Urban/rural application of weather radar for flow forecasting

Proceedings of the informal CEC-workshop in Wageningen, december 1990

Editor: J.N.M. Stricker

Financial support:
- CEC under contract no. EV4C - 0039
- Commission for Hydrological Research - TNO

RAPPORT 26 Juli 1992

Vakgroep Waterhuishouding
Nieuwe Kanaal 11, 6709 PA Wageningen

ISSN 0926-230X

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PREFACE

One of the most challenging but pressing areas of research in hydrology is how to describe adequately hydrological processes for a wide range of spatial scales and how to link the descriptions of neighbouring scales by certain 'rules' of parameterization.
In this context weather radar for rainfall measurements may be considered as an excellent tool of observation. It combines high spatial resolution (=pixel) with a relatively long reach (=range) and thus bridges several spatial scales by a single observation. And what can be stated about spatial scales can also be stated about temporal scales for weather radar.
By the above mentioned reasons it is not surprising that research toward the use of weather radar for hydrological applications is fastly expanding. This is further encouraged by improved radar technology.

Under the Research Programme 'Climatology and Natural Hazards' (1987-1990) the CEC has financed a project, entitled 'Application of Weather Radar for the Alleviation of the Effect of Climate Hazard'.
As part of the activities project-partners meet at least once a year to discuss results, to exchange ideas and to set up further cooperation. After three earlier meetings, held in Grenoble (France), Padua (Italy) and Salford (England), a workshop was held in Wageningen (the Netherlands). This report is the outcome of the successful meeting.
Although the attention of the meeting was mainly focused on the use of weather radar for flow forecasting there was also some room for presentation of other work, related to weather radar.
Finally, all contributors are thanked for their efforts, of which this report is the concrete result.

H. Stricker

A Calibration Study of Ingham Radar

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Abstract

This paper presents the results of an extended study of the Ingham weather radar carried out as part of the wide-ranging three-year research and development project called the Anglian Radar Information Project. A part of this project was to develop procedures for adjusting the radar image in real-time and off-line using the regional network of telemetering raingauges. In order to determine the most relevant factors affecting precipitation production and radar precipitation estimation in the region a detailed investigation was carried out. In particular, the analysis focussed on the problems of precipitation estimation at long-range, a major consideration for the National Rivers Authority sponsoring the work, on problems due to bright-band, and on altitudinal effects. Additionally, the existing real-time raingauge-based adjustment scheme applied by the Meteorological Office was assessed.

INTRODUCTION

The National Rivers Authority, Anglian Region is the largest of the ten NRA Regions in England and Wales, covering a total area of 27000sq km. Within this region are 5800km of main river, 1400km of embanked water courses, and 1300km of tidal sea defences. The region is generally low lying, one-third of the land below normal river levels or below sea-level (some of the rich agricultural lands of the Fens are 3m below sea level as much as 50km inland). The region has less rainfall than any other part of the country, <600mm/yr on average and droughts (river flows greatly reduced, soils dried up) are normal in the summer months.

The region is served by two weather radars operated by the U.K. Meteorological Office, one located north-west of London at Chenies, and the other just north of Lincoln at Ingham. About one-third of the land area falls inside the 'quantitative range' of the radar (75km), with the furthermost range from either radar being about 175km. The entire region therefore is covered qualatively. Of major hydrological importance is the corridor aligned east-west running between the radars and beyond the quantitative coverage. In this area there are a number of small ungauged catchments, and upland sources of some of the major river systems in the region. A reasonably dense network of telemetering raingauges exists in this area.

METEOROLOGICAL OFFICE REAL-TIME RADAR ADJUSTMENT

The Meteorological Office routinely adjust all weather radars using a small number of raingauges for each (six for Ingham) in conjunction with domains which are either a function of topography if the synoptic type is judged to be frontal or rain shadow, or simpler influence zones around each gauge in the case of showers and bright-band situations.

An investigation of the raingauge derived adjustments applied has been carried out for a total of 27 days data (selected according to the presence of significant rainfall in the Anglian Region). For this period, the radar data were adjusted just over 50% of the time. Within this period, frontal systems were found to be most frequent (64%) with showers occurring 18% of the time. Bright-band was identified 16% of the time. The mean assessment factor applied (radar/gauge) was 1.05 (standard deviation of 0.85); the factor increasing for bright-band and showers (1.35, 1.24 ; 1.26, 1.06) and decreasing for frontal storms (0.92, 0.6).

INFLUENCE OF RANGE ON RADAR PRECIPITATION ESTIMATION

The problems associated with radar precipitation measurement at long range are well understood. The problems are almost entirely due to the height of the beam centre above ground itself due to earth curvature.

The range effect was studied via an analysis of a 22 day subset of the radar data (only those days that a rainfall threshold was exceeded). Raingauge data were directly compared to provide cross-checks, and additional visual analyses were also made.

The scattergraphs in figure 2 illustrate the influence of range on radar precipitation for a sub-region of the Anglian Region (Northern Area) to a range of 140km. The fall in average rainfall intensity with range is apparent, with a strong suggestion of overestimation at short range. The variance of the adjusted data is significantly lower than the unadjusted data. Although not presented here, these observations are repeated when the same analysis is applied for the whole radar image (i.e to a range of 210km), with rainfall amounts at the extreme range being only a small fraction of the average rainfall. An analysis of those periods when bright-band was present produces a scattergraph with high average rainfall amounts and high variance at ranges corresponding to the bright-band, whilst if bright-band periods are excluded, average rainfall amounts and data variance both fall significantly. The strength of the range relation is to an extent, temporally related though analysis for data over shorter time periods still displays the features discussed with significant regularity.

Directional analysis has revealed anisotropies in the range effect, though these are not strong and it is doubtful whether they are significant. The extent to which these can be related to topography has not been investigated.

THE PROBLEM OF BRIGHT-BAND

Bright-band remains perhaps the most intractible of problems regarding radar precipitation estimation in the U.K. The analysis has shown bright-band to be dynamic temporally and spatially making adjustment by raingauge extremely difficult. Indeed the 'hit-or-miss' nature of the raingauge becomes as much as a hindrance as a help. It is likely that the problem cannot be consistantly solved satisfactorily with the real-time network of raingauges available.

INFLUENCE OF ALTITUDE ON RAINFALL IN THE AREA

The effect of rainfall in the region has been examined for raingauge rainfall data over the 29 day period. Due to the subdued nature of the relief (little land over 150m) only a weak positive correlation has been identified. The relation only really becomes apparent or at all significant over long periods (many days) and for shorter time periods such as individual storm events or parts of events, the relation is certainly not significant. An extension of the study to the radar data themselves is considered desirable though not practical until a digitised database of topography becomes available.

RADAR ADJUSTMENT SCHEMES

A number of radar adjustment schemes have been developed. Amongst these are procedures which incorporate interpolation and surface fitting of raingauge/radar 'assessment factors' to a regular grid, the assessment factor field then being applied as a node by node multiplier of the unadjusted radar data. A number of different interpolation and surface fitting procedures have been investigated and a detailed contract report is in preparation.

CONCLUSION

The study has highlighted those factors which are of greatest importance in the production and measurement of rainfall in the Anglian Region of England. Of these, problems due to long range (beam height overshooting rainfall and attenuated signal) and close range (perhaps due to beam infilling) are probably the most significant. Bright-band remains a major problem and a satisfactory solution is not perhaps feasible with the real-time raingauge network available (insufficient density). Altitude is not a major factor in the rainfall process and only provides weak enhancement of rainfall (low relief).

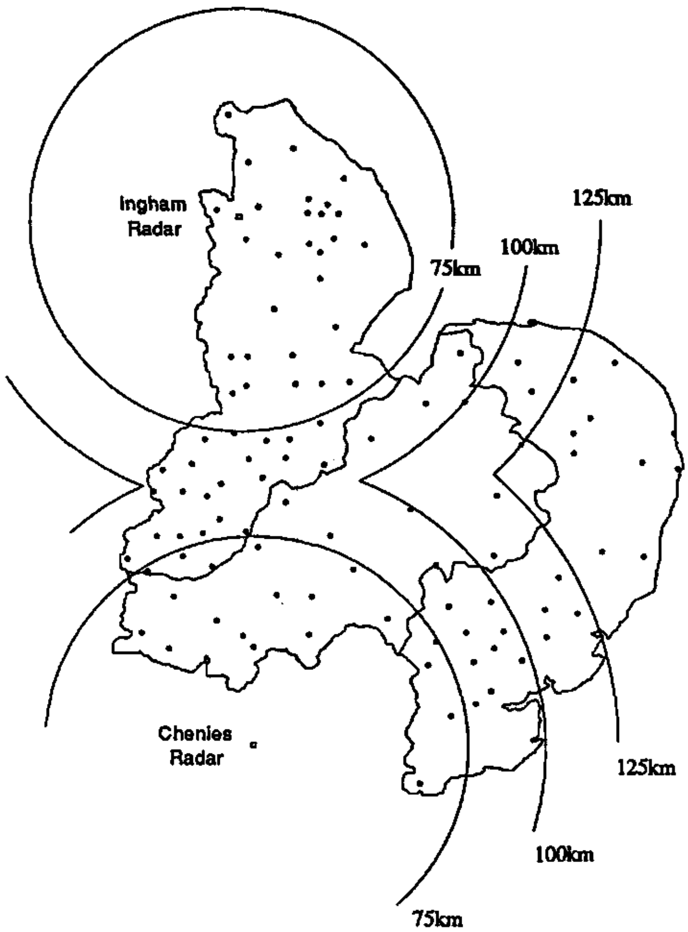
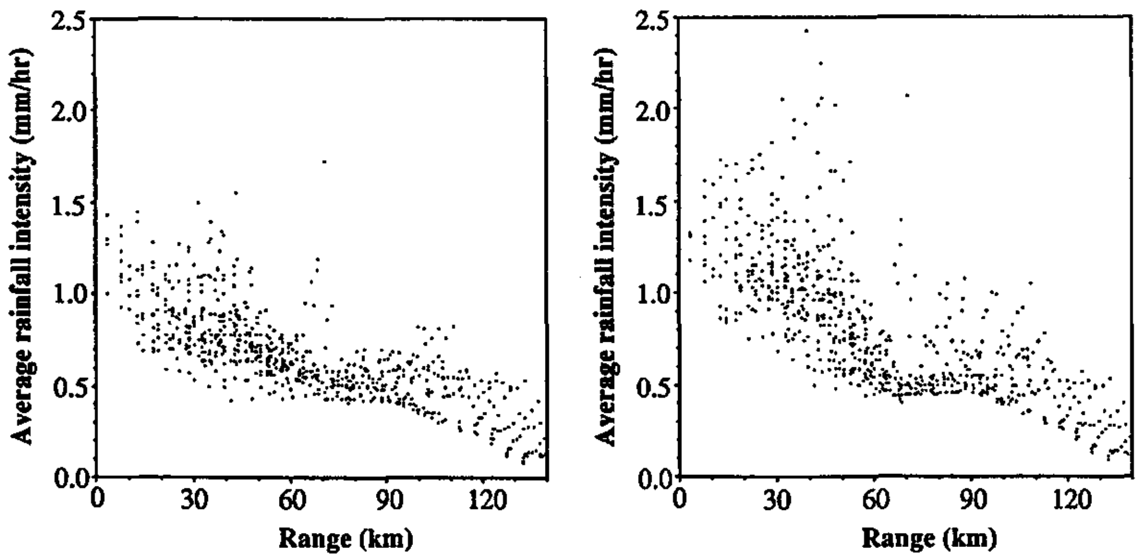


Figure 1: Combined Radar and Telemetering Raingauge Coverage



ii) scattergraph: adjusted data

iii) scattergraph: unadjusted data

Figure 2: Effect of range on rainfall measurement over
NRA Anglian Region, Northern Area

THE RADAR SITE AT DELFT UNIVERSITY OF TECHNOLOGY

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1. Introduction

Radar technology has since long been a topic of primary interest at the Faculty of Electrical Engineering of Delft University of Technology. Two weather radars were developed, both working according to the FM-CW principle. One is the high resolution Delft Atmospheric Research Radar DARR, which is a multi-polarized Doppler radar that operates at 3.3 GHz. The other radar is a weather surveillance type with a fixed polarization, operating in at 9.6 GHz. Both radars are able to estimate rainfall amounts. However, the accuracy differs for both types, because of different features involved. In this paper both radars will be described, and the implications for hydrological research will be discussed.

2. The Delft Atmospheric Research Radar

The Delft Atmospheric Research Radar DARR is a high resolution FM-CW radar, operating at 3.3 GHz. It is capable of measuring the Doppler velocity-spectrum as well as the relative polarization-dependent scattering matrix of rain. The Doppler velocity spectrum is based on windspeed and the fall-velocity of precipitation particles. The Doppler spectrum contains information about hydrometeor types and rain-intensity [1,2]. In order to achieve sufficient data reduction and to ease data interpretation three quantities are derived from the Doppler spectrum: the mean reflectivity Zd, the mean velocity Vd and the variance S. The polarization-dependency of the radar signal is caused by the mean shape of the hydrometeors in the radar volume. Raindrops tend to become flat during falling. This is a result of the air-resistance the particle experiences. Wind tunnel investigations have shown that the degree of oblateness depends on the size of the raindrops [3]. When the mean oblateness is measured through the polarization dependency, the mean dropsize, and, consequently, the rain intensity can be estimated [4].

The polarization-dependent radar observables that are measured with DARR are the horizontal reflectivity Zh, the differential reflectivity Zdr and the linear depolarization ratio Ldr. The combination of Zh and Zdr is useful for an accurate estimation of the rain-intensity. Ldr depends on the asymmetry of the precipitation particles. Ldr and Zdr can both be used to identify hydrometeor types, because each type has its characteristic shape. The characteristics of DARR are summarized in Table 1.

Table 1. Characteristics of the Delft Atmospheric Research Radar

Transmit power	1 W
Frequency	3.3 GHz
Effective beam width	2.3 degrees
Maximum range	2/5/10 km
Range resolution	30/75/150 m
Velocity resolution	0.28 m/s
Maximum unambiguous velocity	± 9 m/s
Doppler parameters	Zd, Vd, S
Polarization parameters	Zh, Zdr, Ldr

All radar observables are obtained in real time. In order to do so the raw data is integrated over 3.2 seconds before a set of data is released for further analysis. The complexity of the system is fully benefitted from when the radar is used in a non-scanning mode.

3. The weather surveillance radar SOLIDAR

The weather surveillance radar SOLIDAR is an FM-CW radar, operating at 9.6 GHz. Unlike DARR it is not able to measure the Doppler velocity-spectrum or polarization-dependency of the radar signal, but it is capable to measure rainfall within a radius of 15 km with a high temporal and spatial resolution. Each 15 seconds the area around Delft is scanned with an elevation-angle of 1.7 degrees for the appearance of rain cells, and, if appropiate, data is stored on optical disk. The initial range resolution is 30 meter, but during data-processing four range bins are summated, which results in an effective resolution of 120 meter. Four rain-gauges are used to calculate the assessment factor. SOLIDAR was designed as part of a collaboration program with the Dutch PTT, who funded it. SOLIDAR has been, and still is, used in telecommunication research programs, that require knowledge of rain-cell geometry. Attenuation of the radar signal can not be neglected at 9.6 GHz. The radar-derived rain-intensity will underestimate the real one. However, the signal-processing procedures that are employed with SOLIDAR are equipped with algorithms to correct for the rain-induced attenuation. The influence of the attenuation is also limited by the small maximum range of SOLIDAR. Usually, stratiform rain-cells contain a region of strongly reflecting melting snow. This so-called bright band is located just below the 0 degree isotherm. The enhanced reflectivity can be as large as 10 dB, and may therefore introduce large errors in the derivation of the rain-intensity. At 15 km the maximum height that is still within the main beam of the radar antennas is approximately 700 meter, which is below the commonly observed height of the bright band, and so the chance of occurence of the above mentioned error is reduced. Table 2 summarizes some of the characteristics of SOLIDAR.

Table 2. Characteristics of SOLIDAR

Transmit power	1 W
Frequency	9.6 GHz
Effective beam width	2.8 degrees
Rotational speed	4 rpm
Maximum range	15 km
Range resolution	30\120 m
Elevation angle	1.7 degrees
Features	Attenuation correction; Clutter suppression

A detailled description of SOLIDAR is given in [5].

4. The combination of DARR and SOLIDAR

When the reflectivity that is measured by SOLIDAR is converted into rain-fall amount, the Marshall-Palmer dropsize distribution is used. This straight-forward method is prone to errors due to deviations in the dropsize distribution, and to attenuation of the radar signal. When the Zdr-capability of DARR is used to estimate more parameters of the dropsize distribution the accuracy can be increased. The DARR-derived dropsize distribution is not sensitive to attenuation of the radar signal, and can be used to estimate the attenuation at 9.6 GHz, thereby enabling the verification of SOLIDAR measurements. Usually, hydrological weather radars have a large radar volume (in the order of 1 km). Measurements with DARR and SOLIDAR enables the study of the effects of the sampling size, because of their small, variable range resolution. The Doppler-polarimetric features of DARR allow the discrimination between hydrometeor types: the melting layer can be identified, which results in a more accurate interpretation of radar data.

6. Conclusions

The radar site at Delft University of Technology is well equipped with two FM-CW weather radars, one operating at 3.3 GHz and one at 9.6 GHz. The radars are complementary: SOLIDAR is rotating in a horizontal plane and only measures reflectivity, while DARR measures with fixed antennas, although the antennas are steerable. DARR is a multi-polarized Doppler radar, and is capable to identify the hydrometeor types and to estimate the dropsize distribution. DARR can be used to estimate the attenuation along the radar path.

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USE OF X-BAND OVER URBAN AREAS - WHAT RESOLUTION IN TIME AND SPACE IS REQUIRED?

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1. PROBLEM

Whenever rainfall-runoff simulations are carried out the question of the reliability of the results arises. Reliabilty cannot be expressed absolutely but only in relevance to the problem. The tolerable error margins depend on the accuracy with which the problem has to be solved. The determination of set values for real time control of regulators e.g. requires much more detailed and reliable data than the decision to issue a flood warning.

The exactness of the rainfall data as input to the models has to be compared to the simulation procedures and the parameters of the runoff process (e.g. wetness, losses). There is not much sense in detailed simulation if the rainfall input data is poor. Investigations have shown that good rainfall data are of the highest importance. Errors or uncertainties concerning the rainfall have much greater effects on the runoff results than questionable parameters.

What resolution in time and space is required depends to a great part on the catchment type and scale. Urban catchments with fast reaction times and generally smaller calculation units (subcatchments) require a higher resolution in time and space than rural catchments with larger subcatchments. The necessary time resolution is directly connected with the time interval used in the simulation model. A higher resolution than the simulation time interval leads to excess rainfall data that have to be integrated over the simulation time interval whereas with rainfall data in time steps larger than the simulation time interval the input data are not good enough for the model.

For real time operation besides the required amount of data some restrictions concerning data sampling and transmission are important. The possible sampling rate depends on the rotational speed of the antenna and the number of scans with different elevations. With data transmission and processing the possible transfer rates and the amount of data has to be looked at.

This investigation was carried out to find some quantitative answers to these qualitatively known facts.

2. CRITERIA

To evaluate the effects of the variations of time and spatial resolutions the simulation model was run with different input data for the same catchments, and the results for

- Total areal rainfall
- Total runoff
- Impermeable runoff
- Permeable runoff

were compared.

3. REFERENCE DATA

For the comparisons the reference data were achieved by running the simulations with the highest available resolutions in time and space. From the X-band radar located at the meteorological station at Essen rainfall data with

- 1 min sampling intervals for
- 600 x 600 m squares

over an area of 30 x 37 km were available.

These were used as input to a hydrodynamic rainfall-runoff model (HYSTEM/EXTRAN) for which the catchment data for the two catchments were available.

4. CATCHMENTS

The investigations were carried out for two catchments:

BOYE catchment (see Fig. 1)
mixed (urban and rural)
77 km^2 (25 km^2 impervious = 32%)
56 km open channels,
the sewer sub-systems were not modelled
53 subcatchments
220 rain squares (600x600 m)

BREMEN catchment (see Fig. 2)
lumped urban sewer system
9.2 km^2 (50% impervious)
35 km main sewers
55 subcatchments
46 rain squares

The subcatchments were of different size, the size depending on the information about the surface runoff conditions. The rainfall for each subcatchment was computed as the mean of the rainfall of all squares covered by the sub-catchment area. As the allocation of the squares to each catchment was done manually some of the squares were allocated to more than one sub-catchment.

Fig. 3 shows the frequency distribution of the squares per subcatchment for BOYE and BREMEN. For the BOYE catchment the largest sub-catchment covers 23 squares, whereas in BREMEN no sub-catchment has more than 4 squares.

In the BOYE catchment out of 220 squares 62 (28%) were multiple used (58 twice, 4 thrice), whereas in BREMEN with the smaller sub-catchment sizes 25 (54%) out of 46 squares were multiple used, one even six times (see Fig. 4).

5. RAINFALL DATA

For the investigations two sets of rainfall data were used.
For the simulations of the BOYE catchment:
9 events, Jul - Dec 89
4.2 - 17.2 mm / event

For the simulations of the BREMEN catchment:
13 events, Feb - Aug 90
5.7 - 38.8 mm / event

6. RESULTS

6.1 Resolution in space

The resolution in space was reduced to squares of 1.2 by 1.2 km and 1.8 by 1.8 km. This was achieved by averaging the minutely rainfall data over 4 and 9 squares respectively. Each 600x600m square was then allocated this mean rainfall value.

Table 1 shows the results for the BREMEN catchment. For all events the total areal rainfall (N), total runoff from impervious (Qu) and pervious areas (Qd) is given for the three resolutions:
- highest resolution (600x600m) (= RADAR)
- reduction to 4 squares resolution (= Reduzierung auf 4 Quadrate)
- reduction to 9 squares resolution (= Reduzierung auf 9 Quadrate)

The differences of the reduced resolutions to the highest one are stated in % (=Abw.).

Table 2 shows the range of percentage differences for both catchments. The differences for runoff are generally larger than for the mean areal rainfall. The errors resulting from reduced resolution are higher for the BREMEN catchment than for the BOYE catchment.

The effects of the reduced resolution in space on the hydrograph is shown in Fig. 5 where for one sub-catchment of BREMEN the simulated hydrographs derived from rainfall data with 600x600m and 1.8 x 1.8 km resolution are plotted.

6.2 Resolution in time

The reduction of the resolution in time was done in two variations:

a) the minutely sampled data were integrated over 5 and 10 min
Method : Integration
b) only every 5th and 10th data set was used, these rainfall data were supposed to be valid over the next 5 and 10 min thus simulating sampling intervals of 5 and 10 minutes
Method : Sampling

Table 3 shows the results of the BREMEN catchment for the integration of data over 5 and 10 minutes. As all rainfall data were used there are no differences with total areal rainfall.

The differences for the runoff from impervious areas are:

ΣQu	:	±0.01%	with 5 min
		-7.6 - 0.0%	with 10 min

Table 4 shows the results for two events for which both variations (Integration and Sampling) were carried out.

I05 means "Integration over 5 minutes", S05 means "Sampling every 5 minutes", I10 and S10 are the same but for 10 minutes. The table shows the differences in % in comparison to the integrated rainfall data. The sign of the differences is purely accidental dependent on whether the sampled data over or under estimate the true rainfall within the next 5 or 10 minutes respectively. As only two events were tested the size of the errors cannot be representative in any way but show that the differences are not negligable.

The differences in Table 4 are mean values for the whole catchment. For an individual catchment the error can be much larger as Fig. 6 shows. The differences of the total areal rainfall for each subcatchment calculated from 10-min sampling in comparison to the rainfall from 1-min sampling (and integration over 10 min) are shown. For a larger catchment with 23 sub-catchments the errors range from -12 to +20%, for a catchment with 46 small subcatchments the error span is even higher: -26 to +36%.

6.3 3-bit and 7-bit resolution

The quantification of the original data is done with a 7-bit resolution. This means that the rainfall intensities are given in 128 classes with mean values that are spaced linear til 2.6 mm/h and logarithmic over 2.6 mm/h (see Table 5).

To test the effects of a reduction to 3-bit resolution 8 classes were defined each of them covering 16 of the 7-bit classes. The rainfall intensity for each of the 8 classes was assumed to be the central value of the 16 7-bit-classes forming the 3-bit class (see Table 5).

The results for the BREMEN catchment are given in Table 6.

The differences in comparison to the 7-bit resolution are

N :	-0.4 ÷ +13.4%	mean: +3.9%
Q(imp):	-1.0 ÷ +14.8%	mean: +4.7%
Q(perv):	+2.4 ÷ +52.5%	mean: +17.4%

The positive means are a systematic error due to the assumed central values of the classes.

7. CONCLUSIONS

The resolution in time depends on the reaction of the catchment and the simulation time interval. An integration up to 10 minutes may be possible for catchments up to 100 km^2.

The sampling interval, however, should be as short as possible in order not to loose any data over the catchment. For urban areas with fast reaction times and small sub-catchments a sampling interval of 1 min should be the aim.

The resolution in space depends on the subcatchment sizes. The following resolutions can be recommended:

- distributed sewer systems : 600 x 600 m
- lumped sewer systems : 1.2 x 1.2 km
- open channel and river systems : up to 2x2 km

The reduction to 3-bit data may lead to no significant errors, if the rainfall intensity values are so adjusted that the mean error will be zero. The reduction is sensible if the radar signal is of about the same exactness. If high quality components for quantitative measurement of rainfall are used the 7-bit resolution should be maintained, as the computation time and the amount of data is not much higher.

