Accuracy of radar rainfall estimates compared to raingauge measurements and a hydrological application

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PREFACE

This report is the final result of a study to investigate the accuracy of rainfall estimates, especially for hydrological purposes, obtained by a C-band weather radar and a network of raingauges.

The Commision of the European Communities provided financial support for this project, which is a follow-up of a study carried out by ir. S. van den Assem at the Department of Water Resources of Wageningen Agricultural University.

The present study was carried out at the same department by ir. H.A.M. Hakvoort, supervised by ir. J.N.M. Stricker and ir. R. Uijlenhoet. The Water Authority West-Brabant provided essential information with respect to the hydrological application of the obtained radar rainfall estimates.

ABSTRACT

Since it is possible to estimate rainfall intensities using a weather radar, it is interesting to know the accuracy of such radar rainfall estimates as compared to raingauges. Moreover, there are various procedures to adjust radar rainfall estimates using raingauge measurements in order to reduce their bias error. This report deals with the accuracy of unadjusted and adjusted radar rainfall estimates. In addition, the accuracy of radar rainfall estimates for hydrological purposes has been investigated.

During the period 1987 - 1990 raingauge measurements have been collected in the area of the Water Authority West-Brabant in the South-West of the Netherlands. The corresponding radar reflectivity measurements of a C-band radar were provided by the Royal Netherlands Meteorological Institute in De Bilt. Radar rainfall estimates were obtained using the Marshall-Palmer Z-R relationship.

In the first part of this study radar rainfall estimates have been considered only at the raingauge locations. Later, the entire spatial field of radar rainfall estimates has been used for adjustment.

The accuracy of unadjusted radar rainfall estimates at raingauge locations was investigated using the raingauge measurements for verification. In approximately half of the considered rainfall events the radar rainfall estimates were found to match well with the raingauge measurements, whereas for the remaining events the radar rainfall estimates both over- and underestimated the raingauge measurements.

Adjusted radar rainfall estimates at raingauge locations were obtained using either one (preselected) raingauge or all operational raingauges for adjustment. In the last case an arithmetically averaged adjustment factor was computed.

Furthermore, radar rainfall estimates at all radar pixels were adjusted using an increasing number of raingauges. In this procedure each raingauge was thought to represent a sub-area corresponding to a Thiessen polygon. After assigning the raingauge measurement to all radar pixels within a sub-area, an average adjustment factor was computed from the individual adjustment factors within a sub-area. Averaging of adjustment factors has been done arithmetically, geometrically and volumetrically.

It was found that adjustment of radar rainfall estimates generally improves the accuracy. The accuracy of adjusted radar rainfall estimates using one raingauge greatly depends on which raingauge is chosen. The effect of one particular raingauge on the accuracy of adjusted radar rainfall estimates is smoothed in case more raingauges are used for adjustment.

With respect to the hydrological application of weather radar, radar rainfall estimates have been used as input in an urban waterbalance model, which describes the transformation process of rainfall and sewage to discharge at a regional purification plant and overflows from the local sewer systems. Again adjusted radar rainfall estimates using all operational raingauges for adjustment (minus 1 for verification) provide, on the average, the best result in terms of accuracy of modelling the outflow hydrograph at the purification plant. This method apparently compensates the disadvantage of adjusting radar rainfall estimates at 'bad raingauge locations' with the advantage of adjusting radar rainfall estimates at 'good raingauge locations'.

1 INTRODUCTION

Apart from raingauges, radar is another instrument to obtain information about rainfall intensity. A weather radar provides instantaneous areal rainfall estimates with a high spatial resolution. Although an extremely dense network of raingauges could provide the same resolution as radar does, this is practically impossible for reasons of maintenance and cost.

In july 1987 a project to investigate the variation of precipitation on a small scale in time and space, using a network of raingauges and a C-band weather radar, was initiated. A better understanding of the spatial and temporal variability of precipitation offers perspectives for hydrological purposes. The project was funded by the Netherlands Organisation for Scientific Research (NWO) and will further be referred to as the NWO-project.

The objective of the NWO-project was to develop and test techniques and methods to reduce the inaccuracy of weather radar rainfall estimates. The NWO-project has been completed by a report, of which results will be summarized in chapter 2.

To reach the original objective of the NWO-project, a follow-up study was initiated in july 1992. The duration of that study was one year and financial support was provided by the Commission of the European Communities (CEC). The study will further be referred to as the CEC-project.

Since the CEC-project is a continuation of the NWO-project, datasets and results of the NWO-project have been used for the CEC-project.

Since the areal rainfall estimates of a (conventional) C-band radar are often biased with respect to raingauge measurements, a certain number of raingauges seems necessary for adjustment. With this in mind the objectives of the CEC-project can be formulated as follows:

i. To determine the accuracy of C-band weather radar rainfall estimates in comparison with raingauge measurements.

ii. To examine the effect of a number of adjustment methods - using a variable number of adjustment raingauges - on the accuracy of radar rainfall estimates.

iii. To evaluate the accuracy of radar derived rainfall amounts for hydrological purposes, in particular the use of radar derived rainfall amounts as input for a precipitation-runoff model of a regional sewer system.

This report is the final result of the CEC-project.

2 INSTRUMENTS AND SITES

2.1 NWO-project: A summary

2.1.1 Instruments and sites

During the NWO-project rainfall data have been collected using a network of tipping bucket raingauges. These gauges were equipped with an automatic registration of tipping times. The network was located in the area of the Water Authority 'West-Brabant' (WBR-area) in the south-western part of the Netherlands. Fig. 1 depicts the locations of the raingauges in the WBR-area.

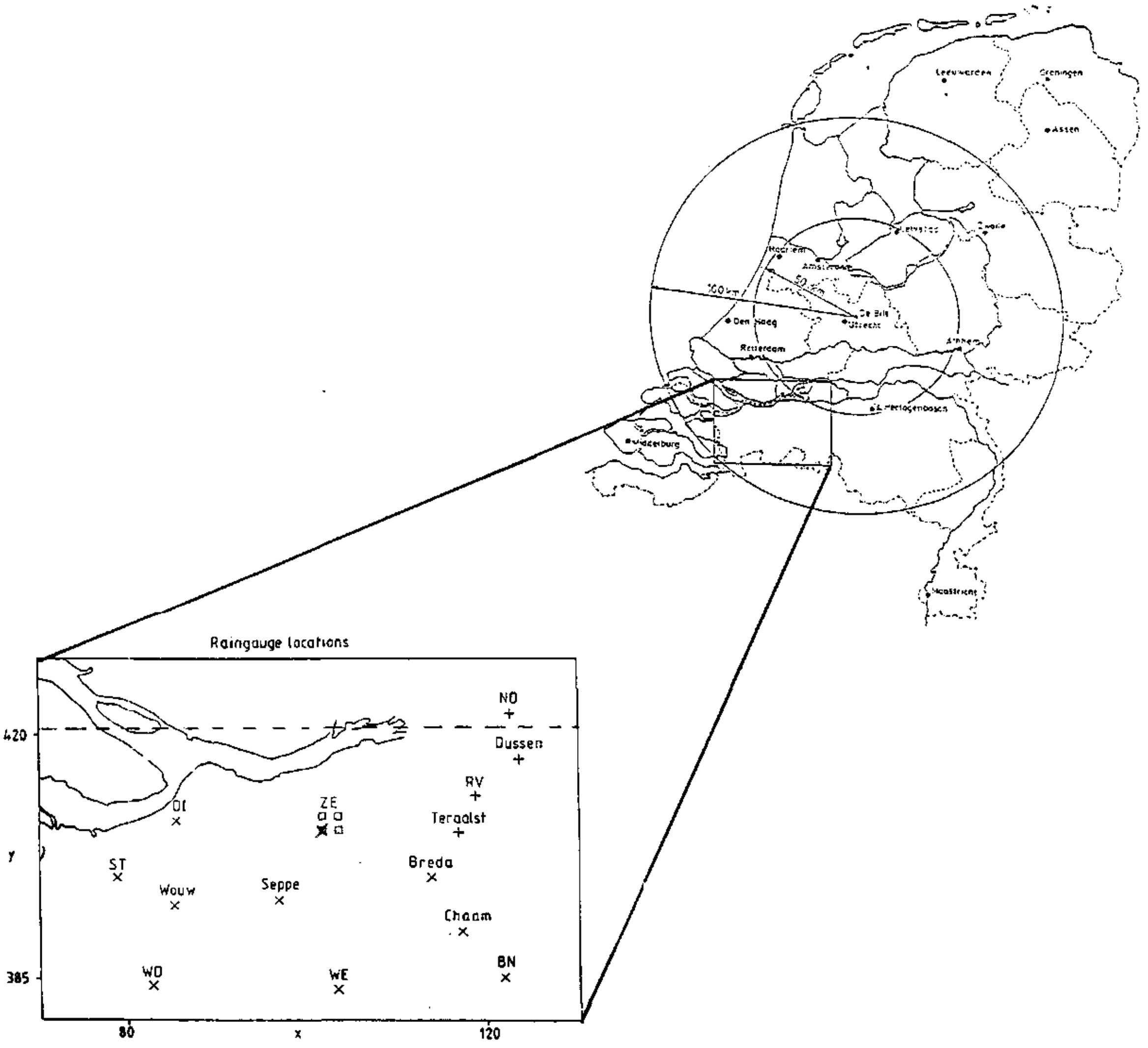

Fig. 1. Locations of raingauges in the WBR-area. Location of the weather radar with 50 km and 100 km range markers. ☐ *= PIXEL, x = NETWORK, + = ROW. - - - - denotes the upper boundary of the radarquadrant.*

Although the tipping bucket raingauges are reported to have fixed resolutions of 0.16 or 0.20 mm per tipping, laboratory calibrations showed that the tipping values were slightly intensity dependent [van den Assem, 1988]. This effect was taken into account during the data analysis.

Three different configurations of raingauges have been used during the experimental phase:

i. PIXEL - configuration: temporarily, five raingauges clustered in an area of 2 * 2 km (i.e. one radar pixel) near Zevenbergen.
ii. NETWORK - configuration: permanently, ten raingauges distributed homogeneously over the WBR-area ($32 * 48 = 1536$ km^2).
iii. ROW - configuration: temporarily, six gauges installed at four locations in and partly outside (raingauge ND) the WBR-area. The locations formed a line configuration with a mutual distance of about six kilometres.

The configurations PIXEL and ROW were not in operation simultaneously.

The weather radar is located at the Royal Netherlands Meteorological Institute (KNMI) in De Bilt (see Fig. 1). The C-band pulse radar scans once every 15 minutes.
Because the KNMI provides maps of the radar reflectivity factor Z [mm^{6}m^{-3}], a conversion from radar reflectivity factor Z to rainfall intensity R [mm hr^{-1}] is needed. For this, the following relation is used:

$$Z=a*R^b \tag{1}$$

Marshall and Palmer [1948] derived for stratiform rainfall with intensities up to 25 mm hr^{-1} a mean Z-R relation with $a = 200$ and $b = 1.6$. For other meteorological conditions, the coefficients a and b may change [Battan, 1973]. In the NWO-project, the Marshall-Palmer relation has been used.

