since May 1991, creating an extensive data archive. Data are displayed as reflectivity values (dBZs) in the form of a Height-Time Indicator (HTI) from which a qualitative analysis of bright-band characteristics can be undertaken. Figure 2 is a frequency distribution showing the mean monthly height of the bright-band for the period May 1991 to August 1993 and clearly indicates a seasonal trend in the data, as might be expected. Figure 3 shows fluctuations in the height of the bright-band during the winter 1992-1993. The data plotted represent heights recorded both within and between events, hence the non-linearity of the time scale. The highly variable nature of the bright-band, even at the shortest time span, is prominent. A number of interesting height-change events have been selected and are catalogued in Table 2. Included are double bright-band events and instantaneous 'jumps', as well as more gradual height changes during the passage of frontal systems. Figure 4 shows HTI's from two of these events.

Figure 2 *Mean monthly height of bright-band layers over Salford*

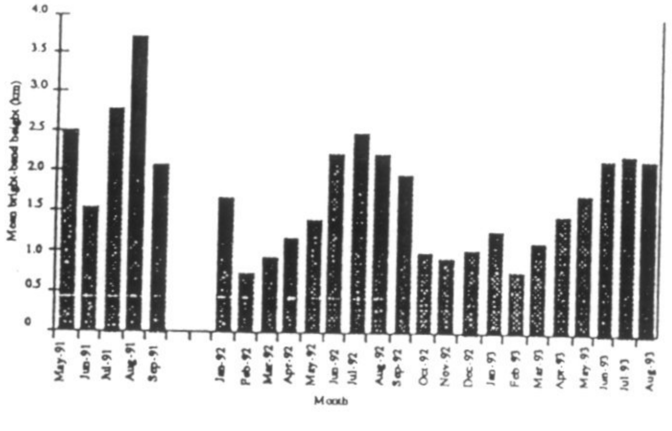


Figure 3 *Daily changes in bright-band height during the winter 1992/1993*

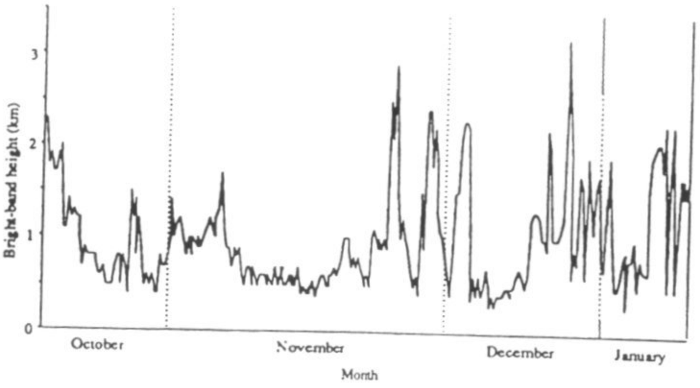
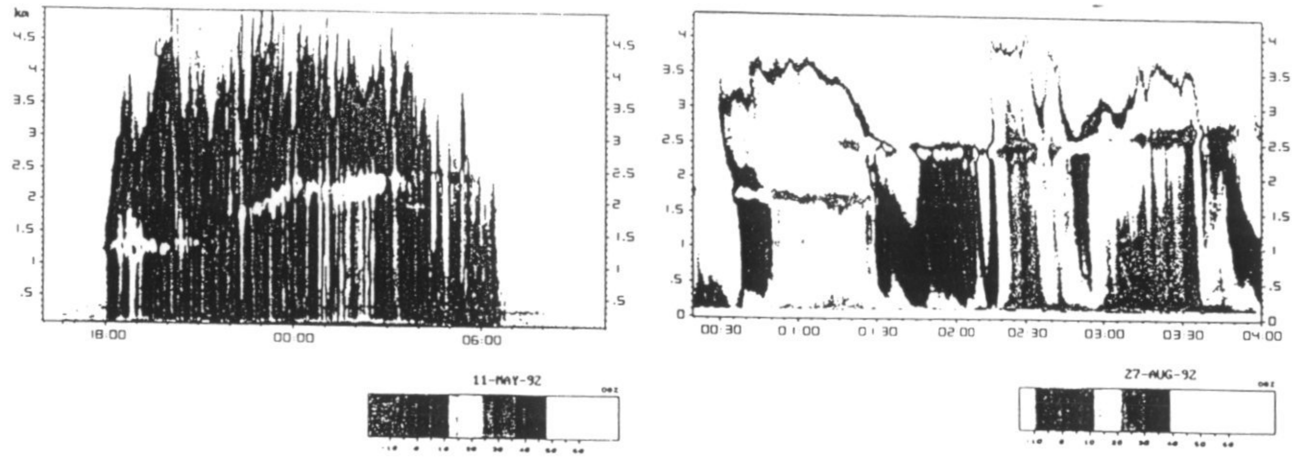


Figure 4 *HTIs showing (i) gradual height change in bright-band and (ii) double bright-band event*


(i)

(ii)

Table 2 Summary of height changes in the bright-band layer

(i) Gradual changes

Date	Time (GMT)	Duration (hr)	Height change (km)	Vertical distance (m)	Direction	Gradient (m/min)
14 Feb 92	1000-1330	3.5	0.85-1.4	550	rising	2.6
21 Mar 92	1900-0730	12.5	0.75-1.7-1.35	950, 350	rises then falls	1.6 (up)
11 May 92	1800-0530	11.5	1.25-2.4	1150	rising	1.7
21 Nov 92	1010-1610	6.0	0.95-2.5	1550	rising	4.3
02 Dec 92	1130-1650	5.33	2.25-0.95	1300	falling	4.1
27 May 93	0200-0740	5.67	2.7-2.25	450	falling	1.3
13/14 Nov 93	0800-0700	23	0.7-1.7-0.35	1000, 1350	rises then falls	3.2 (down)

(ii) Sudden changes

Date	Event time	Time of height change	Vertical distance (m)	Direction of jump
02 Dec 92	1400-1615	15.30	250	down
23 Jan 93	0900-1330	11.30	1100	up
26 Apr 93	1930-1950	19.38	300	down
13 Sep 93	1325-1515	13.35	300	up

(iii) Double bright-band layer events

Date	Event time	Lower bright band height (km)	Upper bright band height (km)	Duration of double bright band (min)
02 Jun 91	0900-0945	1.5	1.75	8
08 Jul 91	1155-1225	2.5	3.0	4
27 Aug 92	0030-0400	1.75	2.5	15
09 Dec 92	0000-0135	0.9	2.0	15

(iii) Comparison of VPR and scanning radar rainfall estimates

A prototype scanning C-band weather radar has recently been commissioned and installed at Harrop Edge, approximately 16 km east of Salford. The radar is located close to the Manchester/Salford conurbation and provides rainfall estimates of a high spatial and temporal resolution. Rainfall data of this quality are the primary requirement for hydrological applications in the urban environment. Duncan *et al* (1992) gives a detailed overview of the Salford C-band project and associated hardware and operational specifications.

A mobile VPR will be placed at or near the C-band radar site to provide high resolution (7.5m, 2 secs.) data on the vertical reflectivity profile. With the availability of this type of data, Fabry *et al* (1992) produced parameterised estimates of the bright-band height and mean reflectivity profile and used them to correct for range dependant biases in scanning radar data that are attributable to variations in the vertical reflectivity profile.

(iv) Orographic rainfall

Two west-east transects have been selected across the north of England. One runs from Liverpool, over the Pennines to the Doncaster region; the more northerly transect runs from Lancaster, over the Forest of Bowland and the Pennines, to York. Both traverse areas are known to be important for orographic enhancement of rainfall (Chuan and Lockwood, 1974). Permission to park the mobile radars and operate at strategic sites is currently being sought from the relevant authorities in order that the experiment can get underway early in 1994. Scanning radar data will be made available in real-time, from Hameldon Hill and from the UK network, for monitoring frontal systems moving in from the Atlantic and to instigate timely operation of the VPRs.

The aim of the experiment will be to have all three (along the southern transect) VPRs static and operating as a storm moves across the region from west to east. The first of the mobile devices will be deployed near the coast, and the second on higher ground to the east, where it is hoped that some degree of enhancement of near-surface rainfall rates will be observed if meteorological conditions in the lowest levels of the atmosphere are favourable (Hill *et al.*, 1981; Hill, 1983). The VPR will reveal valuable information on the vertical structure of the storms and the enhancement process.

(v) Correction of errors in scanning radar data

The development of a fully automatic bright-band correction technique that will work accurately and reliably whatever the meteorological conditions is still in its early stages. Work has commenced on a detection algorithm which uses changes in the reflectivity gradient in the vertical to identify the bright-band. Once a bright-band can be reliably detected, a means of evaluating the magnitude of and calculating correction factors for any discrepancies in the surface rainfall rate that might have been introduced by the presence of the bright-band in the scanning beam must be sought.

A prerequisite to this stage of the research has been the development and testing of software to facilitate the handling, analysis and display of the VPR data. All event data are now transferred to a DEC VAX computer for subsequent processing (a number of computer programs have been created to decode the data values) and display. A program which averages out near-surface reflectivity over one-minute intervals and then converts these to an equivalent rainfall rate (using a standard empirical relationship) and depth has just been completed. The rainfall values generated can thus be checked against raingauge recordings for selected events.

CONCLUSIONS AND ADDITIONAL REMARKS

(i) The Salford VPR has proved to be an invaluable tool in the study of the vertical structure of precipitation and its causative mechanisms in the North West region. High resolution data are provided up to an altitude of 12km and have facilitated a detailed assessment of bright-band characteristics (height, width, intensity), frequency and temporal variability.

(ii) A mobile VPR system has been successfully deployed at another location within the urban area and an intercomparison of the two data records is currently underway to investigate the spatial variability of the vertical reflectivity profile.

(iii) Two projects involving the trailer-mounted radars will commence in January 1994. The first forms part of the HYREX study programme investigating X-band attenuation and bright-band modelling in conjunction with the University of Reading and the Rutherford Appleton Laboratory using the Chilbolton meteorological radar. The second project will involve the two radars being positioned at strategic sites along a predefined transect and their simultaneous operation in order to examine the structure and mechanism of orographic rainfall over the uplands of the North West.

(iv) Development of software for use in the analysis and display of the VPR data continues, as does the work on a procedure for the correction of errors in scanning radar data due to the bright-band and variations in the vertical reflectivity profile.

After completion of the static transect experiments in the North West of England and the HYREX involvement, there exists the potential to carry out a series of dynamic transect experiments involving both of the mobile VPRs being operated simultaneously and then relocated and operated further along the transect during the course of a single storm. Evidently a slow-moving depression travelling in from the Atlantic will provide the prolonged rainfall conditions necessary for this type of experiment, and the meteorological situation will have to be closely monitored in real time.

REFERENCES

Chuan, G.K. & Lockwood, J.G., 1974. An assessment of topographical controls on the distribution of rainfall in the Central Pennines. *Met. Mag.*, 103, 275-287

Duncan, M.R., Fabry, F., Cluckie, I.D. & Singh, A. , 1992. The McGill/Salford C-band Hydrological Radar. 2nd. International Symposium on Hydrological Applications of Weather Radar, Hannover, 7-10 September 1992.

Fabry, F., Austin, G.L., & Duncan, M.R., 1992. Correction of the Vertical Profile of Reflectivity using a Vertically Pointing Radar. 2nd. International Symposium on Hydrological Applications of Weather Radar, Hannover, 7-10 September 1992.

Hill, F.F., 1983. The use of average annual rainfall to derive estimates of orographic enhancement of frontal rain over England and Wales for different wind directions. *J. Clim.*, 3, 113-129

Hill, F.F., Browning, K.A., & Bader, M.J., 1981. Radar and raingauge observations of orographic rain over South Wales. *Q.J.R.Met. Soc.*, 107, 643-670

Institution: Dept of Meteorology, University of Reading, United Kingdom

Project Leader: Anthony J. Illingworth

Institutions cooperating: Rutherford Appleton Laboratory

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

IMPROVED RADAR ESTIMATES OF RAINFALL USING DIFFERENTIAL PHASE TECHNIQUES

MAIN OBJECTIVES:

The scientific goals of the project are:

(i) Gather preliminary differential phase radar data in precipitation.

(ii) Establish algorithms for obtaining the best estimates of differential phase shift over various distances.

(iii) Make additional observations of differential phase for a large range of meteorological situations.

(iv) Investigate the efficiency of the differential phase shift for measuring rainfall, its applicability for measuring rainfall over hydrological basins, and compare its efficiency with estimates of rainfall made from conventional measurements of radar reflectivity.

METHODS AND MATERIALS

This study involves gathering data with the RAL dual polarisation radar situated in Southern England. The radar has recently been Dopplerised and is also able to transmit (and receive) pulses which are alternately horizontally and vertically polarised. This project concentrates on the measurement of a new radar parameter - the differential phase shift - which is a propagation effect.

Raindrops are oblate and dielectrically lossy. As a result the phase of a horizontally polarised wave progressing through a medium containing rain is delayed by more than the vertically polarised radiation. This differential phase shift, ϕ_{DP}, is detected on backscatter from the precipitation . The phase difference ϕ_{DP}, increases monotonically with range, and theory predicts that the gradient of ϕ_{DP} with range, called K_{DP}, and measured in °/km, should be almost linearly proportional to the rain rate.

RESULTS TO DATE (JANUARY TO DECEMBER 1993)

In the first year our task was to complete objectives (i) and (ii). This has been achieved as described below.

(i) Data gathering

The ϕ_{DP} data have been gathered in raw time series form. In other words the phase of the return at each gate is recorded for each transmitted pulse. After the event this phase information from the individual pulses can be analysed and the performance of the various algorithms for estimating ϕ_{DP} evaluated.

The data flow is very high. Typically the data are recorded at 512 gates, separated by 75m, at a pulse repetition rate of 610Hz. The phase is obtained by an eight bit digitisation of the I and Q outputs of the IF phase comparator. To improve the dynamic range, a limiting IF amplifier is used ahead of the phase comparator, and the intensity (Z) magnitude is derived from a separate IF amplifier with 96dB range. Each data point is 4 bytes, so the flow rate is 4*512*610 = 1.2MBytes per second.

Data have been recorded on six separate occasions and has included both RHIs and PPIs and also a series of long dwells. The long dwells of up to 15 seconds have been particularly useful for comparing the various algorithms for estimating ϕ_{DP}.

(ii) Algorithms for estimating differential phase shift

The differential phase concept is fairly straightforward, but in practice the horizontal and vertical phases have to be measured using sequentially transmitted pulses. If the targets had a constant Doppler velocity, then the phase between successive H (or V) returns at a given gate would change linearly with time (for example, a phase shift of 180° would correspond to a displacement of one quarter of a wavelength), and the interpolation to correct for the staggered sampling would be straightforward. In practice the spread of velocities (finite width of the Doppler spectrum) places a fundamental restriction on the accuracy of the ϕ_{DP} estimate. Two algorithms have been proposed (Sachidananda and Zrnic, 1986). We have found that the second of these algorithms is much the better (Blackman and Illingworth, 1993). In this algorithm ϕ_{DP} is computed by taking the phase difference (ϕ_V - ϕ_H) for each triplet of transmitted pulses, adding all the real and imaginary parts, and then taking the phase of the averaged vector sum.

The standard deviation of the ϕ_{DP} estimate increases for larger Doppler widths. Various semi-analytic expressions have been suggested for this relationship and at present we are carrying out an empirical study for targets with a large range of Doppler widths to confirm and refine these expressions.

(iii) Comparison of rainfall from phase shift and reflectivity

Two examples are illustrated in Figures 1 and 2. The first is a case for heavy rain, with Z exceeding 50dBZ recorded on 11 June 1993. The second is for a case of widespread light rain on 9 July 1993.