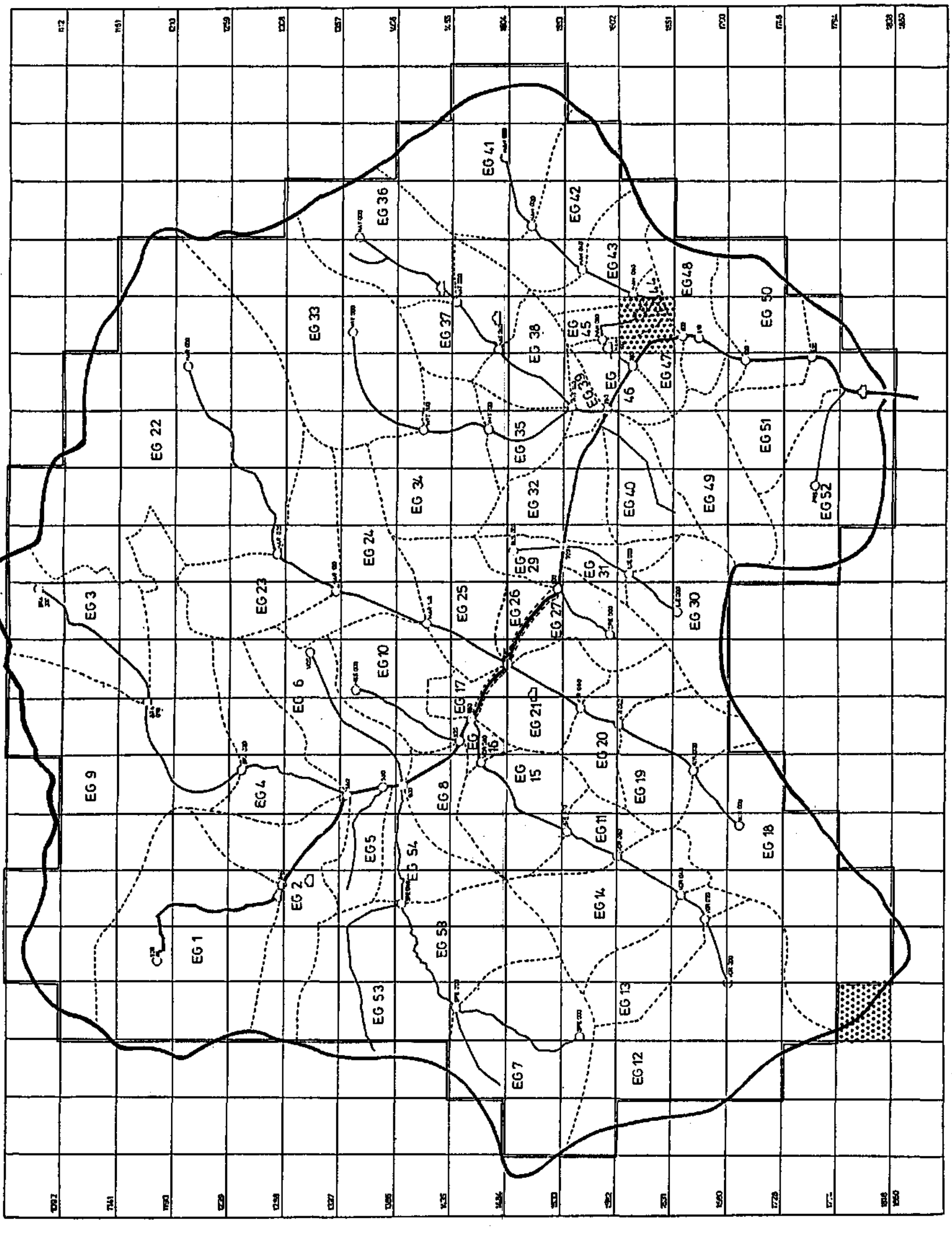

Fig. 1 : Boye Catchment

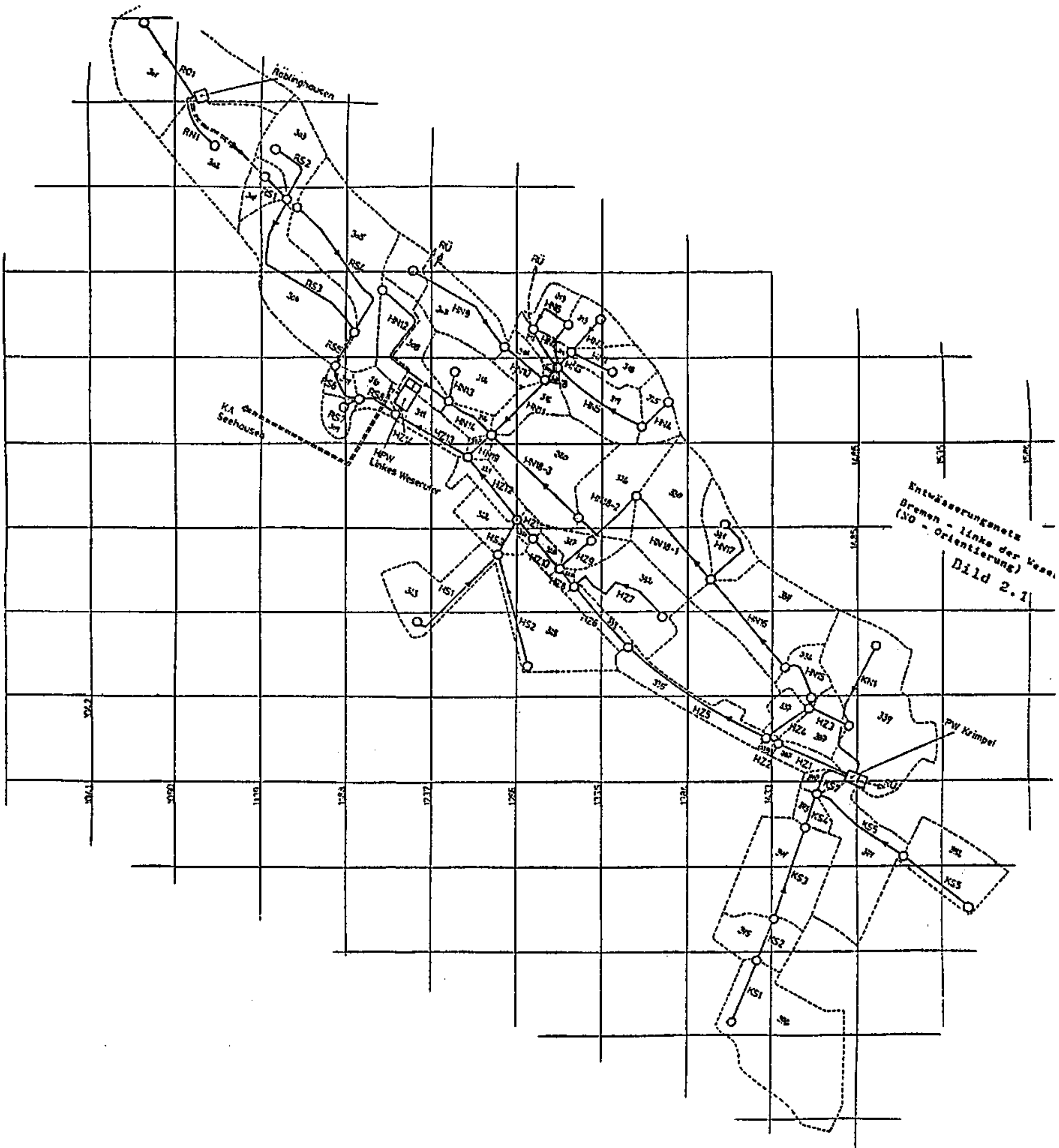

Fig. 2 : Bremen Catchment

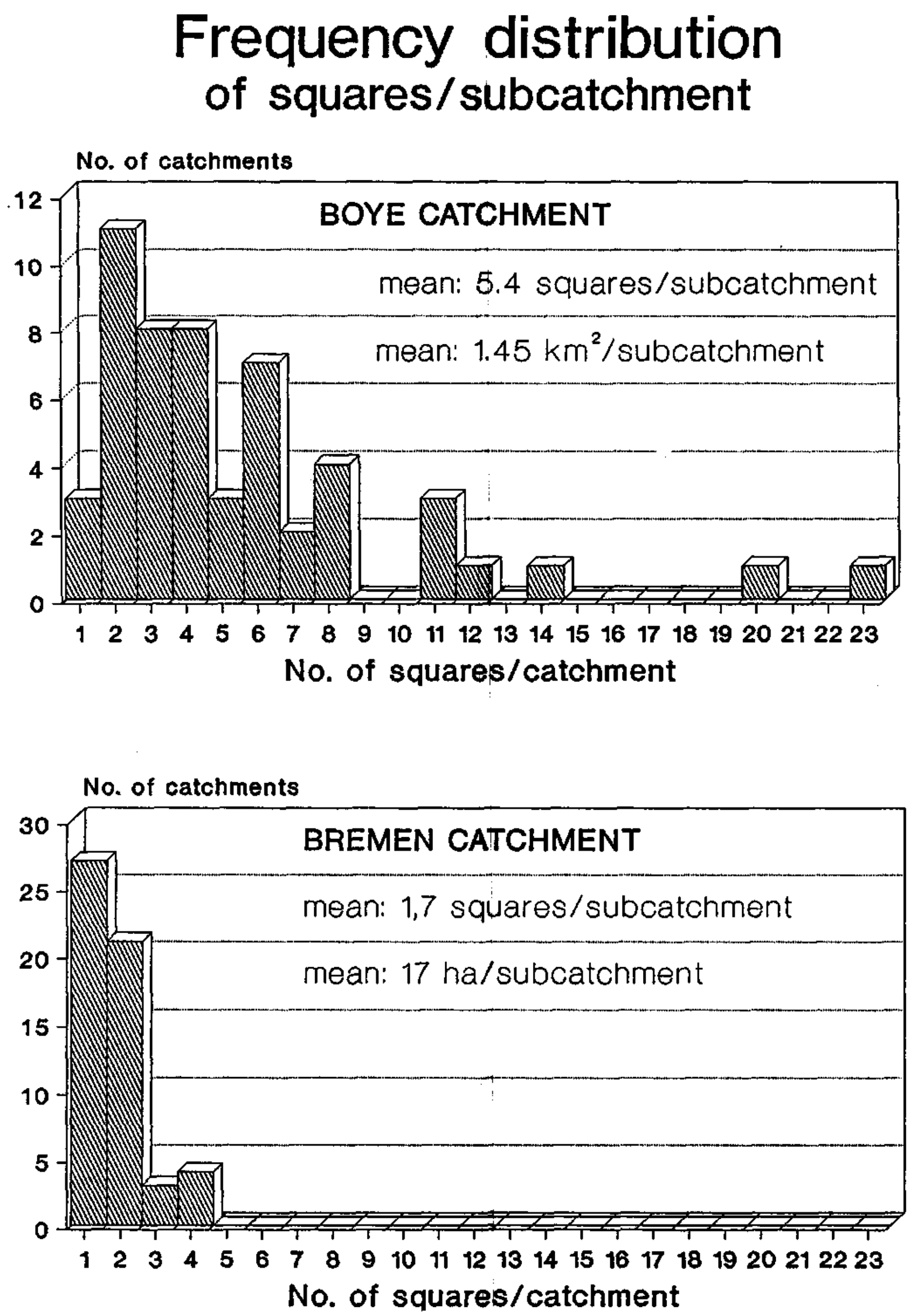

Fig. 3 : **Frequency Distribution of Squares per Subcatchment**

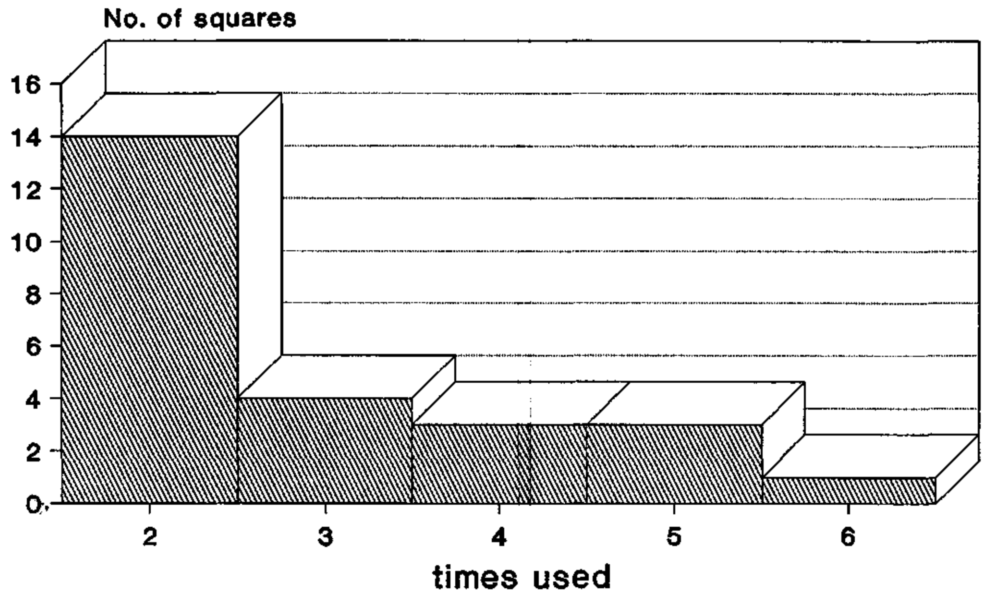

Fig. 4 : **Multiple Allocation of Squares to Subcatchments in the Bremen Catchment**

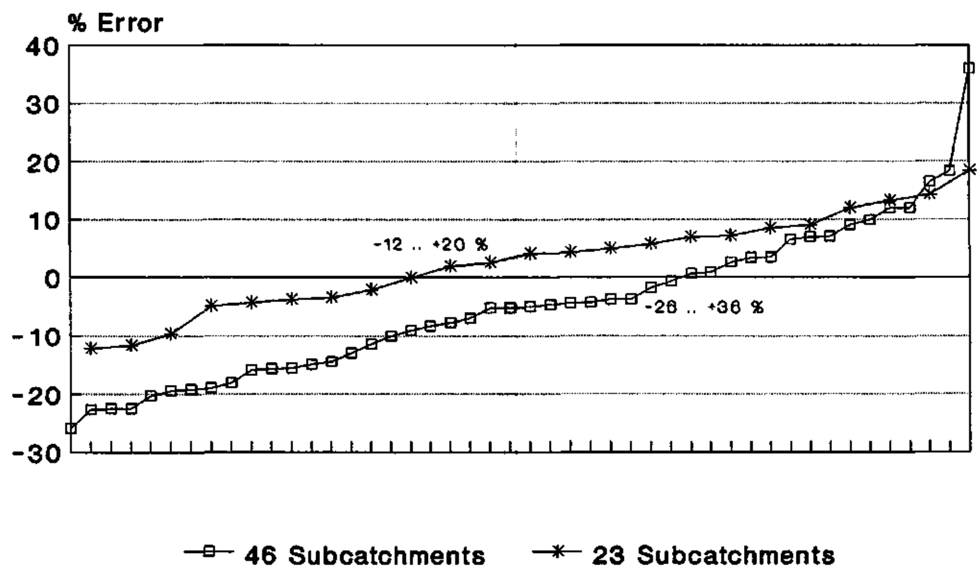

Fig. 6: **Errors with 10-min Sampling in Comparison to Integration over 10 min for all Subcatchments**

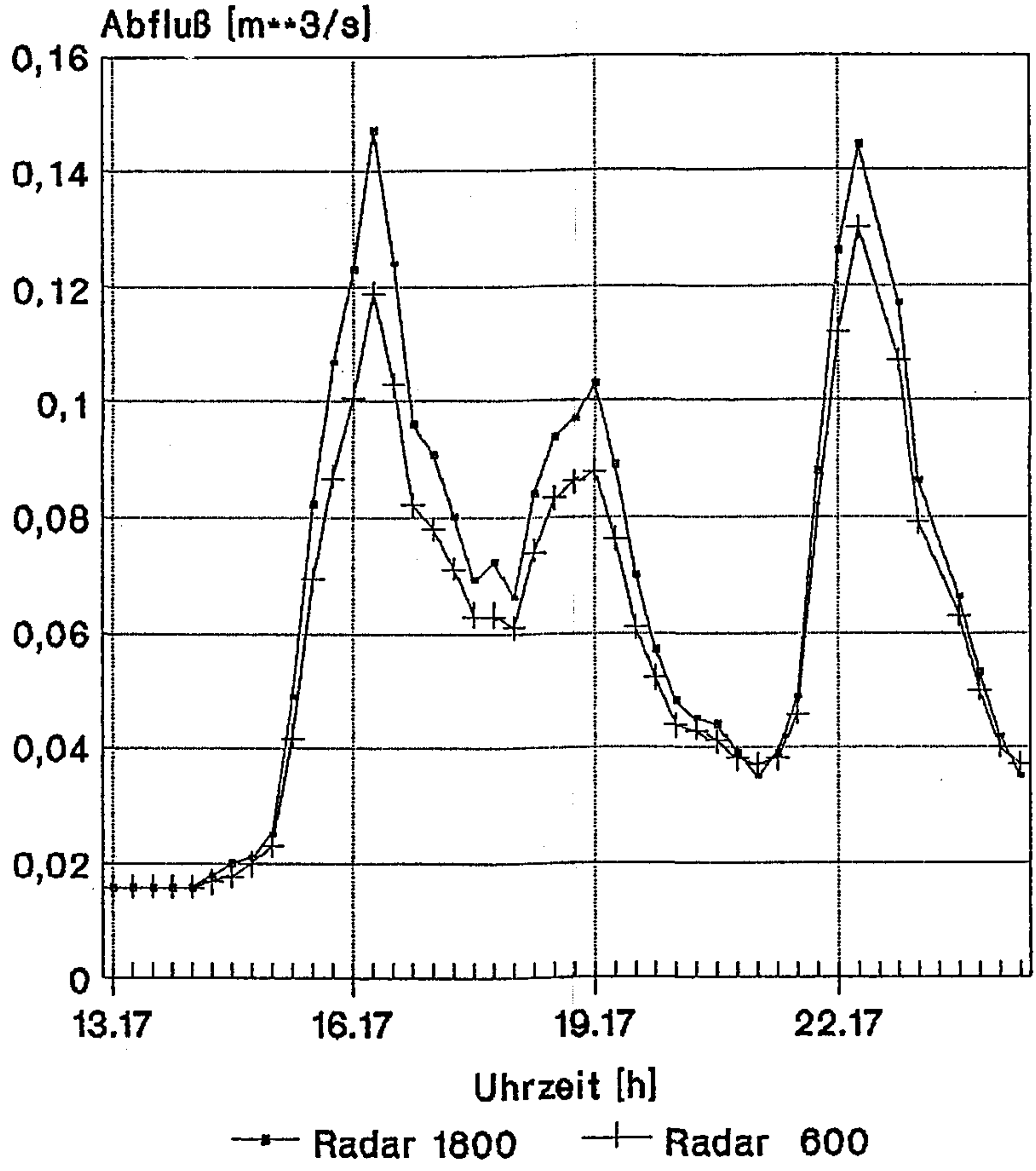

Fig. 5: **Comparison of Hydrographs Computed with Rainfall Resolution of 600x600m and 1800x1800m**

Table 1: **Comparison of Rainfall and Runoff for Reduced Spatial Resolution**

Legend:

RADAR	Reference data, 1min, 600x600m
ΣN	Total rainfall
ΣQu	Total runoff from impervious areas
ΣQd	Total runoff from pervious areas
Abw.	Difference in %
Reduzierung auf 4 Quadrate	Reduction to 4 squares (1200x1200m)
Reduzierung auf 9 Quadrate	Reduction to 9 squares (1800x1800m)

Vergleich:	RADAR			Reduzierung auf 4 Quadrate						Reduzierung auf 9 Quadrate					
	ΣN [mm]	ΣQu [m3]	ΣQd [m3]	ΣN [mm]	Abw. [%]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]	ΣN [mm]	Abw. [%]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]
02.02.90	11,80	38021	26	12,00	1,6	38710	1,8	33,2	26,2	11,8	0,0	38281	0,6	14,8	-43,7
02.02.90 *	13,10	42125	5							13,1	0,0	41806	-0,8	1,3	-71,7
26/28.2.90	38,80	139622	8105	39,40	1,5	143064	2,5	7139,0	-11,9	39,2	1,0	142088	1,8	7160,0	-11,7
28.02.90	12,64	39276	1	12,79	1,2	40246	2,4	0,2	-84,4	12,8	1,2	40246	2,5	0,2	-84,4
28.02.90 *	14,34	46754	1							14,4	0,1	47023	0,6	0,0	-100,0
15.04.90	14,39	45819	1094	14,35	-0,3	45723	-0,2	1082,0	-1,1	14,4	0,3	45966	0,3	1117,0	2,1
15.04.90 *	13,11	42136	111							13,1	-0,1	41869	-0,6	125,0	12,3
07.05.90	26,20	86845	25662	26,00	-0,8	85962	-1,0	25159,0	-2,0	26,5	1,1	87215	0,4	26881,0	4,8
07.05.90 *	16,40	50944	5402							16,4	0,0	51616	1,3	5043,0	-6,6
06.06.90	5,65	14514	0	5,66	0,2	14562	0,3	0,0	0,0	5,6	-0,2	14455	-0,4	0,0	0,0
20.06.90	9,10	26801	28	9,30	2,2	27542	2,7	9,4	-66,0	9,3	2,2	27340	2,0	6,0	-78,3
27.06.90 (1)	12,02	38401	84	12,02	0,0	38355	-0,1	37,0	-56,0	12,0	-0,4	38161	-0,6	12,0	-85,7
27.06.90 (2)	7,90	21893	0	8,00	1,0	22514	3,0	0,0	0,0	8,2	4,0	22951	5,0	0,0	0,0
27.06.90 *	8,29	23656	0							8,1	-2,4	22901	-3,2	0,0	0,0
29.06.90	7,23	19587	0	7,26	0,4	19753	0,9	0,0	0,0	7,3	0,8	19835	1,3	0,0	0,0
29.06.90 *	6,30	16500	0							6,3	0,3	16572	0,4	0,0	0,0
05.07.90	6,91	18585	0	6,96	0,7	18861	1,5	0,0	0,0	7,0	1,0	18895	1,7	0,0	0,0
06.07.90	5,99	15819	0	6,10	1,8	16185	2,0	0,0	0,0	6,1	1,8	15987	1,0	0,0	0,0
06.08.90	11,86	38474	649	11,85	0,0	38679	0,5	586,0	-9,7	11,7	-1,4	38100	-1,0	464,0	-28,5
06.08.90 *	11,59	36843	413												

Table 2: **Range of Percentage Errors for Reduced Spatial Resolution**

	1.2 km squares		1.8 km squares	
	Boye	Bremen	Boye	Bremen
ΣN	-0.4 ÷ 0.1	-0.8 ÷ 2.2	-0.4 ÷ 0.4	-2.4 ÷ 4.0
ΣQ	-1.8 ÷ 0.5	-1.0 ÷ 3.0	-3.7 ÷ 0.1	-3.2 ÷ 5.0

Table 3: Comparison of Rainfall and Runoff for Reduced Resolution in Time

Legend:

RADAR	Reference data, 1min, 600x600m
ΣN	Total rainfall
ΣQu	Total runoff from impervious areas
ΣQd	Total runoff from pervious areas
Abw.	Difference in %
Reduzierung auf 5 Minuten	Reduction to 5-min integrated values
Reduzierung auf 10 Minuten	Reduction to 10-min integrated values

Vergleich:	RADAR			Reduzierung auf 5 Minuten-Intervalle				Reduzierung auf 10 Minuten-Intervalle			
	ΣN [mm]	ΣQu [m3]	ΣQd [m3]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]
02.02.90	11,80	38021	26	38021	0,0	23	-12,5	38021	0,0	20	-25,5
02.02.90 *	13,10	42125	5					42125	0,0	3	-32,6
26/28.2.90	38,80	139622	8105	139619	0,0	5090	-37,2	139619	0,0	4230	-47,8
28.02.90	12,64	39276	1	39276	0,0	0	-100,0	39276	0,0	0	-100,0
28.02.90 *	14,34	46754	1					46735	0,0	0	-100,0
15.04.90	14,39	45819	1094	45795	-0,1	1036	-5,3	45792	-0,1	970	-11,3
15.04.90 *	13,11	42136	111					42112	-0,1	86	-22,7
07.05.90	26,20	86845	25662	86841	0,0	25560	-0,4	86836	0,0	25270	-1,5
07.05.90 *	16,40	50944	5402					50942	0,0	5072	-6,1
06.06.90	5,65	14514	0	14514	0,0	0	0,0	14514	0,0	0	0,0
20.06.90	9,10	26801	28	26798	0,0	9	-67,4	26795	0,0	1	-97,9
27.06.90 (1)	12,02	38401	84	38401	0,0	0	-100,0	38401	0,0	0	-100,0
27.06.90 (2)	7,90	21893	0	21871	-0,1	0	0,0	21855	-0,2	0	0,0
27.06.90 *	8,29	23656	0					21855	-7,6	0	0,0
29.06.90	7,23	19587	0	19587	0,0	0	0,0	19587	0,0	0	0,0
29.06.90 *	6,30	16500	0					16500	0,0	0	0,0
05.07.90	6,91	18585	0	18587	0,0	0	0,0	18586	0,0	0	0,0
06.07.90	5,99	15819	0	15819	0,0	0	0,0	15819	0,0	0	0,0
06.08.90	11,86	38474	649	38473	0,0	541	-16,7	38473	0,0	353	-45,6
06.08.90 *	11,59	36843	413					36843	0,0	271	-34,4
mittlere Abweichung [%]					-0,02		-26,12		-0,40		-31,27

Table 4: Comparison of 5 and 10 min Integration and Sampling

	I05	S05	Δ%	I10	S10	Δ%
ΣN	4.04	4.13	+2.2	4.04	3.81	-5.7
ΣQ	8096	8353	+3.2	8077	6973	-13.7
ΣN				12.33	11.07	-10.2
ΣQ				45265	40737	-10.0
imp				41309	37550	-9.1
perv				3956	3187	-19.5

Table 5: **7-Bit (128 Classes) and 3-Bit (8 Classes) Resolution with Allocated Rainfall Intensity Values**