The electro-magnetic waves transmitted by the C-band radar can be severely attenuated by rain. Although radar signals can be corrected for attenuation, this has not been done for the C-band radar signals in the NWO-project. Analysis has shown that correction does not increase the accuracy of the radar rainfall estimates [van den Assem, 1991]. This is due to the fact that the data were provided already in cartesian coordinates, whereas attenuation correction can only be performed properly when the data are in polar coordinates.

Further details about the KNMI radar system and the experimental set-up can be found in van den Assem [1991]. The theory of radar observation of the atmosphere has been described by Battan [1973].

During 1987, 1988 and 1989 a total of 31 rainfall events have been recorded, by raingauges as well as radar. The rainfall events are listed in appendix 1 and for each event the number of operational raingauges out of a maximum of 16 and synoptic meteorological information are given.
Two important meteorological phenomena, mentioned in appendix 1, are briefly outlined

here:
i. A zone of high reflectivity may appear on the radar screen. This phenomenon, called bright band, is caused by the presence of melting snow in the radar beam. Melting snow flakes are seen by the radar as huge raindrops, and may therefore lead to serious overestimation of rainrates.
ii. The second meteorological phenomenon is anomalous propagation (anaprop). The transmitted electro-magnetic waves can be refracted towards the earth-surface because of a temperature inversion in the lower atmosphere.

Reflection of radarwaves from obstacles at the earth creates so-called groundclutter and causes high, unwanted, reflectivities. Detection and elimination can be performed relative easily.

2.1.2 Results of the NWO-project

In order to compare radar rainfall estimates to raingauge measurements, the instantaneous radar rainfall estimates need to be integrated to depth of rainfall per 15 minutes. Van den Assem [1991] proposed four methods:

i. The radar scan [mm hr^{-1}] at the beginning of a 15-minute period is considered to be constant for the duration of the period (forward extrapolation).
ii. The radar scan [mm hr^{-1}] at the end of a 15-minute period is considered to be constant for the duration of the period (backward extrapolation).
iii. Linear interpolation in time between two sequential radar scans [mm hr^{-1}].
iv. Linear interpolation in time and space between sequential radar scans [mm hr^{-1}], using a displacement vector of the precipitation field. With this technique, it is assumed that storms move with constant travelling velocities between radar scans and that their intensities vary linearly [v.d. Assem, 1991].

Van den Assem calculated radar rainfall estimates for five different areal resolutions within the WBR-area:

i. 2 * 2 km, i.e. the size of 1 radar grid square (pixel).
ii. 6 * 6 km (9 pixels).
iii. 10 * 10 km (25 pixels).
iv. 16 * 24 km (¼ WBR area).
v. 32 * 48 km (WBR area).

For area size i, ii and iii, one raingauge was located somewhere in the centre of the area. For area size iv and v, several raingauges were located in the area. All raingauges in an area were used for comparison with radar rainfall estimates.

Two different statistics were computed, in an attempt to quantify the accuracy of the radar rainfall estimates with respect to raingauge rainfall estimates:

i. A bias error, which accounts for the systematic error in the areal radar rainfall estimates with respect to the raingauge measurements.
ii. A random error, which accounts for the spatial and temporal variabilities of the areal radar rainfall estimates with respect to the raingauge measurements.

Five rainfall events were selected for analysis in the NWO-project.

Van den Assem concluded that unadjusted radar rainfall estimates are generally biased. The bias is not homogeneously distributed in space and depends on the meteorological circumstances.
The space-time interpolation method (using a displacement vector to calculate radar rainfall amounts) gave the best results, compared to the raingauge measurements.

Adjustment of 15-minute accumulated radar rainfall estimates has been done using adjustment factors. An adjustment factor is defined as the ratio of raingauge measurement and radar rainfall estimate. Radar rainfall estimates can be adjusted by multiplication with an adjustment factor. Van den Assem used a variable number of 1, 2, 4 and 6 raingauges to adjust radar rainfall estimates. Then 1, 2, 4 and 6 adjustment factors can be calculated per 15-minute time period.
Assigning adjustment factors to each pixel in the whole WBR-area has been done in two ways:

i. arithmetical averaging of adjustment factors per time period,
ii. interpolation of adjustment factors per time period using the inverse distance method; this method implies that at every location (pixel) different adjustment factors may be used.

When the areal resolution of radar rainfall estimates is covering the entire WBR-area (case v.), 8 raingauges were used for adjustment. In that case the adjustment factors were arithmetically averaged; no inverse distance interpolation was applied.

Van den Assem concluded that the use of mean, non-interpolated, adjustment factors in the WBR-area leads to almost equal results as the application of spatially interpolated adjustment factors. Furthermore he stated that adjustment of mean areal radar rainfall estimates of an area with a size of 1536 km^2 (WBR-area) by 4 to 8 raingauges results in a decrease of the bias error and random error of the radar data. However, when only 1 or 2 gauges were used for adjustment, an increase of the bias error and random error occurred. Apparently, the use of 1 or 2 raingauges is not sufficient to derive representative adjustment factors for the whole WBR-area.

Unadjusted as well as adjusted radar rainfall estimates which were obtained by the space-time interpolation method gave better results than radar rainfall estimates obtained by any of the other extrapolation and interpolation methods.

2.2 CEC-project

For the CEC-project, a subset of 13 precipitation events have been selected out of 31 events. The applied selection criteria were:

i. Number of operational raingauges ≥ 6;
ii. Number of 15-minute periods for which both radar rainfall estimates and raingauge rainfall estimates are available ≥ 20.

In this way, small rainfall events are not taken into account and a minimum number of values is available for statistical calculations.

Table 1 shows basic information about the 13 selected events.

Rainfall event nr.	begin	end	missing periods	nr. of 15-minute periods	rain [mm]	nr. of oper. rain-gauges
1	880912 14.15 hr	880912 19.00	-	20	2 - 13	8
2	880914 0.30	880914 12.00	4.15 - 10.30	21	1 - 6	7
3	880923 8.30	880923 16.00	-	31	4 - 8	7
4	880924 8.15	880925 9.00	17.30 - 18.00 0.00 - 0.15 1.30 - 2.30	90	24 - 61	7
5	881020 11.15	881020 21.45	-	43	11 - 23	12
6	881130 1.00	881201 9.00	9.15 - 19.00 20.15 - 22.00 0.00	80	7 - 20	13
7	881204 0.15	881204 10.30	2.15 - 3.00 6.15 - 8.00 9.15 - 9.30	28	6 - 9	13
8	881209 0.15	881209 5.30	-	22	2 - 7	10
9	881218 16.15	881218 23.45	-	31	5 - 9	10
10	890219 11.45	890219 23.45	-	49	7 - 11	10
11	890307 9.15	890308 5.45	11.30 - 13.15	75	18 - 23	8,
12	890316 8.30	890316 22.15	-	56	9 - 17	8
13	890723 1.15	890723 8.00	-	28	4 - 17	12

Table 1. Information about the selected rainfall events. Millimeters of rain have been measured by raingauges.

The column 'missing periods' denotes (an interval of) time periods for which radar data and/or raingauge data are missing. During some rainfall events time periods have been deleted on purpose, because no rainfall was estimated during those time periods.

Synoptic meteorological information about the selected events is listed in appendix 1.

3 ACCURACY OF RADAR RAINFALL ESTIMATES COMPARED TO RAINGAUGE MEASUREMENTS

3.1 Introduction

For many years research has been carried out on estimating the spatial and temporal variability of precipitation, using radar. Battan [1973] discussed the theory of radar observation of the atmosphere. He noted that it is not likely that radar will ultimately replace raingauges for operational areal rainfall measurement.

Joss and Waldvogel [1987] gave an overview of precipitation measurement using radar and its hydrological application. They summarized various sampling error sources, which cause differences between radar rainfall estimates and raingauges measurements: (1) The spatial variability of rainfall at the earth-surface can reach such large values that $2 * 2$ km^2 can not be representatively sampled by one raingauge; (2) With increasing distance from the radar, the radar sampling volume increases too. The radar sampling volume can be only partly filled with raindrops; (3) The vertical distance between the radar sampling volume and the earth-surface also increases with distance. This can cause differences in rainfall intensity recorded at the surface by raingauges and recorded aloft by radar, because of wind-effects and changes in drop size distributions. Apart from these sampling error sources, Joss and Waldvogel [1987] also discuss other error sources like beam shielding and attenuation of radar waves.

Collier [1986a, b, c] investigated the accuracy of radar rainfall estimates for C-band radar within 75 km of the radar site, using a network of raingauges to adjust the radar data. He found that in case of frontal rainfall radar generally underestimated the rainfall amount with increasing distance from the radar. As for convective rainfall, the opposite was true.

Van den Assem [1991] investigated changes in the accuracy of radar rainfall estimates for an increase in temporal resolution from 15 to 60 minutes and an increase in areal resolution from 4 (pixel) to 1536 km^2.

More recently, an investigation towards the influence of different types of radar on the accuracy of estimating rainfall amounts research was initiated at the Department of Water Resources of Wageningen Agricultural University, and is underway in close cooperation with the Department of Telecommunication- and Remote Sensing Technology, Faculty of Electrical Engineering, Delft University of Technology and the Royal Netherlands Meteorological Institute.

During the NWO-project, the accuracy of radar rainfall estimates was determined only in pixels where a raingauge was located. The complete areal field of radar rainfall estimates was not considered. In the CEC-project, this approach has been followed again (section 3.2). In addition, to benefit fully from the spatial advantages of radar, the accuracy of radar rainfall estimates in all pixels of the WBR-area has been determined too. The results of this analysis are presented in section 3.3.

3.2 Comparison of radar rainfall estimates with raingauge measurements - using radar data at raingauge locations only

3.2.1 Introduction

For each selected rainfall event, sets of estimates of rainfall with raingauges (P_g) and radar (P_r) are available. It has already been described in paragraph 2.1.1 how raingauge measurements and radar rainfall estimates were obtained.

In order to be able to compare radar rainfall estimates with raingauge measurements, it is required that both types of measurements are calculated at the same temporal and spatial scales. As already mentioned, radar scans instantaneously and thus delivers rainfall intensities instead of accumulations. The smallest time scale on which tipping bucket raingauges operate, is the duration between two tippings of the bucket. The duration of this period varies reciprocally with the intensity of precipitation. Several options are now possible to synchronize both types of measurements:

i. The radar time scale stays unchanged, while the tipping interval between the tipping before and after the representative radar scan is used to calculate the raingauge rainfall intensity.

ii. The raingauge accumulation is increased to a period of 15 minutes, being the time expired between two radar scans. To calculate the amount of rain measured by raingauges in a 15-minute time period, all full or broken tipping intervals within a 15-minute period need to be accumulated. In case tipping intervals exceed the 15-minute units, the amount of rain will be lineary divided between the sequential 15-minute periods.