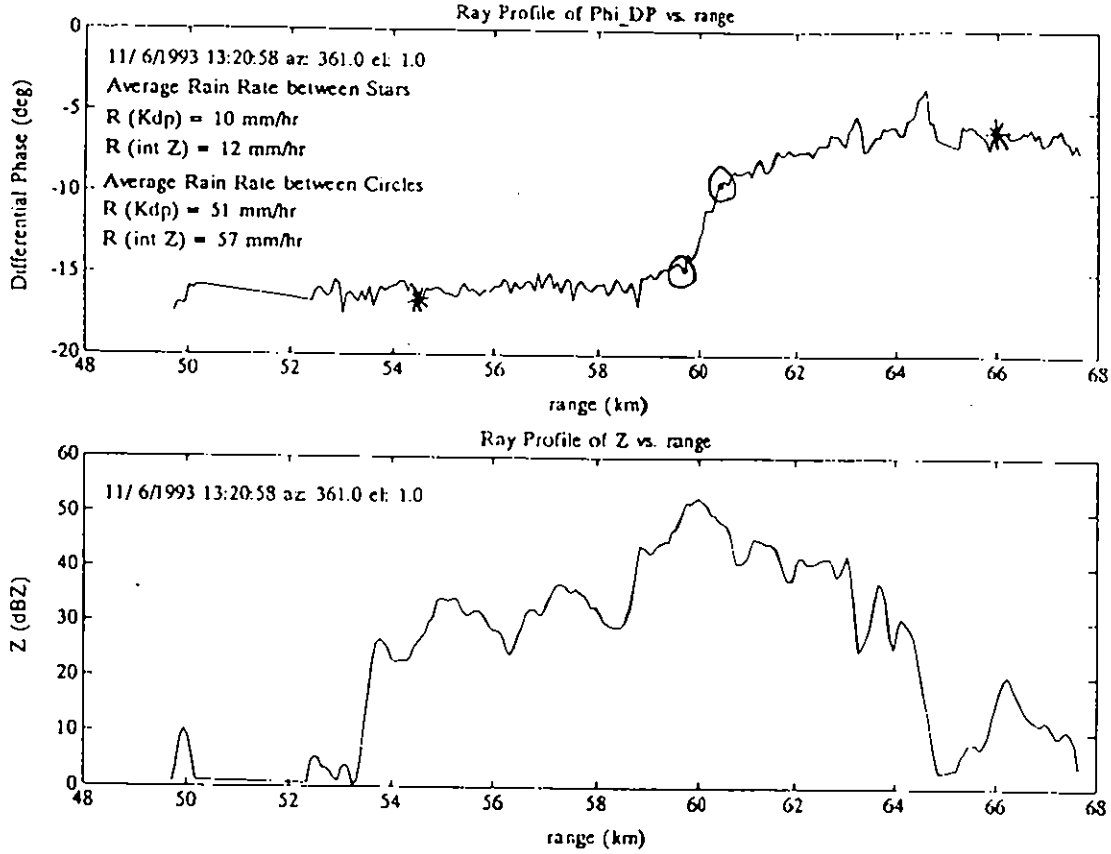


Figure 1 *Ray profiles of ϕ_{DP} and Z versus range: heavy rain case on 11 June 1993*

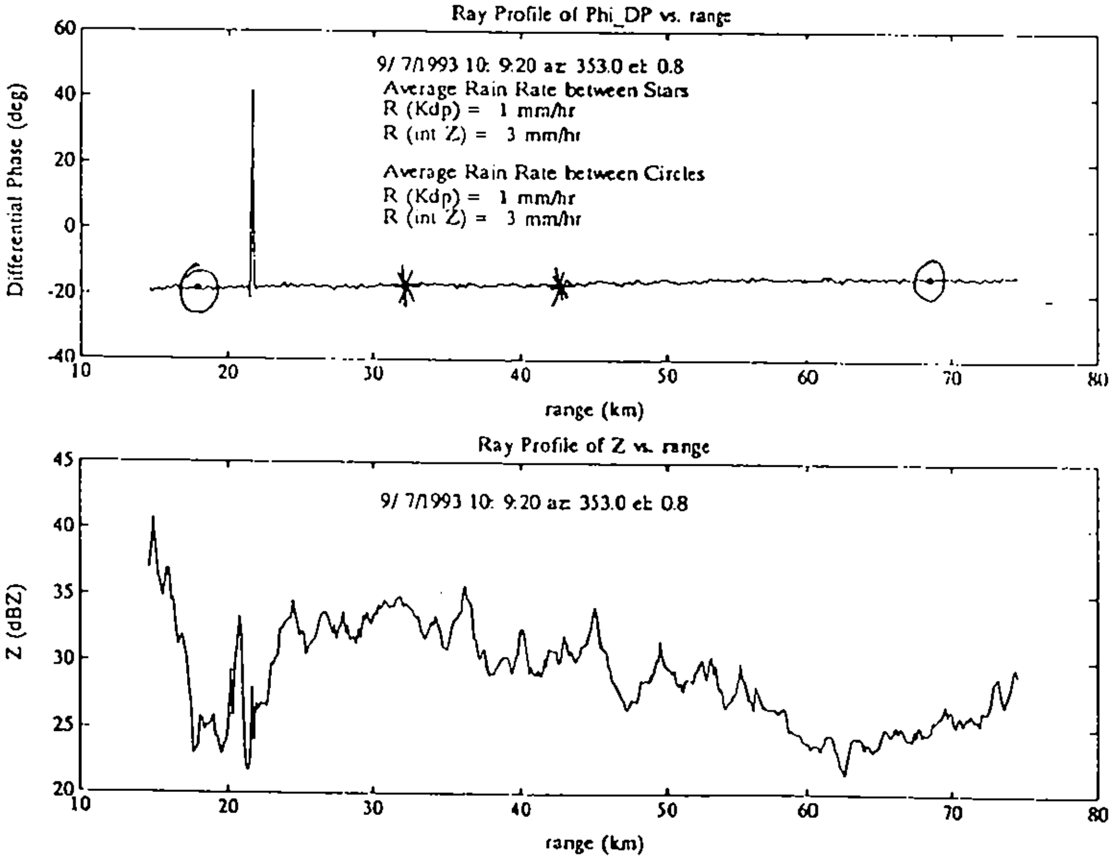


Figure 2 *Ray profiles of ϕ_{DP} and Z versus range: widespread light rain on 9 July 1993*

The ϕ_{DP} technique has several potential advantages over a simple measurement of Z which we address below:

a) Is the phase shift between two points on a range profile equal to the integrated rainfall between these two points?

b) Does the phase technique measure only the rain but not respond to the hail which can dominate the reflectivity?

c) In regions where heavy clutter precludes the measurement of Z, is it possible to estimate the integrated rainfall by the phase shift from one side of the clutter region to the other?

11 June 1993

The data for this case are for a 6 second dwell at 1° elevation and so the radar beam is in the rain and does not penetrate the ice. The maximum value of reflectivity, Z, at a range of 60km of >50dBZ coincides with the steepest gradient of the differential phase. In this example the other polarisation parameters (such as differential reflectivity and the linear depolarisation ratio) indicate that there is no hail present and so we would expect reasonable agreement between rainfall from the phase technique and the reflectivity approach.

The average rainfall has been estimated using the total phase difference between two different ranges and then compared with that taken by a gate by gate integration of the rainfall from the reflectivity. If we consider the two stars at ranges 54 and 66km range then phase shift gives 10mm/hr and Z gives 12mm/hr. Concentrating on the heavy rainfall region between the circles at 58.8km and 60.4km then the phase gives 51mm/hr and the integrated Z gives 57mm/hr.

9 July 1993

In this case the reflectivities are much lower and the phase is only increasing very slowly with range. Between the stars at 32 and 42km the phase method gives 1mm/hr and the integrated Z yields a value of 3mm/hr; for the two circles at 18 and 68km the rates are again 1 and 3mm/hr respectively. To illustrate the ground clutter technique, we draw attention to the phase spike of 60° at 22km range caused by differential phase shift on scattering from ground targets, and note that the phase on either side of this spike is unaffected.

CONCLUSIONS AND ADDITIONAL REMARKS

We have established reliable algorithms for estimating differential phase and shown with a few examples that the results are consistent with those obtained using the conventional reflectivity technique.

The next stage is to gather data and compare with a line of rain gauges deployed along an azimuth from the radar. This will provide independent confirmation of the rainfall rate, and should demonstrate whether the phase technique is able to provide improved rainfall estimates.

REFERENCES

Blackman & Illingworth (1993) Proc 26th Int Conf on Radar Meteorol, Amer Meteorol Soc, Boston.

Sachidanada & Zrnic (1986) Rad Sci, **21**, 235-247.

Institution: Dept. of Water Resources, Agricultural University, Wageningen, The Netherlands

Project Leader: Han Stricker

Institutions cooperating: Dept. of Telecommunication and Remote Sensing Technology, Faculty of Electrical Engineering, Delft University of Technology, Delft, The Netherlands (TUD)

Royal Netherlands Meteorological Institute, De Bilt, The Netherlands (KNMI)

Water Authority of Delfland, Delft, The Netherlands

Water Authority of West Brabant, Breda, The Netherlands

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

The scientific goals of the CEC project involve investigation into the following:

(i) the rainfall measurement problem

(ii) the rainfall forecasting problem

(iii) application to flood warning and control

(iv) application to storm hazard assessment

METHODS AND MATERIALS

The Dutch contribution to the project aims to address these problems along three lines of research:

(i) A dataset of 41 rainfall events from the KNMI C-band weather radar and a network of 16 tipping bucket raingauges sampling an area of 1500 km^2 within the Water Authority of West Brabant has been collected, analyzed and calibrated during an earlier investigation. The accuracy of radar rainfall estimates obtained using different adjustment procedures as compared to raingauge measurements will be investigated. Moreover, the rainfall fields obtained will be used as input to a previously developed urban waterbalance model describing a regional wastewater transportation system.

(ii) A dataset of 5 rainfall events from colocated X-band and multiparameter S-band research radars (both operated by TUD) and a network of 10 tipping bucket raingauges sampling an urban area of 100 km^2 within the Water Authority of Delfland has been collected during the current and an earlier CEC project. For 2 additional events data from the C-band weather radar and the X-band research radar are available. Since the rainfall fields are measured on 4 different spatial scales and a range of temporal scales, a nested approach will be adopted to tackle the associated sampling problems.

(iii) The above-mentioned sampling problems will be explored more fundamentally through the development of mathematical and computer models at different complexity levels describing the space-time structure of rainfall at the droplet scale and radar and raingauge measurements.

Results (January to December 1993)

(i) Accuracy of Radar Rainfall Estimates Compared to Raingauge Measurements and a Hydrological Application

The objectives of this study were (Hakvoort *et al.*, 1993):

- to determine the accuracy of C-band weather radar rainfall estimates in comparison with raingauge measurements;
- to examine the effect of a number of adjustment methods - using an increasing number of adjustment raingauges - on the accuracy of radar rainfall estimates;
- to evaluate the accuracy of radar-derived rainfall amounts for hydrological purposes, in particular their application as input to a rainfall-runoff model of a regional sewer system.

During an earlier investigation (of which the results were presented in the Final Report of the CEC-EPOCH project "Weather Radar and Storm and Flood Hazard") rainfall data from both radar and raingauges were collected for a total of 41 events. To allow for a statistical approach, a subset of 13 events was selected for which the number of operational raingauges was at least 6 and the number of 15-minute periods covering the event was at least 20.

Two types of verification were applied, namely one in which the accuracy of radar rainfall estimates was determined only in pixels where a raingauge was located and another in which the complete areal field of radar rainfall estimates was considered. In the first case, the accuracy of unadjusted radar data was compared with the accuracy of radar data adjusted using either one or the arithmetic mean of all available raingauges. In the second case, radar rainfall estimates at all radar pixels were adjusted using an increasing number of raingauges. Each raingauge used for adjustment was thought to represent a sub-area corresponding to a Thiessen polygon. After assigning the raingauge measurement to all radar pixels within the corresponding adjustment domain, an average adjustment factor was computed from the individual adjustment factors. Three different ways of averaging the individual adjustment factors within the adjustment domains were considered, namely arithmetically, geometrically and volumetrically. As the number of adjustment raingauges increased, the number of raingauges left for verification decreased. In order to avoid biased statistics, all possible combinations of adjustment and verification raingauges were taken into account.

The accuracy of radar rainfall estimates was determined assuming raingauges to represent the "ground truth". Radar and raingauge data were compared on the basis of the differences between individual pixel values and on the basis of their ratios. Both for the absolute and for the relative comparison, the statistics considered were the mean and the standard deviation computed over all relevant locations and all time steps in the event.

As for the synchronization of radar and raingauge data, two types of radar rainfall accumulation were compared, namely forward extrapolation and a space-time interpolation method based on the displacement vector principle (van den Assem, 1991). Two different accumulation periods were compared, namely 15 minutes (corresponding to the time period between two radar scans) and 30 minutes.

Some of the previously obtained rainfall fields were used as input for a rainfall-runoff model designed to simulate at a 15 minute time step the transformation process of both sewage and rainfall water from 27 urban areas through a regional pressure pipe system to discharge at the purification plant. The rainfall fields considered were measurements from all operational gauges interpolated using Thiessen polygons and radar rainfall estimates without adjustment and with adjustment by one and all minus one raingauges (obtained using the space-time interpolation method and the adjustment domain approach). Measured and simulated outflow hydrographs at the regional purification plant were compared on the basis of several statistics, of which the relative mean bias error and the relative root mean square error corrected for bias were the most important. Figures 1 and 2 show examples of model inputs and outputs, respectively.

The most important results of this study are:

- The absolute comparison of radar rainfall estimates with raingauge measurements is more transparent and especially for hydrological purposes more valuable. The relative statistic fluctuates heavily and is therefore hard to interpret.

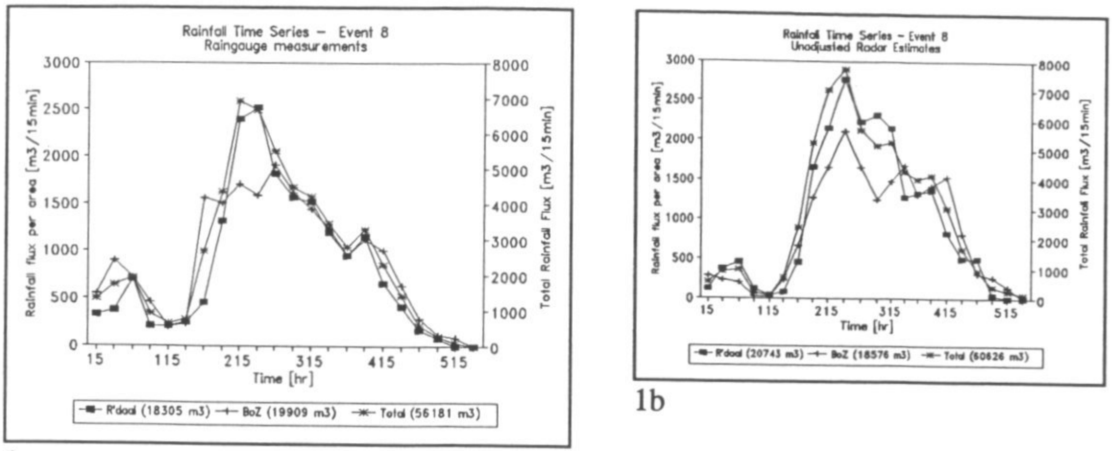
- Radar rainfall estimates calculated according to the space-time interpolation method provide more accurate results than those calculated according to the forward extrapolation method. This is especially true when the radar rainfall estimates are adjusted and when special meteorological circumstances (bright band, anaprop) are present.

- For 4 out of 13 rainfall events the unadjusted radar rainfall estimates, on the average, overestimate the raingauge measurements, whereas for 3 events they underestimate the raingauge measurements. For the remaining 6 rainfall events the radar rainfall estimates match well with the raingauge measurements.

- Increasing the length of the time period for which radar rainfall estimates and raingauge measurements are accumulated from 15 minutes to 30 minutes does not increase the accuracy of the radar rainfall estimates.

- Arithmetical averaging of individual adjustment factors provides better results in terms of reducing the bias error than geometrical or volumetrical averaging.

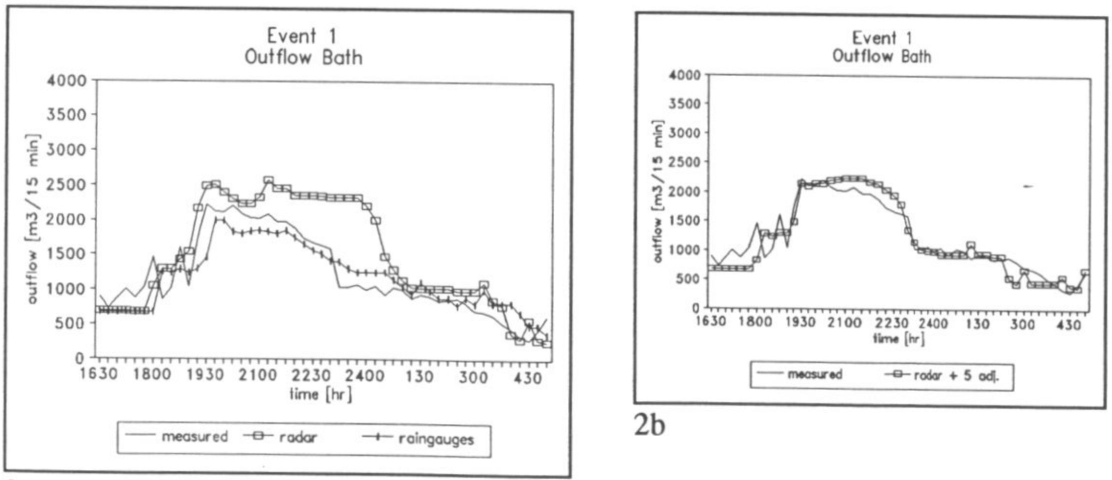
- For 10 out of 13 rainfall events adjustment of radar rainfall estimates using all operational raingauges minus 1 results in an increase of the accuracy as compared to unadjusted radar rainfall estimates.



1a

1b

Fig. 1 *Time series of rainfall flux used as input for rainfall-runoff model for event 8 (December 9th, 1988). R'daal = rainfall input volume for the urban area of Roosendaal; BoZ = rainfall input volume for the urban area of Bergen op Zoom; Total = total rainfall input volume for all 27 impervious areas. a: raingauge measurements; b: unadjusted radar estimates.*



2a

2b

Fig. 2 *Hydrographs of measured and simulated outflow at regional wastewater purification plant Bath for event 1 (September 12th, 1988). a: comparison of measured discharge with simulated discharges using unadjusted radar data and raingauge data; b: comparison of measured discharge with simulated discharge using radar data adjusted with 5 raingauges.*

- When radar rainfall estimates adjusted with 1 raingauge and radar rainfall estimates adjusted with all operational raingauges minus 2 are compared, it can be concluded that the accuracy only slightly increases in favour of using more raingauges for adjustment.

- The effect of computing an adjustment factor using all radar pixels (including those in which no raingauge was installed) and using limits to restrict the value of the mean adjustment factor appears to be rewarding for reducing the random error, especially in case of special meteorological circumstances.

- Concerning the accuracy of radar and raingauge rainfall estimates for hydrological purposes, it can be concluded that raingauge measurements provide more accurate rainfall estimates than unadjusted radar data. Adjusting the radar rainfall estimates using one raingauge can both improve and deteriorate the accuracy of the simulated outflow hydrograph, depending on which raingauge is chosen for adjustment. Adjusting radar rainfall estimates using all operational raingauges minus 1 does not yield the best nor the worst result in terms of accuracy of the simulated outflow hydrograph, but appears to be the most reliable method on the average.