Klasse.		R/mm h^{-1}	Klasse		R/mm h^{-1}	Klasse		R/mm h^{-1}	Klasse		R/mm h^{-1}
Ø		0,0	32		3,5	64		15,1	96		66,1
1		0,1	33		3,6	65		15,8	97		69,2
2		0,2	34		3,8	66		16,6	98		72,4
3		0,3	35		4,0	67		17,4	99		75,9
4		0,4	36		4,2	68		18,2	1ØØ		79,4
5		0,5	37		4,4	69		19,1	1Ø1		83,2
6		0,6	38		4,6	7Ø		20,0	1Ø2		87,1
7		0,7	39		4,8	71		20,9	1Ø3		91,2
8	0,75	0,8	4Ø	4,9	5,0	72	21,4	21,9	1Ø4	93,35	95,5
9		0,9	41		5,2	73		22,9	1Ø5		100,0
1Ø		1,0	42		5,5	74		24,0	1Ø6		104,7
11		1,1	43		5,8	75		25,1	1Ø7		109,6
12		1,2	44		6,0	76		26,3	1Ø8		114,8
13		1,3	45		6,3	77		27,5	1Ø9		120,2
14		1,4	46		6,6	78		28,8	11Ø		125,9
15		1,5	47		6,9	79		30,2	111		131,8
16		1,6	48		7,2	8Ø		31,6	112		138,0
17		1,7	49		7,6	81		33,1	113		144,5
18		1,8	5Ø		7,9	82		34,7	114		151,4
19		1,9	51		8,3	83		36,3	115		158,5
2Ø		2,0	52		8,7	84		38,0	116		166,0
21		2,1	53		9,1	85		39,8	117		173,8
22		2,2	54		9,5	86		41,7	118		182,0
23		2,3	55		10,0	87		43,7	119		190,5
24	2,35	2,4	56	10,25	10,5	88	44,7	45,7	12Ø	195,0	199,5
25		2,5	57		11,0	89		47,9	121		208,9
26		2,6	58		11,5	9Ø		50,1	122		218,8
27		2,8	59		12,0	91		52,5	123		229,1
28		2,9	6Ø		12,6	92		55,0	124		239,9
29		3,0	61		13,2	93		57,5	125		251,2
3Ø		3,2	62		13,8	94		60,3	126		263,0
31		3,3	63		14,5	95		63,1	127		275,4

Table 6: Comparison of Rainfall and Runoff for 7-Bit and 3-Bit Resolution

Legend:

RADAR	Reference data, 1min, 600x600m, 7-bit
ΣN	Total rainfall
ΣQu	Total runoff from impervious areas
ΣQd	Total runoff from pervious areas
Abw.	Difference in %

Reduzierung auf 8 Regenklassen
= Reduction to 8 classes (3-bit resolution)

Vergleich:	RADAR			Reduzierung auf 8 Regenklasen					
	ΣN [mm]	ΣQu [m3]	ΣQd [m3]	ΣN [mm]	Abw. [%]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]
02.02.90	11,80	38021	26	12,0	1,6	39000	2,6	34	29,0
02.02.90 *	13,10	42125	5	13,4	2,3	42890	1,8	9	95,7
26/28.2.90	38,80	139622	8105	44,0	13,4	160258	14,8	12366	52,5
28.02.90	12,64	39276	1	13,3	5,4	41996	6,9	2	8,3
28.02.90 *	14,34	46754	1	15,0	4,4	48922	4,6	0	-45,0
15.04.90	14,39	45819	1094	14,4	0,1	45880	0,2	1104	0,9
15.04.90 *	13,11	42136	111	13,1	-0,2	41959	-0,4	165	48,2
07.05.90	26,20	86845	25662	28,7	9,5	94684	9,0	32472	26,5
07.05.90 *	16,40	50944	5402	17,2	4,8	53931	5,9	6428	19,0
06.06.90	5,65	14514	0	5,9	4,4	15466	6,6	0	0,0
20.06.90	9,10	26801	28	10,0	9,8	30126	12,4	41	50,0
27.06.90 (1)	12,02	38401	84	12,0	-0,2	38170	-0,6	80	-4,8
27.06.90 (2)	7,90	21893	0	8,0	1,0	22320	2,0	0	0,0
27.06.90 *	8,29	23656	0	8,3	-0,4	23418	-1,0	0	0,0
29.06.90	7,23	19587	0	7,5	3,7	20626	5,3	0	0,0
29.06.90 *	6,30	16500	0	6,5	3,2	17084	3,5	0	0,0
05.07.90	6,91	18585	0	7,2	4,1	19639	5,7	0	0,0
06.07.90	5,99	15819	0	6,4	6,9	17238	9,0	0	0,0
06.08.90	11,86	38474	649	12,1	2,2	39527	2,7	670	3,2
06.08.90 *	11,59	36843	413	11,9	2,3	37742	2,4	423	2,4

USE OF DOPPLER RADAR IN VENETO REGION AND IMPROVEMENT OF PRECIPITATION MEASUREMENT

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SUMMARY: Since 1988 a doppler radar is been operating in Veneto Region - Italy. This paper would evidence different applications of such tool; first of all wind field analyses, and also precipitation measurement. Refering to better capacity of detecting and measuring precipitation, doppler radar should be an operational tool for hydrology too.

1 INTRODUCTION

Experimental Centre for Hydrology and Meteorology (C.S.I.M.) manages an integrated system for hydrometeorological studies and forecasting. It is composed by (1):

- a digital C-band dual-polarization doppler weather radar,
- a ground stations telemetering network,
- a cluster of computer machines.

The core of the system is a weather radar (2) which collects volumes of doppler and no-doppler (normal) data. Such data can be managed in real time and compared with ground data available at the same computer system (see fig. 1).

2 DOPPLER PROCESSING OF DATA

No-doppler mode gives only reflectivity (Z) data. This mode uses clear-day maps to suppress clutter. On the contrary, doppler processing allows hardware cancellation of clutter for Z measurements. It gives also wind information, measuring the following two parameters:

- mean radial velocity (W),
- spectrum width (T).

Doppler processing of data uses a 32 point Fast Fourier Transform (FFT).

3 USE OF DOPPLER DATA

Every quarter of hour the system collects W, T and Z data. Reflectivity is available both in doppler and non-doppler mode. So it is possible to study precipitation and wind distribution in real time and also to assess a forecast of precipitation. W and T data are used operationally to evidence some interesting features of windfield.

For example wind-shears can be easily seen comparing CAPPI presentations at different levels or looking to VAD output.

The capability of doppler radar in monitoring extreme meteorological events was evidenced. A tornado occurred the afternoon of June, 8th 1990 and was continuously monitored during its development phases: it was the first time in Italy that such type of meteorological phenomenon was observed by radar.

Refering to precipitation measurement a detailed study has been made to compare the radar information obtained using radar in normal and doppler mode. The comparison was based (3) and (4) on computing Hourly Assessment Factors (HAF) starting from normal and doppler radar data. All radar data referred to precipitation events observed during the whole 1989 and part of 1990. The selection considered only hours when both normal and doppler radar data were available. One-hour intervals have been chosen time-adjacent and not overlapping. HAF have been computed for three different raingauge stations:

a) AGORDO: a mountain station, sited at 600 m over msl, and 106 Km distant from radar;
b) CASTANA: a mountain station, sited at 300 m over msl, and 58 Km distant from radar;
c) SAN BELLINO: a flat-plane station, sited at 7 m over msl, and 38 Km distant from radar.

These stations are representative of different geographical situations and range positioning. If a raingauge did not record more than 0.2 mm of precipitation related HAF were discarded. This selection takes into account the discretness in measuring precipitation with raingauges. HAF were computing using radar data coming from two different CAPPI levels: the so called pseudoCAPPI (that is the lowest possible CAPPI, with a height of 0.5 km over the radar, up to 80 Km form radar; beyond this distance the lowest PPI, with an elevation of 0.5°) and CAPPI 1 (1.5 km over radar).

It turns out that doppler measures precipitation better than non-doppler one for CASTANA and S.BELLINO (see fig. 2 and 3), while both modes give similar results for AGORDO (see fig. 4).

4 CONCLUSIONS

More than two years use of Veneto radar has evidenced operational reliability of doppler processing of data. It was evidenced not only the well-known capability of study the windfield, but also the capacity of improving precipitation measurement. Likely such feature is related to the hardware suppression of clutter used by doppler. As a remarkable conclusion, it can be assessed that doppler is an interesting tool not only for meteorological surveillance but also for hydrological applications.

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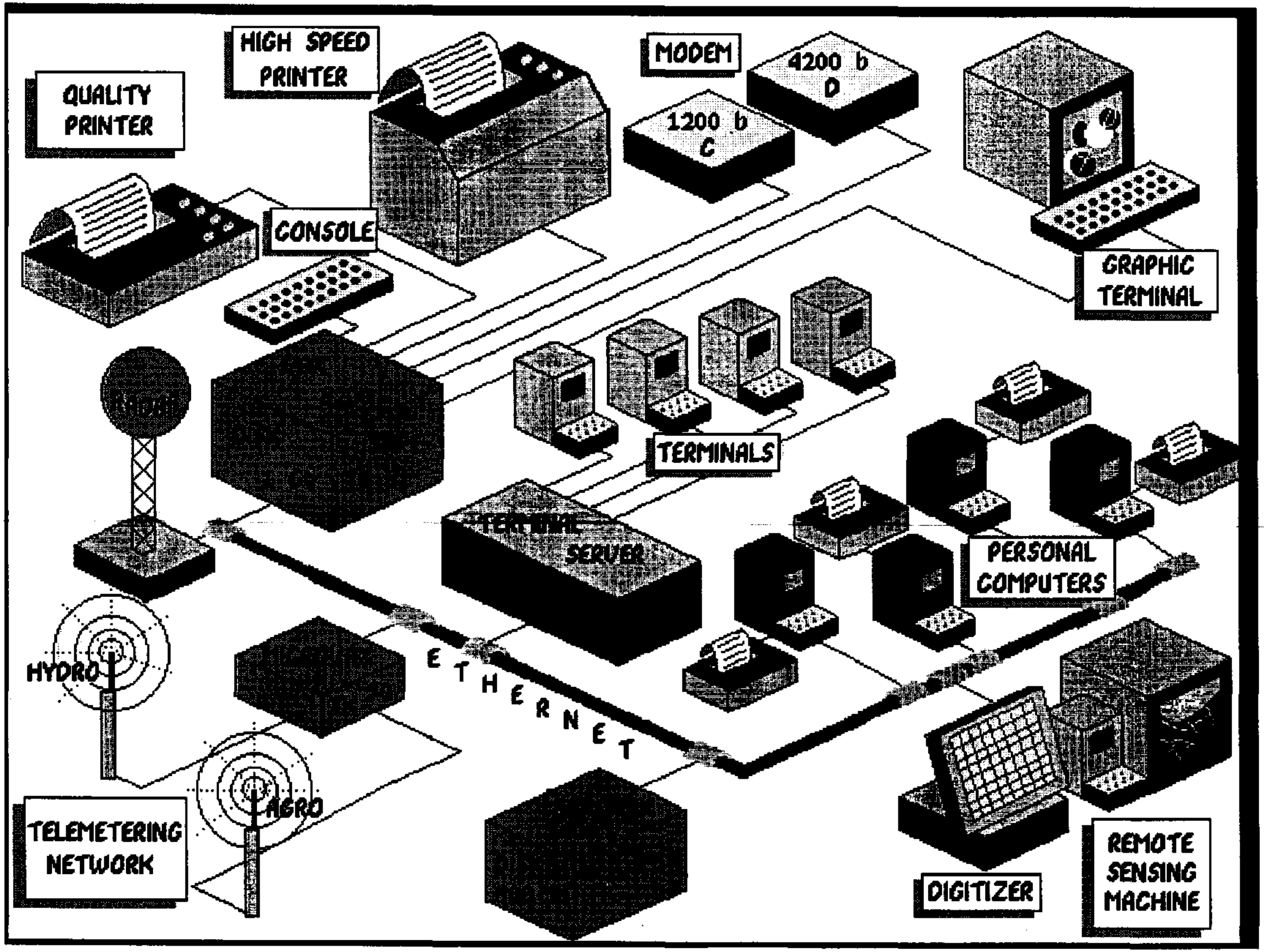

Fig 1 : Computer system architecture

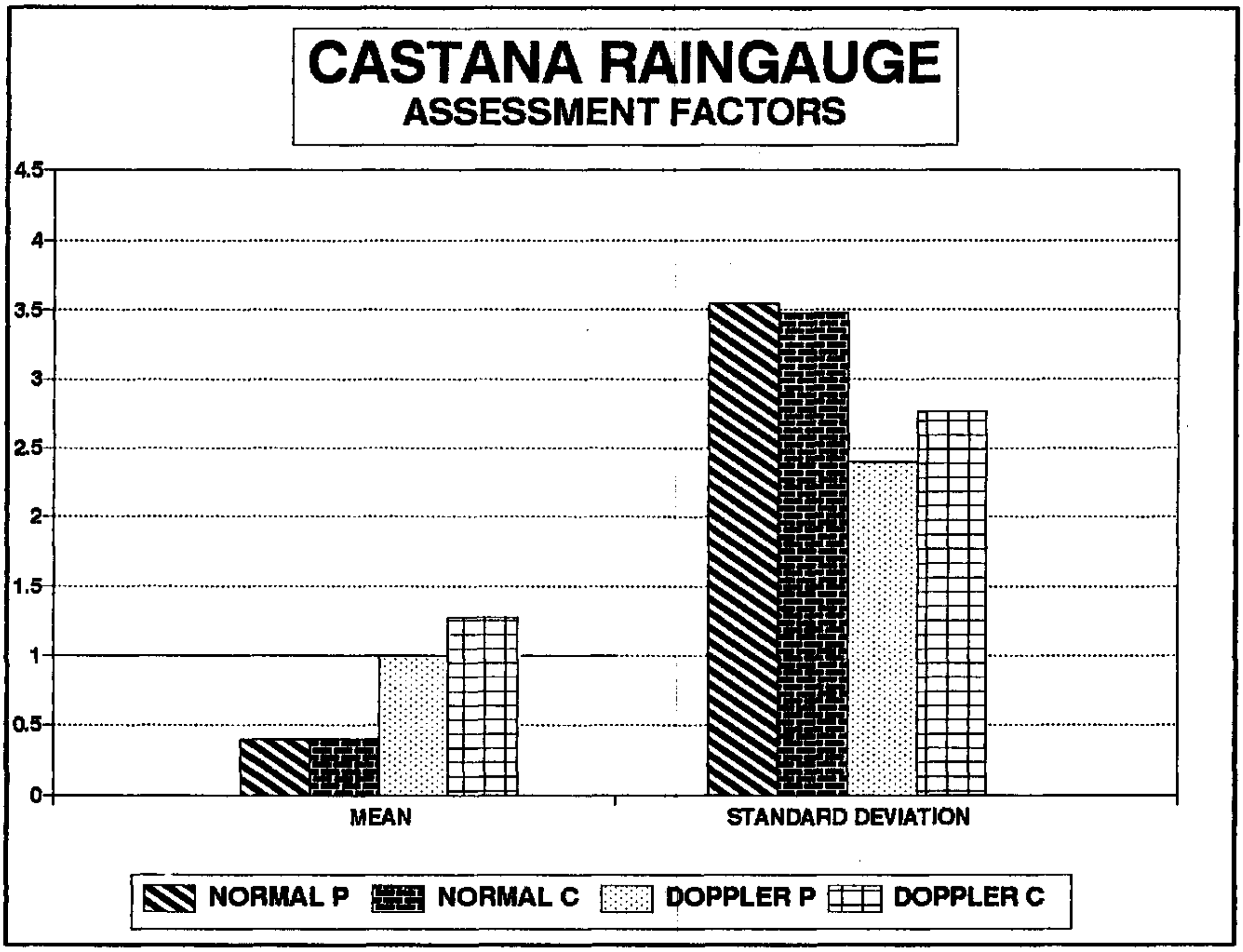

Fig 2 : Castana station : mean and standard deviation of Assessment Factors.

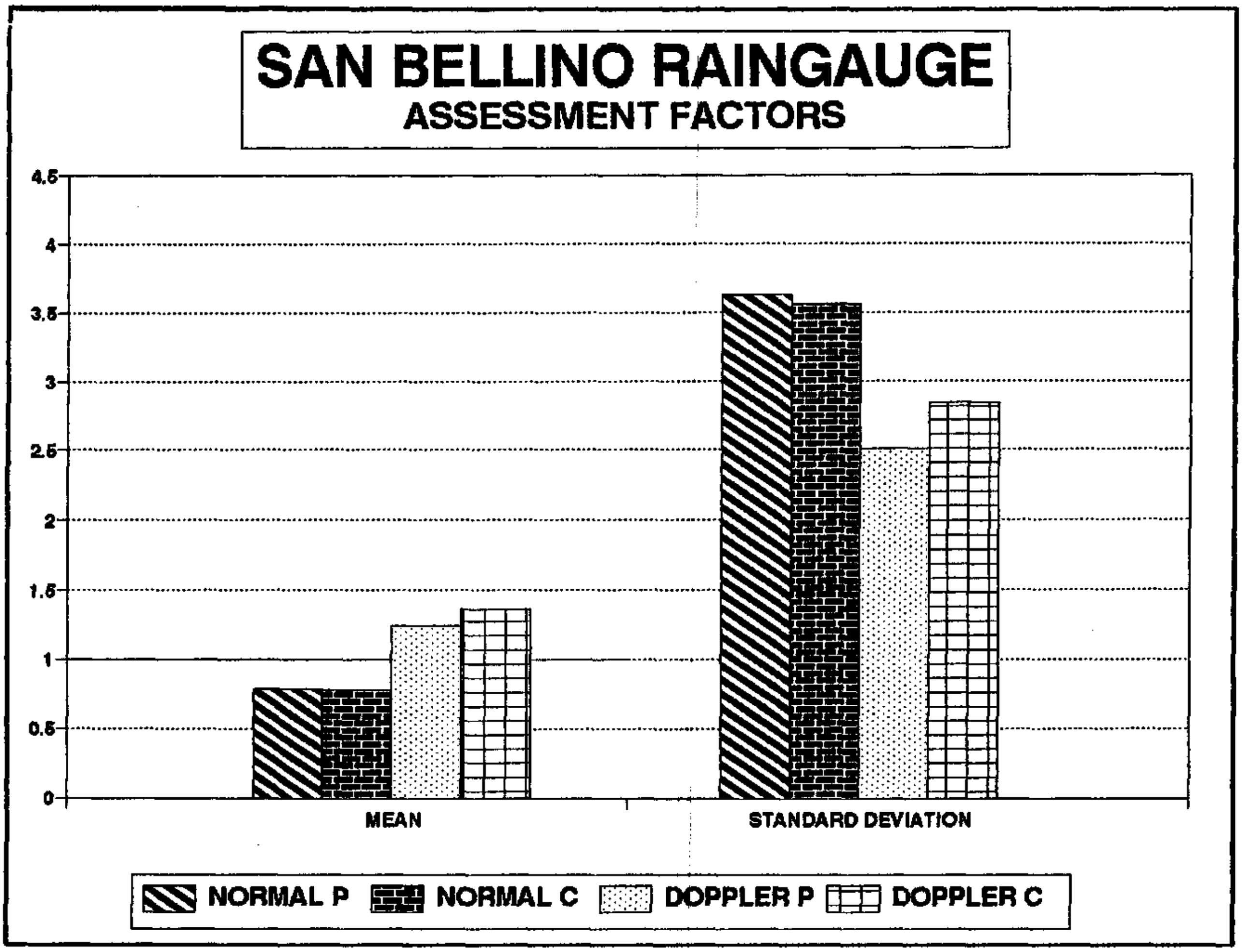

Fig 3 : San Bellino station : mean and standard deviation of Assessment Factors

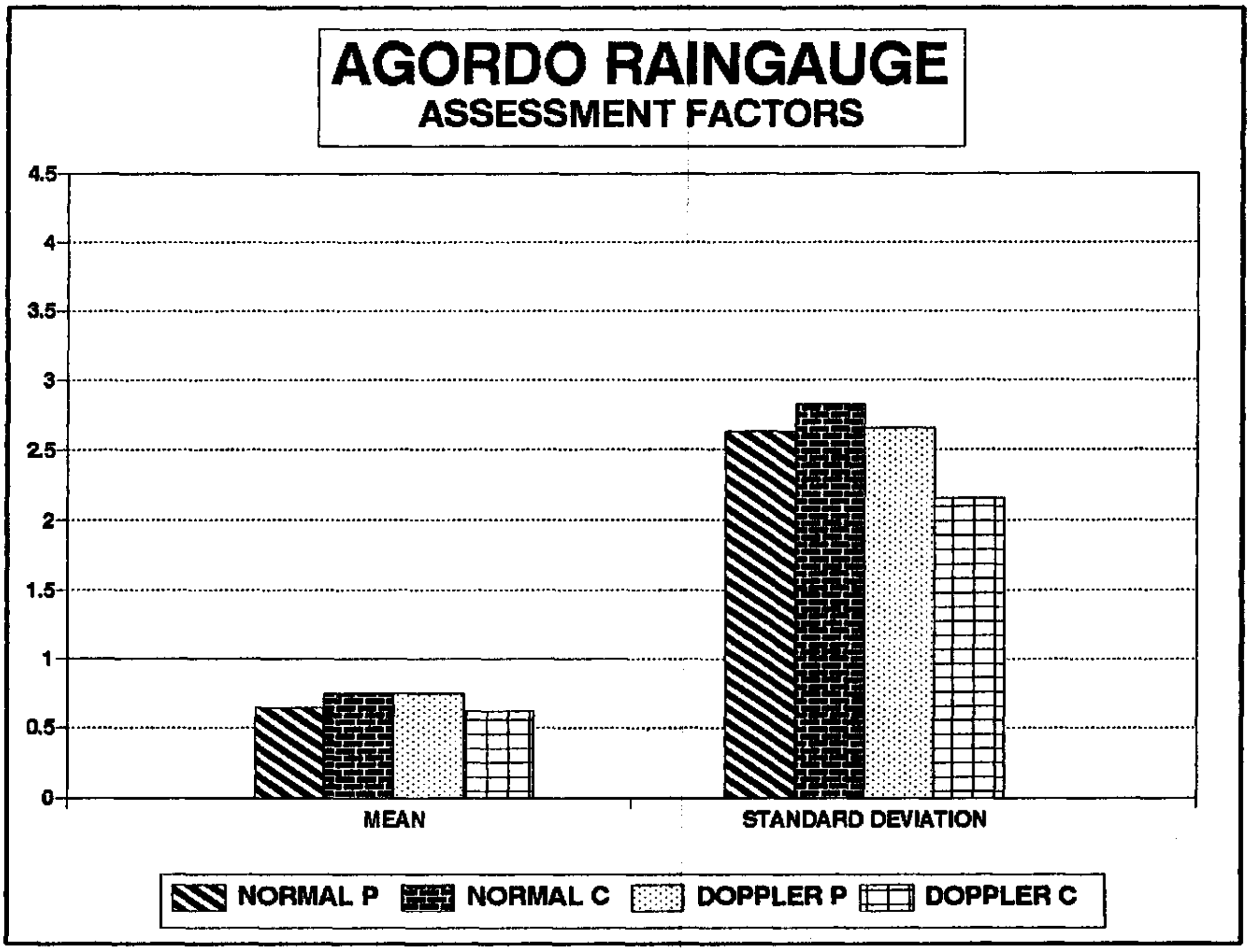

Fig 4 : Agordo station : mean and standard deviation of Assessment Factors.

ADJUSTMENT OF RADAR-RAINFALL TOTALS OVER ALENQUER BASIN USING A TELEMETERING RAINGAUGE

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INTRODUCTION/OBJECTIVES

Alenquer river basin is an interesting basin for hydrological research, where detailed studies are being performed aiming at the hydraulic and hydrological characterization of floods and inundations.

An off-line method for adjustment of radar-rainfall totals for this basin is purposed.

The radar coverage of the basin is described. Reference is also made to the connection of the telemetering raingauge in Alenquer basin to the TELERAD system.

METHOD/DATA

THE TELEMETERING RAINGAUGE AT ALENQUER RIVER BASIN

Located in the southwest of Tagus river, between 39º 10' 02"and 39º 00' 32" in latitude N and 9º 09' 46" and 9º 00' 24" in longitude W, Alenquer river basin is round shaped and spreads along NW-SE. It has a catchment area of 129 Km^2 and a perimeter of 54 Km. Its mean level is 156 m.

It is a predominantely rural basin with several urban agglomerations.

Considering the great hydrological interest of the basin, which suffers frequent floods, and aiming at the improvement of rainfall data, collected through the classic network and in order to make these data available, a telemetering raingauge was installed approximately in the basin geographic center. (Fig. 1)

The automatic precipitation gauge with tipping bucket has a resolution of 0.1 mm of precipitation. The entrance surface of the measuring ring is 200 cm^2.

The measuring value transmitter is connected to a field station, and automatically collects measuring data in programable intervals. The station interrogates the connected sensor and stores the values or mean values (up to 8 days) in an electronic semiconductor memory. We can operate the field station over the keyboard putting in the essential parameters of the station such as sampling interval and averaging factors.

The microprocessor module has 32 KBytes of RAM Memory.

The field station is connected to the public telephone network by means of a modem. In this way, the measuring values collected or stored in the field station can be interrogated and transmitted to a central station

RADAR COVERAGE OF ALENQUER RIVER BASIN

The weather radar station is based on a C-band single channel radar sensor interfaced with a computer system for radar data acquisition and processing.

Most of data processing concerning the precipitation measurement is performed at the radar station using numerical algorithms.

The Lisbon weather radar has a bad horizon due to hills, mainly N and NW, and buildings surrounding it, and very extensive clutter areas.

To minimize their effect, a multiple scan data acquisition strategy is used, with four elevations (0.8, 1.30, 2.30 and 3.50). A clutter filter (noncoherent MIT - System) has also been installed.

Alenquer river basin is located, in reference to the radar, between 358^0 and 32^0 in Azimuth and 30.5 Km and 43.5 Km in range.

Analysing the radar coverage of Alenquer river basin, we can find the most relevant obstructions in the sector between 5^0 and 20^0 in Azimuth.

For the particular area of Alenquer river basin the used mask selects the cells concerning nominal surface precipitation field using the following strategy:

In the first elevation signficative occultation occurs. In the second one the occultation is either absent or irrelevant, and beam axis is reasonably low, even in the farthest zone of the basin.