   To calculate the amount of rain estimated by radar in a 15-minute time period, van den Assem [1991] proposed four methods (mentioned in section 2.1.2).

iii. The accumulation time is further increased. When the rainfall amounts at 15-minute time periods are calculated for both raingauge and radar, this can be easily extended to, for instance, 30-minute time periods.

In the CEC-project, radar rainfall estimates have been calculated for 15- and 30-minute time periods using the forward extrapolation method and the space-time interpolation method. With method i, the time scale becomes very small for larger rainfall intensities and therefore it is impossible to exactly synchronize the periods for which the rainfall intensities are calculated. Moreover, method i is less interesting from a hydrological point of view, because the rainfall information between two time periods is not considered.

In appendix 2 the estimated storm travel velocities and directions are listed, which are needed to initiate the calculations for the space-time interpolation method. These estimates were obtained from the wind field at the 850 mbar level.

With respect to the spatial scale, it is supposed implicitly that inside a pixel no variability of rainfall exists.

To obtain radar rainfall estimates a weighted averaging procedure was used, because most raingauges are not exactly centrally located in a pixel. A raingauge is considered to be the centre of an imaginary pixel, which partly covers some of the neighbouring pixels. Weights can be calculated based upon the area of the imaginary pixel in each specific pixel, and a weighted radar rainfall estimate can be calculated.

To actually quantify the accuracy of the radar rainfall estimates (P_r) compared to raingauge measurements (P_g), two statistics were used:

i. Comparison in an absolute way. The arithmetical average P_g-P_r of the ($n * m$) differences between P_g and P_r is assumed to indicate the bias error in the radar rainfall estimates with respect to the raingauge rainfall estimates. The standard deviation $\sigma(P_g-P_r)$ is referred to as indicating the random error.

ii. Comparison in a relative way, i.e. using the ratio P_g/P_r. In this case an arithmetically averaged F factor can be calculated according to equations 2 and 3, and with the addition of equations 4 and 5 to avoid unrealistic values:

$$\overline{F} = \frac{1}{n*m}\sum_{i=1}^{n}\sum_{j=1}^{m} F(i,j) \tag{2}$$

with

$$F(i,j) = P_g^*(i,j) - P_r^*(i,j) \tag{3}$$

where

$$P^* = \ln(P) \qquad if \qquad P > P_{thr} \tag{4}$$

and

$$P^* = \ln(P_{thr}) + \frac{P}{P_{thr}} - 1 \qquad if \qquad P \le P_{thr} \tag{5}$$

n = number of time periods.
m = number of operational raingauges/corresponding radar pixels.
P_{thr} = threshold value.

In essence, F represents the logarithmic value of the geometrical average of all $n * m$ ratios ($P_g(i,j)/P_r(i,j)$).

Formulation (5) is well defined at $P_r = 0$ or $P_g = 0$ and behaves smoothly at the point of intersection $P = P_{thr}$ [Moore et al, 1989].
In this study, the threshold value is arbitrarily set to 0.1 mm, being half the resolution of the tipping bucket raingauges.

Again, the average of F, $\bar{F}$, is referred to as indicating the bias error in the rainfall estimates, and the standard deviation of F, $\sigma(F)$, as indicating the random error.
Because of the natural logarithm appearing in the equation, equal ratios and their reciprocal values will get equal weights. An example:

P_r	P_g	P_r/P_g	F[-]
0.2	1.0	5.0	1.6
1.5	0.3	0.2	-1.6

Table 2. Effect of the natural logarithm appearing in the equation on ratios.

Fig. 2^a to 2^m show the results of the unadjusted radar rainfall estimates compared to raingauge measurements.