- Adjusted radar rainfall estimates using all operational raingauges minus 1 or 2 are more reliable than all other rainfall estimation methods considered. Although adjustment using one raingauge can both improve and deteriorate the results, depending on the location of the raingauge chosen for adjustment, adjusted radar rainfall estimates using the best performing single raingauge are more accurate than those obtained using any other method considered. Therefore, it is recommended to develop a model which decides per time step which raingauge is used for adjustment.

(ii) Application of Different Types of Weather Radars for Rainfall Estimation Over an Urban Area for Water Management Purposes

All three radars involved in this study have not been available for measurements during a significant part of the year as a result of either software or hardware updating. The data-processing software of the KNMI C-band weather radar at De Bilt was improved through the inclusion of a clutter suppression program. The S-band FM-CW Doppler-polarimetric Delft Atmospheric Research Radar (DARR) received an entirely new and ultrafast computer to improve its real-time data-processing capability. Since this mini-supercomputer is equipped with parallel processors, the data-processing software had to be rewritten completely. The subsequent change in the format of the output of this software implied that the analysis software already developed for this study had to be rewritten, too. This process is currently under way and the first results are expected early in 1994. The computer formerly connected with DARR serves now as the data-processor for the X-band FM-CW Solid State weather surveillance radar (SOLIDAR) operated by TUD.

Measurements with the above-mentioned radars and with a network of 10 tipping bucket raingauges installed in an area largely covered with greenhouses within the Water Authority of Delfland were carried out on 5 days in 1993, namely 5, 11 and 12 August, 21 October and 10 November. The data were transferred from the radar sites to Wageningen Agricultural University via Internet and are now waiting to be treated by the data-analysis software. The first results of measurements in the framework of this multi-sensor study have already been reported in the Final Report of the CEC-EPOCH project "Weather Radar and Storm and

Flood Hazard" and were presented at the 4th International Conference on Precipitation held at The University of Iowa in April 1993 (Uijlenhoet, 1993).

(iii) Numerical Studies of the Radar Rainfall Measurement Problem at the Droplet Scale

Most radar observables and rainfall integral parameters can be closely approximated by the product of a moment of the raindrop size distribution and a proportionality factor. This can easily be shown if it is assumed that multiple scattering effects of microwaves on raindrops can be neglected and that the dependence of raindrop terminal fall velocity and the backscattering and extinction cross-sections of raindrops on drop diameter are described by power laws. The validity of these assumptions has been frequently reported in the literature for rainfall rate, liquid water content, kinetic energy flux density, radar reflectivity factor, specific attenuation coefficient and mean Doppler velocity.

Probability distributions that have been used over the years to parameterise observed raindrop size spectra include the gamma, Weibull and lognormal distributions. These are all two-parameter distributions completely characterized by a scale and a shape parameter (of course an additional parameter in the form of a raindrop concentration or arrival rate is necessary to fully characterize actual, not normalized, raindrop size spectra). The widely used exponential distribution is a special case of both the gamma and the Weibull distributions and can be closely approximated by a lognormal distribution. It can be shown that the moments about the origin of all these distributions (including their truncated forms) exhibit a similar functional form. They are all products of two terms, where the first term is a function of the scale parameter and the order of the moment and the second term is a function of the shape parameter and the order of the moment. In the case of the lognormal distribution the form of both these functions is particularly simple, namely power laws, whereas for the gamma and Weibull distributions this is only true for the first function.

Based on this observation, it was possible to derive simple analytical expressions for classical dimensionless distribution shape parameters such as the coefficients of variation, skewness and kurtosis and for characteristic sizes, dimensionless shape parameters and functional correlation coefficients introduced in the literature on raindrop size distributions. This accomplishment, although of limited importance in itself, stimulated belief in the fact that it would be possible to derive closed form expressions for two more important problems that recently received attention in the literature: the properties of the sampling distributions of rainfall integral parameters and radar observables (Smith *et al.*, 1993) and the dependence of the coefficients of power law relationships between rainfall integral parameters and radar observables on the parameters of the raindrop size distribution (Smith, 1993; Smith and Krajewski, 1993).

Smith *et al.* (1993) presented the results of a Monte Carlo simulation study towards the sampling distributions of (among others) normalized rainfall integral parameters and radar observables, i.e. the ratios of sample and the corresponding population values. Based upon the same assumptions, namely that the raindrop concentration follows a Poisson distribution and that the sample volume is independent of the raindrop size distribution, analytical expressions were derived for all relevant statistical properties of these sampling distributions. These expressions are valid not only for the exponential raindrop size distribution as in Smith *et al.* (1993), but for the general case of a gamma, Weibull or lognormal distribution. One important conclusion that can be drawn from this theoretical exercise is that although the sampling distributions are indeed highly skewed toward underestimation for smaller sample sizes (as was shown by Smith *et al.* (1993)), on the average the sample values equal the population values.

Smith (1993) and Smith and Krajewski (1993) presented modeling studies of raindrop size distributions and rainfall rate-radar reflectivity relationships. Using basically the same assumptions as Smith *et al.* (1993), they tied the sample-volume process to the drop-arrival process and demonstrated the importance of the temporal (co)fluctuations of the parameters of the raindrop size distribution. As far as the dependence of the coefficients of power law relationships between rainfall integral parameters and radar observables on the parameters of the raindrop size distribution is concerned, two approaches can be distinguished, namely a physical-deterministic and a statistical. The first approach is associated with the (rather academic) problem of determining the power law coefficients from a set of rainfall integral parameters and radar observables corresponding to one raindrop size distribution. Since this problem contains more unknowns than equations, it is generally tackled through elimination of the most sensitive raindrop size distribution parameter(s). The second approach is associated with the (more practically relevant) problem of determining the power law coefficients from sets of rainfall integral parameters and radar observables corresponding to a time series of raindrop size distributions. Since this problem contains more equations than unknowns, it is generally tackled through linear regression of the logarithms of the rainfall integral parameters on the logarithms of the radar observables.

Due to the convenient functional form of the moments of the lognormal distribution, it was possible to derive various interesting relationships between power law coefficients and distribution parameters for this particular distribution. For instance, it was derived that the observation of three integral parameters of the lognormal raindrop size distribution allows the calculation of a fourth through a simple power law relationship with coefficients that are independent of the parameters of the raindrop size distribution. Of more practical interest are the analytical expressions derived for the coefficients of statistical power law relationships for single and dual parameter radar observation in terms of the variances of and covariances between raindrop size distribution parameters.

CONCLUSIONS AND ADDITIONAL REMARKS

(i) A study to examine the effect of a number of adjustment methods - using an increasing number of adjustment raingauges - on the accuracy of radar rainfall estimates and to evaluate the accuracy of radar derived rainfall amounts for hydrological purposes, in particular their application as input for a rainfall-runoff model of a regional sewer system, has been completed.

(ii) A set of data from the KNMI C-band weather radar, colocated X-band and multiparameter S-band research radars (both operated by TUD) and a network of tipping bucket raingauges sampling an urban area within the Water Authority of Delfland has been collected. Software to process these data and to integrate and analyze them is currently being developed. It is anticipated that the first results of a nested approach adopted to tackle the associated spatial and temporal sampling problems will become available early in 1994.

(iii) Several theoretical models have been developed which describe different aspects of the space-time structure of rainfall at the droplet scale and radar and raingauge measurements. They are currently being applied to a large dataset of dropsize spectra collected at the KNMI and it is anticipated that the first practical results will become available early in 1994. Collaborative work with the French group has been arranged on further development and hydrological application of an available rainfall-radar-raingauge simulation model.

REFERENCES

Assem, S. van den (1991). Calibration of weather radar data in The Netherlands. In: Hydrological Applications of Weather Radar (eds. I.D. Cluckie and C.G. Collier). Ellis Horwood, Chichester, pp. 15-24.

Hakvoort, H.A.M., Uijlenhoet, R. & J.N.M. Stricker (1993). Accuracy of radar rainfall estimates compared to raingauge measurements and a hydrological application. Report 41, Dept. of Water Resources, Agricultural University, Wageningen, 69 pp.

Smith, J.A. (1993). Marked point process models of raindrop-size distributions. Journal of Applied Meteorology, 32, 284-296.

Smith, J.A. & W.F. Krajewski (1993). A modeling study of rainfall rate-reflectivity relationships. Water Resources Research, 29, 2505-2514.

Smith, P.L., Liu, Z. & J. Joss (1993). A study of sampling-variability effects in raindrop size observations. Journal of Applied Meteorology, 32, 1259-1269.

Uijlenhoet, R. (1993). Radar measurements and simulations of precipitation: a multi-polarized FM-CW Doppler radar perspective. Proceedings of the 4th International Conference on Precipitation (Hydrological and Meteorological Aspects of Rainfall Measurement and Predictability), The University of Iowa, April 1994, 130-131.

Institution: Instituto da Água (INAG), Portugal

Project Leader: Vitória Silva

Institutions cooperating: Instituto de Meteorologia (IM)
CEHIDRO - Instituto Superior Técnico

Title of project: **STORMS, FLOODS AND RADAR HYDROLOGY**

MAIN OBJECTIVES

The main goals of the project are:

(i) Adjustment of radar estimates of precipitation with raingauge data;
(ii) Very short precipitation forecasting using weather radar;
(iii) Use of weather radar to develop and to implement flood warning systems.

METHODS AND MATERIALS

The weather radar system used in the project is based on an old C-band weather radar sited at Lisbon Airport. Precipitation and flow data are available from the hydrometric network in the area covered by the weather radar. Development of real-time rainfall-runoff models in the Alenquer river catchment area are supported by telemetering raingauge and water stage stations at Olhalvo and Ponte Barnabé.

The following tasks summarise the activities that are being undertaken:

(1) Development and assessment of algorithms for adjustment of radar estimates of precipitation with raingauge data;

(2) Very short precipitation forecasting based on radar data using numerical algorithms for simulation of rainfall intensity fields;

(3) Improvement of rainfall-runoff models in flood-prone areas. Emphasis will be placed on models appropriate for flood forecasting application using spatial radar data available on a square grid;

(4) Application of available rainfall-runoff models using both statistically calibrated radar data and rainfall data. Comparative analysis of the results;

(5) Studies of selected flood-prone areas in order to improve prevention and control of the risks associated with floods.

RESULTS

Development and assessment of algorithms for adjustment of radar estimates of precipitation with raingauge data

Existing algorithms for adjustment of radar estimates of precipitation with raingauge data have been further developed. Improvements were introduced in the Kalman filter technique used for generating the calibration factors. An algorithm based on multiquadratic interpolation has also been developed to generate a calibration surface using the above mentioned calibration factors. The new algorithms were implemented in a software package running in the computer system environment where radar data are being processed on-line and its performance was successfully assessed using 154 hours of rainfall data over a 256 km^2 area of hydrological interest.

Very-short precipitation forecasting based on radar data

The performance of the existing software package based on an echo centroid tracking algorithm was assessed using 623 hours of rainfall data. Three different success indices were computed for various time periods up to 3 hours. The results of this assessment study, namely the values obtained for the Critical Success Index, suggested the need for further improvements. As a consequence, the echo centroid tracking algorithm was relinquished and a new one based on cross-correlation between images was developed and implemented in a software package to run in the computer system environment where radar data are being processed. The new software package was assessed using the same data and better results were obtained for the Critical Success Index. Along with this performance analysis the speed and direction of echo pattern movement were computed.

Rainfall-runoff modelling

Work on rainfall-runoff modelling was developed on various fronts, related to the following topics:

(1) Digitisation and archival of historical graphic records of precipitation and river water stage;

(2) Quality control, retrieval and processing of digitised hydrological data;

(3) Digitisation and archival of geographical elements of the catchment area;

(4) Retrieval in graphical form of the digitised geographical elements of the catchment area;

(5) Remote polling of rainfall and river water stage stations;

(6) Hydraulic modelling of the flow of the Alenquer river through Alenquer village.

In the context of topic (1) the following four programs were developed:

DIGI: monitors the other three programs.
SIFDIA: digitises and archives graphical chart data from siphon raingauges.
BASDIA: digitises and archives graphical data from tipping bucket raingauges.
LIMNI: digitises and archives graphical water stage data.

The full description of topic (1) can be found in the internal report (in Portuguese) "Digitisation of hydrological variables records: rainfall and water stage".

In the context of topic (2), quality control, retrieval and processing of the hydrological digitised data, the following programs were developed:

DSIFM: draws the siphon raingauge digitised records, a month per page.
RSIFM: makes detailed reports on amounts of precipitation, either on paper or on disk files.
DBASM: same as DSIFM, but for tipping bucket raingauge.
RBASM: same as RSIFM, but for tipping bucket raingauge.

In the context of topic (3), digitisation and archival of geographical catchment basin elements, the DIGITA program was developed, which can handle the various cartographic coordinate systems used in Portugal.

In the context of topic (4), retrieval in graphical form of the digitised geographic catchment area elements, the DESENHO program was developed, which draws the data in any media (display, printers and plotters, as well as exporting the data to other software systems).

In the context of topic (5), remote polling of rainfall and river water stage stations, the following five programs were developed:

TESCOM: tests communications between computers.
DESCK: describes the information of the communication.
TELECOM: friendly communication with the remote stations.
CONVUDO: translates the communications to the digitised rainfall database.
CONVLIM: translates the communication to the digitised water stage database.

Also in this context, the entire Olhalvo rainfall station was revised, the tipping bucket raingauge calibrated and the first INAG water stage remote pollable station (solar powered) was installed near Barnabé bridge in Alenquer village.

In the context of topic (6), hydraulic modelling of the flow of the Alenquer river through Alenquer village, field surveying furnished the cross sections needed by the HEC2 model. This model has been installed and, although still not calibrated, has provided order of magnitude estimates of the limiting discharge in Alenquer.

The work on this set of topics has proved essential in conceiving a flood warning system for Alenquer village. Indeed, the analysis of historical records would have been impossible without the above data management tools. Similarly, work on hydrological distributed modelling, whilst still at an initial stage, could not progress without a geographic information system incorporating Portuguese maps. Furthermore, real-time calibration of radar rainfall and operation of hydrologic and hydraulic models cannot be done without real-time data. In this context, it is important to stress that for the first time INAG has installed and is running remotely polled rainfall and water stage stations.

Finally, the water surface modelling of the Alenquer river through Alenquer village, dramatically and frequently flooded (Figure 1), showed that the urban pressure on the flood plain has strongly reduced the convergence of the channel mainly at the bridges Sta. Catarina and Águas (Figures 2 and 3). As a result, even a relatively small discharge of 100 $m^3 s^{-1}$ can result in flooding of the village. It is foreseen that next year a warning system can be completely and successfully established.

Figure 1 *Flood marks in Alenquer village.*

REFERENCES

Hipólito, J. N. A. R. & Macedo, M. E. (1993) Digitalização de Registos de Variáveis Hidrológicas: Udogramas e Limnigramas. (Internal report. In Portuguese).

Rosa Dias, M. P. (1993) Performance of a Very Short-range Precipitation Forecasting Technique based on Radar Observations. *Workshop on Rainfall Physics for Radar Studies.Barcelona, June 1-3, 1993.*

Hipólito, J. N. A. R. & Hipólito, A. F. (1993) Estação Tele-udométrica de Olhalvo, Descrição e interrogação. (Internal report. In Portuguese).

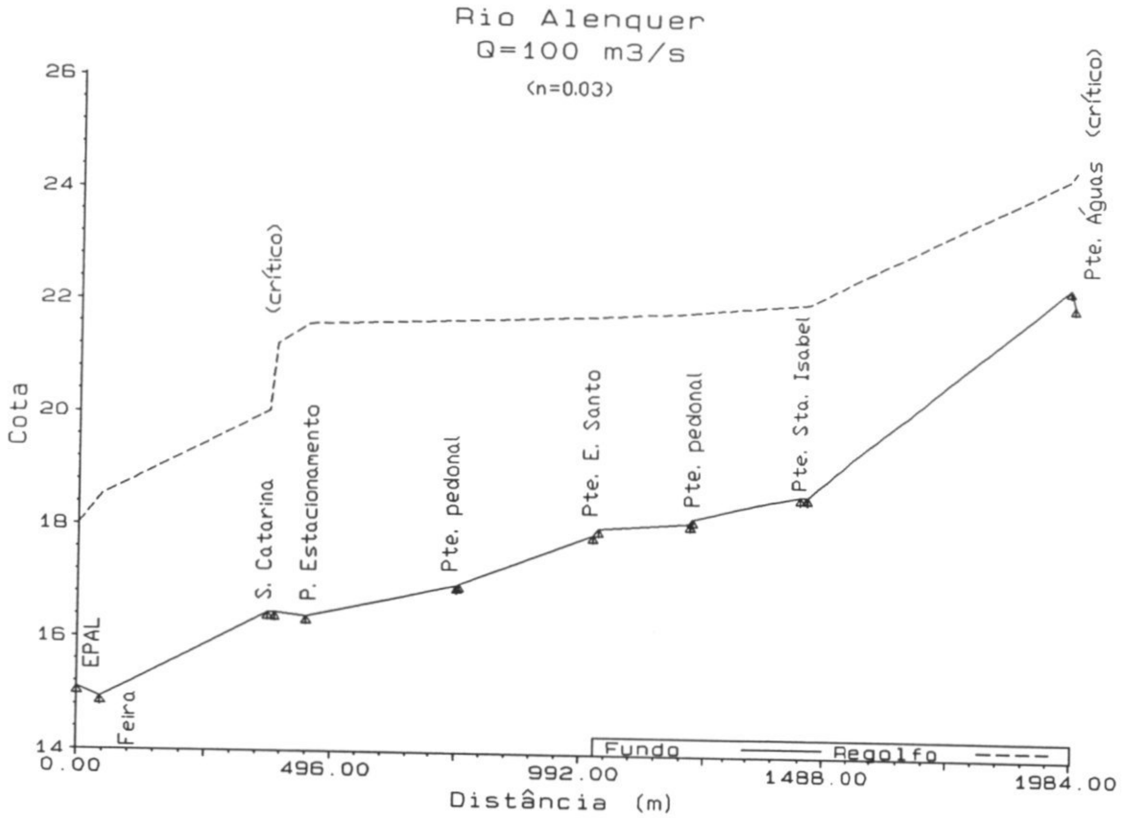


Figure 2 Alenquer River longitudinal profile through Alenquer village

Figure 3 Cross-section upstream of Sta Catarina bridge, Alenquer village

Finally, the water surface modelling of the Alenquer river through Alenquer village, dramatically and frequently flooded (Figure 1), showed that the urban pressure on the flood plain has strongly reduced the convergence of the channel mainly at the bridges Sta. Catarina and Águas (Figures 2 and 3). As a result, even a relatively small discharge of 100 $m^3 s^{-1}$ can result in flooding of the village. It is foreseen that next year a warning system can be completely and successfully established.