That being so, the second elevation is choosen, except for cluttered cells (5 cells). For these 5 cells the third elevation must obviously be used. (Fig. 2 and 3)

INTERROGATION OF THE TELEMETERING RAINGAUGE BY THE TELERAD SYSTEM

Since 1989 a remote processing and display system, named TELERAD, was implemented, and so, the radar information is being received, virtually in real time in the Hydrological Forecasting Center at D.G.R.N. headquarters in Lisbon.

The TELERAD unit under exploitation receives high resolution rainfall information (8 bits on a 2 Km square grid) from the radar station every 5 min. and has the capability to process it both numerically and graphically together with archiving.

The TELERAD unit holds some processing capabilities designed for hydrological purposes. This application software consists of two major packages.

The first one, ART, enables numerical and graphical display of rainfall amount for any number of basins, or other pre-selected areas of interest, over a range of time periods from the last quarter of an hour to the last two days.

The second one, named RDP, performs the interrogation of remote field station in order to collect data from their raingauges.

The structure of RDP consists of a pooling application (user interface), a data base manager and a driver for the station being poolled.

Concerning the installation of the telemetering raingauge in Alenquer basin, its connection to the TELERAD system was performed in order to obtain pre-operational experience in the field of real-time radar-raingauge adjustment.

RDP was successfully tested using this telemetering raingauge of Alenquer. (Fig. 4)

ADJUSTMENT OF RADAR-RAINFALL TOTALS

Considering the small size of Alenquer basin (129 Km^2) and its orographic configuration (about 156 m of mean level), we can expect that the only automatic raingauge installed will alow future real-time radar-raingauge adjustment of the area rainfall totals for the basin.

So the study of adequate methods was carried out.

According to Zawadzki (1973 b), the square shape of radar measurement cell keeps more of the variability of the precipitation than a rectangular one and introduces smaller errors.

That being so, calibration factors will be defined in square shaped areas. The size of this square area will be defined, in a first stage, by the analysis of the correlation between the raingauge total amounts and the radar measured totals, for similar periods, in squares with variable area around the raingauge.

In a second phase we can try to relate that square area with raingauge integration period, using the storm velocity concept (Zawadzki, 1975).

Defined the adjustment factor, and as we intend to calibrate the basin with only one raingauge, we shall use this value to correct the information of the whole pixels integrating the basin.

In order to evaluate the accuracy of the methods, the results will be compared with the basin totals, by using data of every available raingauges located in the basin.

CONCLUSION

Algorithms of the off-line method proposed for radar-raingauge adjustment are now under development, and will probably be used, later, in real-time.

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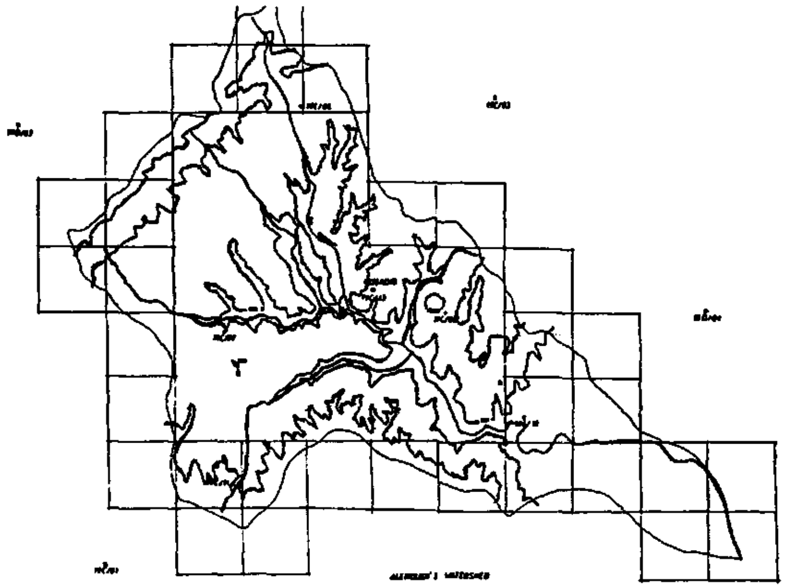

FIG. 1 - ALENQUER RIVER BASIN. RAINGAUGES AND TELEMETERING RAINGAUGE SITE.

FIG. 2 - CLUTTER MAP FOR THE 2ND ELEVATION.

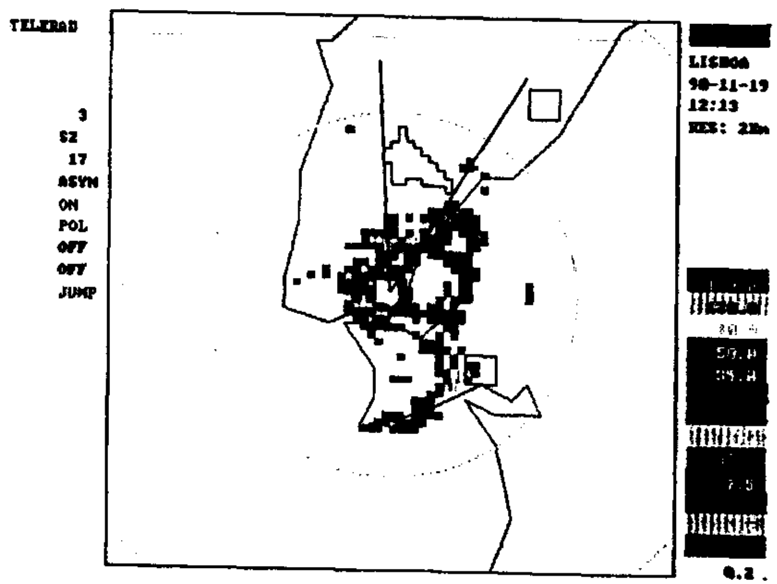

FIG. 3 - CLUTTER MAP FOR THE 3RD ELEVATION.

Numerical Data Output

ALENQUER
Nr. 1 Sens. 1

Date	Time		RainFall (mm)	Date	Time		RainFall (mm)
21/10/90	12:50	---	0.00	21/10/90	15:10	---	0.00
21/10/90	13:00	---	0.00	21/10/90	15:20	---	0.00
21/10/90	13:10	---	0.00	21/10/90	15:30	---	0.00
21/10/90	13:20	---	1.00	21/10/90	15:40	---	0.00
21/10/90	13:30	---	2.00	21/10/90	15:50	---	0.00
21/10/90	13:40	---	1.00	21/10/90	16:00	---	0.00
21/10/90	13:50	---	5.00	21/10/90	16:10	---	0.00
21/10/90	14:00	---	2.00	21/10/90	16:20	---	0.00
21/10/90	14:10	---	1.00	21/10/90	16:30	---	0.00
21/10/90	14:20	---	1.00	21/10/90	16:40	---	0.00
21/10/90	14:30	---	1.00	21/10/90	16:50	---	0.00
21/10/90	14:40	---	1.00	21/10/90	17:00	---	0.00
21/10/90	14:50	---	0.00	21/10/90	17:10	---	0.00
21/10/90	15:00	---	0.00	21/10/90	17:20	---	0.00

F1:Next Values F2:First Values F3:print values Esc:Quit

FIG. 4 - BASIC DATA OBTAINED BY THE TELEMETERING RAINGAUGE.

HYDROLOGICAL USE OF THE "CEVENNES 86-88" DATA LIMITATIONS AND ON GOING STUDIES

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1 - AVAILABLE DATA SET

Eight interesting rainfall events occured during the Radar Cevennes 86 - 88 experiment. Five of them were recorded by the radar representing more than 140 hours of data. The total data set is detailed in the table 1.

Event	Radar data	Raingages (number)	Disdrometers (number)	Meteorological data Peridot Model	radio sondage	H,P,V
13,14 oct.86	20 h	40	2	no	no	no
13,15 nov.86	48 h	40	2	yes	yes	yes
4, 6 oct.87	43 h	38	2	yes	yes	yes
10,11 oct 88	20 h	41	2	yes	yes	yes
19 oct.88	12 h	43	2	yes	yes	yes

The relevant flow data of the catchment Gardon d'Anduze were also collected.

But this data set is not very convenient to test the capability of the radar data in hydrological models :

- the discharge point measurement was moved in 1986, and the new flow discharge profile is not still very accurate.
- because of the experimental aspect of this project (no permanent people at the radar site, computer failures), none of the rain events was completely recorded.

The first part of the work was devoted to the preprocessing stage. The software HYDRORAD is a practical result of this stage.

2 - RAINFALL VARIABILITY AT THE BASIN SCALE

Preliminary studies devoted to the rainfall variability have been initiated. They are based on the comparaison between "radar pictures" and "simplified radar pictures".

A "simplified radar picture" is obtained by the following procedure :

a) the radar image is reduced to the only pixels just over a raingage

b) these data are interpolated to rebuilt a new rainfield picture (by the same way we use to interpolate raingages data).

These "simplified picture" contains only a very little percentage of the initial radar information wich is supposed to be more comparable with gauge information.

What are the first results of this comparison ?

a) the "simplified radar picture" is often similar to the "interpolated raingages picture", showing :

- the good agreement between gauge and radar data and,

- the potential interest of radar in distributed rainfall runoff modeling since a substantial part of the variability appear to be lost when the gauge network resolution is used.

b) at the basin scale of the Gardon d'Anduze (~ 500 km²) there is a very good correlation (r = 0,92) between the rainfall intensities calculated by the "radar images" and the "simplified radar images". This result has been confirmed at the subcatchment scale of Gardon St Jean and Gardon de Mialet (~250 km²) proving that :

- the radar resolution is useless at these space and time scales for lumped modeling,

- the radar data can be substituted to gauge data for this purpose.

3 - ON GOING HYDROLOGIC STUDIES

They are devoted to :

- detailed studies on the variability of rainfall at the basin scale

RADAR RAINFALL AND GROUND DATA - WHAT IS THE TRUTH?

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1. PROBLEM

When rain is measured by radar and conventionally on the ground, differences are quite naturally. Both measuring systems incorporate systematic errors, i.e. errors in connection with the device and the method.

The greatest uncertainties with the radar measurement, however, is believed to be the R/Z-relation which is necessary to transform the reflectivity (derived from the received echo strengths) into rainfall intensity. Calibration data for selecting suitable R/Z-relations were practically non-existent, so that generally the Marshall/Palmer relation is used.

It is to be questioned whether radar derived rainfall over the ground gage has to have the same values as on the ground. The measuring systems are too different to be compared by these results. Especially the measurement of a volume in the air and at a point on the ground are bound to lead to differences.

As in hydrology areal rainfall is needed it has to be found out whether radar data within the limits of quantitative measurement without assessment to the ground will give better results than data "calibrated" (or rather changed) due to the differences at one location.

The comparison to ground data, however, should not be abandoned at all. But it should be a comparison over longer periods, and differences should be taken as normal, as long as the overall means of radar and ground data are within the same magnitude.

2. ACCURACY

Ground data are restricted to the point where the rainfall is measured. The rain gages have wetting and wind losses, if tipping buckets are used the resolution is restricted to the volume of the bucket.

The quality of radar data depends on system constants and their deviation. Furthermore scattering, ground clutter, and polarisation amongst others affect the measurement. Reliable quantitative data can only be achieved if

- the measurement is within the falling rain, i.e. below the clouds
- the pulse volume is homogeniously filled with rain.

Both requirements can only be met within a certain distance from the radar. Otherwise the main beam is too high, above the clouds and bright band effects are likely to occur, and the pulse volume is too large for homogenious rain structures.

The limit for reliable quantitative data is about 40 km.

The main uncertainty is still believed to be the R/Z-relation. This may not be true in spite of the wide range of assessment factors. KREUELS (1989) has shown that even with mean R/Z-relations the mean errors are quite small, in any case smaller than the range of assessment factors and the changes due to these factors. It may well be that not the R/Z-relation but the violation of the requirements for quantitative measurement are responsible for the poor quality of the radar data and their differences to the ground data. In this case assessment factors are even more locally restricted and bound to make radar data worse if applied over large areas.

3. CALIBRATION

The calibration method most widely used is still the fitting of radar data to ground data and applying local assessment factors over large surrounding areas.

Being aware of the uncertainties of radar data and having got used to see ground data as "the truth", it was logical to develop procedures to fit the radar data to the "ground truth". The standard calibration procedure is to compare the radar value of the volume above the ground gage with the reading of the ground gage and compute the assessment factor (radar rain / ground rain). This assessment factor is then used not only for this one radar value but for all values of a predefined area. This implies that the physical and meteorological reasons for the differences on that one point are the same for the whole area, and that these differences change linearly with the intensity.

This procedure yielded perfect results at the check points, at all the other points nobody could bring proof against it. Only when the hydrologist came and used these calibrated radar data, and water balances would not fit doubts came up.

The calibration procedure as the solution for uncertainties and possible errors suppressed investigations into the possible reasons for these errors besides the R/Z-variations. Restrictions for quantitative data like height above ground, puls volume and exactness of radar hardware components, and their effects on the data only recently came into discussion.

If assessment factors are used the time periods for which they are computed should be at least one hour to avoid errors due to short time variations. For the application over large areas they should be computed as a mean from several locations and checked for plausibility.

Another calibration method uses actual R/Z-relations derived from distrometer data (KREUELS, 1989; VERWORN, 1990). Starting from a mean R/Z-relation the parameters of the relation are updated continuously as soon as significant raibfall is measured with the distrometer.

With the experimental X-band radar in Essen (KAMMER, 1989) and the restriction to a range of 37 km (well within the limits for quantitative measurements) even with these actual R/Z-relations the radar derived rainfall values were too low compared to the ground. The reasons for this are

- vertical polarisation of the radar. The generally oblate shape of the drops leads to underestimation in the range of 0 to 5 dB.
- statistical variance of particles within the sampling volume
- change of drops during fall time.

To compensate these errors an emrirical Z correction function was derived. This work is still under progress, and the shown correction function is a preliminary one (Fig. 1).

4. COMPARISONS

This function was derived and verified by using data from 32 ground stations over a period of several months together with the corresponding radar data. Only the total rain from each event or daily sums were used to ensure integration over long periods.

After application of the empirical correction function all values of (radar rain / ground rain) were between 0.5 and 2.0. The results for one location for the period of nearly four months are shown in Fig. 2. This example shows that with the empirical correction function the radar data are slightly overestimated, but no more than 2 mm difference between radar and ground rainfall occur.

Some of these results are due to errors that are often not easy to detect. Fig. 3 shows the cumulative rainfall for the 7th May 1990. Starting with the same gradient the ground gage suddenly changes to a low but constant gradient, probably due to dirt in the funnel and partial blocking of the pipe. Consequently, the difference of total rain is significant though absolutely not very high. An assessment factor derived from these data would surely do more damage than good.

To find out the significance of areal radar data a comparison between radar data and point data extrapolated over an area of 9 km^2 was carraied out. Table 1 gives the absolute values and the relative errors for total rain and total runoff from impervious and pervious areas. The errors in total rainfall range from -32% to +32%, in total runoff from impervious areas from -34% to +38%. These error margin is higher than the one incorporated in the uncertainties for the radar derived rainfall data as shown in Fig. 2.

The effects on the peak runoff is even more dramatic as Fig. 4 and 5 show. For two locations within the catchment the runoff hydrographs computed with uniform areal rainfall from one rain gage and with areal distributed rainfall from radar measurements are shown.

5. CONCLUSIONS

Radar rainfall data are quite reliable with relatively small error margins if

- the measurement is within the quantitative range (below the clouds and not too large pulse volumes (radial resolution is 300 m))
- mean locally valid or actual R/Z-relations are used
- systematic errors are compensated, in this case by applying an empirical Z correction function

If ground data are used for comparisons or calibration, the validity and significance of the data should be checked, the data should be integrated over longer periods, and the means from several stations should be used. Ground data for on-line calibration cannot be used for short time intervals (< 1h).

If areal rainfall is needed, radar data may be more reliable without assessment by ground data.

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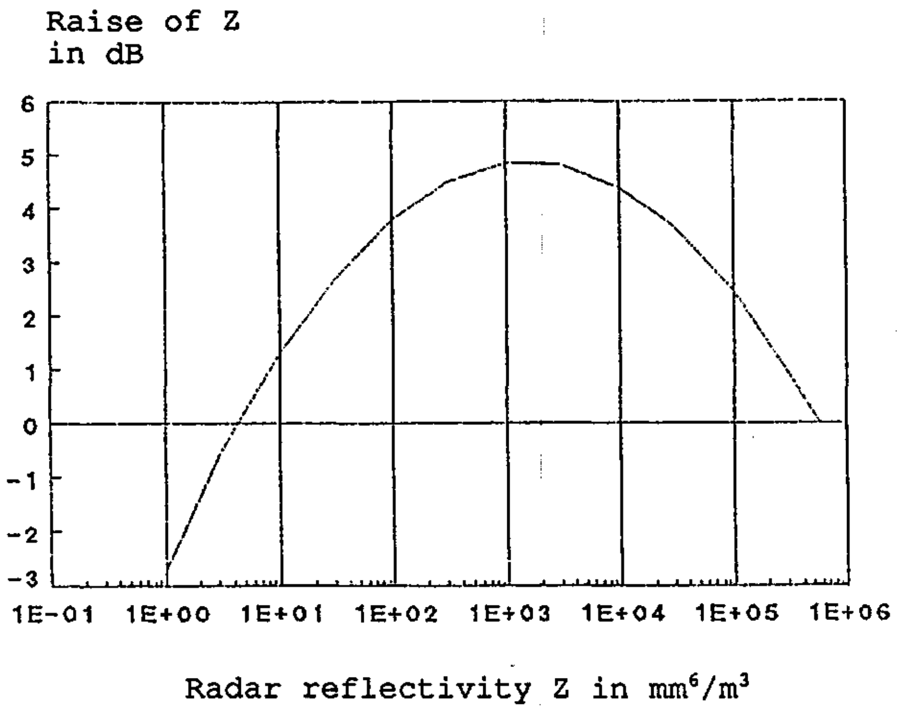

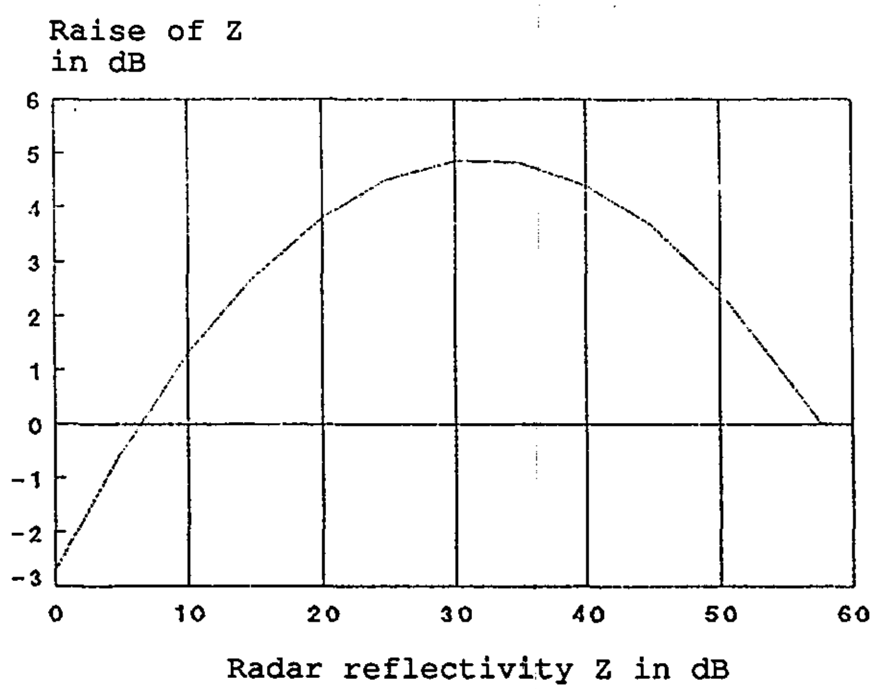

Fig. 1 **Empirical correction function for reflectivity Z**

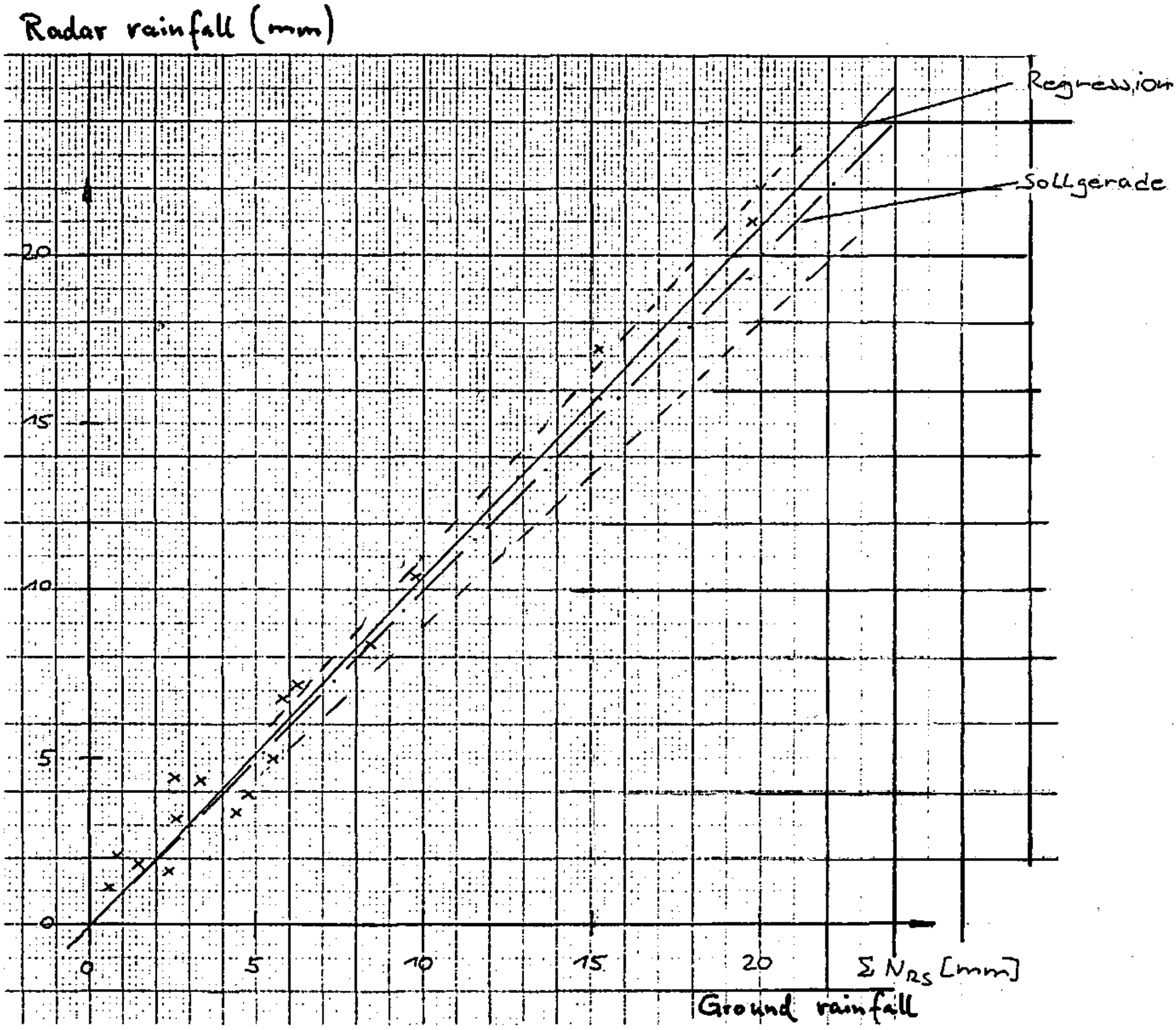

Fig. 2 Daily rainfall from radar and ground gage measurement for location 702 (Eigen), Period April-July 1990

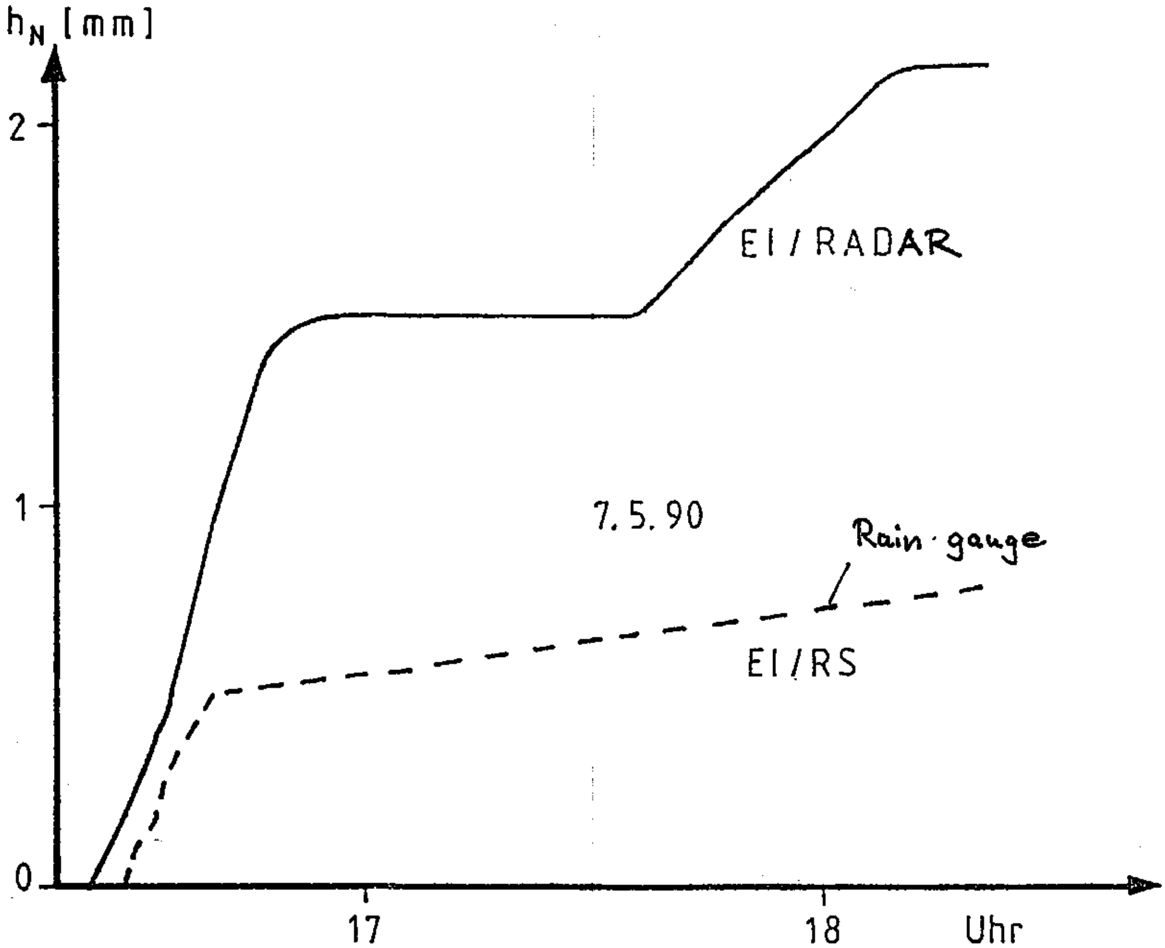

Fig. 3 Comparison of cumulative rainfall from radar and ground measurements

Table 1 **Total rain and runoff from areal distributed rain data (radar) and extrapolated areal rainfall from 3 and 1 rain gages**