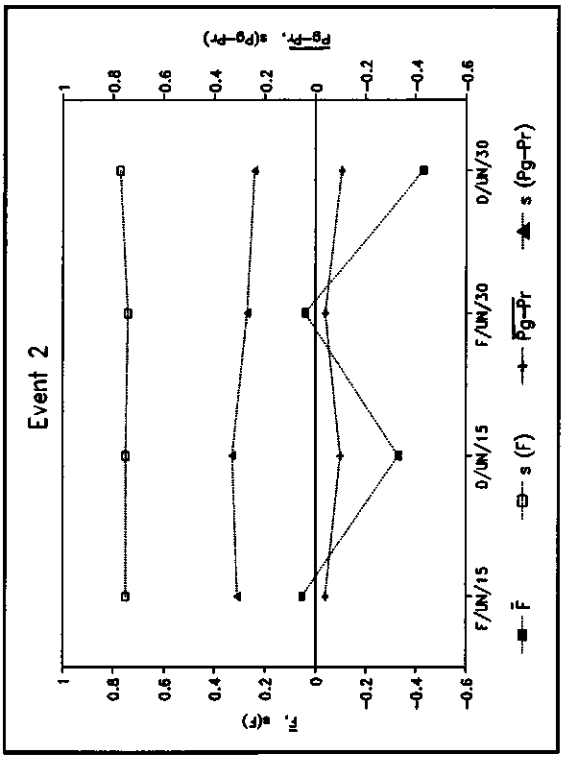

Fig. 2^{b}

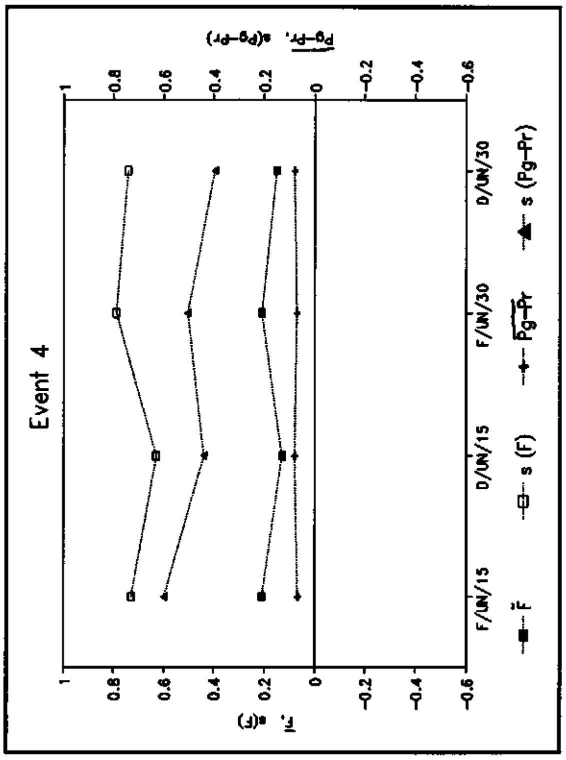

Fig. 2^{d}

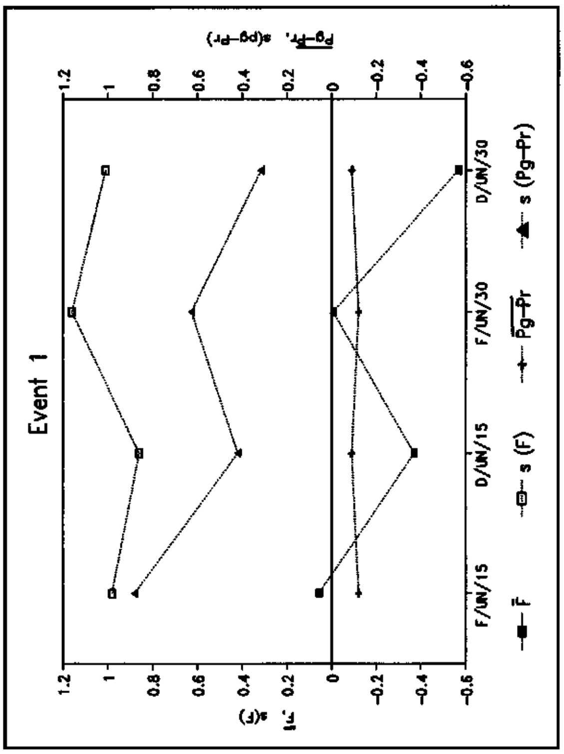

Fig. 2^{a}

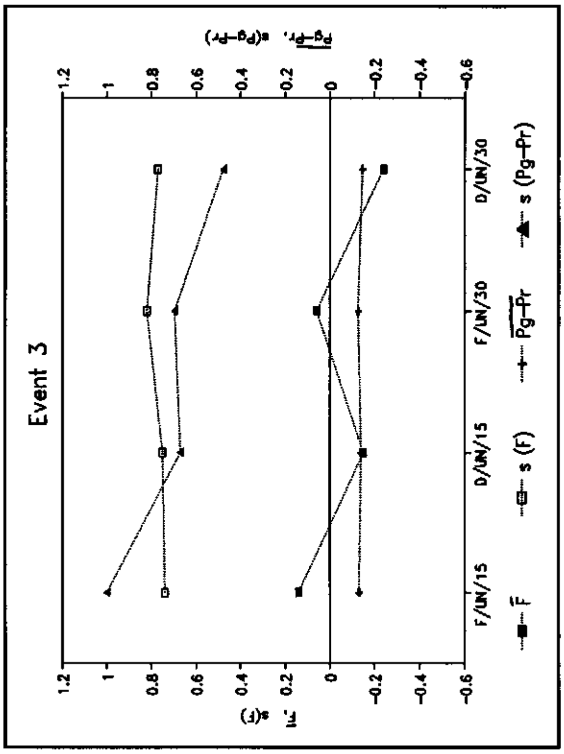

Fig. 2^{c}

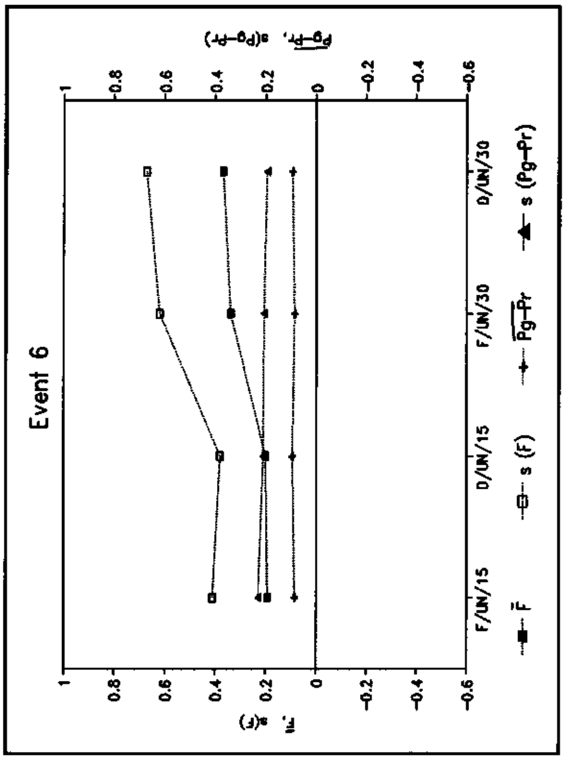

Fig. 2^{f}

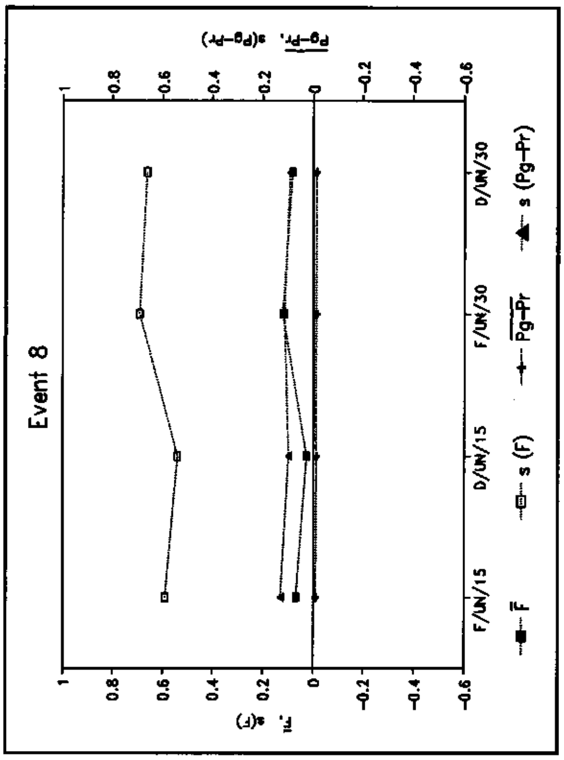

Fig. 2^{h}

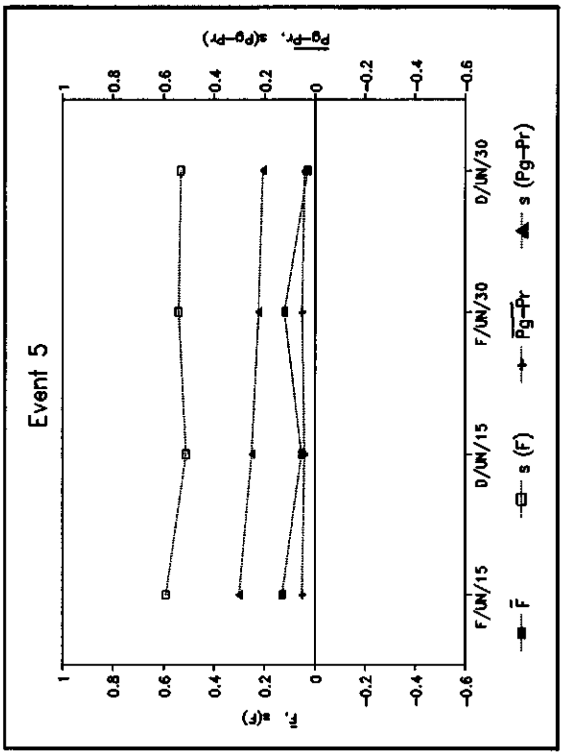

Fig. 2^{e}

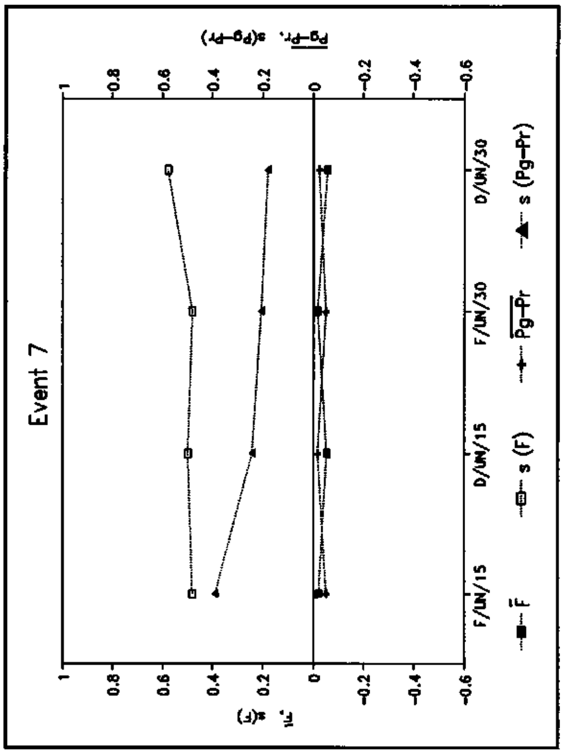

Fig. 2^{g}

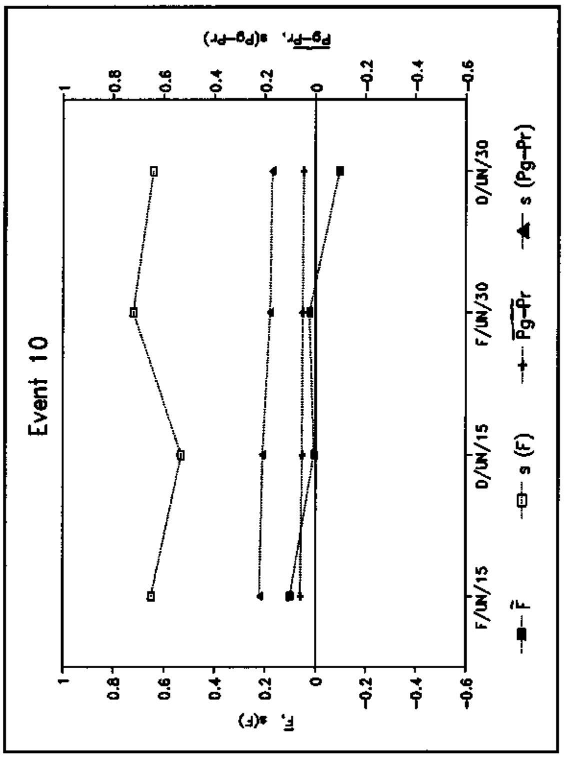

Fig. 2^j

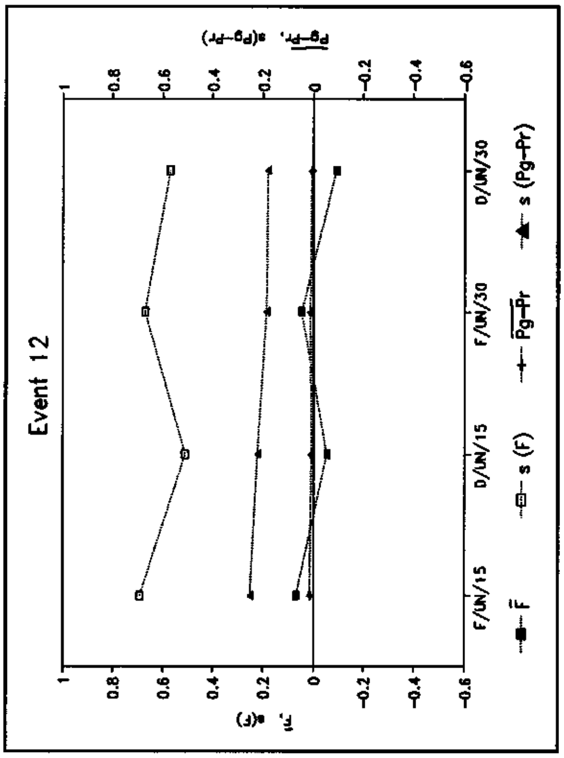

Fig. 2^l

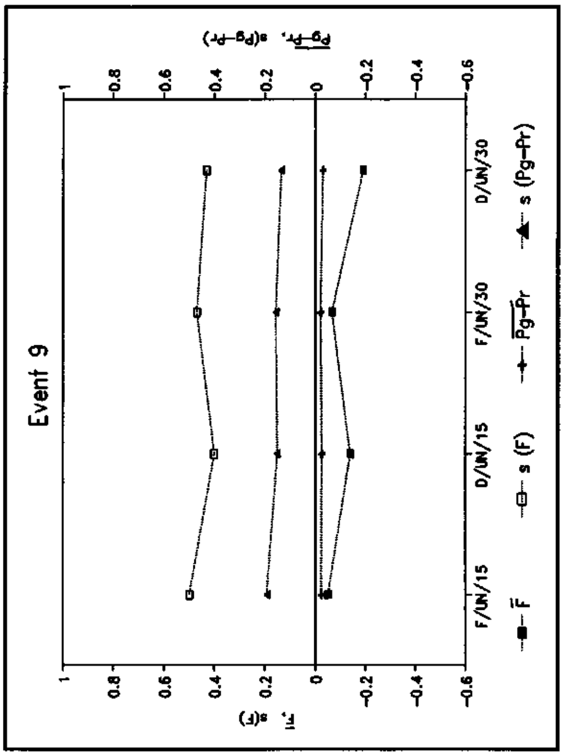

Fig. 2^i

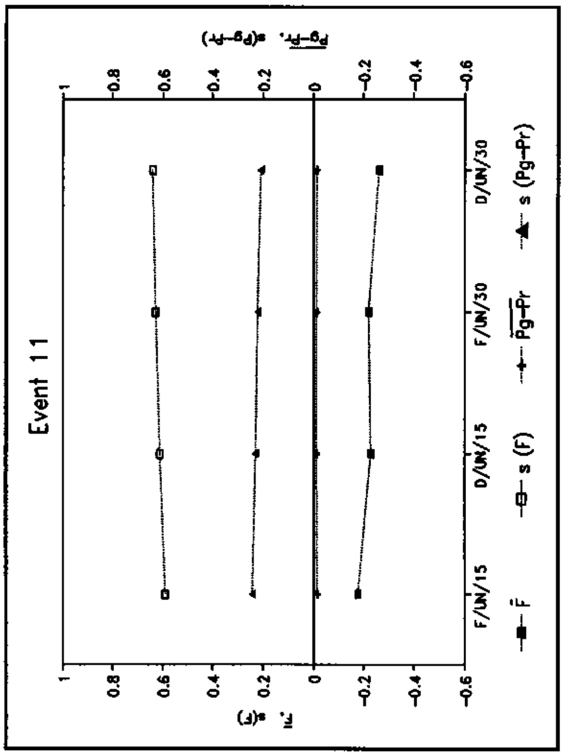

Fig. 2^k

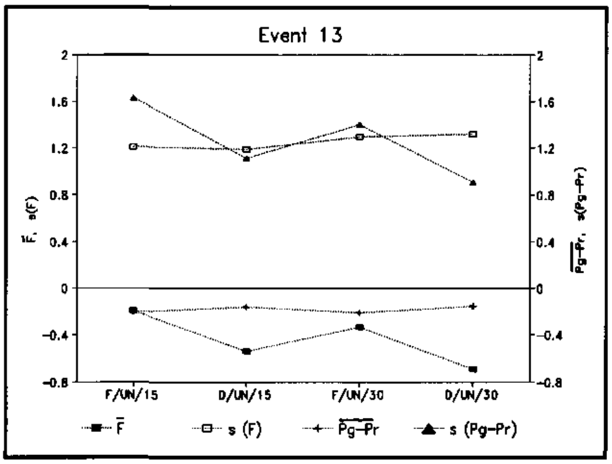

Fig. 2^m

Fig. 2^a - 2^m. *Accuracy of unadjusted (UN) radar rainfall estimates compared to raingauge measurements for thirteen rainfall events. Comparison in a relative ($\overline{F}$ [-] and $\sigma(F)$ [-]) and an absolute way ($\overline{P_g\text{-}P_r}$ [mm 15 min^{-1}] and $\sigma(P_g\text{-}P_r)$ [mm 15 min^{-1}]). The statistics $\overline{P_g\text{-}P_r}$ [mm 30 min^{-1}] and $\sigma(P_g\text{-}P_r)$ [mm 30 min^{-1}] for 30-minute time periods (30) have been adjusted to justify plotting on a 15-minute time scale [mm 15 min^{-1}]. The x-axis denotes the radar rainfall estimation method (F = Forward extrapolation method, D = space-time interpolation method, using a Displacement vector) and the length of the time periods (t = 15 and 30 minutes).*