Figure 1 *Flood marks in Alenquer village.*

REFERENCES

Hipólito, J. N. A. R. & Macedo, M. E. (1993) Digitalização de Registos de Variáveis Hidrológicas: Udogramas e Limnigramas. (Internal report. In Portuguese).

Rosa Dias, M. P. (1993) Performance of a Very Short-range Precipitation Forecasting Technique based on Radar Observations. *Workshop on Rainfall Physics for Radar Studies.Barcelona, June 1-3, 1993.*

Hipólito, J. N. A. R. & Hipólito, A. F. (1993) Estação Tele-udométrica de Olhalvo, Descrição e interrogação. (Internal report. In Portuguese).

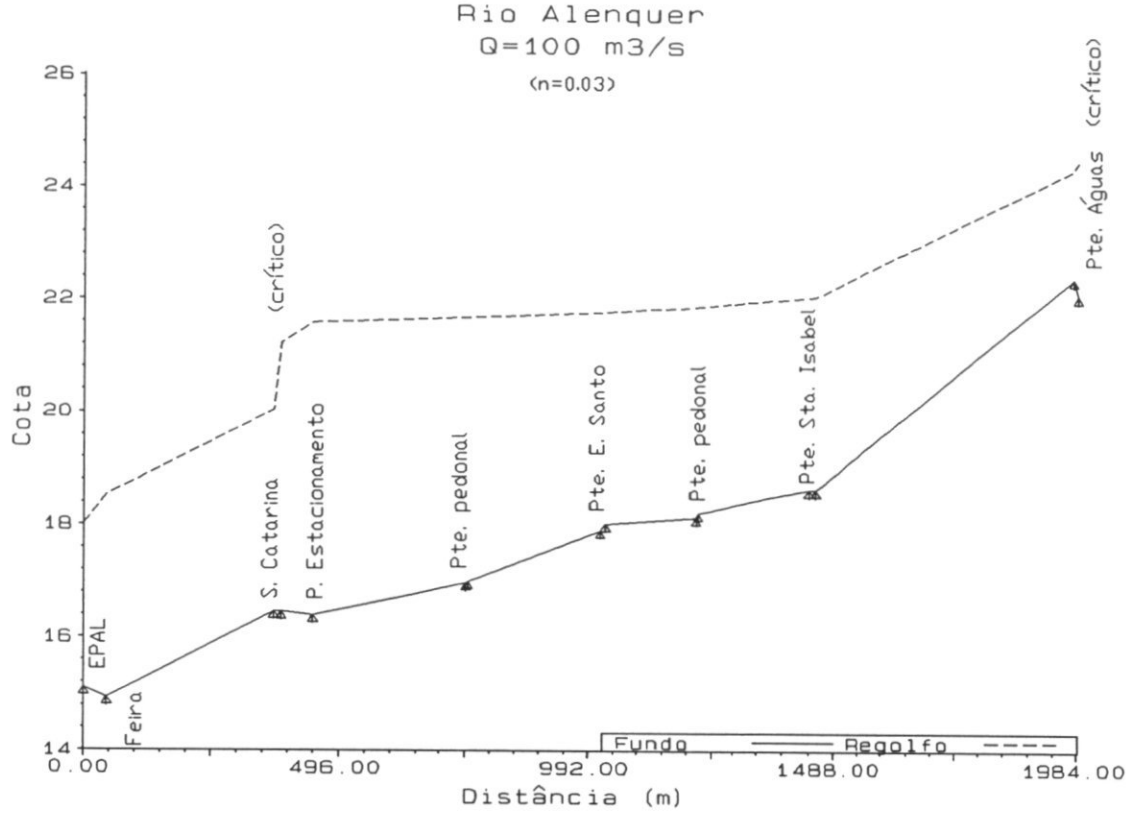


Figure 2 *Alenquer River longitudinal profile through Alenquer village*

Figure 3 *Cross-section upstream of Sta Catarina bridge, Alenquer village*

Institution: Direzione Regionale della Protezione Civile Regione Friuli-Venezia Giulia

Project Leader: Prof. Sergio Fattorelli

Institutions cooperating: Università degli Studi di Padova

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

The scientific goals of the project involve investigation into the following:

(i) analysis of the heterogeneity of the Vertical Profile of Reflectivity (VPR) and development of techniques able to identify VPR in order to improve ground rainfall estimation;

(ii) local rainfall forecasting using raingauge networks and weather radar;

(iii) use of advanced statistical methods to combine radar and raingauge rainfall data;

(iv) development of lumped and distributed real-time flood forecasting models using radar, digital elevation data derived river networks and soil/landuse data; comparison of different techniques for the updating process.

METHODS AND MATERIALS

The study will employ radar data primarily from the Doppler C-band weather radar with multiple beam facility at Monte Grande hill. The area scanned by the radar covers a number of mountainous, flood prone catchments. Volume scans and identification techniques will be used to investigate the experimental spatial distribution of the VPR, while the use of a simulation approach will allow testing of the accuracy of identification techniques in situations where attenuation of the echo signal is relevant and depends on the VPR itself (i.e. bright band). The raingauge network connected with the system will be used to assess radar estimates of rainfall rate and to merge remote sensing and ground based estimates of rainfall. Particular attention will be devoted to the identification and removal of bias between the two estimates. Techniques developed under an earlier CEC project will be extended to VPR identification, and the influence of the improvement of radar-based ground rainfall estimation on flood simulation in mountainous catchments will be assessed. Data from a number of basins located in mountainous regions will support the research on flood modelling and real-time forecasting.

RESULTS (JANUARY TO DECEMBER 1993)

(i) VPR identification and analysis

A methodology was developed for testing an existing technique for Vertical Profile of Reflectivity (VPR) identification. the method considers the VPR constant along the range and is based on the radar reflectivity measurements of at least two elevation angles (PPIs). It initially computes the ratio between the radar reflectivity measurements at the different elevations, which filters out the horizontal variability in the reflectivity fields. Subsequently, the computed ratio values are used in the VPR identification procedure via a system of non-linear equations where the solution is the VPR values at discrete altitudes in the atmosphere. Two schemes for testing the VPR identification method were introduced. The first one uses synthetic radar reflectivity data from a three-dimensional radar-reflectivity simulation model. The model combines two dimensional synthetic rainfall fields, generated from a stochastic space-time model, with physically-based simulation of the hydrometeor phase and the radar measurement sampling volume integration process. Particular attention was paid to the correct parameterisation of the rainfall models (Bacchi & Borga, 1993). The second approach uses simulated radar reflectivity measurements from the previous model based on the 1986 COHMEX convective storm. Sensitivity of the identification method to different factors, such as the radar characteristics and the distance from radar, was assessed.

(ii) Flood forecasting

Earlier work on comparison of different real-time flood forecasting models and on the improvement from available radar-based rainfall estimates has focussed attention on building a framework for assessing the accuracy of different updating techniques using various forms of rainfall estimate. A model was built for real-time flood forecasting based on the combination of a Probability Distributed soil moisture accounting model (PDM) (Moore, 1985) with a simple linear transfer function, and operating in an adaptive mode through a state updating procedure or a parameter updating procedure. The state updating technique is based on a Kalman filter algorithm. The differentiability of the algebraic expressions and the few parameters employed in the model allow reliable parameter estimation procedures to be used. After an objective function is calculated, formed as the sum of squares of the differences between observed and calculated discharges, a function minimisation method can be employed for parameter estimation and also for on-line calibration.

As a first step, particular attention was paid to the identification of a transfer function based on digital elevation data derived river network. In this work channel networks were identified employing the method based on the work of O'Callaghan and Mark (1984). In this type of algorithm, a threshold area is chosen and all cells with more contributing cells than the threshold area are included as part of the drainage network. In this way the threshold area, A_t, represents the minimum support area required to drain to a point for a channel to form. Hence different threshold area values can be chosen to derive networks of different drainage density. The effects of threshold area selection, both on the morphometric and scaling properties (such as drainage density, total channel length, Horton's laws and fractal dimension) (Helmlinger *et al.*, 1993), and the associated network hydrologic response functions, were analysed.

For these purposes firstly automatic procedures were developed for obtaining a quantitative geomorphic description of the basin and its DEM data derived network using the ordering scheme proposed by Horton and Strahler. Hence two different hydrologic response models, obtained in the framework of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) theory, were considered. In the first model the function is parameterized in terms of the associated Strahler stream ordering system, where the geomorphologic description of the basin is given by Horton's laws; the second model is obtained by averaging a flow equation with respect to the network structure that is described by the width function. Applications were performed for the mountainous basins of the Torre and Posina rivers and the different responses obtained by the DEM data derived network for different threshold area values were analysed.

The variability of geomorphic parameters results in an unpredictable instability of the behaviour of the transfer function model with respect to different threshold area values when this is obtained using the Strahler ordering system. Figure 1 shows how these drastic changes result in the unpredictable differences existing through unit hydrographs obtained from different A_t values. Figure 2 shows how the model based on the width function is able to reduce the effects of the variability of morphometric characteristics on the response. A regular reduction of the lag time of the IUH as A_t increases can be observed. This is due to the network centroid approaching the outlet as the drainage density decreases as the result of removing many lower order streams. Moreover it is shown that the shape of the IUH is better related to the actual structure of the channel network.

REFERENCES

Bacchi, B. & Borga, M. (1993) Spatial correlation patterns and rainfall field analysis. Excerpta.

Helmlinger, K.R., Kumar, P. & Foufoula-Georgiou, E. (1993) On the Use of Digital Elevation Model Data for Hortonian and Fractal Analyses of channel Networks. Water Resour. Res. 29(8), 2599-2613.

Moore, R.J. (1985) The probability-distributed principle and runoff production at point and basin scales. Hydrological Sciences Journal, 30, 2, 273-297.

O'Callaghan, J.F. & Mark, D.M. (1984) The extraction of drainage networks from digital elevation data. Comput. Vision, Graphics Image Process, 28, 323-344.

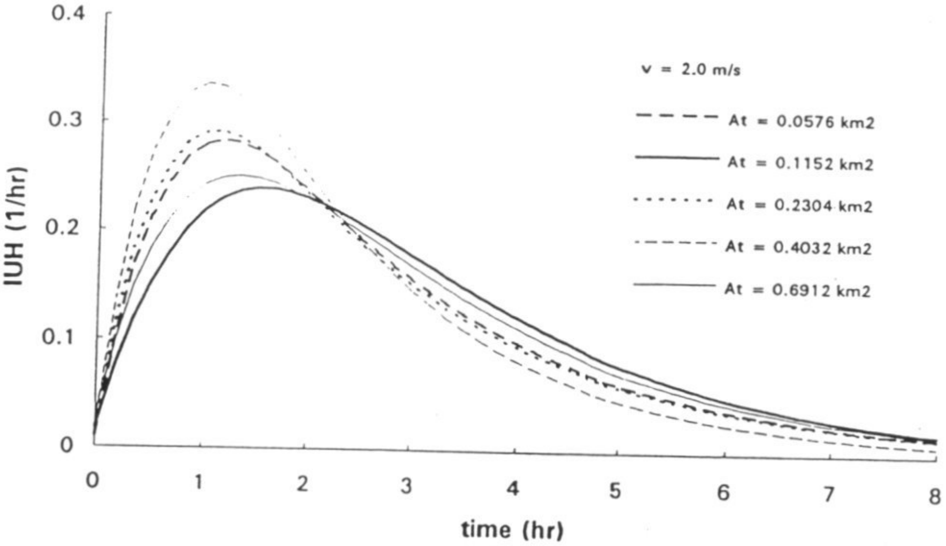


Figure 1 *Effects of threshold area on geomorphologic instantaneous unit hydrograph obtained by digital elevation data derived networks for the mountainous Torre River basin. GIUH is based on the Horton-Stahler ordering system.*

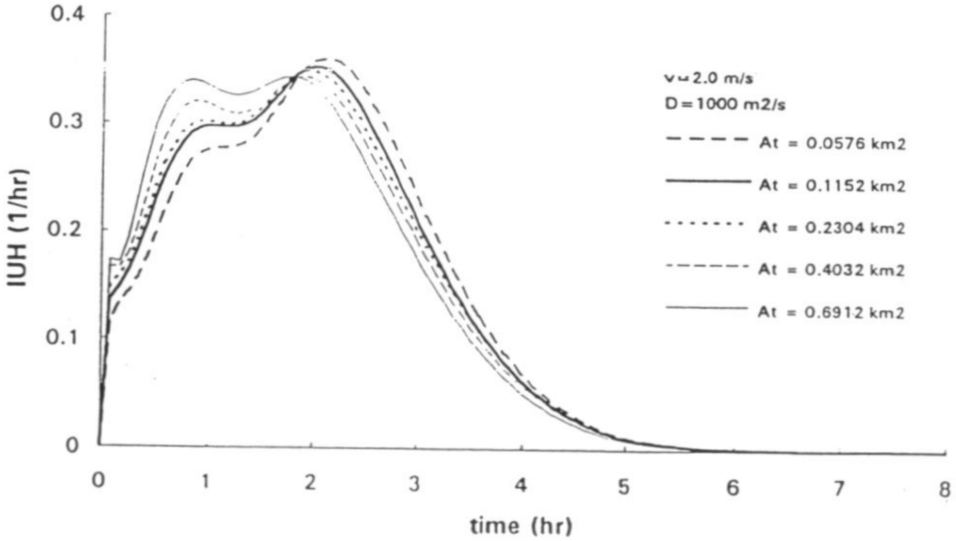


Figure 2 *Effects of threshold area on geomorphologic instantaneous unit hydrograph obtained by digital elevation data derived networks for the mountainous Torre River basin. GIUH is based on the width function.*

Institution: National Technical University of Athens, Greece

Project Leader: M A Mimikou

Institutions cooperating:

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

The research is primarily focused on the implementation of weather radar for hydrological applications and especially for spatial rainfall measurement and estimation, and consequently for storm and flash flood forecasting and warning.

More specifically the scientific goals of the project involve research in the following areas: (i) analysis and processing of acquired radar reflectivity data sets, (ii) development of methods for local short-term rainfall forecasting using weather radar, and (iii) development of procedures for flood flow forecasting using weather radar.

METHODS AND MATERIALS

The study involves the use of a digital WSR-74 S-band weather radar system. The radar scan area covers a significant part of Central and Northwestern Greece including the two catchments of research interest, namely the Venetikos and Pyli basins with drainage areas of 817 km^2 and 135 km^2 respectively. The basin of Pyli is combined with three other basins in order to form a large basin, the Pinios river basin with drainage area of 2763 km^2, for a better utilisation of the weather radar. Twenty five recording raingauges over the two basins are used to support the research by providing ground truth. The study will employ and extend the methods and procedures developed under an earlier CEC project for the assessment of the accuracy of rainfall measurements (Mimikou, 1992). A number of storm events are analysed and processed. Techniques relating to ground clutter suppression, anomalous propagation, beam refraction and merging procedures have been developed. These techniques have been utilised in the implementation of weather radar for short-term rainfall forecasting and consequently flood-flow forecasting. For each storm event, on-site raingauge observations and surface and upper-air meteorological data are obtained. Rainfall forecasting is focused on the development and comparison of two different approaches, namely the linear extrapolation of the centroids of features of rainfall cells and the cross-correlation of radar rainfall fields. Finally, attention will be paid to the evaluation of existing rainfall-runoff models and the development of a distributed flood forecasting model to be used in conjunction with radar rainfall data, both forecast and observed.

RESULTS TO DATE

The results to date are reported under three major topics of the project, namely analysis and processing of radar data for rainfall estimation, development of short-term rainfall forecasting methods and development of a lumped and distributed rainfall-runoff model.

(i) Analysis and Processing of Radar Data

Despite the efforts to maintain a high level of quantitative accuracy in estimating rainfall using weather radar data, it is certain that errors will be encountered in these estimates. Indeed there is a variety of factors that can cause systematic, random, and range dependent errors. These errors can result from the drop-size distribution determining the Z-R relationship, ground clutter occultation and shielding, anomalous propagation, abnormal beam refraction and losses, interference of signal from targets other than rain, attenuation in the atmosphere and calibration of the electronics of the radar (Mimikou et al., 1993c). Suitable rainfall events have been identified for the assessment of the accuracy of rainfall estimation. Initially a ground clutter map was utilised for the detection and suppression of the ground clutter from radar rainfall fields. The Z-R relationship used for the conversion of the reflectivities to rainfall rate was the Marshall-Palmer exponential form where $a=200$ and $b=1.6$. The influence function method, which is able to identify observations which are inconsistent with the spatial correlation in the radar field, has been employed. Two different approaches, namely the Kalman filter method and the Brandes method, have been employed to merge radar and raingage rainfall information and thereby improve radar rainfall estimates in a number of storms. An attempt has been made to explain quantitatively the rainfall amounts indicated by the two different measurement techniques.