Vergleich:	RADAR			Reduzierung auf 3 Regenschreiber						Reduzierung auf 1 Regenschreiber					
	ΣN [mm]	ΣQu [m3]	ΣQd [m3]	ΣN [mm]	Abw. [%]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]	ΣN [mm]	Abw. [%]	ΣQu [m3]	Abw. [%]	ΣQd [m3]	Abw. [%]
02.02.90	11,80	38021	26	11,4	-3,4	36574	-3,8	36	36,5	13,8	16,9	44474	16,9	0	-100,0
02.02.90 *	13,10	42125	5							16,6	26,7	55384	31,5	206	4370,0
26/28.2.90	38,80	139622	8105	38,0	-2,0	140296	0,5	8785	8,4	44,8	15,5	162637	16,5	15991	97,3
28.02.90	12,64	39276	1	13,2	4,7	42259	7,6	2	55,2	13,2	4,0	42094	7,2	0	-100,0
28.02.90 *	14,34	46754	1							15,3	6,8	50345	7,7	0	-100,0
15.04.90	14,39	45819	1094	14,7	1,9	46698	1.9	1591	45,4	12,1	-15,8	38178	-16,7	1	-99,9
15.04.90 *	13,11	42136	111							9,4	-28,2	27980	-33,6	0	-100,0
07.05.90	26,20	86845	25662	29,3	11,8	98542	13.5	33270	29,5	18,1	-30,9	60802	-30,0	5642	-78,0
07.05.90 *	16,40	50944	5402							11,1	-32,3	34261	-32,7	603	-88,8
06.06.90	5,65	14514	0	5,4	-4,2	13940	-4,0	0	0,0	7,0	7,4	15727	8,4	0	0,0
20.06.90	9,10	26801	28	9,0	-1,1	27653	3,1	3	-89,2	10,9	19,8	33751	25,9	0	-100,0
27.06.90	12,02	38401	84	12,2	1,7	38906	1,3	262	211,9	12,9	7,2	51085	7,0	696	728,6
27.06.90	7,90	21893	0	8,4	6,3	24914	13,8	0	0,0	9,6	21,5	28617	30,7	0	0,0
27.06.90 *	8,29	23656	0							7,5	-9,7	20844	-11,9	0	0,0
29.06.90	7,23	19587	0	7,2	-0,6	19952	1,9	0	0,0	7,8	7,1	21772	11,2	0	0,0
29.06.90 *	6,30	16500	0							5,8	-8,4	14632	-11,3	0	0,0
05.07.90	6,91	18585	0	6,9	0,0	19545	5,2	0	0,0	8,8	27,4	25699	38,3	0	0,0
06.07.90	5,99	15819	0	5,3	-11,5	13692	-13,5	0	0,0	6,4	6,9	16879	7,0	0	0,0
06.08.90	11,86	38474	649	12,1	2,3	40670	5,7	960	47,9	15,7	32,2	51080	32,8	2566	395,4
06.08.90 *	11,59	36843	413							11,2	-3,5	34631	-6,0	1179	285,4

Legend:

ΣN	Total rainfall
ΣQu	Total runoff from impervious areas
ΣQd	Total runoff from pervious areas
Abw.	Difference in %
3 Regenschreiber	3 rain gages
1 Regenschreiber	1 rain gage

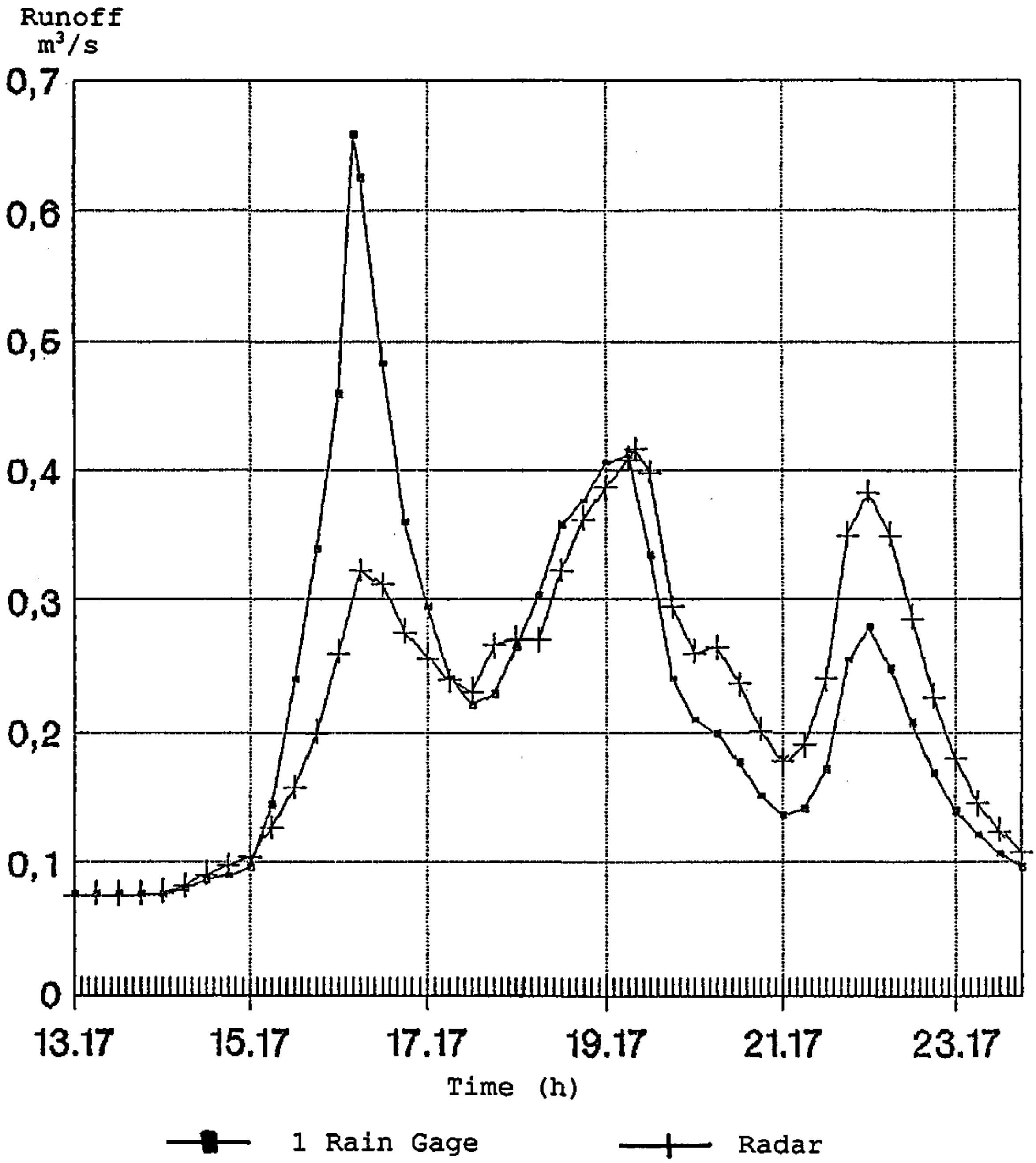

Fig. 4 **Hydrographs from uniform areal rainfall (1 rain gage) radar rainfall for location KS7**

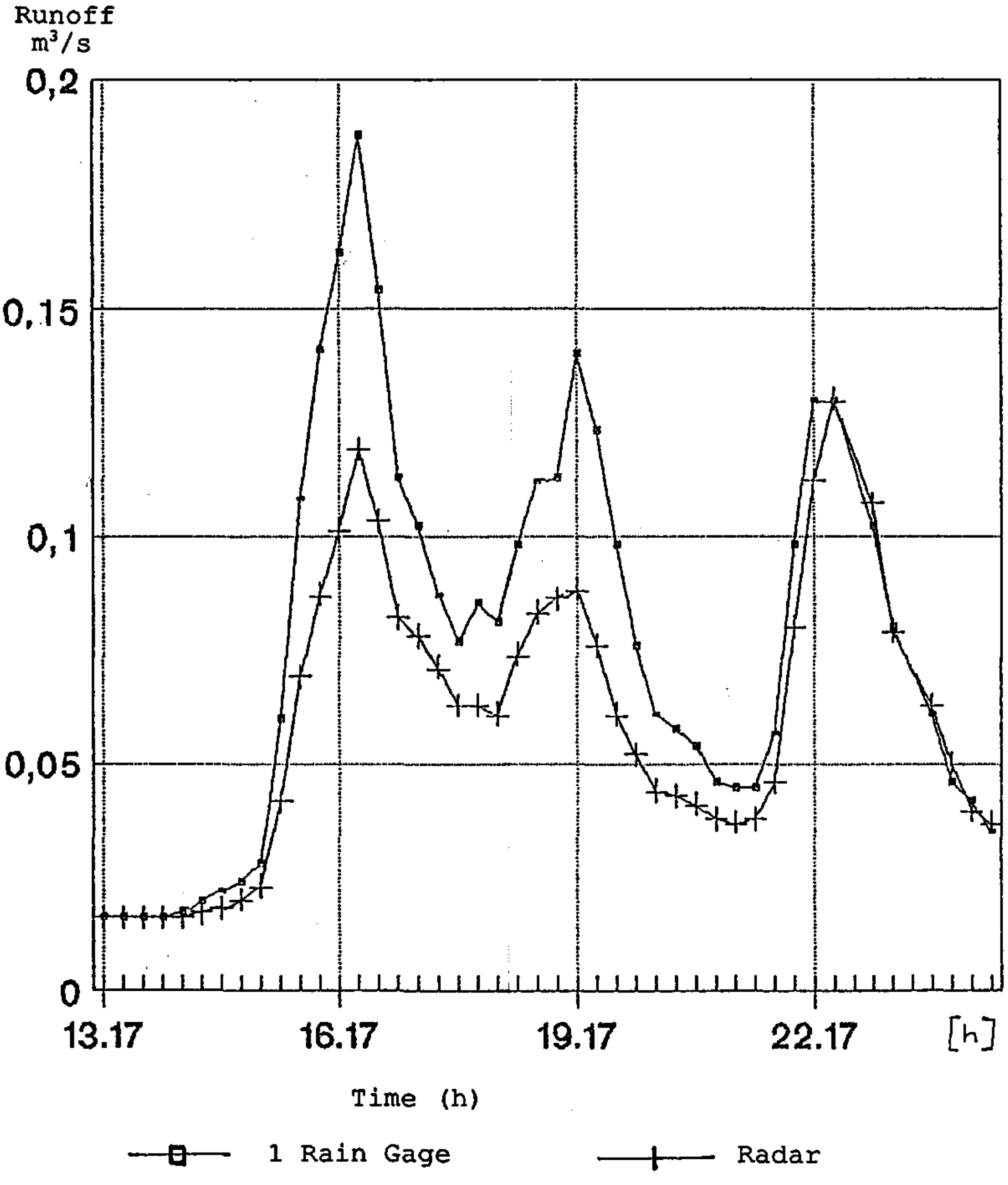

Fig. 5 **Hydrographs from uniform areal rainfall (1 rain gage) and radar rainfall for location RS3**

Grid-square rainfall-runoff modelling for the Wyre catchment in North-West England

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Introduction

The traditional approach to modelling the response of a river basin to rainfall is through a lumped representation in which an estimate of catchment average rainfall is used as input. This traditional approach still persists as the most commonly employed approach, particularly for real-time flood forecasting applications. In such applications it is common to require only a forecast at a "basin outlet" location which is gauged and there is little interest in forecasts at internal locations or in a form of model parameterisation capable of predicting the effect of land-use change. Experience has shown that with adequate calibration data in the form of flow records and with only a sparse sampling of the rainfall field using raingauges that more complex, and possibly more realistic, distributed models fail to provide improved forecast accuracy. A common diagnosis is that the models are "input limited" and that improved performance from distributed models will only be achieved when better measurements of rainfall fields are used as input data. Such measurements are now available in the form of weather radar data, commonly available on a 2 km grid at 5 minute intervals.

The aim here is to develop a simple distributed rainfall-runoff model suitable for use in real-time flow forecasting with weather radar providing the source of rainfall input. Whilst it is neither natural nor essential to configure such a model on the radar grid it is the approach which will be investigated here. Such an approach is by no means new: an early example is provided by Anderl et al (1976). The methodology adopted here was first outlined at a symposium in 1987 (Moore, 1991) but at this time had not been fully implemented or assessed. Other workers have pursued similar lines, but with different model parameterisations, most notably Chander and Fattorelli (1991). Application will be demonstrated using the Wyre basin in north-west England served by a C-band weather radar at Hameldon Hill.

Methodology

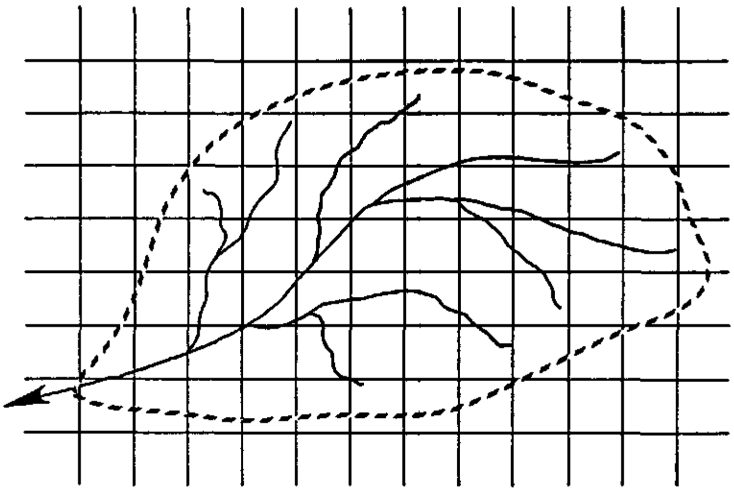
In developing a distributed model suitable for operational use in real-time it is clear that a form of parameterisation is needed that does not involve a large number of parameters in need of optimisation. This dichotomy between the need for distributed parameters and a small number of them needing to be optimised is resolved through the use of contour maps, in the form of digital terrain models (DTMs) if available, and simple "linkage functions". Contour maps are used in two ways. Firstly, the classical isochrone concept is used to "route" water to the basin outlet, essentially through dictating appropriate time delays as a function of travel paths across hillslope and down river channel pathways. Secondly, the slope of the terrain within a grid-square is used as a control on "runoff production", that is water available for routing rather than absorbtion by the soil/bedrock. Figure 1 provides a simple illustration of these two components which are expanded on below.

The construction of isochrones - lines joining points of equal time of travel to the basin outlet - has been achieved by assuming that water travels with only two velocities depending on whether it is associated with a hillslope or in a river channel. In this way it is relatively easy to construct isochrones by direct inference from the distance of a point to the basin outlet. More complex rules can be introduced, for example including slope influences via a flow resistance equation, given the availability of a DTM. Figure 1(b) illustrates a pattern of isochrones superimposed on the radar grid used as the model grid. The areas between isochrones associated with each grid square are calculated and used to apportion runoff from the grid square to a given time delay. In this way a runoff-distributed convolution is achieved to derive the basin flow response at future times. Experience with this simple time-area form of routing subsequently led to the inclusion of an additional nonlinear storage element to represent attenuation effects seen in observed hydrographs.

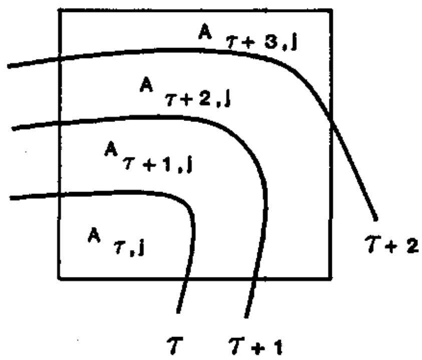
Generation of runoff from a given grid-square is accomplished by conceptualising the grid-square as a box-shaped "soil" column. The key element in the conceptualisation is that the depth of the box, and thus the absorbtion capacity of the soil, is controlled by the average slope within the square as measured from the contour map or DTM. Specifically, the following linkage function is used to relate maximum storage capacity, S_{max}, to the average slope, s, within a grid-square:

$$S_{max} = \frac{(1 - s)}{s^*} S^*_{max}$$

The parameters s* and S^*_{max} are upper limits of slope and storage capacity respectively and act as "regional parameters" for the basin model. Clearly a measurement of slope for each grid square associated with the river basin can be made from the contour map or DTM whilst parameterisation is achieved for all grids using only these two parameters. Additional functions are introduced to maintain a realistic water balance including soil moisture dependent evaporation and drainage functions. A soil moisture dependent infiltration function can be invoked for hydrological environments which experience infiltration-excess, as opposed to *(a) River basin with superimposed weather radar grid*



(b) Isochrones for grid-square j



(c) Block representation of runoff response from grid-square j

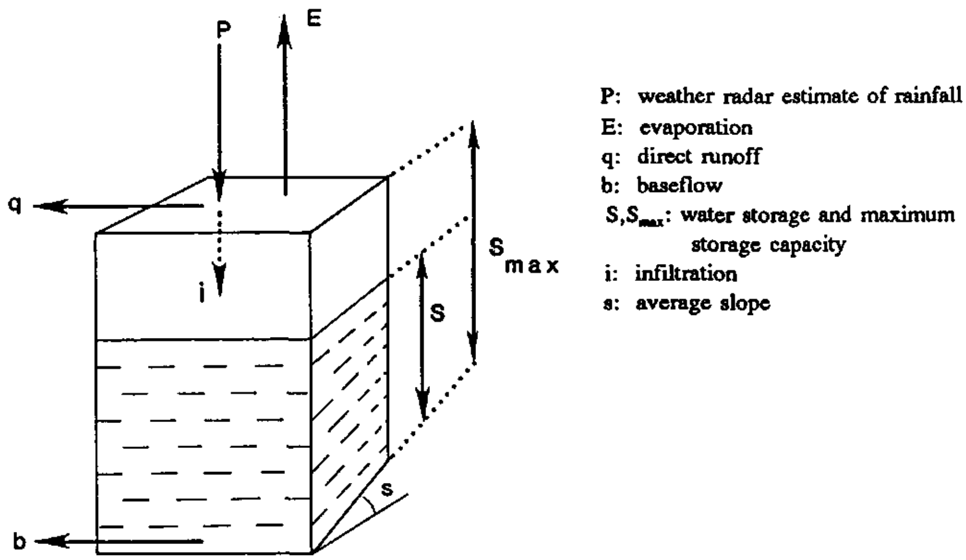


Figure 1 *Grid-square rainfall-runoff model for flood forecasting using radar data*

saturation-excess, runoff.

Results

The above model formulation has been applied to the River Wyre at St Michaels draining an area of 275 km^2 in north-west England. A total of 92 2km square radar grids for the Hameldon Hill radar are associated with its drainage area. Isochrones were constructed assuming translation velocities of 0.1 and 0.5 m/s for hillslope and channel flowpaths respectively. Instantaneous flow measurements at 15 minute intervals for the month of October 1986 were used for model calibration and assessment. Corresponding 15 minute rainfall totals were available for the 2 km radar grid and for a raingauge at Abbeystead located within the basin. An assessment of model results using the uncalibrated radar data as a distributed input and then the gauge value as a constant value for the basin revealed problems with the radar measurements of rainfall over this basin. The failure of the radar to always detect rainfall in some areas is known to be attributed to blockage effects caused by a television mast and hills. Further work is planned to correct for these anomalies, although another basin for model assessment is really required.

Conclusions

A practical methodology for distributed rainfall-runoff modelling using grid-square radar data has been developed. The problem of over-parameterisation has been circumvented through the use of measurements from a contour map or digital terrain model of the basin together with simple linkage functions. These functions allow many model variables to be prescribed through a small number of regional parameters which can be optimised to obtain a good model fit. Assessment of the model has been frustrated by blockages affecting the radar measurements of rainfall in the study region: correcting for these is the subject of future work.

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Radar Rainfall Forecasting over London for Flash-flood Warning

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Introduction

The London Weather Radar Rainfall Forecasting Study aims to provide rainfall forecasts on a 2 km grid over the Thames basin, focussing on lead times up to 2 hours and using automatic methods capable of producing updated forecasts every 15 minutes. In this regard the Study aims to complement the UK national system of radar forecasting, known as Frontiers (Conway & Browning, 1988), which is a coarser resolution product on a 5 km grid extending over the UK. Frontiers uses man-machine interaction to produce forecasts up to 6 hours ahead updated every half hour. The requirement for more frequent, higher resolution forecasts reflects hydrological needs for flood warning, particularly forecasting flooding in urban and smaller rural river basins. This paper presents an outline of the development and assessment of different advection-based radar rainfall forecasting methods. The assessment has provided the foundation for recommending a prototype forecasting system for operational implementation over London and the Thames basin in 1991.

Methodology

An advection model of rainfall field movement forms the basis of all forecasting methods considered in the Study (Moore et al, 1990). Simple linear extrapolation is used to project the current radar rainfall forward, according to the advection velocity, to form forecast fields at successive lead times. The velocity vector is inferred from the current and a previous radar rainfall field by identifying a displacement of the latter which best matches the former.

Formally, using x and y to denote location on the west-east and south-north axes respectively, the x-component of the storm velocity, v_x, is derived from the following description of rain cell position:

$$x(t + \tau) = x(t) + v_x\tau$$

where x(t) denotes the position on the x-axis at the forecast time origin t and τ is the lead time of the forecast. Inference of the velocity vector (v_x,v_y) uses, as the citerion of correspondence, the log root mean square error

$$rmse = \left[n^{-1} \sum_{i=1}^{n} e_i^2 \right]^{½}$$

where the error e_i is defined as

$$e_i = \log\left\{(1 + R_i)/(1 + \hat{R}_i)\right\}$$

and R_i is the observed radar rainfall for the i'th pixel and $\hat{R}_i$ the forecast amount, based on projecting a previous field at the given velocity. For velocities which do not result in displacements which are integer multiples of the radar grid length the formation of $\hat{R}_i$ involves the use of a four-point interpolation formula applied to four adjacent radar cell values.

Identification of a velocity pair which minimises the rmse criterion involves a shrinking-grid search procedure at each forecast time origin. A coarse but extensive grid of velocity pairs is initially used and this is progressively reduced over three steps to smaller but finer grids centred on the previous step's best velocity pair. In all three steps only velocities which result in displacements which are integer multiples of the grid length are used in order to avoid the computational expense of interpolation. At the fourth and final step a direct interpolation in the error field is made, based on a four-point interpolation, to arrive at the final velocity pair to be used for that forecast time origin.

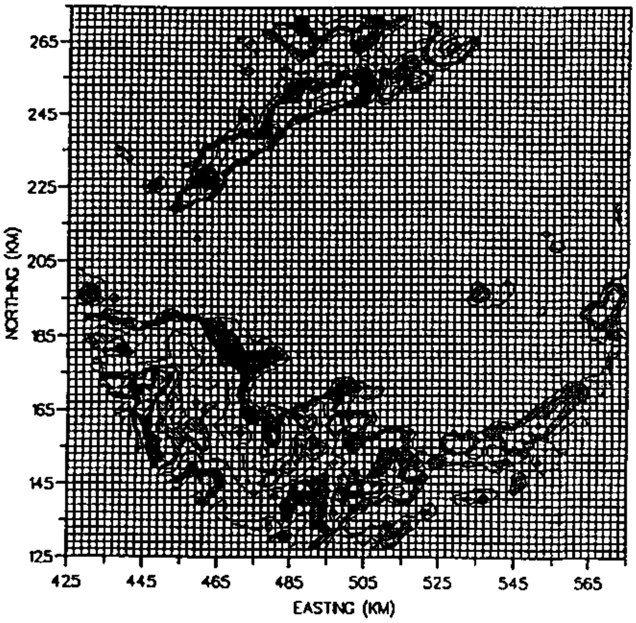
Results

An evaluation of the above basic advection approach to forecasting against a number of alternatives was carried out using radar rainfall fields from 15 storm events. Preliminary results suggested the use of a hybrid formulation in which the advection forecast, $\hat{R}_i$, is shrunk towards the field average value, $\bar{R}$, with increasing lead time, τ, so as to produce the modified forecast:

$$\tilde{R}_i = \bar{R} + a\left(\hat{R}_i - \bar{R}\right)$$

where the shrinkage factor $a = f^{\tau}$, and f is a constant. For the lead times up to 2 hours considered in the evaluation, this hybrid formulation performed better than persistence (a no change forecast), a rain/no-rain pattern matching approach to velocity inference and an extension of the advection method to incorporate acceleration. In general the pattern of rainfall forecasts obtained are reasonable up to a lead time of one hour (Figure 1).