First, it may be useful to give an explanation of the interpretation of the statistics, used in Fig. 2^a - 2^m. When in Fig. 2^a for event 1 option F/UN/15 is regarded, it can be seen that on the average F appears to be quite good ($\overline{F} = 0.057$ equals the geometrical average of $P_g/P_r = 1.06$), but the standard deviation is relatively large ($\sigma(F) = 0.98$). With F(i,j) normally distrubuted, the 95% confidence interval $\mu(\pm\ 2 * \sigma)$ can be calculated: $-1.90 < F(i,j) < 2.02$ and thus $0.15 < P_g(i,j)/P_r(i,j) < 7.52$. In the same way, the 95% confidence interval for $(P_g(i,j)\text{-}P_r(i,j))$ can be derived: $-1.88 < (P_g(i,j)\text{-}P_r(i,j)) < 1.64$. In the last case it means that in about 5% of the 20 * 8 observations, the difference $(P_g(i,j)\text{-}P_r(i,j))$ is smaller than -1.88 or larger than 1.64 [mm 15 min^{-1}]

Table 1 shows that the amount of rainfall, measured by raingauges in case of event 1 ranged from 2 to 13 mm for 20 time periods of 15 minutes. This yields averages of 0.10 - 0.65 mm per 15 min. per raingauge. With the knowledge of these relatively small amounts of measured rainfall, the significance of the statistics $\overline{F}$ and $\overline{P_g\text{-}P_r}$ can be put in perspective.

Concerning the difference between the P_g-P_r and F statistic, it can be said that, especially in case of small amounts of rainfall measured by raingauges, F varies more than P_g-P_r. This leads in general to larger values of $\sigma(F)$ compared to $\sigma(P_g\text{-}Pr)$.

For comparing the 15- and 30 min. results in the same figure, the 30 min. results of P_g-P_r and $\sigma(P_g\text{-}P_r)$ have been divided by 2. In this way, the 30 min. results are represented in the same unit as the 15 min. results [mm 15 min^{-1}]. This may be a somewhat crude approximation, but is sufficient for our purpose.

When $\overline{P_g - P_r}$ is regarded, it can be seen that for events 1, 2, 3 and 13, on the average, the radar overestimates the raingauge measurements. For the events 4, 5 and 6, the radar underestimates the raingauge measurements. For the events 7, 8, 9, 10, 11 and 12 the radar rainfall estimates match well with the raingauge measurements.
Concerning the standard deviation, it appears that both $\sigma(F)$ and $\sigma(P_g - P_r)$ are large for events 1, 3, 4 and 13 compared to the standard deviation for the other events. The accuracy of radar rainfall estimates with respect to the meteorological circumstances is discussed in paragraph 3.2.3.
Radar rainfall estimates calculated according to the space-time interpolation method (D) provide slightly better results compared to forward extrapolated radar rainfall estimates (F).
Increasing the time period from 15 minutes to 30 minutes does not significantly improve the accuracy of the radar rainfall estimates.

3.2.2 Comparison of adjusted radar rainfall estimates with raingauge measurements

To improve the accuracy of radar rainfall estimates, i.e. reduce the bias- and random error, raingauge measurements can be used for adjustment, assuming that raingauges measure true amounts of rainfall (ground truth).
This paragraph deals with time integrated radar rainfall estimates for 15- and 30-minute time periods, respectively. Further increase of the time scale has not been considered in this study.

As already mentioned before, radar rainfall estimates can be adjusted by calculating an adjustment factor:

$$A = \frac{P_g}{P_r} \tag{6}$$

where:

A = Adjustment factor [-].
P_g = Rainfall measured by raingauge [mm.15 min^{-1}].
P_r = Rainfall estimated by radar [mm.15 min^{-1}].

A radar rainfall estimate is adjusted, when it is multiplied by its adjustment factor.

Suppose n raingauges are operational during the rainfall event. If only 1 raingauge is used for adjustment, then n - 1 gauges can be used for verification. Again, it is assumed that raingauge measurements are the ground truth. In case radar rainfall estimates are adjusted with an increasing number of raingauges, a decreasing number of raingauges is left for verification.

When several raingauges are used for adjustment, then several adjustment factors per time period can be calculated. In that case, adjustment factors may be averaged to obtain one adjustment factor for a certain area. Three averages were compared:

i. Arithmetic average

$$A_a(x,t)=\frac{1}{n}\sum_{i=1}^{n}\frac{P_g(x_i,t)}{P_r(x_i,t)} \tag{7}$$

ii. Geometric average

$$A_g(x,t)=\left(\prod_{i=1}^{n}\frac{P_g(x_i,t)}{P_r(x_i,t)}\right)^{\frac{1}{n}} \tag{8}$$

equals

$$A_g(x,t)=\exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln\left(\frac{P_g(x_i,t)}{P_r(x_i,t)}\right)\right) \tag{9}$$

iii. Volumetric average

$$A_v(x,t)=\frac{\sum_{i=1}^{n}P_g(x_i,t)}{\sum_{i=1}^{n}P_r(x_i,t)} \tag{10}$$

The geometric average assigns equal weights to ratios and their reciprocal values, whereas the arithmetic average assigns much greater weight to higher values of the ratio P_g/P_r. With the volumetric average, the total volume of the adjusted radar estimates becomes exactly equal to the total of the raingauge measurements. An example is given below to clarify the adjustment averaging methods:

Suppose $P_g(x_1)$ = 1 mm/15 min $P_g(x_2)$ = 6 mm/15 min
$P_r(x_1)$ = 2 mm/15 min $P_r(x_2)$ = 3 mm/15 min

x_1,x_2 = pixel

Then $A_a = (1/2 + 6/3)/2 = 1.25 \quad \Rightarrow \quad P_r(x_1) = 2{,}5 \text{ mm/15 min}$
$P_r(x_2) = 3{,}75 \text{ mm/15 min}$

$A_g = \sqrt{(1/2 * 6/3)} = 1 \quad \Rightarrow \quad P_r(x_1) = 2 \text{ mm/15 min}$
$P_r(x_2) = 3 \text{ mm/15 min}$

$A_v = (1 + 6)/(2 + 3) = 1.40 \Rightarrow \quad P_r(x_1) = 2{,}8 \text{ mm/15 min}$
$P_r(x_2) = 4{,}2 \text{ mm/15 min}$

Fig. 3 summarizes the most important possibilities to adjust radar rainfall estimates for each time period.

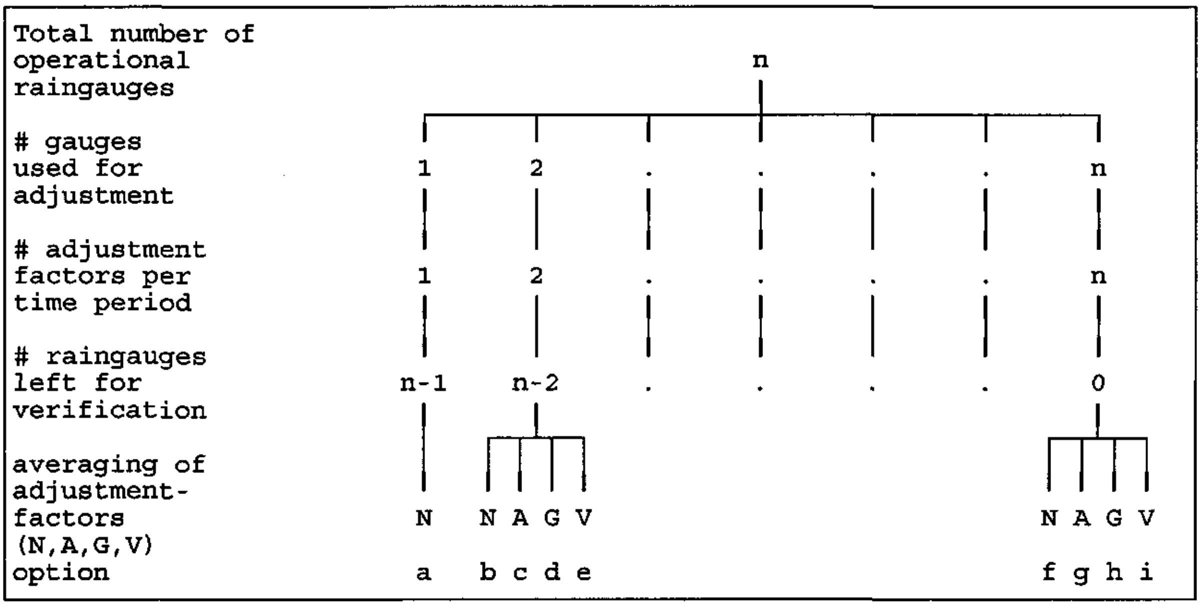

Fig. 3. Possibilities to adjust radar rainfall estimates. N = No average, A = Arithmetic average, G = Geometric average, V = Volumetrical average.

It can be seen that there are many ways to adjust radar rainfall estimates by means of an average adjustment factor per time period. Option b and f (Fig. 3) denote the possibility of having more than 1 adjustment factor and still no averaging of adjustment factors. In this case the study area is divided in resp. 2 and n sub-areas, also called adjustment domains. The relevant adjustment factor is considered to be constant for the sub-area. This can be seen as the simplest way to account for spatial variability of adjustment factors.