(ii) Rainfall Forecasting

A basic rainfall forecasting scheme including two different modified approaches, namely the linear extrapolation of the centroids of features of rainfall cells and the cross-correlation analysis of radar rainfall fields, was developed for short-term rainfall forecasting (Baltas et al., 1993a, b and c). In the first approach centroids of features of rainfall cells at one time are matched with those at a subsequent time. Constraints are usually applied to the calculated motion to aid the matching procedure. Figure 1 shows two successive radar rainfall fields at time t_0 and t_1 used for the definition of the centroids of the features of rainfall cells (shaded area).

The second method using a cross-correlation technique is also used to match portions of one radar image with portions of subsequent ones. The computation of the velocity of a spatial rainfall pattern used for the translation of the current field requires the calculation of the correlation coefficient between the two known spatial rainfall fields at time t_0 and t_1 as shown in Figure 2a and b. The radar field at time t_1 is shifted a single grid point at a time on the x-y plane for both directions $\pm x$, $\pm y$ and the correlation coefficient between the two fields at time t_0 and t_1 only for the overlapping region each time is calculated. Figure 2c shows the radar field at time t_1 shifted right a single grid point. For the overlapping region between the fields at (a) and (c) (the shaded area) the correlation coefficient is calculated.

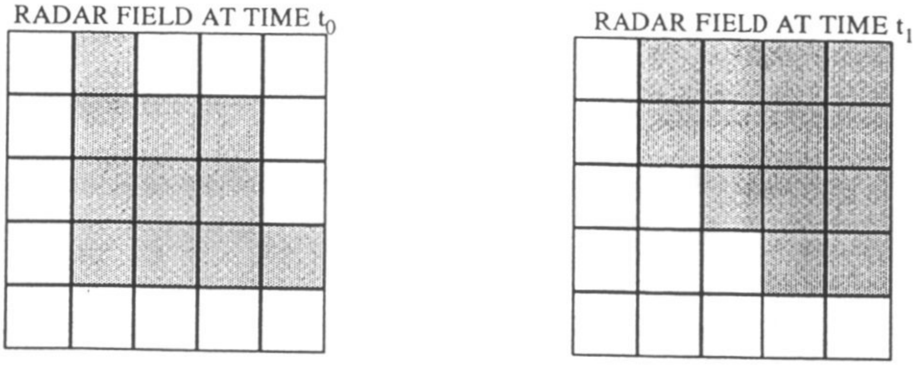


Figure 1 *Definition of features of rainfall cells above the threshold (1 mm/hr) at times t_0 and t_1.*

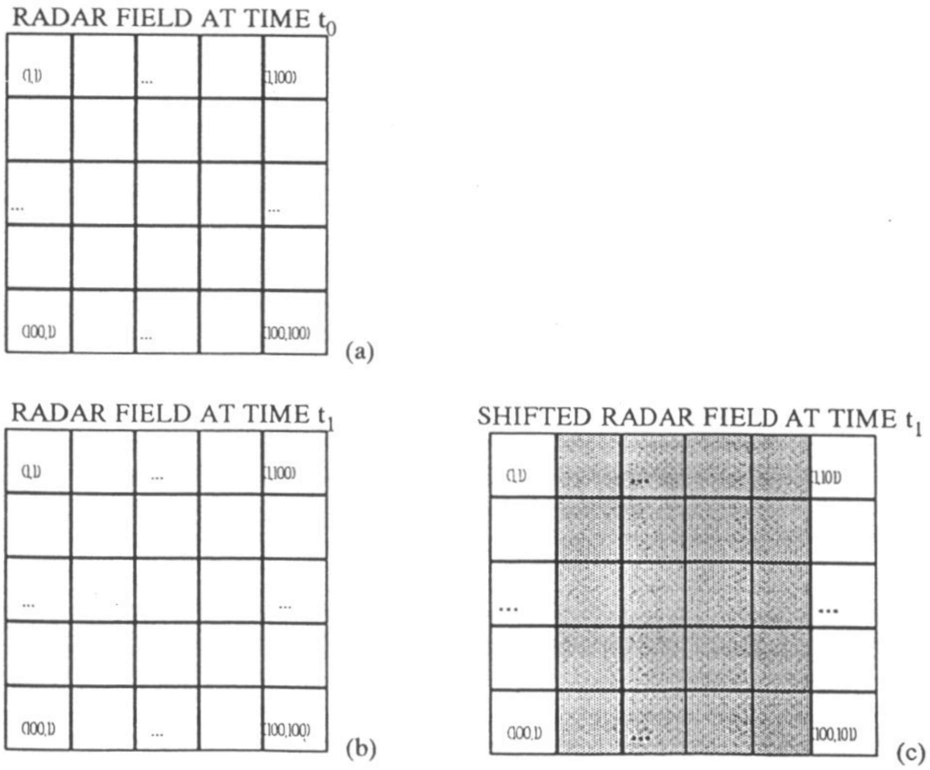


Figure 2 *Procedure of cross-correlating the different radar fields.*

A series of storm events have been analysed with both methods. Various lead-time rainfall forecasts were compared against the rainfall amounts observed on the ground during the forecast interval. Forecasting results evaluated by statistics such as the radar calibration factor, the mean catchment error and mean absolute difference are of acceptable accuracy.

(iii) Flow Forecasting

Application of a region-wide flood forecasting system

Initially the well known HEC1F flood forecasting model has been applied to the Venetikos and Pyli basins. The rainfall-runoff model HEC1F makes short-term forecasts of flood-runoff using a two-parameter unit-hydrograph model, a two-parameter loss model and a three-parameter base flow model. The HEC1F model was calibrated twice, once in a lumped manner using the entire basin and again in a semi-distributed manner by dividing the basin into a number of sub-basins in order to incorporate the extreme spatial variability of the storm events and accurately simulate the evolution of the resulting flash-flood in the study region (Mimikou *et al.*, 1993a and b). A number of storm events were used to demonstrate the quality of calibration of the model. It has been shown that the model performs better in the semi-distributed than in the lumped form, thus justifying the modifications made to the initial lumped form of the model. Furthermore, the HEC1F model was applied using as rainfall input the average radar rainfall over the basin in order to take into account the extremely uneven and non-uniform rainfall distribution in the study region. As depicted in Figures 3 and 4, the model's performance appears to be improved when applied using weather radar data, thus encouraging the use of weather radar for flood flow forecasting.

Development of a distributed flood forecasting model

The results of the previously mentioned study support the idea of developing a flood flow forecasting model in a fully distributed manner on a 2x2 km^2 or 4x4 km^2 grid network combined with distributed on-site and remotely sensed rainfall input information from the nearby S-band radar. This part of the research project is focused on deducing basin structure and isochrones from a digital elevation model (DEM) represented by an array of elevations z(x,y) for integer x and y ignoring the effects of inertia, friction, and infiltration into the soil and sink holes. An instantaneous unit hydrograph (IUH) model will be applied to transform excess rain by a transfer function for each grid square dividing the basin. Optimisation techniques such as the minimisation of the sum of squares between the model forecasts and observed flows will be employed for on-line estimation of parameters. Parameter estimation techniques will be employed to improve the performance of the flood forecasting model.

CONCLUSIONS AND ADDITIONAL REMARKS

(i) An assessment of estimation of spatial rainfall fields over basins of hydrological interest has been conducted. Data quality control methods in terms of ground clutter suppression, anomalous propagation as well as development and assessment of algorithms of deterministic and stochastic procedures for merging radar and raingage data have been completed.

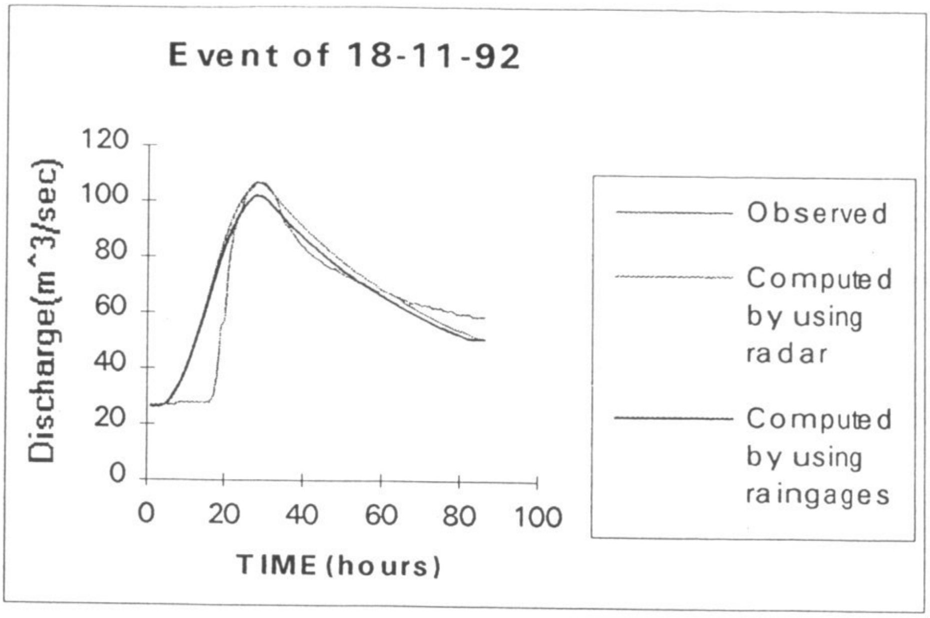


Figure 3 *Observed and modelled flood hydrographs based on raingauge and radar data*

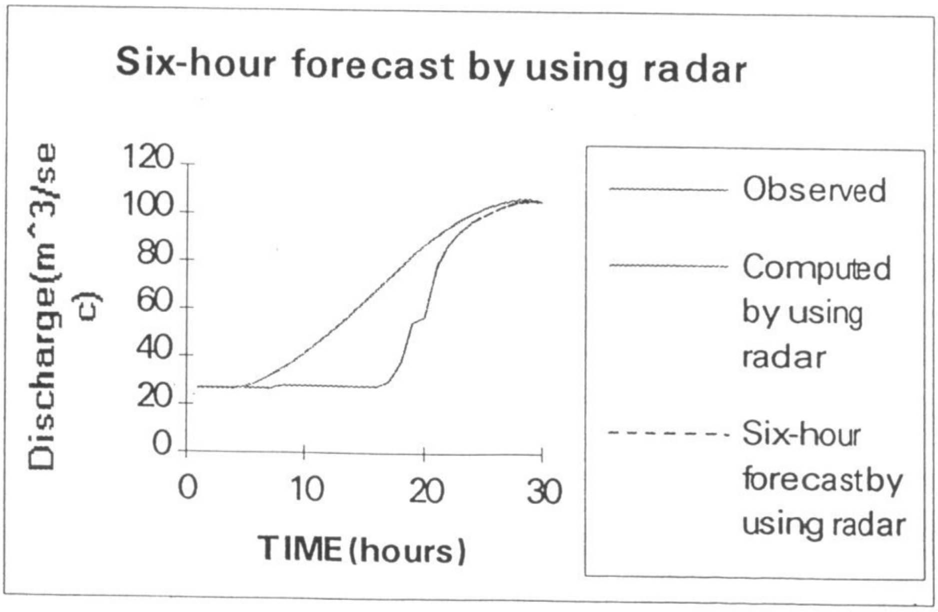


Figure 4 *Six-hour forecast using radar data*

(ii) High resolution short-term rainfall forecasting using weather radar data including two different modified approaches, namely the linear extrapolation of the centroids of features of rainfall cells and the cross-correlation of radar rainfall fields, have been established.

(iii) Initial results have shown that weather radar data are used for flash flood forecasting taking into account the extremely uneven and non-uniform spatial rainfall distribution. Therefore, the development of a fully distributed flood forecasting model arises as a necessary task.

The principal investigator Mr. E. Baltas attended a special interest workshop on Rainfall Physic for Radar Studies in Barcelona, Spain, June 1-2, 1993, where a paper was presented. A visit to Professor Fattorelli's group in Padova is being arranged for early next year in the framework of establishing collaborative links between the two teams involved in flood forecasting research.

REFERENCES

Baltas, E.A. (1993a) Intercomparison of two different methods for rainfall forecasting. Paper presented at the special interest workshop on Rainfall Physics for Radar Studies. June 1-2, 1993, Barcelona, Spain.

Baltas, E.A. & Mimikou, M.A. (1993b) Short-term rainfall forecasting by using radar data. International Journal of Water Resources Development, Vol 10, No 1.

Baltas, E.A. (1993c) Rainfall and Flash Flood Estimation and Forecasting by using Radar Data. PhD plan of work, Dept. of Water Resources Hydraulic and Maritime Engineering, National Technical University of Athens.

Mimikou, M.A. (1992) Weather Radar and Storm and Flood Hazards: Final Report, Contact No. EPOC-CT-90-0026, December, 1992, 12 pp, National Technical University of Athens.

Mimikou, M.A., Baltas, E.A. & Borga, M. (1993a) Flash-flood Forecasting by using the HEC1F Model. International Symposium of Engineering Hydrology, ASCE, Hydraulics Division, July 25-30, 1993 San Fransisco, USA.

Mimikou, M.A., Baltas, E.A. & Borga, M. (1993b) Improving the Efficiency of the HEC1F Model in Flood-Flow Forecasting. International Journal of Modelling and Simulation, (IASTED), Vol. 15, No. 1 (in press).

Mimikou, M.A., Baltas, E.A. & Anagnostou, E. (1993c) Rainfall Estimation by Using Weather Radar and Raingages. Technika Chronika Scient. J., Technical Chamber of Greece (in Greek).

Institution: Institut fuer Wasserwirtschaft, Universitaet Hannover, Germany

Project Leader: Dr. Hans-Reinhard Verworn

Institutions cooperating: Deutscher Wetterdienst (German Weather Service)
Emschergenossenschaft

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

Operational Integration of X- and C-Band Data and Relevance of Rainfall Forecasts for Real-Time Control of Storage Facilities

MAIN OBJECTIVES

The scientific goals of the project involve investigation into the following:

1. Improvement of the accuracy of rainfall data and forecasts by combining the advantages of X- and C-band measurements.
2. Specification of the required accuracy of forecast radar rainfall fields for successful real-time control.
3. Quantification of the sensitivity of control decision-finding procedures to inaccurate forecasts.
4. Investigation and quantification of the significance of differences in the overflow when rainfall data from either radar or ground gauges are used as a basis for the decision-finding procedures.

METHODS AND MATERIALS

The study will employ rainfall data from a C- and an X-band radar at the same location. In addition, rain data from ground gauges and disdrometers will be available. These data will be processed and used for comparison and evaluation to find suitable procedures for the integration of all information sources. This research will be carried out in close cooperation with Italy and the Netherlands where C- and X-band data are also collected and processed.

The investigations concerning the control procedures are to be carried out in an urban catchment with controllable detention tanks, where the overflow is discharged into rather clean and therefore sensitive creeks. The variation of the rainfall distribution is generally quite significant resulting in a high control potential.

The rainfall-runoff dynamics of the catchment will be simulated off-line as well as on-line with hydrological and hydrodynamic models. Control decision-finding will be carried out using an optimisation model. The relevance of various forecasting methods and the sensitivity of the control strategies will be tested through simulation of a representative set of rainfall events with different characteristics.

RESULTS (JANUARY TO DECEMBER 1993)

Adaptation of rainfall-runoff models for the catchment and calibration of runoff parameters

The catchment of the treatment plant Gelsenkirchen-Picksmuehlenbach covers an area of about 1200 ha of which 40% is impervious ($A_{red}=475$ ha). The area is divided into three subcatchments (I to III) with a detention basin at the end of each one. Additionally the foul sewage from catchment IV is routed to the treatment plant. Presently, the system is designed to route a maximum runoff of twice the dry weather flow (2 Qdry) of each catchment to the treatment plant. Surplus runoff is stored in the basins and discharged into the creeks. Figure 1 shows the layout of the system.

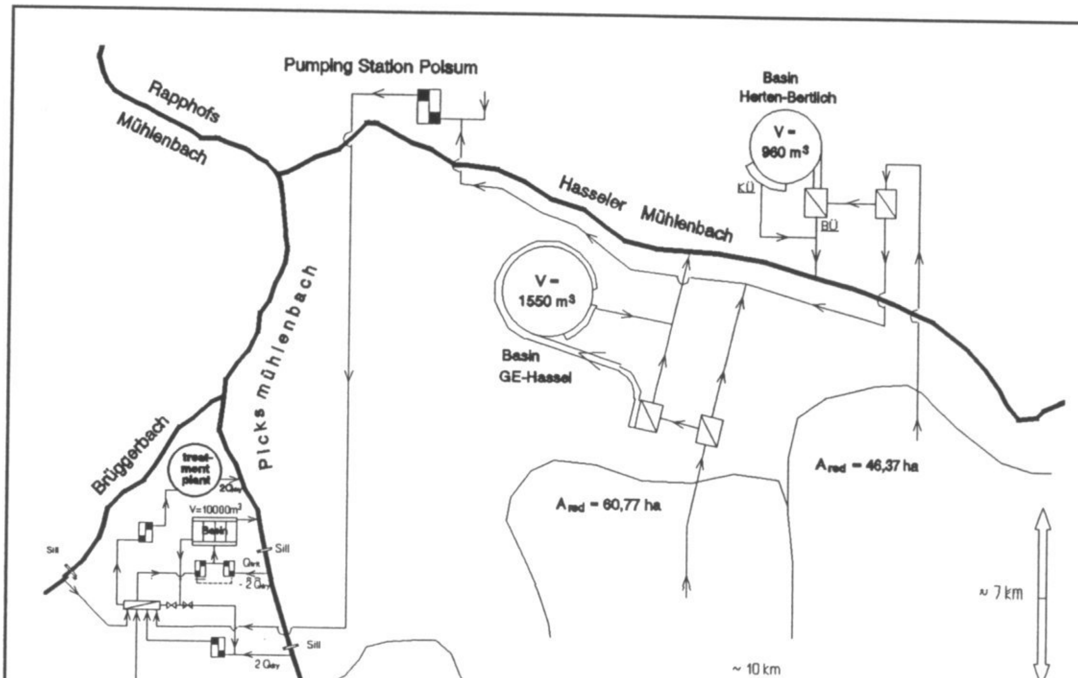


Fig. 1: Schematic layout of the system with control elements

The modelling of the catchment is based on the main sewer system and consists of 39 catchment units, resulting in an average unit size of 0.3 km² which is just smaller than the size of the radar bins for the X-band coverage of the area (0.36 km², see Figure 2).