Observed at 16.15



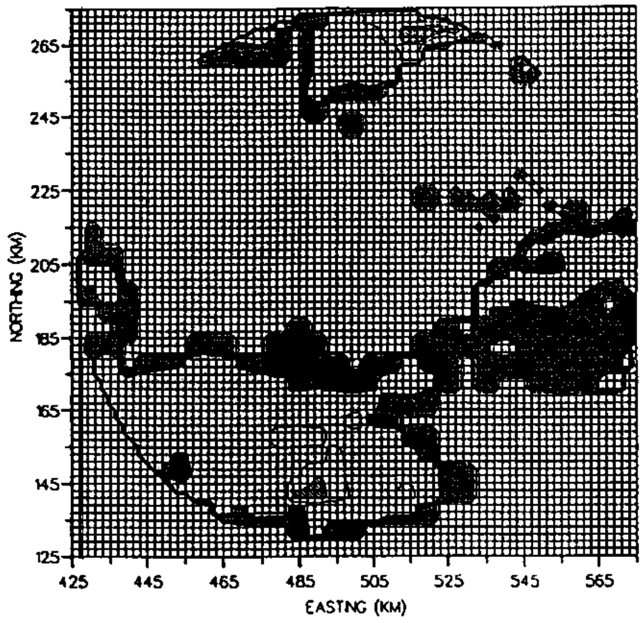


Figure 1 ***The observed 76 km radius rainfall field at 16.15 20 December 1989 and the corresponding one-hour ahead forecast made at 15.15***

The complete forecast algorithm incorporates automatic detection and correction procedures for persistent anomalies and transient clutter. Also included is a procedure to construct a composite field, incorporating radar data available out to a range of 210 km on a 5 km grid, in order to forecast as much of the target 76 km radius field as possible at higher lead times.

Conclusions

The main conclusions that can be drawn so far from the London Weather Radar Rainfall Forecasting Study can be summarised as follows:

(1) A forecasting method based on an underlying simple advection model and shrinking the forecasts towards the field average value with increasing lead time provides the best performance.

(2) More complex methods incorporating an acceleration component, or using a rainfall threshold to define a rain/no-rain pattern field from which to infer the advection velocity, did not perform as well.

(3) The general pattern of the forecast rainfall fields are reasonable up to about one hour ahead.

(4) A novel shrinking-grid search procedure for identifying the storm velocity from two time-displaced radar images, involving interpolation in the forecast error field in the final step, proved to be both reliable and efficient: a two hour forecast, at 15 minute intervals over a radius of 76 km, is generated in 12 seconds on a VAX4200 using this procedure.

(5) Results obtained are sufficiently encouraging to proceed with an operational prototype in 1991.

A second stage of the study, to be completed by September 1991, will compare the results of this Radar Rainfall Forecasting System with forecasts obtained from the Frontiers national system.

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A RAINFALL-DISCHARGE MODEL FOR A REGIONAL SEWER SYSTEM AND A FIRST APPLICATION OF RADAR GENERATED INPUT

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ABSTRACT

For the purpose of investigating the effect of spatial rainfall variability on the feasibility of reduction of the hydraulic capacity of a regional wastewater treatment plant, a simple rainfall-discharge model was developed for simulating 30 min. water balances of the separate (combined) sewer systems and the receiving pressure pipe system transporting their outflows to the purification plant. Two types of distributed precipitation data were compared: optimal interpolations of raingauge measurements only and of different combinations of C-band radar and raingauge measurements. Both types represented the actual temporal variability well, but the spatial variability was underestimated by the former and overestimated by the latter. In both cases, however, reduction of the plant capacity was not found to be feasible, unless the originally designed number and total volume of overflows was increased.

1. Introduction

This paper describes two studies that have been carried out during the period 1987-1990 at the Department of Hydrology, Soil Physics and Hydraulics of Wageningen Agricultural University. Both studies dealt with the quantification of the influence of spatial rainfall variability on the feasibility of the reduction of the hydraulic capacity of a regional wastewater treatment plant. In the first study [*STORA, 1988*], a data set of 30 events consisting of interpolated raingauge measurements was used as input for a simple rainfall-discharge model. In the second study [*Klaarenbeek, 1989*], different combinations of precipitation data from rain gauges with those obtained from weather radar observations for one single event were applied. Thus, a comparison could be made between the two types of distributed precipitation data with respect to the assessed performance of the rainfall-discharge model.

A simple reservoir-based rainfall-discharge model NAMRAP was developed for simulating the storage behaviour of the separate local sewer systems and the regional transporation system connecting them with the wastewater treatment plant. The simulation was done on a 30 min. basis. Various operation schemes (scenarios) for the local pumping-stations were developed and extensively tested. The constraints with respect to the reduction of the hydraulic capacity of the regional treatment plant implied: (1) no increase in the originally designed number of overflows and (2) no increase in the originally designed total volume of overflows [*STORA, 1988; Witter et al., 1989*]. However, little attention will be paid here to the scenarios and their constraints, as the focus of this paper remains limited to a comparison of two types of distributed precipitation data as inputs to the local sewer systems and their subsequent conversions to discharge at the regional wastewater treatment plant as simulated by NAMRAP: (1) Interpolated rainfall point measurements from raingauges alone, and (2) combinations of both raingauge and weather radar measurements.

2. Study Area

The study area West-Brabant is located in the south-western part of the Netherlands at a range between 50 and 100 km from the operational C-band weather radar of the Royal Dutch Meteorological Institute (KNMI) in De Bilt (fig.1). The prevailing traveling direction of frontal precipitation systems entering the West-Brabant area from the North Sea is north-east [*Witter et al., 1989*]. The prevailing flow direction in the regional transportation system on the other hand is just opposite, towards the regional wastewater treatment plant located in the south-west of the study area (Bath, fig.2). This may imply that regional scale spatial rainfall variability will allow a possible reduction of the hydraulic capacity of the regional treatment plant.

The region of interest comprises a total area of about 450 km^2 and contains 29 local sewer systems, of which 26 are designed as combined and 3 as separated sewer systems. It is noted that the two largest urbanized areas, namely Bergen op Zoom and Roosendaal (fig.2), make up about 60 % of the total paved area contributing to the discharge reaching the regional sewage water treatment plant. The transportation system is for the greater part implemented as a pressure pipe system, although a few open channels provide an additional storage capacity.

3. Instrumentation and Data Selection

During the first study (concerned with calibration and verification of the rainfall-discharge model), a total of 9 pluviographs were installed in the study area, whereas during the second study (concerned with radar application) 6 tipping bucket raingauges were used, of which half was located inside one 2*2 km^2 weather radar pixel near Zevenbergen for the purpose of studying the relation between small scale (intra-pixel) spatial rainfall variability and radar reflectivity. Although the tipping bucket gauges are reported to have resolutions of 0.16 or 0.2 mm, laboratory experiments have shown that the tipping values were actually intensity dependent: For high rainfall intensities they were found to be as much as 15 % higher than at low intensities [*van den Assem, 1988*]. The field measurements have been corrected accordingly. The moments at which tippings occured have been linearly interpolated.

The operational C-band weather radar of the Royal Dutch Meteorological Institute (KNMI) in De Bilt transmits a beam of microwaves with a wavelength of 5.3 cm (5.6 GHz) and a half power width of approximately 1°. One rotation of the radar takes 20 sec. and the scanning period of the radar amounts 15 min. The radar performs plan position indicator (PPI) scans at 2 elevations, namely at 0.3° and 1.7°. During the preprocessing stage, both scans are combined to obtain 1 image composed from the reflectivity measurements at 1.7° for ranges smaller than 65 km, those at 0.3° for ranges greater than 70 km and those at the elevation associated with the strongest radar reflections for ranges in between. As a result, the height of the centre of the radar beam in the study area varies roughly between 0.7 and 2.0 km. After preprocessing, the radar images have a spatial resolution of about 2*2 km^2 and an intensity resolution of 1 byte (corresponding to 256 intensity levels) [*Wessels, 1989*].

The precipitation events for the first study (using raingauges only) were selected on the basis of "peak over threshold": Rainfall events during the summer season were selected whenever the daily average precipitation rate from 7 KNMI raingauges exceeded 12.1 mm and during the winter season whenever it exceeded 10.9 mm. In this manner 30 representative precipitation events during a 2½ year period (1983-1985) were selected that were used as input for the rainfall-discharge analysis. Of a total of 125 half hourly time intervals with flow rates greater than 90 % of the current hydraulic capacity of the regional treatment plant, 113 were selected for verification purposes [*STORA, 1988*].

The only precipitation event that was applied during the second study (using radar plus raingauges) was a frontal system of 24 hrs. of continuous rain that passed the Netherlands on September 24 and 25, 1988. The totally observed amount of rain exceeded 50 mm, whereas the maximum intensities amounted 3 to 5 $mm*min^{-1}$. Because the area considered in these studies consists entirely of flat, horizontal and homogeneous terrain, no ground clutter, beam shielding or orographic effects are expected [*van den Assem, 1989*]. Vertical (balloon) soundings and raingauge measurements showed that corrections for bright band or anomalous propagation were not necessary, either. Moreover, it was found that the application of an attenuation correction did not improve the agreement of observed radar reflectivities with raingauge measurements [*van den Assem, 1990*]. Instead of taking variations in the radar reflectivity-rain rate (Z-R) relationship into account, the standard "Marshall-Palmer" relationship ($Z=200*R^{1.6}$, where $[Z]=mm^6*m^{-3}$ and $[R]=mm*hr^{-1}$) without corrections for anomalies was applied to avoid the computational effort of calibrating the coefficients [Battan, 1973].

In order to improve the temporal resolution of the radar images, a space-time interpolation technique based on the advection principle has been applied. This technique assumes that storms move with constant travelling velocities between radar scans and that their intensities vary linearly (to account for decay or growth). By iteratively interpolating forwards and backwards in space and time between 2 successive radar images using the wind velocity at the 850 mb level as predictor, an optimal "displacement vector" can be derived which increases the temporal resolution from 15 min. to 1 min. [*van den Assem, 1991*].

4. Methodology

The rainfall-discharge process in the local sewer systems connected to the regional sewage water transportation system is simulated by means of a water balance model with half hourly computation intervals. This model is incorporated in the computer simulation program NAMRAP. The water balance of the urban area associated with number i during time interval t reads as follows:

$$Q_{out}(i,t) = C(i) * A_p(i) * R'(i,t-t_L) + Q_{in}(i,t) + Q_{dry}(i,t) - Q_{over}(i,t) + \Delta S(i,t) \qquad (1)$$

where:

Q_{out}: discharge injected from local sewer system into regional transporation system [L^3*T^{-1}]
C: discharge coefficient [-]
A_p: paved area [L^2]
R': estimated precipitation (R) minus initial losses (L_o) over paved area [$L*T^{-1}$]
t_L: number of intervals lag time due to internal resistances [-]
Q_{in}: inflow from upstream areas [L^3*T^{-1}]
Q_{dry}: dry weather discharge [L^3*T^{-1}]
Q_{over}: overflowing discharge [L^3*T^{-1}]
ΔS: change in available storage in local sewer system [L^3*T^{-1}]

A subset of 6 precipitation events was selected from the previously mentioned total of 30 events for the purpose of calibrating C, t_L and L_o for each separate local system on the basis of comparisons of simulated with measured discharges at the local pumping stations and at the regional purification plant. The discharge coefficients (C) were determined for all local sewer systems by means of linear regression analysis, taking into account lag times (t_L) of 2 intervals for the 2 largest systems (Roosendaal and Bergen op Zoom, fig.2) and 0 intervals for all smaller ones. Initial losses (L_o) of 1 mm yielded the best results for all local sewer systems.

During the first study, the precipitation amounts at all paved areas (R) within the regional sewer transportation system West-Brabant contributing to the discharge at the purification plant Bath were estimated from the available raingauge measurements alone. The individual point measurements were interpolated by means of the optimal linear interpolation method kriging. This method provides the best (i.e. with a minimal variance of the estimation error), linear (i.e. as a linear combination of the measurements) and unbiased (i.e. with zero expectation of the estimation error) precipitation estimates [*Journel and Huijbregts, 1978*]. Thus, the systematic error is eliminated and the random error is minimized. The exponential semi-variogram model fitted the observed small scale spatial rainfall variability best (fig.3) [*STORA, 1988; Witter et al., 1989*].

During the second study, the rainfall amounts at the paved areas were estimated from a combination of both (point) raingauge and (areal) weather radar measurements. In this case, calibration factors (defined as the reciprocals of the assessment factors) were determined at places where both types of rainfall measurements were available. Two sets of calibration factors were computed on the basis of different functional forms: (1) Exact calibration factors, defined as the ratios of the raingauge measurements at time t and the radar derived rainfall amounts at time t; (2) Smoothed calibration factors, defined as the ratios of the sums of the raingauge measurements during the 4 previous 15 min. time steps and the sums of the radar derived rainfall amounts during the 4 previous time steps (i.e. the preceeding hour). Both sets of calibration factors were interpolated by means of kriging to the paved areas within the regional sewer system and were subsequently multiplied with the associated 15 min. rainfall intensities derived from the radar reflectivities using the standard Z-R relationship. The spherical and exponential semi-variogram models yielded the best results for both types of calibration factors (fig.4).

Both the uncalibrated and the calibrated radar observations were compared with the raingauge measurements on the basis of their ratios and their differences. It was found that both types of calibration improved the accuracy of the radar observations [*Klaarenbeek, 1989*]. Comparisons on the basis of differences, however, provided more useful results than comparisons on the basis of ratios, since the latter do not distinguish between small and large values and tend to overestimate the errors in small values.

5. Results and Discussion

The estimated first order autocorrelation coefficient of the interpolated rainfall point measurements was found to agree well with the value for actual rainfall amounts that can be estimated on the basis of theoretical considerations [*Buishand, 1977*]: for the summer season the difference was merely -0.03 (0.45 vs. 0.48) and for the winter season 0.04 (0.61 vs. 0.57). Hence, the interpolated rainfall point measurements represent the actual temporal variability to a satisfactory degree. However, the estimated dispersion variance of the interpolated raingauge measurements was found to be significantly lower than the value for actual rainfall amounts: for the summer season the difference was -0.29 mm^2 (0.23 vs. 0.52 mm^2) and for the winter season -0.08 mm^2 (0.08 vs. 0.16 mm^2). Hence, the interpolated raingauge measurements underestimate the actual spatial variability. An artificial increase of the spatial rainfall variability through Monte Carlo simulations by means of a multiplication of the interpolated raingauge measurements with a random number generated from a log-transformed uniform distribution was found to decrease the first order autocorrelation coefficient and to increase the dispersion variance [*STORA, 1988; Witter et al., 1989*].

The estimated first order autocorrelation coefficient of the calibrated radar measurements (0.42) was found to be slightly lower than the value for actual rainfall amounts (0.48), whereas the estimated dispersion variance was significantly larger (1.00 vs. 0.52 mm^2). Hence, the spatial rainfall variability is overestimated by the calibrated radar derived rainfall observations and underestimated by the interpolated raingauge measurements. However, some remarks must be made with respect to this observation: (1) only 1 (very) extreme precipitation event was analysed in the second study; (2) only 4 raingauge sites were included in the analysis, which is a rather poor number from a geostatistical point of view.

6. Conclusions

The combination of distributed rainfall data and a simple water balance model (NAMRAP) to simulate the rainfall-discharge behaviour of a regional sewage water transportation system is a reliable approach (fig.5). The application of interpolated raingauge measurements, however, does not indicate that a reduction of the hydraulic capacity of the regional treatment plant is feasible without violating the defined constraints: a moderate increase in the number and volume of overflows seems inevitable unless an additional central overflow storage reservoir is constructed. Precipitation data with a higher temporal and spatial resolution are likely to improve the model's calibration and verification results. Moreover, such data will allow for a more optimal "real-time" water management strategy resulting in: (1) a more regular discharge regime at the purification plant through the reduction of flow rate fluctuations; (2) a modest reduction of overflow (both in number and in volume) without increasing the plant's hydraulic capacity.

The application of calibrated radar derived rainfall measurements as input for the water balance model NAMRAP indicates that spatial precipitation variability indeed has a significant effect on the rainfall-discharge behaviour of the regional sewer system. However, this variability is not large enough to jeopardize the conclusion drawn on the basis of the first study: Reducing the hydraulic capacity of the regional wastewater treatment plant is not feasible without violating the defined constraints.

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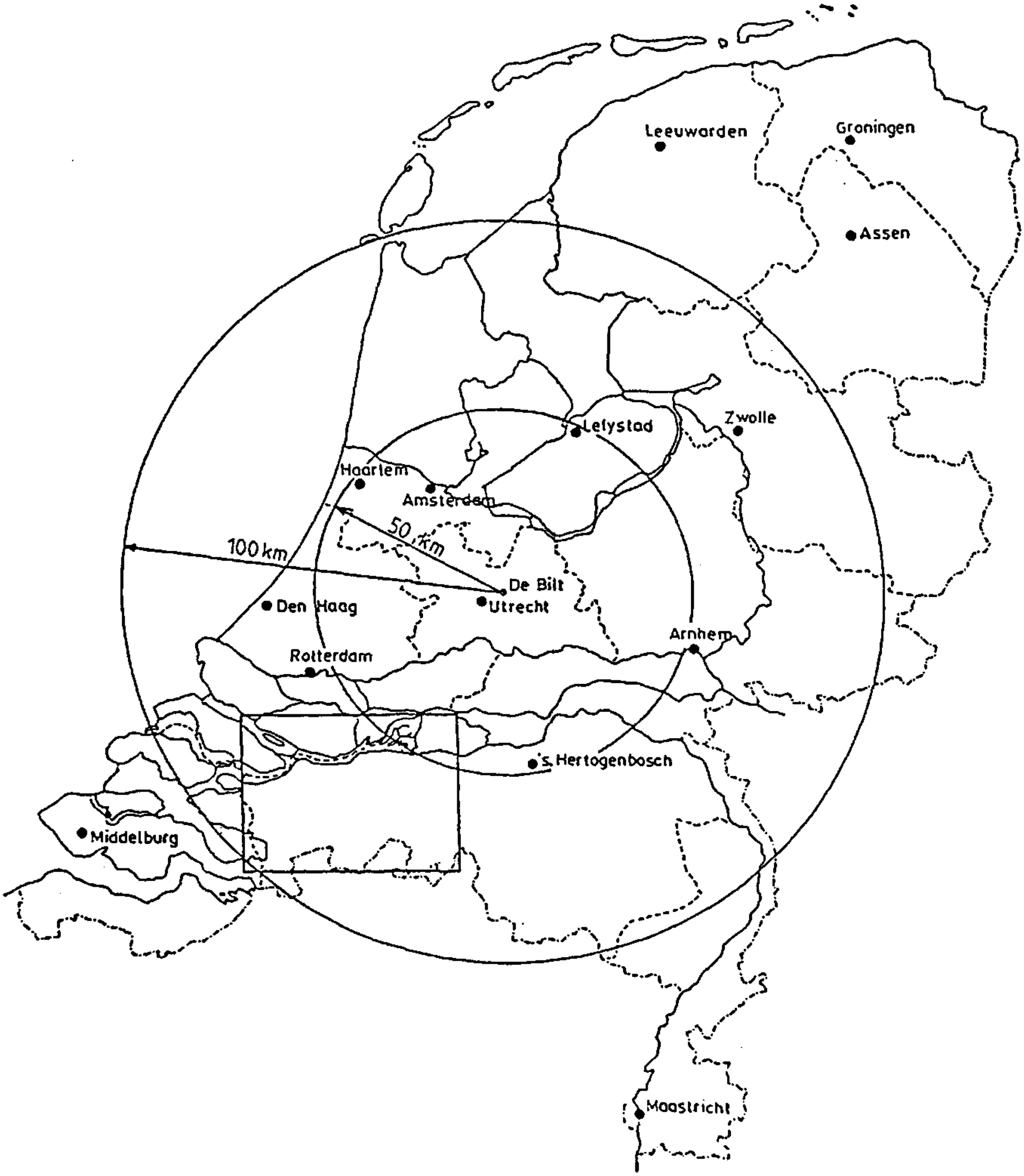

Figure 1. Map of The Netherlands with location of Royal Dutch Meteorological Institute C-band weather radar in De Bilt, study area West-Brabant (box) and 50 and 100 km range markers.

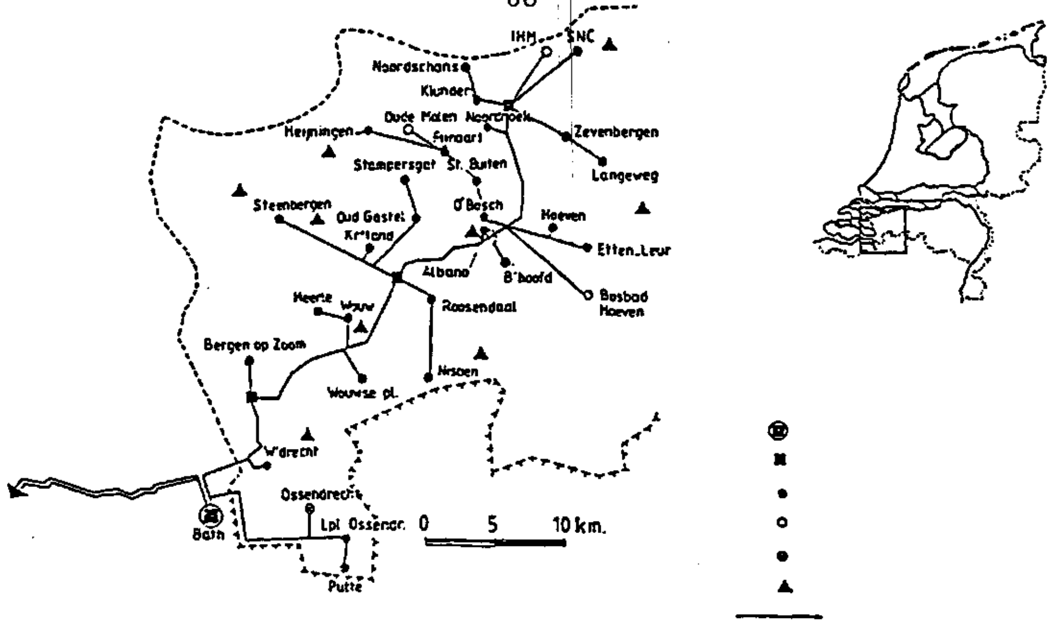

Figure 2. Regional wastewater transportation system West-Brabant and treatment plant Bath. Legend: Regional sewage water treatment plant; Pressure station; Combined sewer system; Separated sewer system; Sludge; Pluviograph; Transportation system.

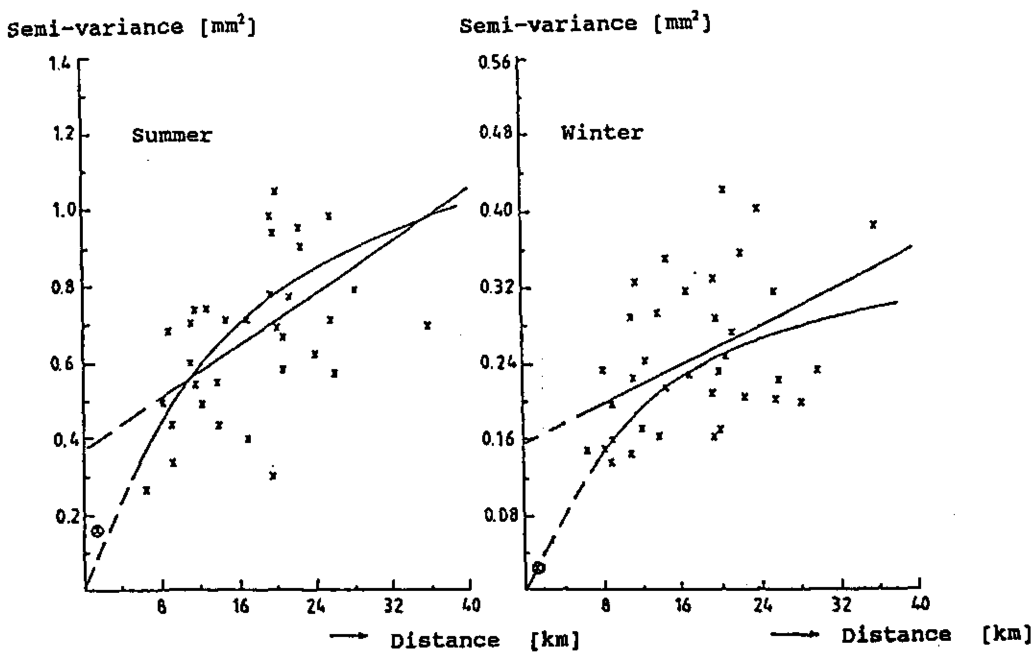

Figure 3. Estimated semi-variances [mm^2] as function of distance [km] and fitted linear and exponential semi-variograms for half-hourly rainfall depths during summer and winter season in the study area.

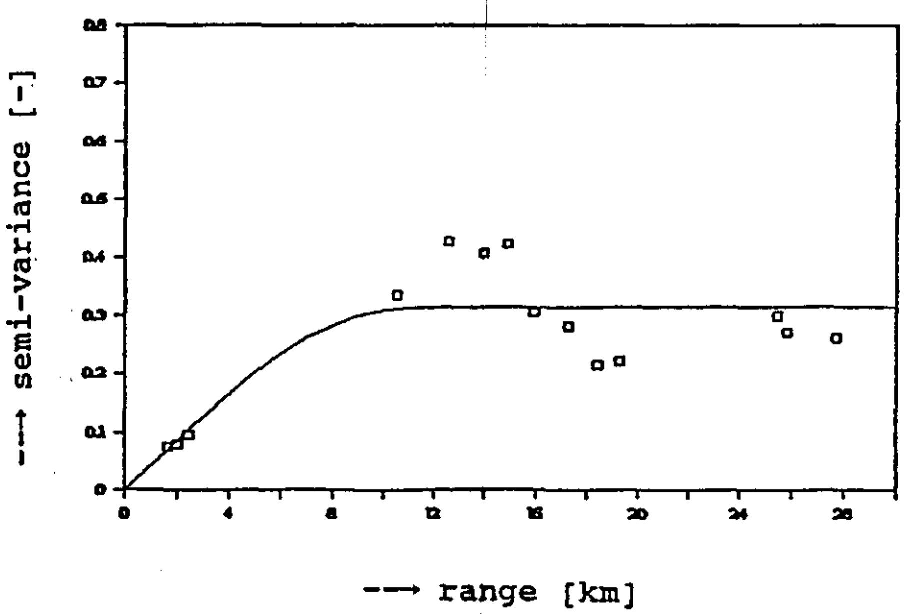

Figure 4. Estimated semi-variances [-] as function of range [km] and fitted spherical semi-variogram for smoothed adjustment factors.