The unadjusted radar rainfall estimates have been adjusted using the two most remote adjustment possibilities in Fig. 3:

i. Only one raingauge is used to adjust the radar rainfall estimates (ONE). From this, one adjustment factor per time period can be calculated, which is applied to radar rainfall estimates in all other raingauge locations (option a).
If possible, raingauge W2 (at location Zevenbergen (ZE); see Fig. 1) has been used for adjustment, otherwise raingauge Seppe. In appendix 3, a list of oper-

ational gauges per event has been printed. The adjustment gauge has been excluded from the verification procedure.

ii. All operational raingauges are used to adjust the radar rainfall estimates. An arithmetically averaged adjustment factor (AVG) is calculated for each time period t, which is applied to radar rainfall estimates in all raingauge locations at time = t (option g).

No other averaging procedures for the adjustment factor have been applied for no other reason than shortage of time.

Quantification of the effects of adjustment in terms of accuracy is done in the same manner as for the unadjusted case.

Fig. 4^a - 4^m show the results. In these figures, also the results of the unadjusted radar rainfall estimates, shown in Fig. 2^a - 2^m, have been incorporated for interpretation.

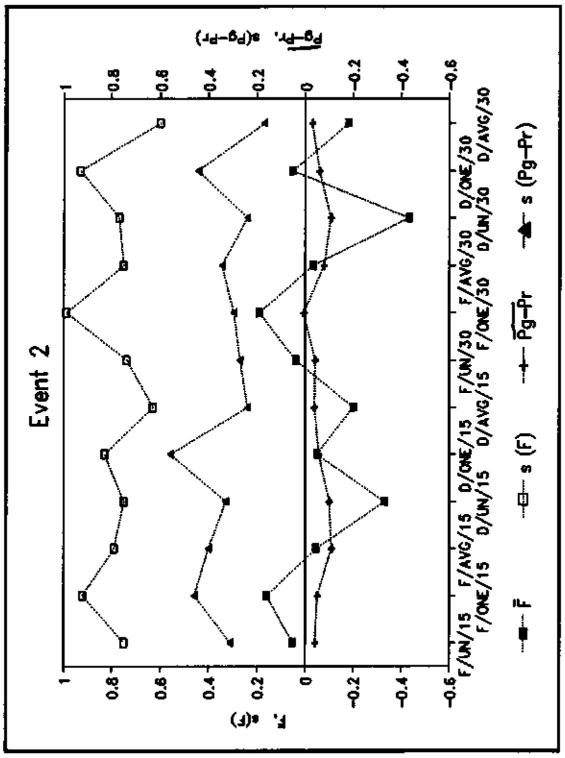

Fig. 4^{b}

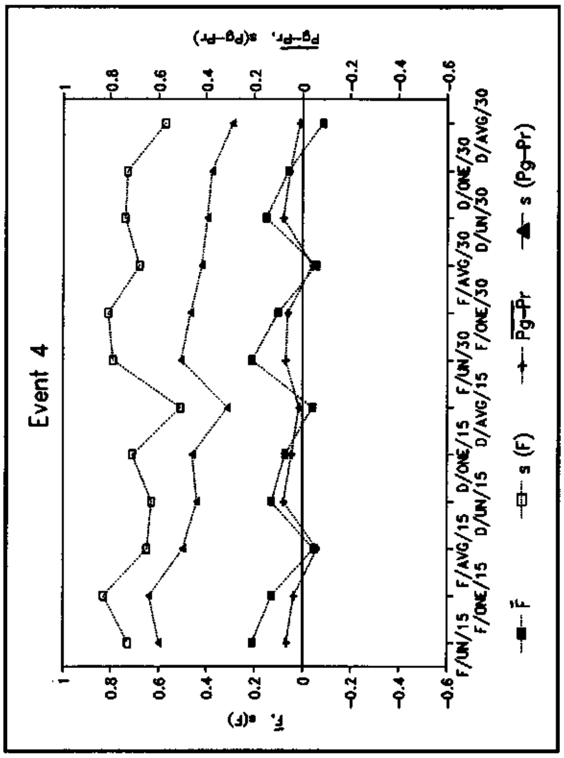

Fig. 4^{d}

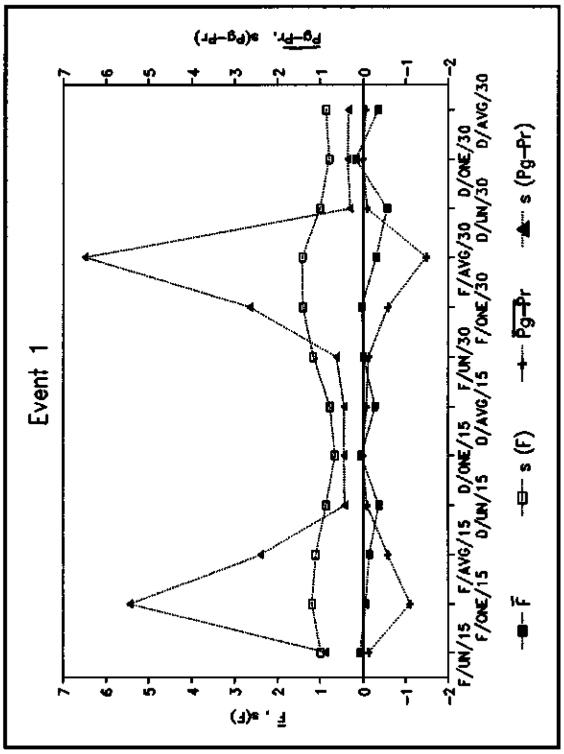

Fig. 4^{a}

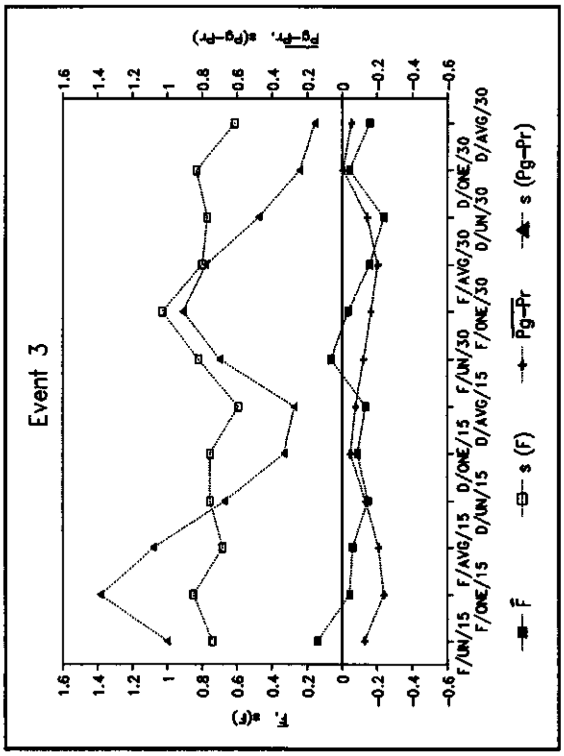

Fig. 4^{c}

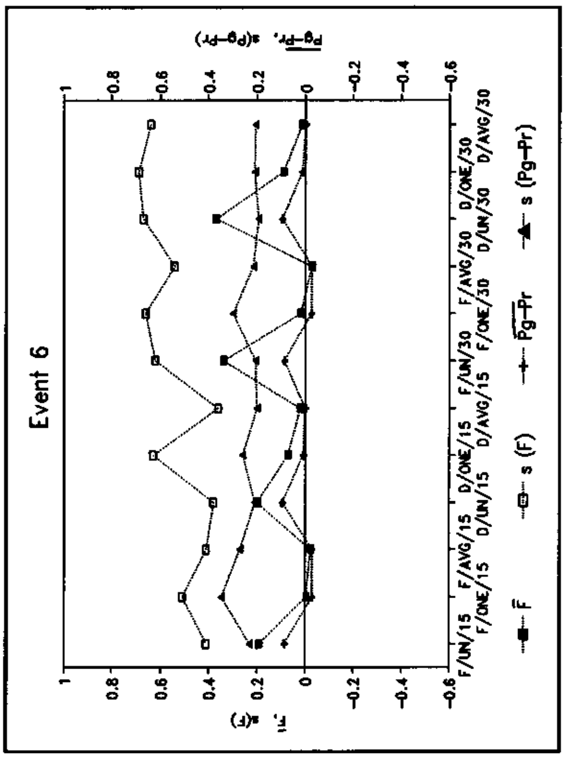

Fig. 4f

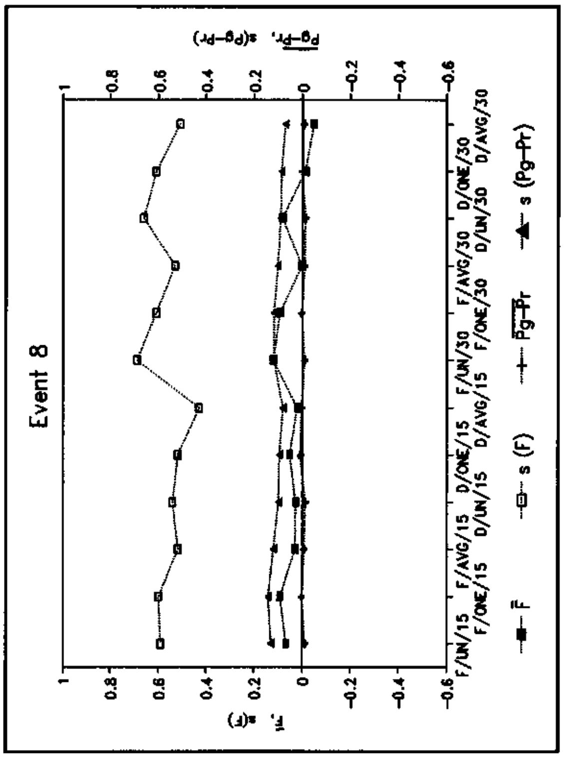

Fig. 4h

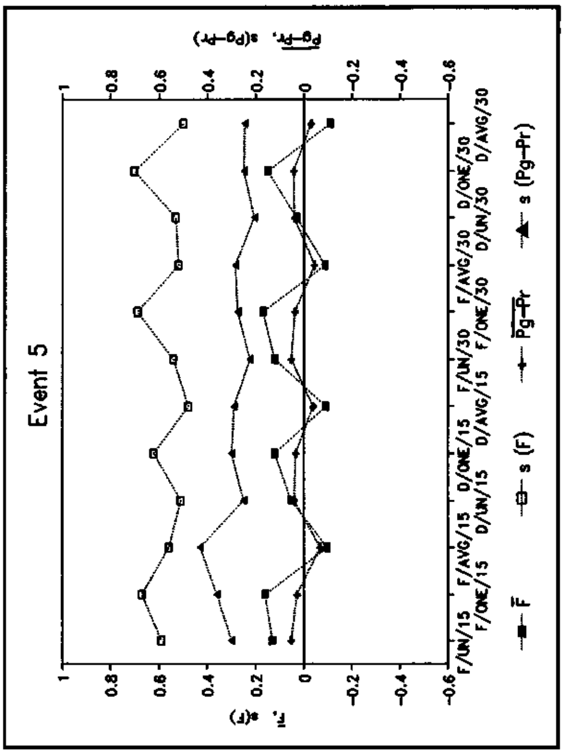

Fig. 4e

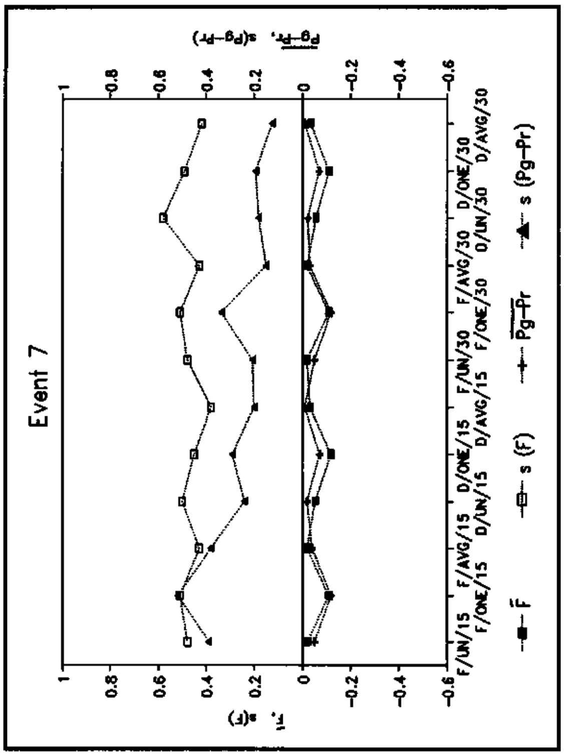

Fig. 4g

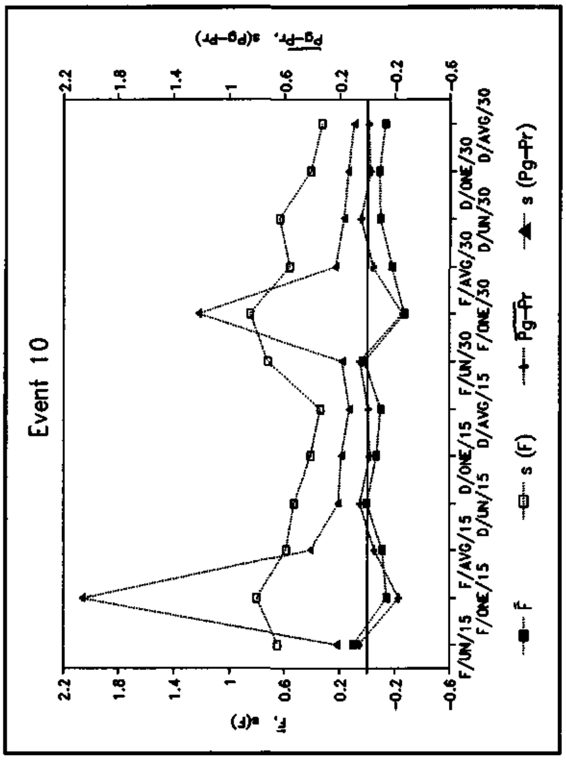

Fig. 4^j

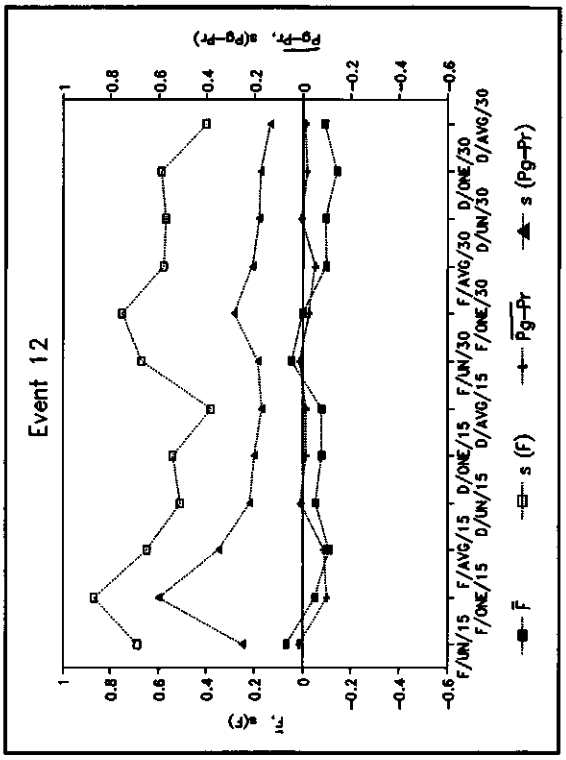

Fig. 4^l

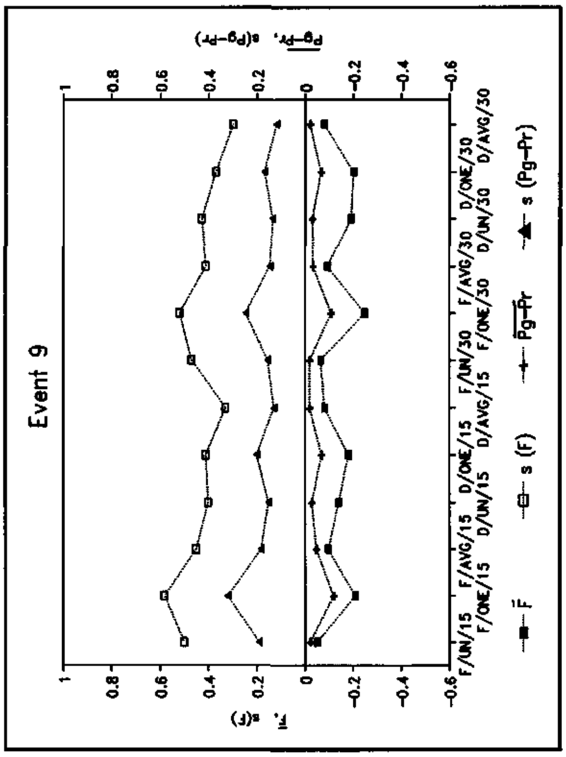

Fig. 4^i

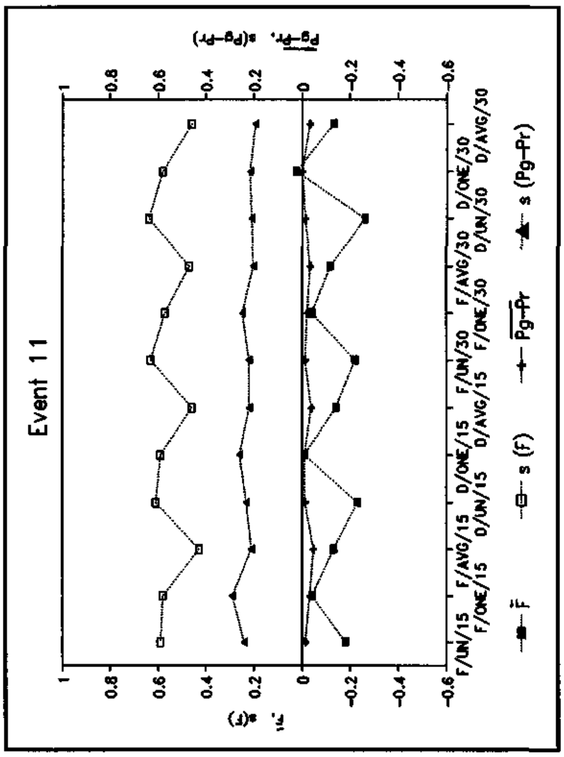

Fig. 4^k

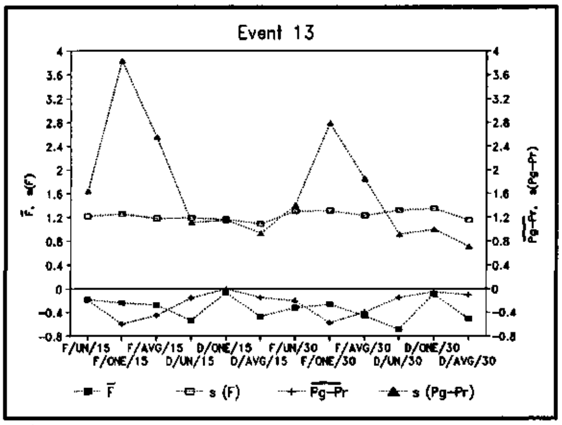

Fig. 4^{m}

Fig. 4^{a} *-* 4^{m}. *Accuracy of (un)adjusted radar rainfall estimates compared to raingauge measurements for thirteen rainfall events. Comparison in a relative (F [-] and* $\sigma(F)$ *[-]) and an absolute way (*P_g*-*P_r *[mm 15* min^{-1}*] and* $\sigma(P_g-P_r)$ *[mm 15* min^{-1}*]).*