For the rainfall-runoff simulations a detailed surface runoff model and a hydrodynamic model for transport in the sewers have been set up. Additionally a simple linear transport model is used in connection with the control decision-finding. Initial simulation results show a satisfactory compliance with the measured values at the sites of the basins and the treatment plant. An improvement of the model results is expected when data from additional measuring devices, now being installed, will be available and used to calibrate the surface runoff parameters in more detail.

Definition of the control system and adaptation of the control decision-finding model

For the application of the optimisation procedure the system had to be further simplified to consist of nodes and transport elements only (Figure 3). This linearised system provides storage at certain nodes and routes the runoff down the transport elements to the next node with a predefined constant velocity, i.e. with fixed travel times. The maximum runoff rate of the transport elements is set dependant on their capacity. Surface runoff for the catchments forms the input at the subcatchment nodes. If the runoff exceeds the capacity of the transport sewer to the next node the excess runoff is modelled to be stored within the catchment. Though these assumptions do not fully comply with the system behaviour more exactly simulated by the hydrodynamic model, various applications and test runs have shown that this does not affect the validity of the control decisions. The aims for the control decisions were defined as follows in order of priority:

1) no or minimum surcharge/storage at the catchment nodes;

2) transport of as much runoff as possible to the treatment plant to make use of its maximum capacity;

3) no or minimum combined sewer overflow into the creeks.

With the surface runoff of various events, local control as well as global optimal control has been simulated to investigate the control potential of the system. The results indicate superiority of the global strategy for all events. While with local control not more than 2 Q_{dry} of each subcatchment is routed on to the treatment plant, the global control strategy allows larger local runoffs to be routed on if only the total capacity of the treatment plant is not exceeded. The control potential of the system, i.e. the amount of overflow that can be reduced by global control in comparison to local control, will be found by multiple event simulations using ground gauge rain data from a 20 year period.

Rainfall data from X- and C-band radars, raingauges and disdrometers

Data from the X-band radar with a spatial resolution of 0.6 x 0.6 km and a time resolution of 1 minute have been collected and processed using a mean Z/R relation as well as actual Z/R relations derived from two disdrometers. The unprocessed Z values in polar coordinates (300m x 0.7°) are stored as well to investigate attenuation effects and validity of Z/R relations. Due to building activities in the area between the radar site and the nearby building of the German Weather Service, where the radar control unit and the computers were located, the cable connection was disrupted. Consequently, the system set-up had to be changed, and the transfer of all control and computer equipment to a newly installed container just besides the radar tower lead to an interruption in data collection.

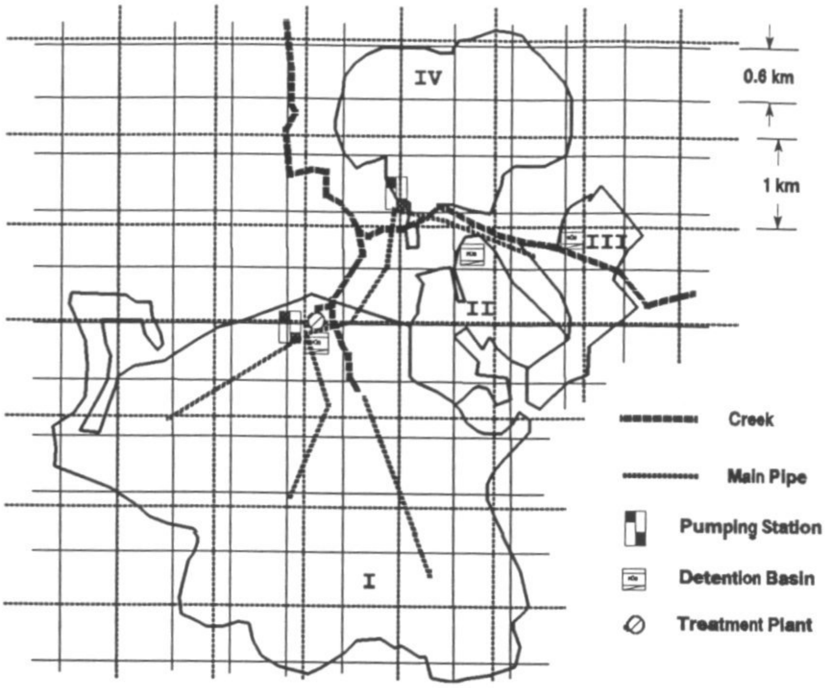


Fig. 2: Catchment with X- and C-band radar grid

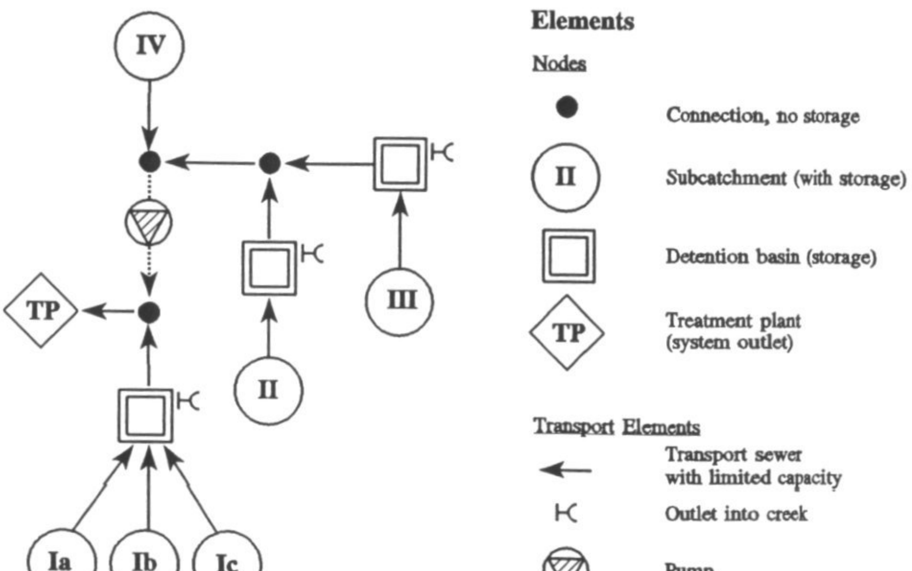


Fig. 3: Simplified linear system for control decision finding

The data from the C-band radar of the German Weather Service are supplied with a spatial resolution of 1 x 1 km every five minutes as rain rates derived from a fixed Z/R relation without any ground gauge calibration. This provides the possibility to degrade data back to Z values for comparisons with the X-band data. The overlapping fabric of the spatial resolution is indicated in Figure 2. Alternatively, reflectivities in polar coordinates (1 km x 1°) may be stored as well.

Data from a set of 19 ground gauges continously and automatically collected by the Emschergenossenschaft are added to the database for evaluations of radar data from both X- and C-band.

CONCLUSIONS AND ADDITIONAL REMARKS

1) The hydrological and hydrodynamic modelling of the catchment has been found to form a sound basis for the evaluation and forecast of the system behaviour as well as for the application of the control decision-finding model. Even better correspondence with the actual runoff is expected when additional measured data can be used to calibrate the surface runoff parameters.

2) An assessment of the advantages of global control strategies over local control has been made. The control potential is to be found out by simulating all relevant events of a longer period comparing both methods.

3) Databases for radar and ground rain data have been set up. Software for the evaluation and comparison of the data has been developed. The databases will provide the necessary input for the development and assessment of forecast procedures to be used with the control decision-finding.

It is planned to further investigate the quality of the radar data by additionally obtaining vertical profiles. Collaborative work with the UK group at Salford has been arranged on applying their vertical pointing radar in the catchment area.

Institution: Laboratoire d'étude des Transferts en Hydrologie et dans l'Environnement.
Institut de Mécanique de Grenoble, France

Project Leader: Jean-Dominique Creutin

Institutions cooperating: Laboratoire Central des Ponts et Chaussées, France.
Universitat Politecnica De Cataluny, Spain
Ville de Marseille, France

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

The objective of the project is twofold: (i) to investigate the complementarity of different rain sensors (namely X- and S- band radars, raingauges and disdrometers) and (ii) to test the relevance of these sensors to the monitoring of storm urban drainage in a Mediterranean city.

METHODS AND MATERIALS

The study mainly employs the data set from the pilot experiment of Marseille (in 1992 and 1993) developed under an earlier CEC project and extended by 12 months during the present project. Due to different delays imposed by the radar manufacturers, the vertical pointing radar was not deployed in time according to the experiment plan. Thus the Cevennes data set, collected under the first CEC radar project, together with volume scan data from the radar of Padova, Italy, will be used for the studies on vertical profiles of reflectivity.

The complementarity between the different rain sensors is explored through data analysis and simulation studies. Data analysis is used to calibrate the physically-based relationships between the various measurements. The simulations are designed in order (i) to analyse the sensitivity of the sensors to the space and time variability of rain features and (ii) to test correction and merging algorithms.

The test of relevance for storm monitoring in urban areas applies (i) to short-term rainfall forecasting using a lumped conceptual model of precipitating cloud and (ii) to rainfall-runoff modelling on selected watersheds.

RESULTS TO DATE

(i) Field activities

During the 12 months covered by this report, the LTHE operated an X-band radar, a disdrometer and an optical spectrometer in Marseille. A detailed list of the rain events observed is given in Table 1 in the LCPC report (participant No. 13) which follows. In addition, a control antenna was designed, built and tested with a twofold objective: (i) to check the radar features (transmitted power, antenna diagram) and (ii) to measure the total rain attenuation between the radar and this antenna (see Delrieu & Caoudal, 1993). The antenna diagram is presently used in a detailed modelling of the mountain detections. The total attenuation could be introduced in the attenuation correction procedures if this kind of antenna was actively operated (which is not yet the case).

(ii) Studies of drop size distributions

The drop size distribution (DSD) is a key factor of the rain measurement problem. The fluctuations of the DSD in space (including the vertical dimension) and in time govern the relations between the measurements of the different sensors. Thus the simulation studies, as well as the establishment of an integrating scheme linking the various sensors, require a reliable characterization of these fluctuations.

Two aspects were examined:

- *sensitivity of drop size measurements to the ground sensor used*

The two DSD sensors installed side by side in Marseille (a Joss-Waldvogel disdrometer and an optical spectrometer) work according to different principles. The first one measures the momentum of the drops while the second one measures their diameter and their speed. As shown from a previous experiment in Grenoble (final report to EPOC-CT-90-0026 contract), the bulk rain variables (reflectivity, intensity, attenuation) derived from the two sensors exhibit significant differences (for instance the disdrometer gives $Z=275\ R^{1.51}$ while the optical spectrometer leads to $Z=267\ R^{1.72}$). A detailed analysis of the sources of these differences (Lecq & Creutin, 1993) points out the key role of the drop speed. As shown in Figure 1 the fall speeds exhibit both a bias and a strong dispersion, as compared to the theoretical formulations appropriate for still air conditions. The fall speed affects two steps of the conversion of the disdrometer signal. The first relates to the working principle: for a given momentum the assessed diameter depends on the fall speed. The second one is common to all devices measuring the flux of droplets: the change into a concentration (all the bulk variables, except the rain intensity, depend on the drop concentration) is governed by the fall speed. Figure 2 illustrates the respective weight of these two steps in terms of Z-R relationships.

- *dependence of the DSD on the rain intensity*

All the DSD models in the literature are written as a function of a selected bulk variable. For instance, the Marshall and Palmer distribution $N(D) = N_o e^{-\lambda D}$ can be written $N(D,R) = N_o e^{-\lambda(R)D}$ since the slope λ depends on the rain intensity R through a power function. The Universitat Politecnica de Catalunya, Spain, as a collaborative contribution to the simulation task of the project, defined a general theoretical framework for the DSD. The following

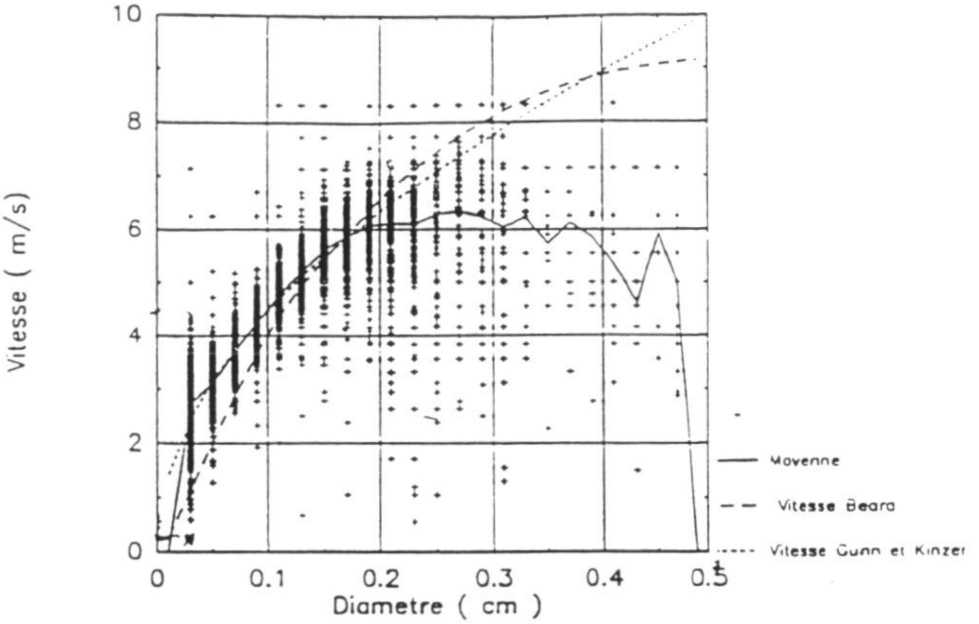


Figure 1 *Scattergram of the fall speed of the rain drops as a function of their diamter measured by the optical spectrometer. Each point represents the mean fall speed of the drips seen during one minute in each class of diameter. The broken line is the mean value of the one minute mean speeds over all the sets of data. The curves represent the theoretical fall speed in still air predicted by Gunn and Kinzer (dotted line) and Beard (dashed).*

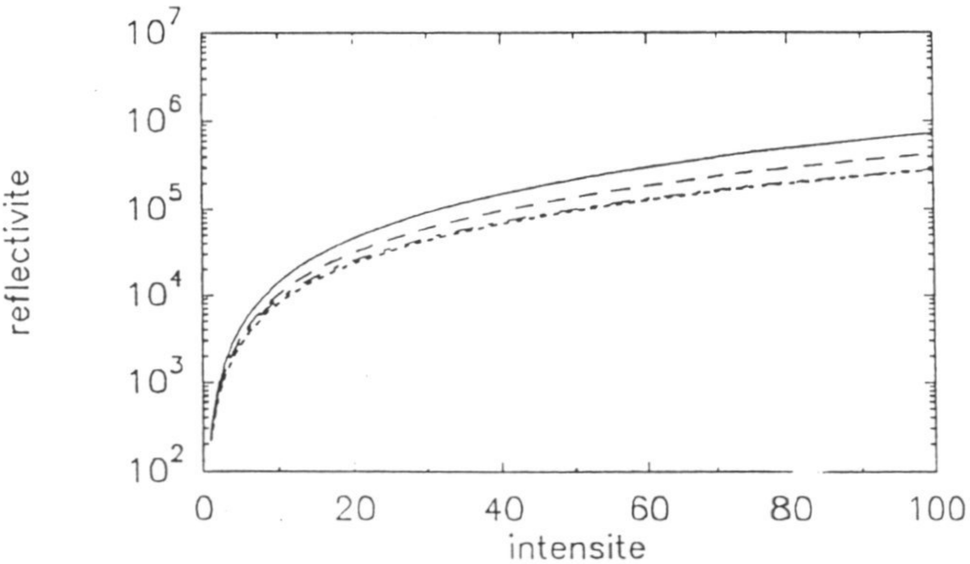


Figure 2 *Z-R relationships derived from the disdrometer (one of the bottom curves) and from the spectrometer (top continuous curve). If a theoretical speed relationship is used in the change of flux into concentration to compute Z, the middle dashed curve is obtained from the spectrometer data. If, in addition, the size of the drops is derived from the measured diamter and speed according to the disdrometer principle (momentum conversion to size for still air conditions) the second bottom curve is obtained.*

scaling formula:

$$N(D,\psi) = \psi^{\alpha} g\left[\frac{D}{\psi^{\beta}}\right]$$

is shown to account for all the existing DSD models if, for a given bulk variable Ψ, α and β are two constants and g is a function independent of the fluctuations of Ψ. As the scaling factor Ψ is a moment of $N(D,\Psi)$, the parameters α and β are linearly related (see Figure 3). This reduction of the number of parameters improves the self-consistency of these formulations and opens promising possibilities in terms of simulation (Sempere *et al.*, 1993).