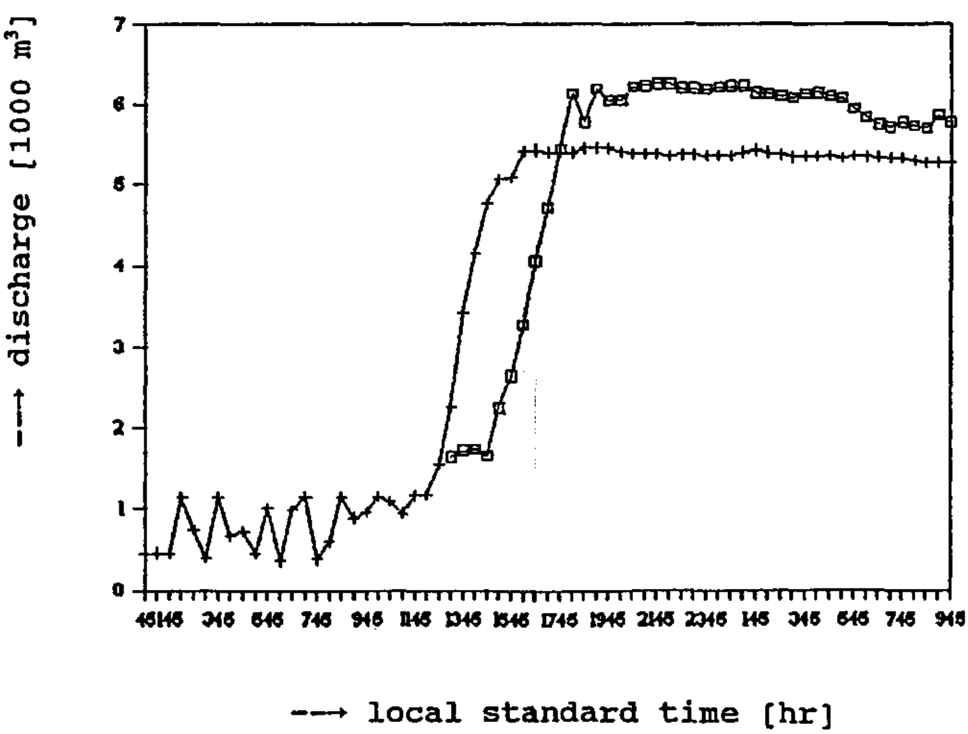

Figure 5. Comparison of measured (▪) and simulated discharge (+) at regional sewage water treatment plant Bath using radar observations adjusted with exact adjustment factors as input for NAMRAP between September 24, 1988, 00:45 hr. and September 25, 1988, 09:45 hr. (Local Standard Time).

SEMIDISTRIBUTED MODELING FOR REAL-TIME FLOOD FORECASTING. THE CASE OF MOUNTAINOUS REGIONS

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Abstract A semi-distributed model, which is capable to adequately represent conditions in steeply sloping watersheds, is presented. The model features an encoding procedure to describe the river network into a two-dimensional planar representation. An ARMA procedure is used to predict the residual behavior on the basis of simulated and observed discharges. The model has been applied to the Posina River basin, by using radar derived rainfall data.

1. Introduction

The radar capacity to quantify actual storms in a quasi-continuous fashion, both in time and space, is generally envisaged to be fully exploited through distributed models. However, the recent trend in research has revealed some fundamental problems in the application of distributed phisically-based models for practical prediction in hydrology (Beven, 1990). These problems arise with more evidence for real-time flood forecasting.

At the same time, it is recognized that the spatial variability of rainfall field can play a role of considerable importance in runoff formation (Milly and Eagleson, 1988).

Several biases constrain the spatial definition of radar derived rainfall data, particularly in mountainous regions. Among others things: the grid-like format of the weather radar data, on a 'bin' size which ranges from 1•1 km to 5•5 km; the radar inability to detect precipitation close enough to the ground surface, due to the rugged orography of the region; the adjustment of radar data to 'ground truth', which implies in many cases 'smoothing' of the radar derived spatially variable rainfall field. This shows the problematic nature of disaggregating spatial and temporal cumulated rainfall data into more refined space and time steps.

Therefore, the more conceptual semi-distributed approach could play an interesting role, at least from a cognitive point of view, in the way of using the information content which is made available by the weather radar.

2. Model structure

Basin and precipitation data are stored and processed at two different scales of representation.

Topographic information is obtained from topographic maps through digitization; in this way a 200 m cell size DTM is generated.

Precipitation data (radar and rain-gauge derived) are stored and processed into a 1 km grid size. Rain gauge derived precipitation data are spatially interpolated by using the reciprocal distance rain-gauge interpolation technique. Brandes technique (Brandes,1975; Dalezios, 1989) is applied to adjust radar rainfall data on the 'ground truth' rain gauge rainfall measurements.

The model operates on a sub-basin (cell) scale. The cell incorporates a 'production function', which is based on a storage approach. There are three storage components: a surafce store (SS), a subsurface darcian store (SDS), and a subsurface quick response store (SQRS) (Ormsbee and Khan, 1989). The precipitation is divided into input to SQRS and to SDS. The model does not take into account flow into the unsaturated zone. In its simplest form the model represents a sub-basin as a single rectangular hillslope providing inflow to a channel running along the base of the slope.

The subsurface storage components are described in the following sections.

2.1 Subsurface darcian storage

The kinematic storage model of Sloan and Moore (1984) provides a realistic component model for slow response subsurface saturated flow through thin mountain soils perched on bedrock. Consider that the flow within the saturated zone on an hillslope rectangular element of slope θ can be described by a darcian law. If it is assumed that the flow lines are parallel to the slope and the hydraulic gradient is equal to the slope of the water table, discharge Q is given by the following equation:

$$Q=-K\,h\left(\frac{\delta h}{\delta x}\cos\theta-\sin\theta\right) \tag{1}$$

where:

Q = lateral discharge in the downslope direction x;
k = hydraulic conductivity;
h = depth below the water table measured orthogonal to the impermeable bed;
θ = ground slope.

Assuming that the hydraulic gradient in the saturated zone is equal to the bed slope, equation (1) becomes:

$$Q=K\,h\sin\theta \tag{2}$$

In this case, the partial difference equation for the variable h takes the form of the simple kinematic wave equation. Water table is assumed to behave like a straight line pivoted at base point, and discharge from the hillslope is given by (2).

If water table is high enough to intersect the ground profile, precipitation falling on the saturated part of the slope is immediately added to surface flow, and the process of runoff generation accelerates.

SDS is divided into a gravity store (SDS_g) and an available water store (SDS_a). When the store content (S_i) is lower than SDS_a, input is entirely absorbed by the store.

The model recalibrates the ratio (S_i/S_{sdsa}) at the start of the forecasting period, thus adjusting the soil moisture parameter.

2.2 Sub-surface quick response store.

This store is characterized by the maximum amount of water that can be stored ($SQRS_{max}$). When SQRS is filled, input is diverted to SDS. SQRS is modelled as a linear store, and discharge is expressed as:

$$Q_{SQRS} = K_{SQRS} S_{SQRS} \tag{3}$$

where:

Q_{SQRS} = sub-surface quick response discharge;
K_{SQRS} = SQRS storage coefficient;
S_{SQRS} = effective SQRS storage.

Actually, distinguishing sub-surface quick response flow from overland flow, (which is simply added by the model to the river network) is not a trivial task.

Cell responses are combined by using a channel routing model to produce total watershed outflow.

2.3 Channel network and routing scheme description.

The model features a procedure in order to numerically encode a river network into a two-dimensional planar representation.

The topological information regarding the network is condensed by a (n,2) matrix, where n is the number of cells. In each row of the matrix the corresponding element is recorded togheter with the channel element immeadiately downstream (the successor reach). Thus, the elements are ordered according to a 'computationally oriented' scheme.

In this way a network description is made available and can support flood routing schemes which require only upstream boundary flow conditions.

A simplified version of the Muskingum scheme (Jones and Moore, 1980) is used in this case. The model is based on only one parameter (the ratio between time step and travel time trough the river reach), and allows wave travel speed to vary.

2.4 Real-time updating procedure.

An ARMA model is used to correct the forecast in real time. Since the model works in real time, it is possible to compare the results obtained with the deterministic rainfall-runoff model ($Q_1(t)$) with observed runoffs ($Q_2(t)$). This allows a time serie of residuals ($r(t)$) to be defined:

$$r(t) = Q_1(t) - Q_2(t) \tag{4}$$

An autoregressive moving average process is used to forecast the residuals r(t+i) from the last observed residuals. In the case of the Posina River basin, an AR(2) model has been found to adequately represent the forecastable information contained in the residual time series.

Fig. 2 represents (as a split-sample test) a three-hours ahead forecast for the 07.03.1989 event on the Posina River basin (fig. 1), with perfect rainfall forecast.

3. Conclusion

A semidistributed model for real time flood forecasting has been developed on the basis of a conceptual approach. The comparison between model performances with raingauge derived and radar derived precipitation is under development. Forecasted discharges with a lead time of three hours show a good agreement with the observed ones.

For storm events, which were studied, the autoregressive corrections give a considerable improvement of the forecasted discharges. Unstability has been shown in some cases, due to the short lenght of the residual time series and to the discontinuities in observed runoffs. Updating procedures which are able to distinguish between amplitude and phase error and to account for both error types are developing.

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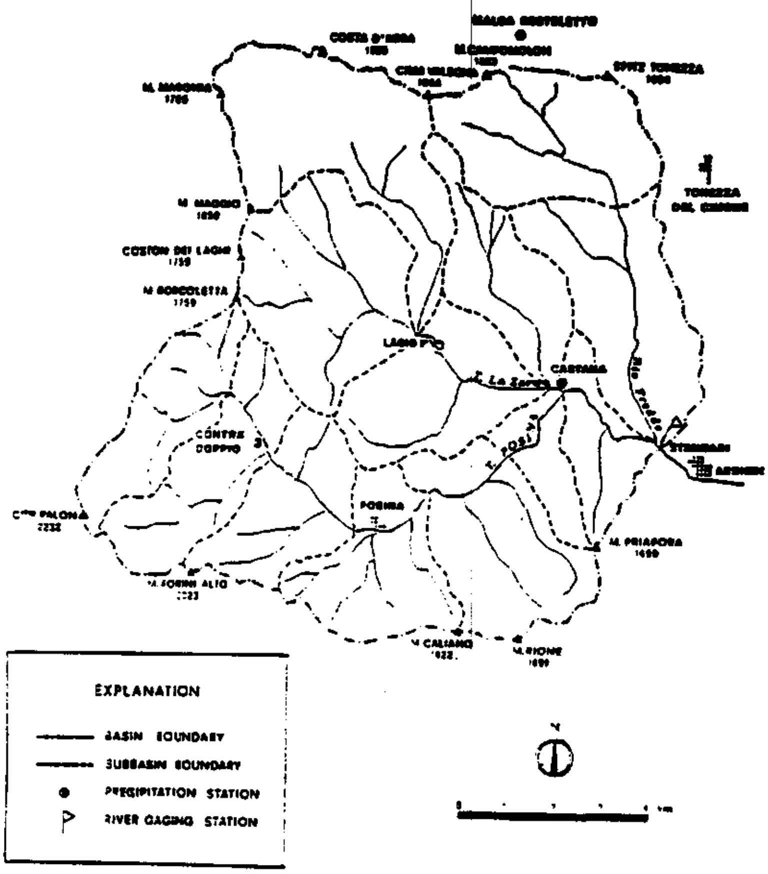

Fig. 1 Posina River basin (114 km²)

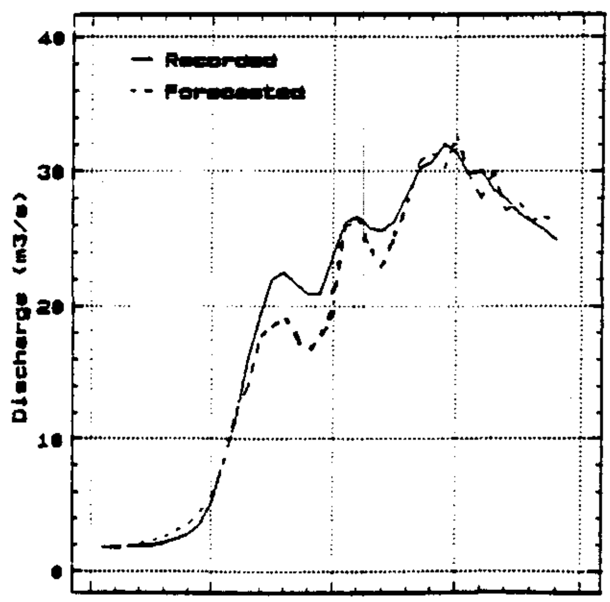

Fig. 2. 3 hours ahead forecast for the 07.03.1989 event with perfect rainfall foresight.

Recent Applications of Weather Radar to Urban Drainage Systems

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Abstract

This paper reports on work undertaken at the University of Salford as part of the North-West Urban Radar Project. The work is an extension of that carried out by the Water Resources Research Group using smaller models and it investigates the sensitivity of large models to different forms of data resolution. Use is made of the extended WASSP model software 'MEGA-WASSP' developed by the Water Research Centre (WRC) and also of the simulation model of Bolton belonging to North-West Water PLC.

OBJECTIVES

The objectives of the series of studies were to investigate the behaviour of the simulation model when stimulated by data having different resolutions. The different forms of data used were as follows:

- Temporal resolution
- Spatial resolution
- Data quantisation

METHODOLOGY

The method of analysis used to quantify the sensitivities of the models to the various forms of data was as follows. A large drainage network model was assembled using the WASSP-SIM module of the Wallingford Procedure[1] . The network had approximately 1300 pipes, 117 overflows and 4 subsidiary outfalls. The area covered by the physical network required the identification of 29 main catchment areas and their associated rainfall hyetographs.

The data extraction for each catchment was carried out semi-automatically using radar data analysis software developed within the group. The output from the software was in a form suitable for direct use as a control file to the WASSP-SIM software.

The temporal resolution of the software was adjusted from five minutes to fifteen minutes by integration. and the hydrographic behaviour of certain nodes on the network compared by means of the root mean square error (RMSE) between the two sets of discharge hydrographs.

The spatial resolution of the data was modified from a two km^2 grid to an average value across the whole network.. This average value was then applied to the model and the resultant discharge hydrographs compared using the RMSE technique.

The effect of data quantization was investigated using eight-bit data and three-bit data for the same storm events. The three-bit data were generated from the eight-bit data by applying a slicing procedure shown in Table 1. Hyetographs from the storm event were produced and the resulting discharge hydrographs compared using the RMSE technique as before.

DISCUSSION OF RESULTS

[1] Thanks are due to Mr D. Walters of Bolton City Council for the use of the network model and data, WRC for the MEGA version of WASSP-SIM, and Professor G. Austin of McGill University for the provision of radar data.

The results all tended to compliment those previously obtained from the smaller models.

The general sensitivity of the large model to temporal variations of the rainfall data were small and were restricted to the pipe sections on the extremity of the network.

The sensitivity of the model to distributed or lumped rainfall parameters was small and once again limited to those pipe lengths located at the extremities of the network.

The effect of the quantization of the data was also small.

CONCLUDING REMARKS

The results are very much as expected from the work reported by Cluckie, Tilford and Shepherd, 1989[2], and this is because the information content of the data is still sufficiently detailed to allow the model to function correctly.

The temporal effect is smaller on large models because the models integrates the local small scale effects caused by the smaller time-step data and may be viewed as a low-pass filter. The loss of the detailed behavioural data at the extremities of the model may be acceptable for most drainage studies.

The spatial effects are similar to those of temporal displacement and for the same reasons. The use of lumped data should not be confused with the use of data from a single raingauge. The lumped radar data contains information about the whole of the rainfall domain across the total catchment area. The application of lumped radar data would avoid the need for distributed storm models except for studies of the behaviour of pipe sections on the extremities of the network. Once again, these shortcomings may be acceptable.

The variation in the data quantization only caused local effects on the extremities of the network. Although the data are debased in terms of intensity resolution, the basic structure of the precipitation field is implicitly retained in the data.

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Table 1: Slicing Intervals for Converting Eight-Bit Data to Three-Bit Data

Intensity Level	Eight-bit Range (mm/hr)	3-Bit Values (mm/hr)
0	$I < 0.125$	0.0
1	$0.125 \leq I < 1$	0.56
2	$1 \leq I < 4$	2.5
3	$4 \leq I < 8$	6.0
4	$8 \leq I < 16$	12.0
5	$16 \leq I < 32$	24.0
6	$32 \leq I < 126$	79.0
7	≥ 126	320.0

ON THE USE OF DISTROMETERS FOR QUANTIFICATION OF RAINFALL

L. Breuer, R. Kreuels, Bonn, and H.-R. Verworn, Hannover

1. DEVICE

The distrometer is used to measure the number and sizes of raindrops hitting a specified area. Within the on-going research the RD-69 distrometer built by a Swiss firm is used. It consists of two units:

- the transducer which is exposed to the rain
- the processor

For the recording of drop size measurements on personal computers an A/D converter adapter is required to act as interface between the distrometer and the PC.

Fig. 1 is a schematic drawing of the system and its components.

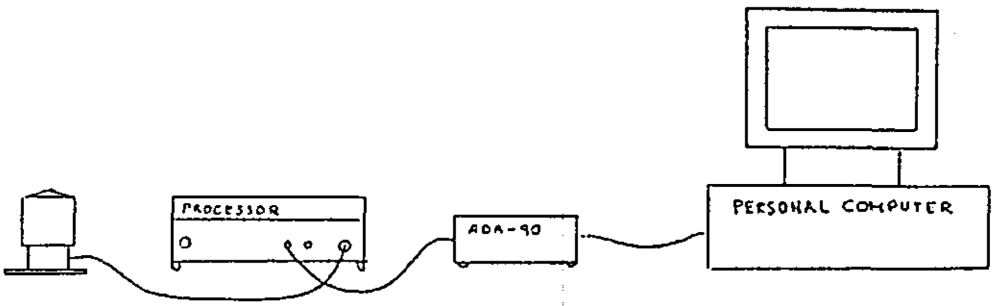


Fig.1 **Distrometer RD-69 with Analyzer ADA-90 and PC**

2. ACCURACY

Analysis of the first data showed inconsistencies whenever the number of drops per time unit were high. As the signals from the processor showed no irregularities, the cause for the errors had to be with the analyser or the PC. The construction and the software on the PC showed that indeed drops could get lost. The error, however, could not be quantified.

Therefore a new analyser was developed by Breuer (Meteorologisches Institut, University of Bonn) and built by a electronic firm specialized in rapid signal procession. With this new analyser (RA-1) connected to the distrometer parallel to the ADA-90 adapter (Fig. 2) the system was tested for several weeks on a number of rainfall events. Data from the ADA-90 were directly transferred to the PC and stored there, where the data of the RA-1 were stored within the device and retrieved after the end of the event. In this way the signals from the distrometer were identical for both analyzers, and so should have been the results. This, however, was not the case.

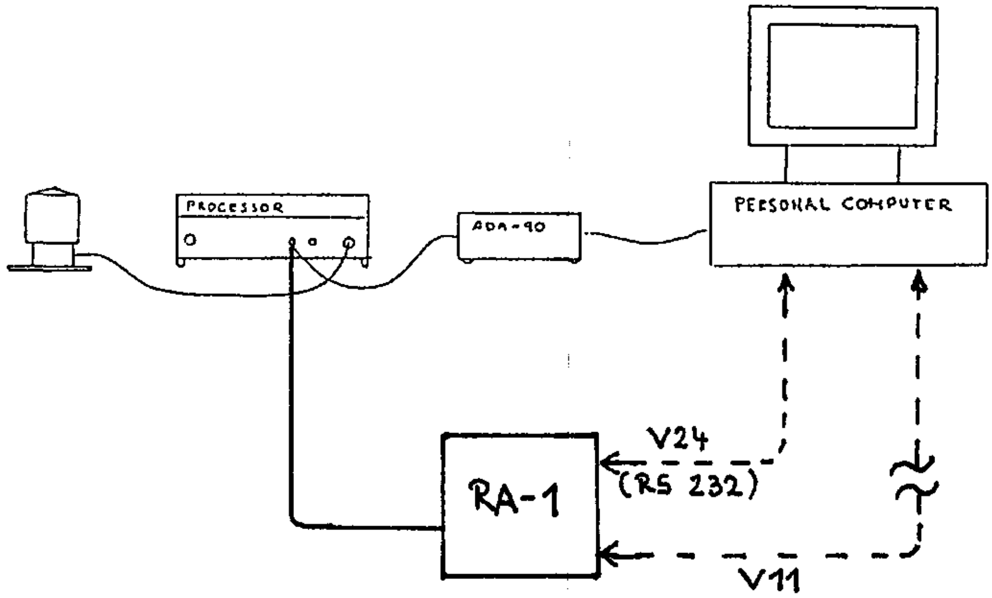


Fig.2 **Distrometer RD-69 with Parallel Analyzers ADA-90 and RA-1**

Fig. 3 shows that from 300 drops per min on the 50 cm^2 of the transducer the loss of drops increases to a mean maximum value of about 7%. This means that with nearly all rains losses occur as the number of 300 drops per min is generally exceeded with intensities of more than 1 mm/h. Fig. 4 shows the relation between intensity and number of drops for the mean and the mean plus standard deviation.

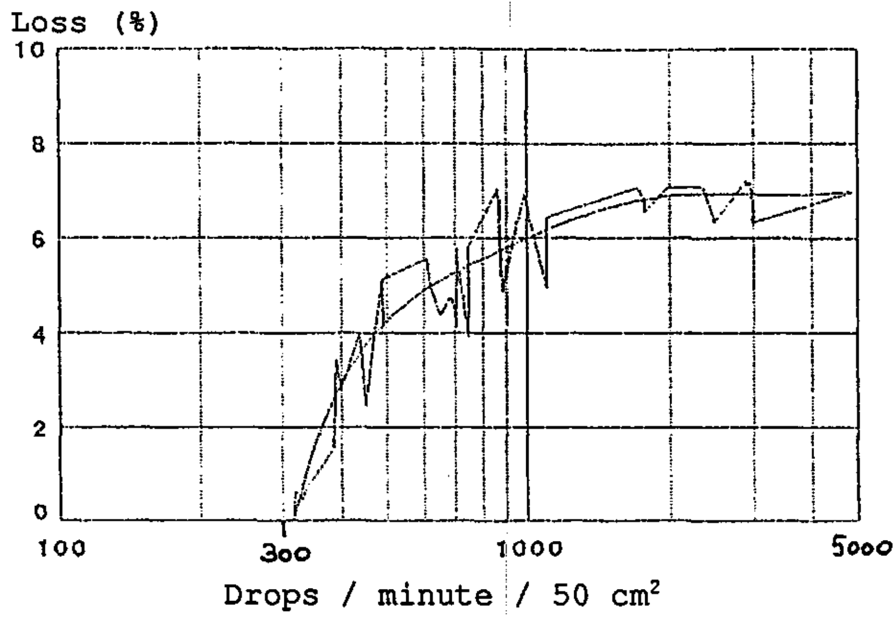


Fig. 3 **Percentage of drop losses as a function of drop count per minute**

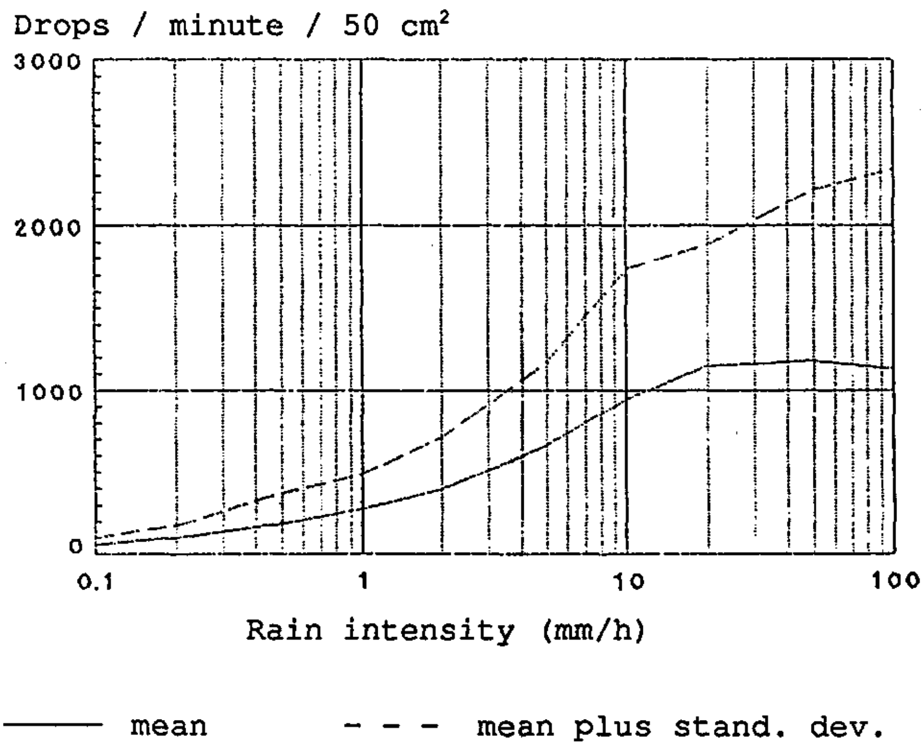
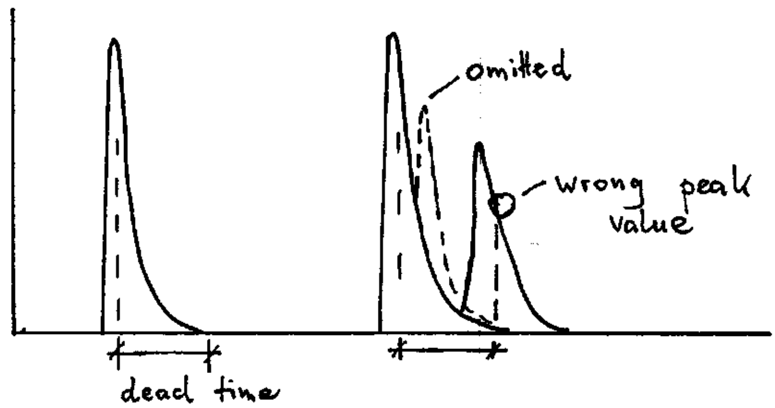


Fig. 4 **Number of drops per minute as a function of rainfall intensity**

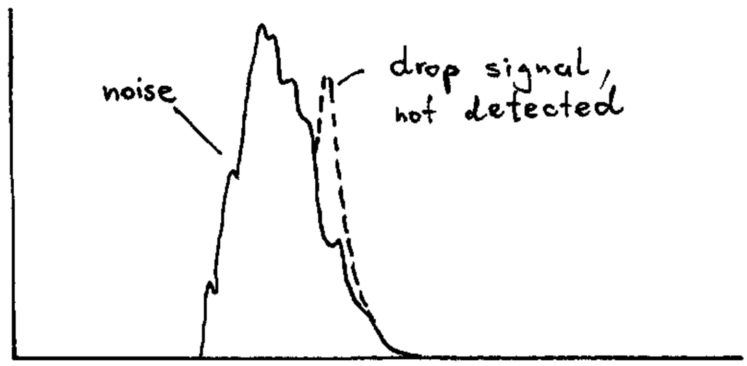
The reasons for the errors with using ADA-90 and the PC to collect the data are

- Counting problem
  Whenever data are sent to the computer in rapid succession and the computer is busy doing other things than monitoring the serial interface data are lost.