x-axis denotes: F = the radar rainfall estimation method (Forward extrapolation method, D = space-time interpolation method, using a Displacement vector), UN = unadjusted radar estimates, ONE = adjusted radar estimates, using one raingauge, AVG = adjusted radar estimates, averaging of adjustment gauges, 15, 30 = length of time periods [minutes].

3.2.3 Results and discussion

Analysis of Fig. 4^{a}-4^{m} reveals several interesting results.
Increasing the time period does not significantly improve the results of the unadjusted or adjusted radar rainfall estimates. In most cases this has even increased σ(F). Therefore only radar rainfall estimates at 15-minute periods will be considered further.

Fig. 4^{a} - 4^{m} show that generally radar rainfall estimates, calculated according to the space-time interpolation method (D), provide more accurate estimates then the time extrapolated radar rainfall estimates (F). This is especially true when adjustment of radar rainfall estimates is applied. The space-time interpolation method (D) behaves so well because the method itself has a smoothing effect on the assignment of radar rainfall to each pixel.

In case of forward extrapolation in time of the radar data (F) the best results are produced without any adjustment. This can clearly be seen for events 1, 10 and 13 (Fig. 4^{a}, 4^{j} and 4^{m}), where adjustment of the radar rainfall estimates results in an enormous increase of the standard deviation $\sigma(P_g$-$P_r)$. For the same events the adjusted radar rainfall estimates overestimate the raingauge measurements (P_g-P_r negative).

The fact of getting outliers can be best explained by considering an example:

Suppose for a pixel, used for adjustment, the following data are valid at time t:

$P_g(t) = 0.6$ and $P_r(t) = 0$

Then F(t) becomes:

$$F(t) = \ln(P_g/P_r) = \ln(0.6) - (\ln(0.1) + (0/0.1) - 1) = 2.79$$

Thus, the adjustment factor for time period t equals:

$$A(t) = \exp(F(t)) = \exp(2.79) = 16.28$$

This extremely large adjustment factor will be applied to radar rainfall estimates in all raingauge locations, in order to adjust these values. If, for instance, $P_r(t)$ at location W2 equals 2 mm, then the adjusted value will be 2 * 16.28 = 32.56 mm rainfall.
For adjustment method ONE, the occurrence of such a situation is disastrous for the adjusted results, while the occurrence of such an anomaly in case of adjustment method AVG is less severe, but still negatively influences the result.