(iii) Attenuation studies

The complementarity between the X-band radar and the gauge network was analysed using the first selected rain event for which a significant attenuation was observed (ground intensities over 50 mm h^{-1}). The integrating scheme used included the following aspects: level of detection of the sensor, fluctuations of the mountain detections at distance (see Figure 4), and mean regional features of DSD. In a first step the uncertainties due to the DSD fluctuations in time and space, to the sampling differences between radar and gauges and to the vertical modifications of rain were not taken into account. In addition, an optimization method was used in order to cope with these uncertainties. The results presented in Figure 5 show two levels of complexity of the integrating scheme. The first scheme (simple Hitshfeld-Bordan correction) does not incorporate the fluctuations of the remote ground detection while the second one does (path integrated algorithm). In spite of some significant discrepancies with the ground values, the more complete scheme gives better results: the correlation coefficient goes from .79 to .85 when 180 couples are compared. The raw data have a correlation of .66 (see Delrieu & Caoudal, 1993).

REFERENCES

Delrieu, G. & Caoudal, S. (1993) Radar météorologique de configuration légère: methodes de correction d'atténuation et développement d'une balise d'étalonnage. Rapport LTHE R93/012, 32 pages.

Lecq, S. & Creutin, J.D. (1993) Granulométrie des précipitations: sensibilité de la relation Z-R au choix du capteur utilisé. Rapprot LTHE R93.013, 67 pages.

Lecq, S., Creutin, J.D. & Delrieu, G. (1993) Sensitivity of ground based Z-R relationships on the sensor used. IVth Internat. Conf. on Precipitation, Iowa City.

Lefebvre O. (1993) Métrologie et modélisation de la relation pluie-débit sur le bassin versant No. 17 du réseay d'assainissement de Marseille. Rapport LTHE R93/014, 45 pages.

Sempere-Torres, D., Porra, J.M., Salles, C. & Creutin, J.D. (1993) Scaling the raindrop size distribution: a methodology. XVIII EGS General Assembly, Wiesbaden.

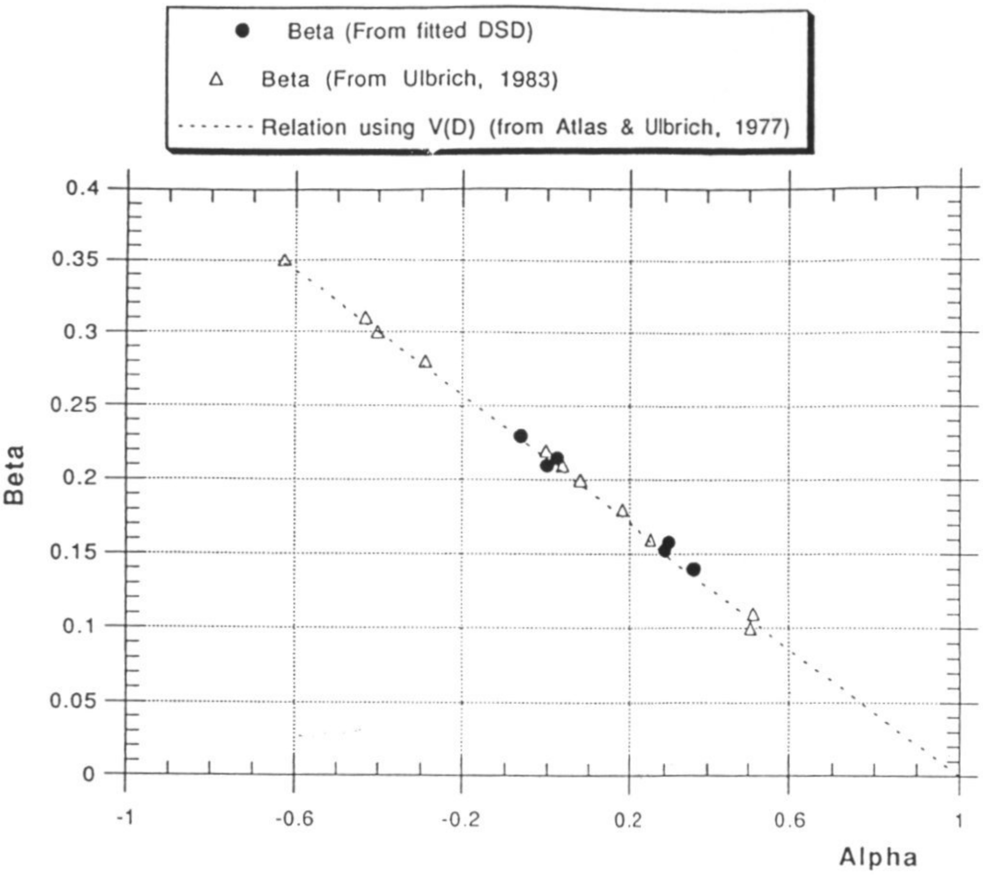


Figure 3 *Scattergram of the parameters α and β of the DSD scaling law for various models proposed in the literature. The dotted line gives the theoretical relationship.*

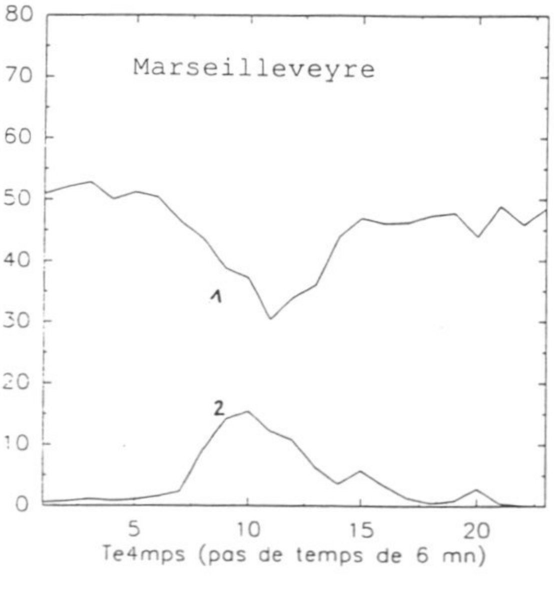
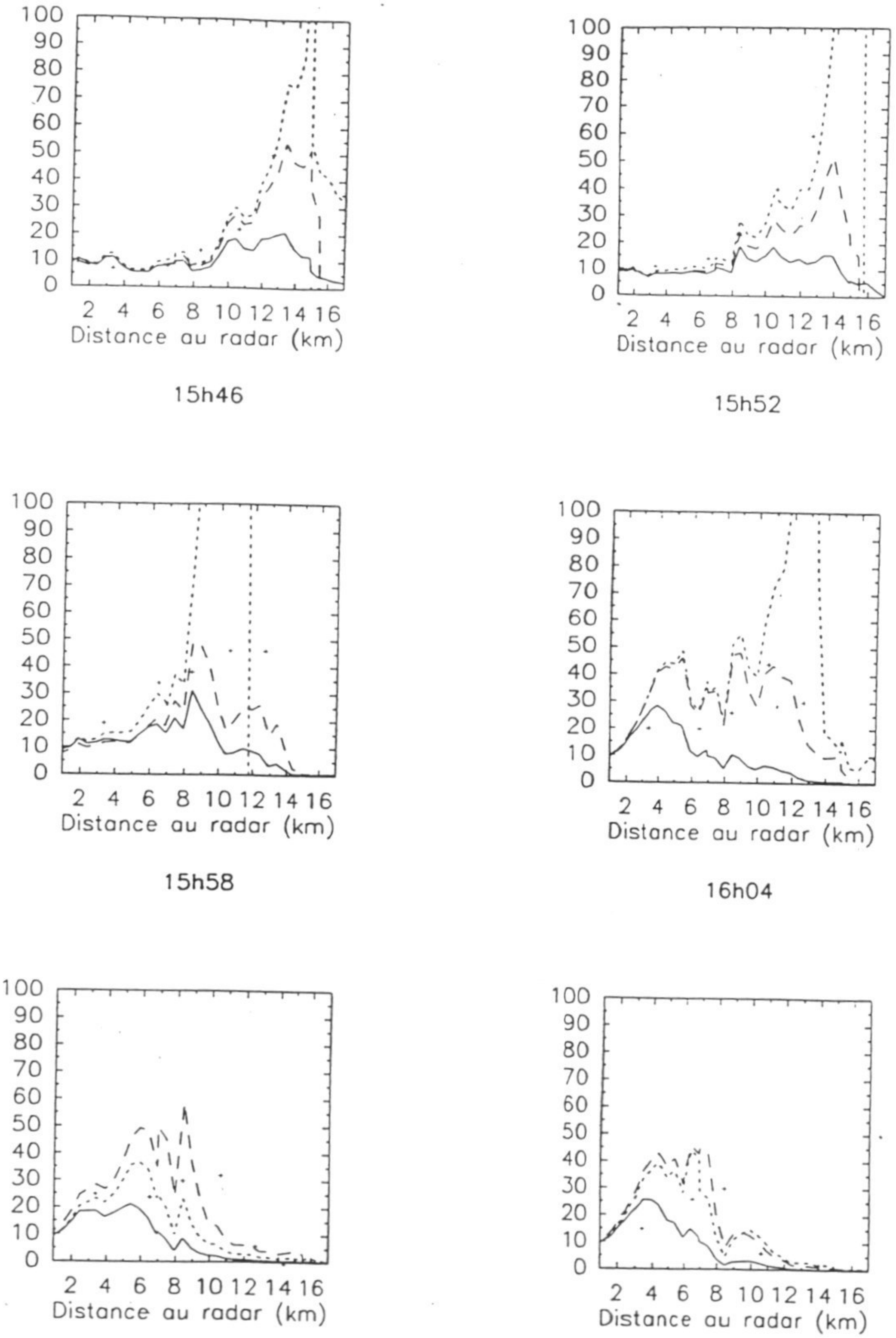


Figure 4 *In function of time (6 minute time steps) the top curve represents the apparent reflectivity of Mount Marseilleveyre while the bottom curve indicates the total attenuation along the path radar-mountain as derived from the raingauge measurements.*



15h46

15h52

15h58

16h04

16h10

16h16

Figure 5 *Rain profiles (in mm h^{-1}) along the azimuth including the Mount Marseilleveyre at 17 km range. The block curve represents the raw data measurements. The other curves are obtained using the Hitshfeld-Bordan algorithm (dotted line) and the Path Integrated Attenuation algorithm (dashed line). The crosses are the readings from 5 gauges operated along this azimuth. Six time-steps are considered.*

Institution: Laboratoire Central des Ponts et Chaussées, Division Eau, France

Project Leader: Hervé S. Andrieu

Institutions cooperating: Institut de Mécanique de Grenoble
Ville de Marseille

Title of project: **STORMS, FLOODS AND RADAR HYDROLOGY**

MAIN OBJECTIVES

The objective of the project is to improve the hydrometeorogical survey of urban Mediterranean regions prone to long and intense rain events. Jointly with the IMG group, the investigation concerns the following tasks:

(i) Contribution to the Marseille Experiment by collecting and processing of data recorded by Meteo France;

(ii) Correction of the errors due to the Vertical Profile of Reflectivity

(iii) Test of a short-term rainfall forecasting model based on radar data and a conceptual rainfall model.

(iv) Evaluation of the complementarity between a local radar (X-band) and a radar of the national meteorological network

METHODS AND MATERIALS

The first part of the project focuses on experimental aspects. The goal of the Marseille 93 experiment is to collect all hydrological and meteorological data useful to describe intense rain events affecting a big Mediterranean city. The initial part concerns the constitution of the database, grouping all the recorded data. This task includes different stages : collection of data, consistency of data coming from different sensors working at different spatial and temporal recording resolution, and preprocessing of radar data recorded by the radar located in Nimes. The work devoted to the vertical profile of reflectivity (VPR) will be based on data of the Cevennes Experiment and data recorded by the Italian group. The goal is to extend a VPR identification method in order to define local VPR instead of a mean VPR and to test the hydrological interest of this VPR correction procedure. Rainfall forecasting consists of testing the conceptual approach proposed by the University of Iowa. This test will be based on the rain events recorded during the Cevennes Experiment which have a strong orographic component.

RESULTS IN 1993

(i) Experimental Database

The database contains data recorded by the following sensors :

- a meteorological station installed in the Marseille city during the experiment. It measures: pressure, temperature, relative humidity, wind (velocity and direction) every 30 minutes
- X-band light configuration radar
- S-band radar located near Nimes (80 km far away from Marseille)
- Meteosat satellite (visible and infrared images)
- a raingage network of 20 devices

It is planned to collect the analysis and forecasts performed by the meteorological model ARPEGE for the most interesting rain events.

The main rain events presently available occured during the last Autumn season (September and October 1993). Table 1 details the present content of the Marseille database (Faure et al, 1993) and Figure 1 compares images from the two radars.

(ii) Identification of Vertical Profile of Reflectivity

The vertical variability of reflectivity in the radar beam is one of the main sources of error in estimating radar rainfall intensity. This vertical variability is characterized by a function called the Vertical Profile of Reflectivity. A method for identifying the vertical profile of reflectivity has been proposed. In its initial version this procedure only requires the use of radar images from at least two different elevation angles. The efficiency of the proposed method is appreciated from a hydrological point of view. A comparison is performed at the catchment scale between hourly rainfall intensities measured with a dense network of raingauges and radar data. The analysis shows that the introduction of the identification and the correction of the influence of vertical profiles of reflectivity improve the accuracy of rainfall estimates from radar. Preliminary results show that the method could be operationally applicable (Faure, 1993). On-going work will consist of extending this method to full volume scan data. In this respect, a collaboration with other groups of the project (Salford, Padova) is envisaged.

(iii) Rainfall Forecasting

The study of rainfall forecasting is based on a recent approach well adapted to hydrological applications, proposed by the Hydrometeorological group of the University of Iowa. The basic idea is that the rain cloud over a basin can be represented by an atmospheric column, the rainfall at the ground level depending on the liquid water content of this column. The temporal evolution of this column is assumed to be described by a conceptual model which can be combined with a classical advective scheme. Work was initiated during a six months stay at the University of Iowa (Andrieu, 1993 and French et al, 1993). Ongoing work concerns evaluation of the dynamical part of the model in the orographic context of rain events recorded during Cevennes Experiment (Berthier and Thauvin, 1993 and Thauvin, 1993).

Table 1 *Rain events and data*

Date Evénement	Données Radar bande X (Δt = 6mn)	Données Radar Calamar (Δt = 5mn)	Données Radar Météotel (Δ t=15mn)	Données Météosat en IR (Δt = 30mn)	Données Météosat Visible (Δt = 30mn)	Mesures Pluvio (Δt = 6mn)	Données Météo (Δt = 30mn)
Le 2 Mars 1993	du 2 9h34mn au 2 11h40mn le 2 11h52mn (2x23 images)	▨	du 2 6h00mn au 2 16h00mn	du 2 6h00mn au 2 16h00mn	du 2 7h00mn au 2 16h00mn	le 1er Mars 24 Pluviomètres le 2 Mars 25 Pluviomètres	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité relative
Du 1 au 2 Avril 1993	du 1 18h04mn au 1 22h04mn (2x41 images)	du 1 18h00mn au 2 18h00mn	du 1 16h00mn au 2 12h00mn	du 1 17h00mn au 1 23h00mn du 2 2h00mn au 2 12h00mn	du 2 7h00mn au 2 12h00mn	le 1er Avril 24 Pluviomètres le 2 Avril 25 Pluviomètres	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité relative
Du 24 au 28 Avril 1993	du 24 17h28mn au 24 23h58mn (2x44 images) du 28 05h34mn au 28 10h28mn (2x50 images)	du 24 10h00mn au 25 24h00mn du 27 15h00mn au 28 15h00mn	du 24 10h00mn au 25 8h00mn du 25 12h00mn au 25 20h00mn du 26 22h00mn au 27 6h00mn du 28 1h00mn au 28 10h00mn	du 24 10h00mn au 25 8h00mn du 25 12h00mn au 25 20h00mn du 26 22h00mn au 27 6h00mn du 28 1h00mn au 28 10h00mn	du 24 10h00mn au 25 8h00mn du 25 12h00mn au 25 18h30mn du 28 6h00mn au 28 10h00mn	les 24 et 25 Avril : 25 pluviomètres le 26 Avril : 24 pluviomètres le 28 Avril : 25 pluviomètres	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité relative
Du 22 au 24 Septembre 1993	du 22 19h28mn au 23 02h28mn (2x37 images) du 23 14h16mn au 23 18h28mn (2x36 images) du 24 04h46mn au 24 05h28mn (2x8 images)	du 22 20h00mn au 23 20h00mn	du 22 17h45mn au 23 13h45mn du 23 14h15mn au 23 17h00mn du 23 17h30mn au 23 18h00mn	du 22 17h00mn au 23 11h30mn du 23 13h00mn au 23 15h00mn du 23 16h00mn au 23 18h00mn du 23 19h00mn au 23 20h00mn	du 22 7h00mn au 23 11h00mn du 23 12h00mn au 23 15h30mn le 23 16h30mn	le 22 Septembre : 23 pluviomètres le 23 Septembre : 23 pluviomètres le 24 Septembre : 22 pluviomètres	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité Relative
Le 30 Septembre 1993	EN COURS DE TRAITEMENT	▨	le 30 9h15mn du 30 10h15mn au 30 14h00mn du 30 14h30mn au 30 18h00mn	le 30 9h00mn du 30 10h30mn au 30 18h00mn	du 30 11h00mn au 30 14h30mn le 30 15h30mn le 30 16h30mn	EN COURS DE TRAITEMENT	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité Relative
Le 02 Octobre 1993	EN COURS DE TRAITEMENT	du 02 3h25mn au 02 8h00mn	du 02 3h00mn au 02 8h00mn	du 02 3h00mn au 02 6h00mn	▨	EN COURS DE TRAITEMENT	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité Relative
Le 07 Octobre 1993	EN COURS DE TRAITEMENT	du 07 13h40mn au 07 16h00mn	du 07 13h00mn au 07 14h30mn le 07 15h00mn du 07 15h30mn au 07 16h45mn	du 07 13h30mn au 07 17h00mn	du 07 12h00mn au 07 16h30mn	EN COURS DE TRAITEMENT	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité Relative
Le 29 Octobre 1993	EN COURS DE TRAITEMENT	du 29 8h30mn au 29 17h00mn du 29 17h30mn au 29 20h00mn	du 29 7h00mn au 29 19h00mn	du 29 7h00mn au 29 14h00mn	du 29 8h30mn au 29 15h30mn	EN COURS DE TRAITEMENT	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité Relative
Le 31 Octobre 1993	EN COURS DE TRAITEMENT	du 31 8h00mn au 31 15h00mn	du 31 7h00mn au 31 14h00mn	le 31 7h00mn du 31 8h00mn au 31 14h00mn	du 31 8h00mn au 31 15h30mn	EN COURS DE TRAITEMENT	Température sous abri Pression,Précipitations Vitesse Moy. du vent Vitesse Max. du vent Direction Moy du vent Direction Max du vent Humidité Relative

Nota : Les données du radar de Marseille (bande X) et les mesures pluviométriques sont exprimées en heures locales. Les autres données en heures TU.
Les images du radar de Marseille sont multiples. Ici deux images par pas de temps : une image à 0°, une image à 4°.
Etat de la base de données le 20/11/93.