- Dead time problem
  The analyzer has a certain dead time for the analysis of a drop signal. If another drop signal within the dead time occurs it is omitted.



- Indifferent evaluation of peaks
  There is no clear destinction between drop signal peaks and noise peaks. Pulses in the receding flank are not detected if the relative rise is too small.



- The number of drops in the lower classes was too high, the number in the higher classes consequently too low. There was no apparent reason for this shifting.

- No exact definition of class boundaries.
  Some classes tended to get more drops than others. The reason for this was not detectable.

As a result the rain amount lost by the ADA-90/PC system was between 13% for rain events with up to 0.2 mm and 10% for rain events between 1 and 40 mm total rainfall.

With the RA-1 device the above errors did not occur.

The loss of data due to the computer being busy is avoided by having two CPUs and a large data buffer. One CPU is responsible for the detection and analysis of the signals from the transducer, the other handles storage and data transfer to a computer.

Because of very fast A/D-converters there is practically no dead time. Noise and signal peaks are separated by sufficient software.

All data can be temporarily (up to 6 hours) stored within the RA-1 if the communication link to the computer or processing unit is down. Communication is made easy by a clearly defined protocol.

Under normal conditions the RA-1 sends data to the computer every minute. These data consist of the number of drops within each of the 20 classes. These data can then be used within the computer to calculate the actual R/Z-relations.

3. ACTUAL R/Z-RELATIONS

From the number of drops within each of the drop size classes the rain intensity R as well as the reflectivity Z can be calculated.

$$R = const * \int n(D) * D^3 dD$$

$$Z = \sum D_i^6 = \int N(D) * D^6 dD$$

with

$$N(D) = \frac{n(D)}{v(D) * t * A_T}$$

where $n(D)$ = number of drops with diameter D, measured within time t (60 sec) on transducer area A_T (50 cm^2 = 0.005 m^2)

$N(D)$ = number of backscattering particles of diameter D in unit volume (1 m^3)

$v(d)$ = final fall velocity of drops with diameter D

If the R and Z values from the measurements of at least 10 minutes are plotted on a diagram with logarithmic axes the parameters a and b of the R/Z-relation

$$R = a * Z^b$$

can be calculated by linear regression.

Fig.5 shows an example of R and Z values on-line calculated from distrometer data. The minutely values for a period of 47 minutes are plotted together with actual R/Z relation calculated by linear regression from thes values and the mean R/Z relation.

This mean relation is used when there is less than 10 minutes of significant rain at the location of the distrometer. Significant rain rain is defined to have

- rain intensities R of more than 0.1 mm/h
- reflectivities Z of more than 10 mm^6/m^3.

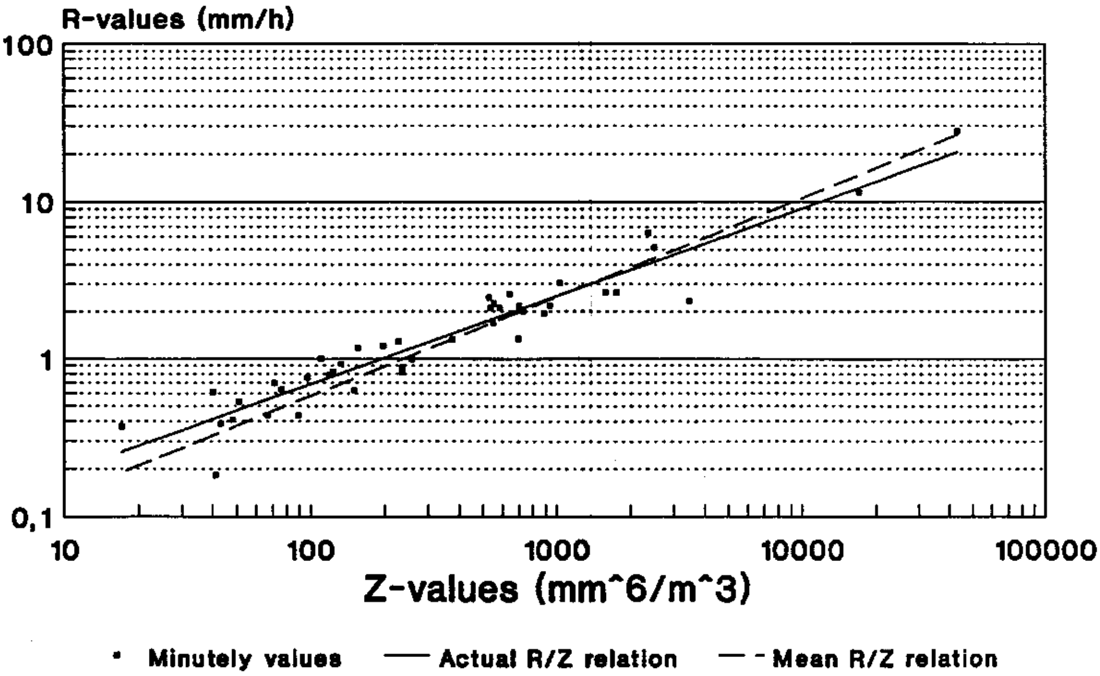


Fig. 5 **Minutely R and Z values and R/Z relations for the period from 5:44 to 6:30 h on Sep 21, 1990**

APPLICATION OF RAINFALL-RUNOFF MODEL HEC-1 TO THE ALENQUER'S WATERSHED

by: Valdemar Silva
Directorate General for Natural Resources - Portugal

INTRODUCTION/OBJECTIVES

This report presents the work developed in rainfall-runoff models for flood forecasting in small watersheds.

Considering that a telemetric station is already operational at Alenquer's watershed, an hydraulic and hydrologic characterization of flood regime was performed in order to understand and compare all the rainfall data measured by the measuring device mencioned.

In this study the flood package HEC-1 of the U.S. Army Corps of Engineers was utilized.

METHOD/DATA

The input rainfall and runoff data was obtained and selected. Then, the following data was obtained: physiographic parameters of the watershed, Thiessen coefficients, isochrones and parameters relative to the base flow for each flood.

The obtention of the physiographic parameters for the watershed and of the areas between isochrones was performed in an automatic way after digitazing the cartographic elements (with software developed at this institution).

On Fig.1, the Alenquer's watershed obtained with the graphic capabilities of the program DIGDES is presented.

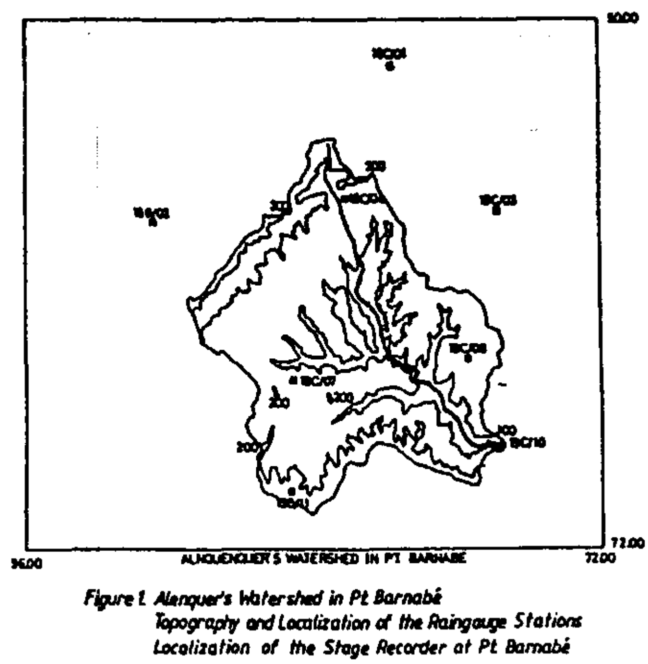


Figure 1. Alenquer's Watershed in Pt Barnabé
Topography and Localization of the Raingauge Stations
Localization of the Stage Recorder at Pt Barnabé

On Table 1, some of the physiographic parameters presented, computed with program ISOHU.

TABLE 1 - PHISIOGRAFIC PARAMETERS VALUES OF THE ALENQUER'S WATERSHED AT PT. BARNABÉ

WATERSHED AREA = 113.24 Km2 ;	WATERSHED CONTOUR = 54.47 Km2
CENTER OF THE GRAVITY COORDINATES:	MB = 82.396 Km PB = 63.323 Km

MEAN ALTITUDE = 156.24 m ;	BASIN AVERAGE WEIGHT = 128.24 Km
EQUIVALENT RECTANGLE DIMENSIONS:	LENGHT = 22.123 Km WIDTH = 5.119 Km
MEAN SLOPE OF THE WATERSHED (%) =	17.287

HIPSOMETRIC CURVE

ALTITUDE (m)	AREA ABOVE THE ALTITUDE (Km2)	AREA BETWEEN ALTITUDES (Km2)	ALTITUDE MEDIA (m)	
			BETWEEN ALTITUDES	WEIGHTED BETWEEN ALTITUDES
28.	113.244	17.937	64.00	10.14
100.	95.307	74.649	150.00	98.88
200.	20.658	18.537	250.00	40.92
300.	2.121	2.121	336.50	6.30
373.				

LENGHT OF THE MAIN RIVER =	18.489 Km
LENGHT TO THE CENTER OF GRAVITY =	9.317 Km
MEAN SLOPE OF THE MAIN RIVER (Taylor e Schwärs) (%) =	.691
REACH 1 - SLOPE (%) = .512	; LENGHT = 14.076 Km
REACH 2 - SLOPE (%) = 2.512	; LENGHT = 3.913 Km
REACH 3 - SLOPE (%) = 20.321	; LENGHT = .492 Km
REACH 4 - SLOPE (%) = 27.039	; LENGHT = .007 Km

The time series of rainfall and stage were obtained with programs adapted to the digitalization of the existing records. The runoff values were obtained from the rating curves calibrated anually by the Directorate General for Natural Resources.

For the application of the model HEC-1 for the Alenquer's watershed, the observed time series of rainfall and runoff were introduced and the numerical models that are going to be used in the simulation of the hydrologic subsystems were selected.

For the study of this watershed it was selected Clark's unit hydrograph, with the parameters time of concentration (tc) and storage coefficient (r) and the loss model concerning initial losses (STRTL) and losses of constant rate (CNSTL) during the rainfall event.

The values of the parameters for those models were estimated using the automatic calibration option of HEC-1, that obtains them according to the best reproduction of the observed flood hydrograph.

In numerical terms the best reproduction provided by HEC-1 is the one that minimizes the objective function.

In each run with HEC-1 the values of the parameters obtained in the previous run are utilized, until a minimum in the objective function is reached. Special care must be taken in order to verify that the obtained minimum is not a local one.

RESULT/DISCUSSION

On Table 2, a synthesis of the more important characteristics of the flood hydrographs obtained for all events with HEC-1, as well as the observed hydrographs, is presented including the parameters of Clark's unit hydrograph (**tc** and **r**) and the ones of the loss model (**STRTL** and **CNSTL**).

EVENTS DATE	t_c	k	I_a	f	Q_{pc}	t_{pc}	V_{tc}	Q_{po}	t_{po}	V_{to}
12/81	3.0	3.6	20.5	4.85	82	110.0	3.2	72	111.5	3.2
2/85	3.0	3.6	23.0	0.55	60	55.0	4.1	61	55.0	4.1
4/85	3.0	3.6	10.0	3.30	58	131.0	2.3	58	131.0	2.3
2/87	3.0	3.6	29.9	1.18	111	108.5	3.9	89	110.5	3.9
1/88	3.0	3.6	3.3	1.28	49	121.5	2.5	38	122.5	2.5

Table 2. Characteristics Hydrographs Values for Observed and Correspondent HEC-1 Computed Floods

CONCLUSION

From the observation of the results it can be stated that there is a good aproximation between the computed and observed hydrographs, and that the peak flows are well estimated as well as the time to the peaks.

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A Real-time Flow Forecasting system for Region-wide Application

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Introduction

The actual requirements of a real-time flow forecasting system extend far beyond the requirement to model streamflow. One of the requirements is to use to the full data available in real-time via telemetry. This includes the use of weather radar as an initial form of flood alert, as a basis for rainfall forecasting and as input to flow forecasting models. More extensive requirements arise when a forecasting system is needed to produce forecasts at many points within a region, possibly in support of a range of river management functions such as flood warning, river control, intake protection and drought management. Concern with both drought and flood management implies the use of models capable of forecasting over the full flow range. The need for region-wide application is even more demanding. The River Flow Forecasting System, or RFFS, has been developed with all these requirements in mind. In meeting the need for region-wide application a System has been developed which is reconfigurable to any river network, without recoding. A modular, generic design allows a free choice of models, river control algorithms and input pre-processing routines. This paper highlights some aspects of the functionality of the RFFS and reports on its implementation to the Yorkshire Region of England, which has an area of 13,500 km^2 within which nearly 200 locations have been identified as requiring flow and level forecasts. Further details of the design underpinning the RFFS are available in Moore et al (1990).

Methodology

The ICA

At the heart of the RFFS is an algorithm which controls the flow of data required to make forecasts and which selects model algorithms to be used in their construction. This is the Information Control Algorithm or ICA. Two main types of data file external to the code of the ICA are used to define the connectivity of forecast points and associated models for a given river network. "Model Component" files define the model structure to be used by selecting appropriate model algorithms and also select the data to be used in forecast construction. "Forecast Requirement" files exist for each forecast point and select the Model Component to be used and the type of forecast (eg. river level, flow, snowmelt). By selecting the Model Component, which in turn selects data inputs to be used, the necessary model connectivity is established. This can subsequently be used to control access of data and the construction of forecasts as a chained set of model algorithm operations working down the model river network. In practice an "order-of-execution list" is created by processing the Model Component and Forecast Requirement files for a given model river network. Operational running of the RFFS then uses this list to control the production of forecasts for a user selected "Subnetwork". A Subnetwork may simply define a forecast point within the region, or a selection of forecast points (eg. a set of headwater forecast points requiring frequently updated flash-flood forecasts), or the entire region including running of a tidal hydraulic model. Subnetworks are set up by the user who would commonly preconfigure a standard set for the region; however, new subnetworks are readily set up as part of an operational run.

Model Algorithms

The Model Algorithms invoked by the Model Component files employ a generic subroutine structure which allows models to be formulated at will, which might range from a simple model which calculates catchment average rainfall, by weighting raingauge or radar grid square values, to algorithms as complex as a hydrodynamic river model, possibly incorporating control rules on river gate settings. A total of 16 Model Algorithms are used in the current implementation of the RFFS. The five algorithms of most hydrological interest are summarised below:

(i) The PDM: The Probability Distributed Model or PDM is a fairly general conceptual rainfall-runoff model which uses a probability-distributed soil storage to partition water between fast and slow response systems: these systems are represented by nonlinear storages or by a transfer function discretely coincident with a cascade of two linear reservoirs. Updating of the conceptual stores in real-time is achieved through an empirical state correction procedure. Further details are contained in Moore (1985, 1986, 1988).

(ii) The KW model: The KW model is a generalised form of kinematic wave model which incorporates a discharge dependent wave speed and threshold storage function representations of out-of-bank flows and lateral inflows. Early forms of the model are described by Moore and Jones (1978) and Jones and Moore (1980).

(iii) PACK: The Pragmatic Snowmelt Model, PACK, employs a simplified representation of the snowmelt process. Melt from a "dry pack" store, controlled by a simple temperature index equation, enters the "wet pack" store. This store releases water very slowly until a critical liquid water content is reached after which rapid breakup of the pack occurs. An areal depletion curve is used to account for shallow, older packs only partially covering the basin. "Point" and "Basin" forms of the algorithm allow manual snow core observations to be used for updating of the basin-scale snowmelt models. Further details are contained in Harding and Moore (1988).

(iv) The Tidal Hydraulic Model: A four-point implicit scheme to solve the Saint Venant equations is used based on the DWOPER/NETWORK program of the US National Weather Service (Fread, 1985). The algorithm represents a substantial revision of this program to conform with the ICA's generic structure, to operate in a real-time environment and with extended functionality, particularly to model static washlands and multiple branched river systems and to incorporate tidal barrier control rules.

(v) ARMA error predictor: Single and multiple forms of ARMA error predictor algorithm are used for updating the KW and tidal river models. These exploit the dependence in past model errors to predict future model errors which are used to construct updated forecasts.

Calibration facilities, separate from the ICA model algorithms, are provided within the RFFS for off-line calibration of the above models to historical flow data.

System Resilience

A particularly important requirement met by the RFFS is to be totally resilient to missing values, possibly in past data due to faulty telemetry and in future data due to the absence of forecasts. This is naturally achieved when data are missing at internal points within the model river network by using model forecasts in place of the absent observations, and proceeding by using these as input to models further down the network. More difficult is the problem of missing data on the outer extremities of the model network, for example when raingauges or radars fail to operate. This problem is overcome through the construction of Model Algorithms which perform a merging or data substitution function. For example, a basin average rainfall model algorithm may combine rainfall totals from n raingauges according to a weighting scheme, but provision is made within the algorithm to detect missing gauges and to select an appropriate set of weights for those remaining. When all gauges fail then the algorithm may introduce radar data as the next priority data source and use these. Similarly, external forecasts of rainfall, derived from radar or synoptic analysis, may be included. Given no data from other sources in the defined hierarchy of priority a "backup profile" is provided which represents a "typical rainfall" series. Updating further down the model network tree will help to quickly correct for such poor quality data and the RFFS's resilience to data loss is assured.

Operational System

Operationally, in the Yorkshire Region implementation, the RFFS has been configured to run routinely once a day at about 7 am following routine data gathering by the Regional Telemetry System. As well as producing a standard daily forecast for the whole region this run also serves to store a set of model "states". Subsequent runs, possibly later in the day in response to a telemetry alarm, can start forecast construction from the time these states were stored, thus circumventing the need for a long warm-up period for every forecast run. The state variables will be, for example, the water contents of the PDM rainfall-runoff model stores, or flows at sections within the KW channel flow routing model. In essence they provide good initial conditions for the model network and thus provide "seamless" forecasts quickly and efficiently. A new set of states can be stored on each run of the RFFS within a flood event allowing the progress of the flood to be rapidly monitored and forecast, at frequent intervals if necessary.

Conclusions

The adaptibility of the RFFS means that it can be configured to any river system or reconfigured to an existing region to accomodate new forecast points and data from new telemetered outstations. Its use of a generic and modular algorithm structure also allows new models and control rules to be incorporated to keep pace with new developments or changing requirements. At present it is being configured and calibrated to the Yorkshire Region and is planned to be used operationally, initially for trial purposes, in the autumn of 1991.

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A BRIEF PRESENTATION OF THE SOFTWARE HYDRORAD

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J.D. CREUTIN, Groupe Hydrologie de l'I.M.G.

The software HYDRORAD is a practical result of the "Radar Cevennes" experiment. It is a simple device devoted to the processing of radar data for hydrologists in charge of catchments and receiving radar images (for instance from the french network ARAMIS). This software works on a Personal Computer.

It includes two stages : a preprocessing one and a hydrological one.

1 - PREPROCESSING OF RADAR DATA

The purpose of this stage is :

- to correct some of the anomalies affecting very often the radar data and,

- to make them available for hydrologic applications.

- To suppress the ground detection, each polluted value is replaced by the mean of the surrounding and unpolluted data.

- The partial occultation of the beam is corrected taking into account the horizon line. The use of a digitized map is developed to realize this task.

- The vertical heterogeneity of reflectivities is introduced by two parameters : the echotop level, and the zero degree level. According to this profile the PPI is transformed in ground level equivalent rates.

- A mean assessment factor can be applied.

2 - THE HYDROLOGICAL STAGE

This stage includes :

- The estimation of radar rainfall over raingages (in order to compare raingages and radar data at the same point)

- The calculation of spatial mean rainfall intensities on digitized watersheds.

- A simple "manual automatic" procedure to carry out the nowcasting of rainfall intensities. The movement of the rainfield is visually identified and the extrapolation of this movement is made automatically.

This software is being tested by the hydrologic service of Britanny (France)

note : Everybody can get HYDRORAD free of charge

APPENDIX 1

LIST OF PARTICIPANTS

From outside the Netherlands

Dr. Hervé Andrieu	France,	Lab. Central des Ponts et Chaussées
Ing. Marco Borga	Italy,	Univ. of Padua
Dr. Vince Collinge	U.K.	Univ. of Lancaster
Dr. Dominique Creutin	France	Inst. de Mecanique, Grenoble
Mr. Joao Hipólito	Portugal	Dir.-Geral dos Recursos Naturais
Dr. Dawn Hotchkiss	U.K.	Inst. of Hydrology
Miss Maria Emilia Macedo	Portugal	Dir.-Geral dos Recursos Naturais
Dr. Marco Monai	Italy	Exp. Centre for Hydrology and Met.
Dr. Bob Moore	U.K.	Inst. of Hydrology
Dr. Geof Shepherd	U.K.	Univ. of Salford
Eng. Vitoria Mira da Silva	Portugal	Dir.-Geral dos Recursos Naturais
Mr. Valdemar Silva	Portugal	Dir.-Geral dos Recursos Naturais
Dr. Kevin Tilford	U.K.	Univ. of Salford
Dr. Hans Verworn	Germany	Univ. of Hannover

From the Netherlands

Ir. Stan van den Assem	Agric. Univ. Wageningen, Dept. of Water Resources
Ir. Hans Geerse	Dept. of Water Management, City of Rotterdam
Ir. Herman Russchenberg	Technical University Delft
Ir. Han Stricker	Agric. Univ. Wageningen, Dept. of Water Resources
Ir. Remko Uijlenhoet	Agric. Univ. Wageningen, Dept. of Water Resources
Ir. Peter bij de Vaate	Dept. of Water Management, City of Rotterdam
Drs. Herman Wessels	Royal Met. Office, De Bilt
Dr. Victor Witter	Water Authority 'West-Brabant'

APPENDIX 2

PROGRAM

Workshop: Urban/rural application of weather radar for flow forecasting
Place : International Agricultural Centre, Wageningen
Dates : 3 and 4 December 1990

Time schedule for presentations, including discussion

Monday, 3 December

9.00	Welcome and shake hands
9.15	- Opening by Prof.Dr.-Ing. J.J. Bogardi, Head of the Dept. of Water resources, Wageningen Agricultural University - Short communication by H. Stricker
9.30-10.10	K. Tilford A calibration study of the Ingham Radar
10.10-10.35	H. Russchenberg The Delft experimental radars and their potentials for estimating precipitation
10.35-10.50	Coffee/tea break
10.50-11.40	H. Verworn Use of X-band radar over urban-areas. What resolution in time and space are required
11.40-12.15	M. Monai Use of doppler radar in Veneto region and improvement of precipitation measurements
12.15-13.30	Lunch/walk

13.30-13.55	M. Macedo Adjustment of radar-rainfall totals over Alenquer basin using a telemetering raingauge
13.55-14.20	D. Creutin Hydrological use of Cevennes 86-88 radar data: limitations and on-going studies
14.20-15.00	H. Verworn Radar rainfall and ground truth data. What is the truth
15.00-15.20	Coffee/tea break
15.20-15.55	R. Moore/D. Hotchkiss Grid-square rainfall-runoff modelling for the Wyre catchment in North-West England
15.55-16.20	Video film: Urban water management system of Rotterdam
16.20-17.00	J. Geerse It's rainging radar-images (in Rotterdam)

Tuesday, 4 December

9.00- 9.35	R. Moore/D. Hotchkiss Radar rainfall forecasting over London for flash-flood warning
9.35-10.20	R. Uijlenhoet A rainfall-discharge model for a regional sewer system in West-Brabant and a first application of radar generated input
10.20-10.35	Coffee/tea break
10.35-11.00	M. Borga Semi-distributed models for real time flood forecasting
11.00-11.45	G. Shepherd Some recent studies of radar in urban hydrology

11.45-12.30	H. Verworn On the use of distrometers for quantification of radar rainfall
12.30-13.30	Lunch/short walk
13.30-13.55	V. Silva Application of HEC-1 rainfall-runoff model to the Alenguer river basin at Ponte de Barnabé
13.55-14.30	R. Moore A real-time flow forecasting system for region-wide application
14.30-15.15	Open session: H. Andrieu A brief presentation of the software Hydrorad
15.15	Closing and coffee/tea
15.30	Informal visit to 'Meteoconsult', Wageningen