▨ Pas de données

░ Données non continues : des imagess sont manquantes

☐ Données continues

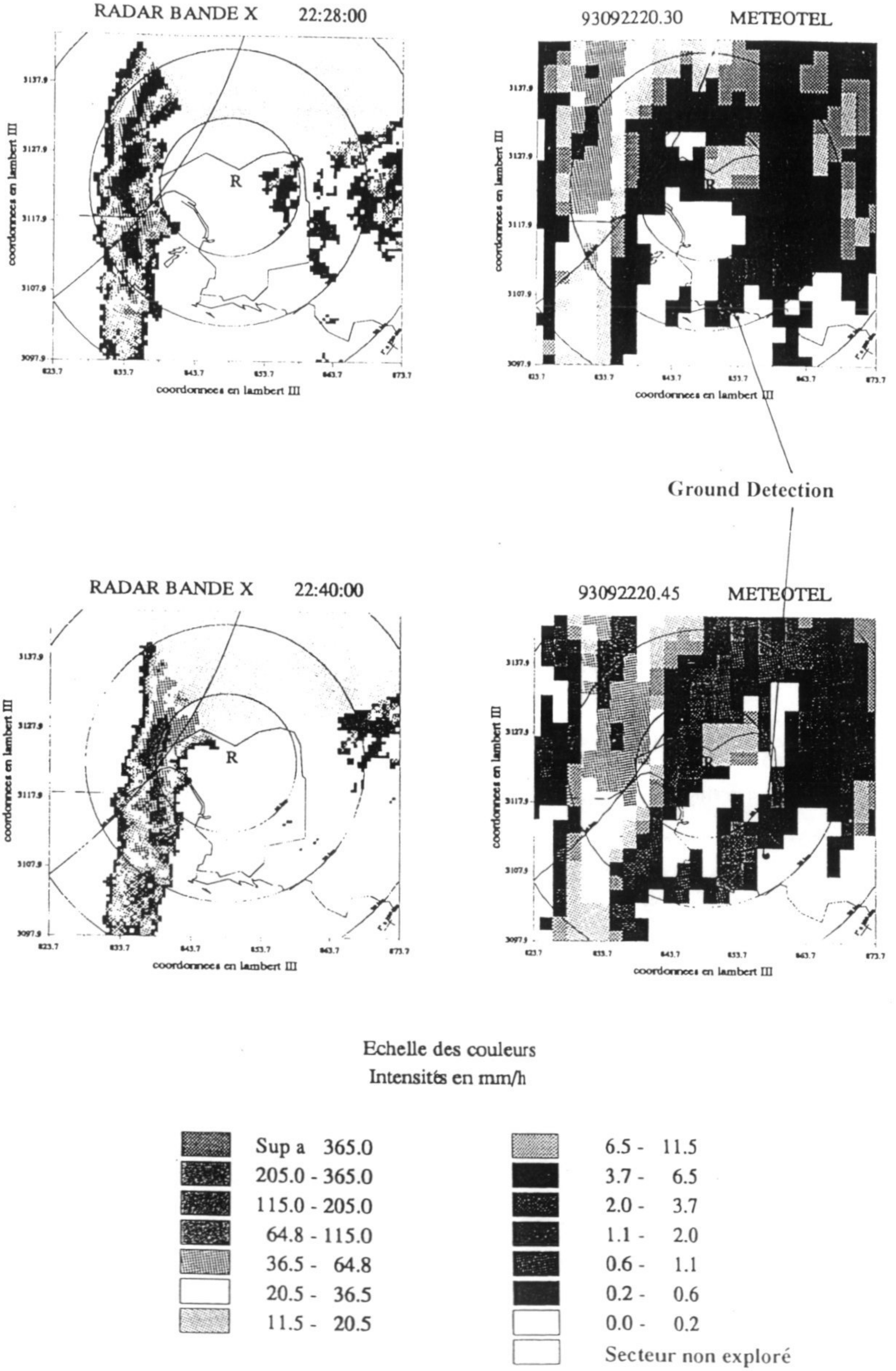


Figure 1 *Images from the X-band and S-band (Meteotel) radars.*

CONCLUSIONS AND ADDITIONAL REMARKS

(i) The initial effort consists of building a structured data set regrouping numerous parameters representative of the rainfall variability. This preliminary effort is very time consuming, but it is a necessary step to further use of these data in good conditions.

(ii) A collaboration with other national groups would be very fruitful to test and evaluate the VPR identification and the associated correction in a more robust way.

(iii) Radar rainfall forecasting based on full volume scan radar data coupled with a conceptual model remains to be evaluated carefully. But it appears to be a convenient and simple means to approach microphysical and dynamical models of rainfall forecasting.

REFERENCES

Faure, D. (1993) Application à l'Hydrologie du Radar Météorologique - Comparaison d'Estimations Radar et Pluviométriques pour des Lames d'eau Horaires sur de petits Bassins Versants Cévenols, Doctorat de l'Université de Grenoble, 310 pages

Faure, D., H. Andrieu, J.M. Rouaud: (1993) Constitution d'une base de données et premières comparaisons des images des radars de Nimes et Marseille, Rapport LCPC/IMG, 45 pages.

French, M.N., H. Andrieu & W. Krajewski (1993) A Model For Real-Time Rainfall Forecasting Using Remote Sensing: 2 Cases Studies, to appear, Water Res. Research.

Berthier, E. & V. Thauvin (1993) Préalable à l'évaluation d'un modèle de prévision par radar des intensités pluvieuses à très courte échéance, Rapport LCPC, 64 pages+ Annexes.

Andrieu, H. (1993) An Introduction to Rainfall Forecasting for Hydrological Needs, 2nd Workshop on Rainfall Physics for Radar Studies, Universiti Polytechnique de Catalogne, 1-2 June.

Andrieu, H. (1993) The interest of Correcting The effect of Vertical Profiles of Reflectivity, 2nd Workshop on Rainfall Physics for Radar Studies, Universitat Polytechnica de Cataluny, 1-2 June.

Thauvin, V. (1993) Rain Forecasting in the Cevennes Region: a Preliminary Study, 2nd Workshop on Rainfall Physics for Radar Studies, Universitat Politecnica de Cataluny, 1-2 June.

Institution: University of Ljublyana, FAFF - Hydraulics Division, Slovenia

Project Leader: Mitja Brilly

Institutions cooperating: Biotechnical Faculty - Agronomy Department, Faculty of Sciences - Chair of Meteorology, Hydrometereological Institute, and Water Management Institute.

Title of project: STORMS, FLOODS AND RADAR HYDROLOGY

MAIN OBJECTIVES

The scientific goals of the project include investigation into the following:

(i) Setting up a network for telemetering and acquisition of hydrometeorological data for the validation and proper operation of hydrological mathematical models. A hydrometereological database for 3 events will be established using GIS for model calibration and validation. Study of historical data for flood events in Soča watershed.

(ii) Use deterministic and stochastic procedures for merging radar and raingauge precipitation data.

(iii) Development and calibration of real-time flood forecasting model. Development of interfaces to the GIS. Creation of the cartographic and topographic database for Soča river.

METHODS AND MATERIALS

The study will employ radar data primarily from the Teolo (Italy) and Lisca (Slovenia) radars which have been in operation for a few years. Meteorological radar data from Grado (Italy) and Slavnik (Slovenia) will be also used if they are in operation next year. PC computers and a mainframe computer with UNIX operating system will be used with Geographical Information Systems GEO/SQL and SPANSE.

Hydrometeorological data from 9 raingauge stations and 8 river level gauges are to be used (Figure 1). Topographic data are digitised from maps at a scale of 1:25000.

RESULTS (JUNE TO DECEMBER 1993)

(i) Historical data analysis

The Soča (Isonzo) river watershed is a region which experiences the maximum precipitation in Slovenia, and in Friuli-Venezia Giulia, ranking also very high in Europe. It is also a part of a belt (at the southern flank of the Alps, from Mediterranean to the Pannonian climate), where there is most probably a European maximum of days with storms. High mountains with a lot of snow being accumulated during the winter contribute to the danger of floods as well.

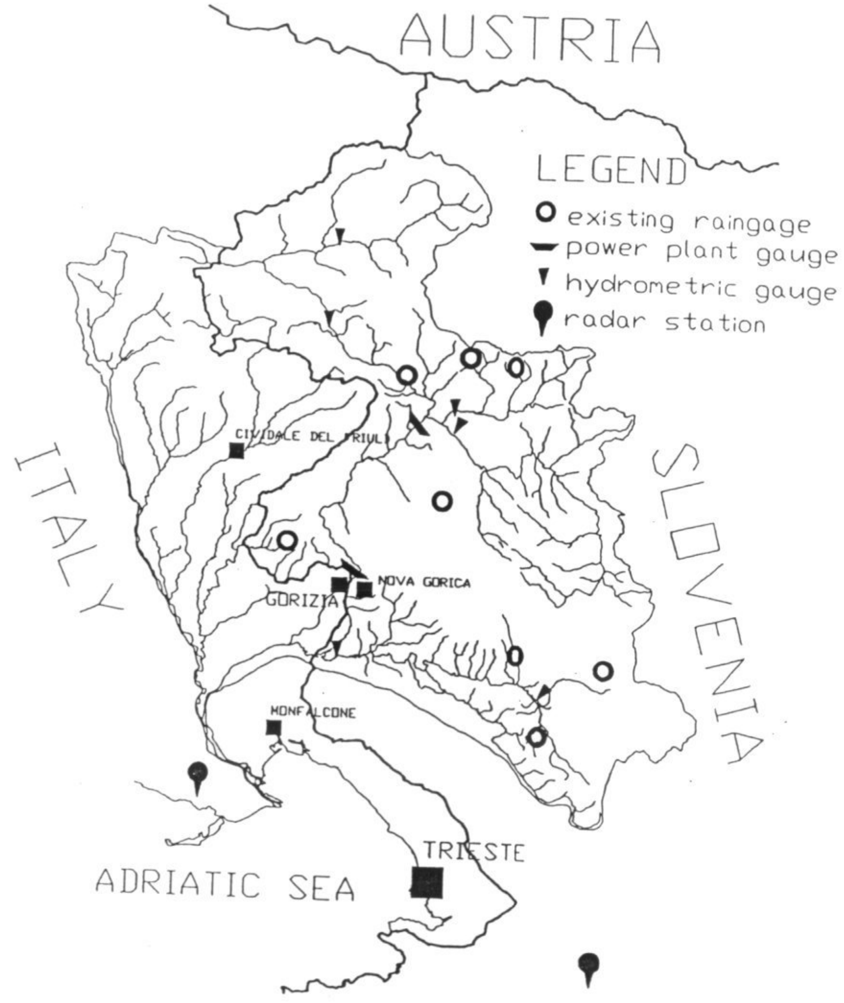
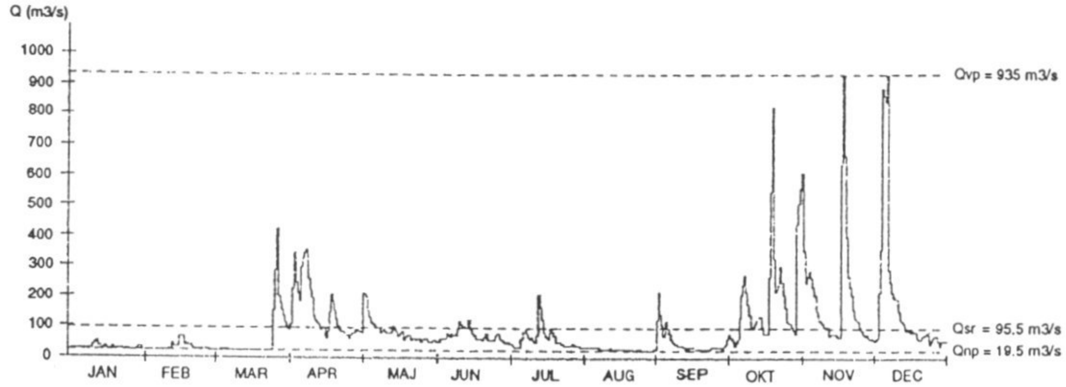


Figure 1 *Soča river watershed with gauge stations*

On the upper part of the Soca river basin thunderstorm and flood events are quite frequent. Long term statistical analysis of thunderstorms shows more than 40 events per year. Statistics data for analysed gauges are presented in Table 1.

During 1992 and 1993 more than six floods have occurred. Hydrographs for the Soca river for the years 1992 and 1993 are presented in Figure 2. Flood events were chosen for further analysis and data collection. Precipitation data at five minutes time intervals were collected for stations presented in Figure 1.

(a) *1992*



(b) *1993*

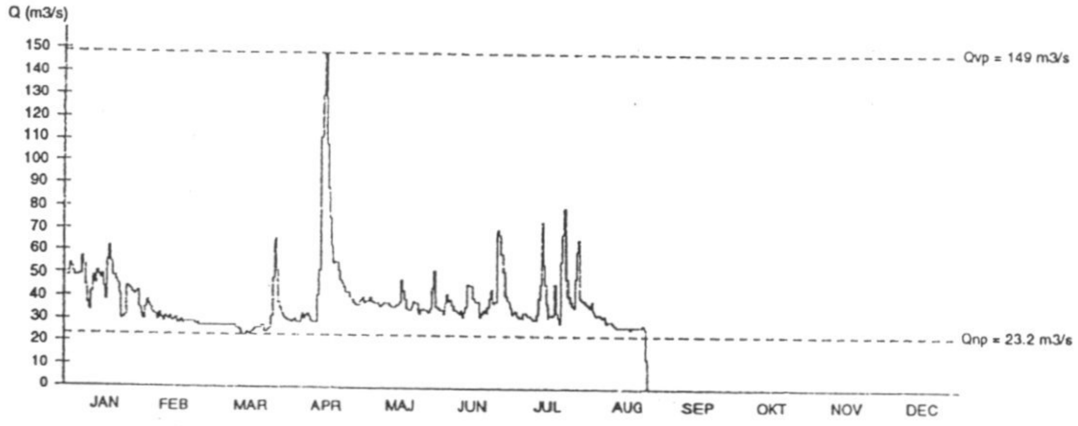


Figure 2 *Hydrographs for the Soča river at gauging station Solkan, near Nova Gorica*

Three of the selected flood events with the best meteorological radar measurements will be treated in further hydrological analysis.

Table 1 *Statistical parameters on the days with thunderstorms per year (data: 1951 - 1986)*

Station	Mean	Mod	s^2	Coef var.	Max.	Min.	Var.	Max. month int. (%)	month
Bovec	48.1	50	160.69	26	75	17	58	10.2	(6)
Čepovan	49.4	52	80.87	18	72	24	48	10.4	(7)
Godnje	42.6	45	132.13	27	65	14	51	8.4	(7)
Komen Na Krasu	34.2	41	184.44	40	63	4	59	6.2	(7)
Kredarica	37.3	41	49.86	19	53	24	29	8.3	(7)
Novelo Prit	27.6	37	112.78	38	47	10	37	5.5	(6)
Postojna	37.2	44	177.95	36	61	5	56	7.6	(6)
Rateče-Planica	31.7	30	44.93	21	44	20	24	7.4	(7)
Rovte	18.4	26	84.91	50	36	0	36	4.8	(6)
Slap pri Vipavi	29.8	31	119.03	37	55	12	43	6.1	(6,7)
Stara Fužina	40.9	43	86.93	23	64	25	39	8.8	(7)
Tolmin	25.9	28	125.42	43	44	6	38	6.0	(7)
Vojsko	47.1	58	94.69	21	60	22	38	10.4	(7)

(iii) Creating GIS database

Streams with watershed boundaries were digitised from maps at a scale of1:25000. A digital model of relief with a mesh of 100 x 100 metres was also constructed.

CONCLUSIONS AND ADDITIONAL REMARKS

A great number of flood events occur each year in the Soča basin giving very good experimental data for further investigation and analysis.

The Slovenian component of this CEC project was only given formal approval in October 1993. As a result there has been limited progress to date. Visits to the Italian partners and to the coordinator in the UK have taken place in order to progress integration of this new partner into the project.

REFERENCES

Brilly, M. & Rakovec, J. (1992) "Using Meteorological Radar for Flood Warning", 2nd International Symposium on Hydrological Applications of Weather Radar, Hannover.

Natural
Environment
Research
Council