In addition to these large adjustment factors, this problem may also arise for (extremely) small adjustment factors. Small values of the adjustment factor may be caused by bright band or anaprop. Again the effect will be demonstrated by an example:

Suppose:

$$P_g(t) = 0.4 \text{ and } P_r(t) = 4.8$$

Then F(t) becomes:

$$F(t) = \ln(P_g/P_r) = \ln(0.4/4.8) = -2.48$$

Thus, the adjustment factor for time period t equals:

$$A(t) = \exp(F(t)) = \exp(-2.48) = 0.083$$

Again, when such high reflectivities appear only locally and are selected for adjustment, these small adjustment factors will reduce relatively accurate radar rainfall estimates elsewhere to nearly zero.
A solution to this problem is in the first place the use of the displacement (D) approach and secondly the localization of the area for which an adjustment factor is valid. The ideal size of this area, also called adjustment domain, would be just that area in which only one type of weather occurs (per time period). The results of adjustment method ONE show that the optimal size of such an adjustment domain has to be smaller than the entire WBR-area.
A combination of assigning adjustment domains together with upper- and lower limits for a reliable factor might probably further improve the result. This will be investigated in the next section.

It is not really possible to draw general conclusions with respect to the success of adjustment methods ONE and AVG in reducing the bias- and random error of the radar rainfall estimates in case of space-time interpolation. With adjustment method AVG, all operational raingauges are used for adjusting the radar rainfall estimates. Taking the

same raingauges for verification purposes leads to biased statistical results.
With adjustment method ONE the accuracy of the adjusted radar rainfall estimates depends strongly on the location of the preselected adjustment-raingauge. Measurements of rainfall between raingauges - even at short distance - may vary enormously. To illustrate this, a cross-validation procedure has been applied to event 11. Radar rainfall estimates according to the forward extrapolation method have been adjusted using one adjustment raingauge. Each time a different raingauge has been used for adjustment and all remaining raingauges have been used for verification. Fig. 5 shows the result:

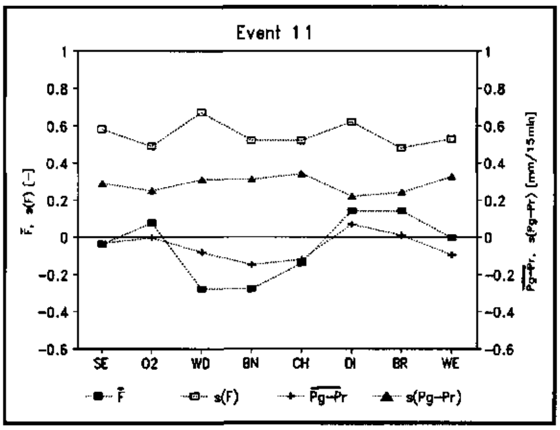

Fig. 5. Cross validation for all operational raingauges during event 11 (F/ONE/15). The x-axis denotes the abbreviated raingauge names (see appendix 3).

It can be seen from Fig. 5 that changing the adjustment raingauge and thus changing the location greatly influences the bias error $\overline{F}$ and $\overline{P_g\text{-}P_r}$. The effect of the choice of the raingauge location on the random error $\sigma(F)$ and $\sigma(P_g\text{-}P_r)$ appears to be less important.

Both the unadjusted and the adjusted results can also be interpreted in terms of the meteorological circumstances. Therefore the selected rainfall events have been classified according to the meteorological situation, see Table 3. This information is also listed in appendix 1.

Meteorological situation	Rainfall event
unknown	1, 2
nothing special	3, 4, 5, 6, 9
bright band	7, 8, 10, 11
anaprop	13
circular discontinuity	12, 13

Table 3. Synoptic meteorological information about the 13 selected rainfall events.

With respect to the bright band events, it can be concluded that radar provides quite good unadjusted rainfall estimates. Apparently bright band did not occur at raingauge locations or radar signals were not severely influenced by bright band at the raingauge locations.

During event 13, relatively large bias- and random errors exist. The bias error indicates overestimation by radar, which is probably caused by anaprop.

Circular discontinuity means that a clear circular discontinuity appears on the radar screen during the event or during a certain time period within the event. Regarding the limited meteorological information available, no explanation can be given for the circular discontinuity phenomenon.

3.3 Comparison of radar rainfall estimates with raingauge measurements - using the entire spatial field of radar data.

3.3.1 Introduction

To benefit fully from the spatial advantages of radar, in this section the radar rainfall estimates, based on the time-space interpolation method for 15 min. time periods, in all pixels of the WBR-area are used. In the previous section only radar rainfall estimates in the raingauge locations were considered.

As has been expressed already in section 3.2.3, the adjustment domain, in which a constant adjustment factor is valid, probably needs to be smaller then the size of the WBR-area. Another suggestion was to introduce a correction scheme in order to prevent adjustment factors from becoming either (extremely) large or (extremely) small.

These aspects, in combination with the use of the entire field of radar data, will be outlined here.

When a spatial field of radar rainfall estimates is used for calibration, raingauge measurements or estimates in each pixel need to be available as well. Since rainfall only has been measured in certain pixels (raingauge pixels), raingauge derived estimates have to be assigned to pixels where rainfall is not actually measured by a raingauge (radar pixels).

To assign raingauge measurements to radar pixels, several methods are available. The raingauge rainfall amounts can be interpolated using surface fitting techniques [Hayes and Koch, 1984], inverse distance methods [Shearman and Salter, 1975] or kriging [Journel and Huijbrechts, 1978]. Another method is to divide the study-area into a number of Thiessen polygons, equal to the number of raingauges that will be used for adjustment. The rainfall amount measured by the raingauge, centrally located in a sub-area, is thought to be constant for all pixels within the sub-area over a 15-minute period.

For each pixel in a sub-area a different radar rainfall estimate and an assigned raingauge estimate is available for each time period. From this an adjustment factor for each pixel can be derived. An average adjustment factor can be computed from all adjustment factors within a sub-area.

In order to prevent an average adjustment factor from becoming very large or very small, the P_g/P_r value for each pixel within a sub-area can be allocated in one out of three classes. The boundaries are formed by an upper limit R_{up} [-] and a lower limit R_{low} [-]. The allocation procedure, and the consequences for each class are stated in Table 4.

Ratio P_g/P_r in a pixel	Ratio P_g/P_r used in procedure to derive average adjustment factor A	Adjustment
$P_g/P_r < R_{low}$	No	$P_r = P_g * A$
$R_{low} \leq P_g/P_r \geq R_{up}$	Yes	$P_r = P_r * A$
$P_g/P_r > R_{up}$	No	$P_r = P_r * A$
$P_r = 0$	No	$P_r = P_r$

Table 4. Procedure to derive an average adjustment factor A for a sub-area per time period and to adjust radar rainfall estimates.

The explanation of Table 4 follows hereafter.

$P_g/P_r < R_{low}$:	The adjustment factor exceeds the lower limit when either P_g is relatively small compared to P_r, or when a relatively large value of P_r occurs (caused by bright band, anaprop or groundclutter). In this case the radar rainfall estimates are not considered for adjustment anymore, but the raingauge measurements are assumed to represent the groundtruth. If P_g is close to zero it is possible that the radar rainfall estimate P_r might be more accurate. However, this situation is not considered separately.
$R_{low} \leq P_g/P_r \geq R_{up}$:	To restrict the value of an average adjustment factor, only individual adjustment factors in the range between R_{low} and R_{up} will be taken into account for calculating an average adjustment factor. Multiplication of radar rainfall estimates by the average adjustment factor yields the adjusted rainfall estimates. In the sporadic cases of no individual adjustment factors occur in a sub-area, the average adjustment factor A is set to 1.
$P_g/P_r > R_{up}$:	In case of high spatial variability of rainfall, assigned raingauge measurements in a radar pixel often will not represent the groundtruth. When an assigned P_g value is large compared to the radar estimate, the adjustment factor possibly exceeds R_{up}. Adjustment factors exceeding R_{up} do not contribute to the average adjustment factor. Again, multiplication of radar rainfall estimates by the average adjustment factor yields the adjusted rainfall estimates.

$P_r = 0$: If P_r equals zero, an adjustment factor cannot be computed. In paragraph 3.2.1, a threshold equation for this situation has been introduced (equation 3). This equation has not been applied here, because, in contrast with the previous situation, already enough adjustment factors are available to compute an average adjustment factor.

The radar rainfall estimate is considered to represent the truth and therefore no adjustment of P_r will take place.

In appendix 4, some patterns are shown where for every pixel in the WBR-area the ratio P_g/P_r is calculated. It can be seen that very often clustering of pixels with $P_r = 0$ occurs. It indicates that these are not anomalies and that the decision not to adjust those pixels can be justified. The patterns in appendix 4 also clearly demonstrate that one raingauge for assignment over the whole WBR-area is not appropriate. Too many pixels fall outside the adjustment range for P_g/P_r. When 5 raingauges are used for assignment slightly more pixels contribute in calculating an average adjustment factor.

The choice of the values for R_{low} and R_{up} is arbitrary. If, for instance, the objective of R_{low} is to eliminate influence of bright band on the average adjustment factor, it should be realized that the intensity of the bright band varies.

Collier [1986a] used adjustment factors in the range 0.3 - 3 (R_{low} - R_{up}) in a procedure to derive an average adjustment factor. He found that the limits 0.3 and 3 were sometimes inappropriate in situations of bright band and that the overestimation in rainfall derived from the uncalibrated radar data was not removed completely after calibration. Therefore the decision was taken to relax the limits to 0.2 - 10 [Collier, 1986a].

In this study, initially the limits are set to $R_{low} = 0.33$ and $R_{up} = 3$. Section 3.3.4 deals with the effect of the values of R_{low} and R_{up} on the accuracy of radar rainfall estimates.

3.3.2 The effect of the number of adjustment-raingauges on the accuracy of radar rainfall estimates

A variable number of raingauges can be used for adjustment of radar rainfall estimates. Each raingauge is assumed to represent the groundtruth of a sub-area, corresponding to a Thiessen polygon. In this paragraph, the effect of an increasing number of adjustment raingauges on the accuracy of the radar rainfall estimates is investigated. The number of adjustment raingauges varies from 1 to n - 1. With the maximum of n - 1 adjustment raingauges, 1 raingauge is left for verification.

The set of operational raingauges per event is listed in appendix 3. In order not to bias the verification results, only 1 raingauge inside the pixel Zevenbergen (gauges W0, W1, W2, W3 and O2) has been used for adjustment and verification calculations. The redundant raingauges have been removed temporarily from the set of operational raingauges. So, the number of operational raingauges per rainfall event varies from 5 to 11.

Since the accuracy of adjusted radar rainfall estimates greatly depends on the location of the adjustment-raingauge(s) (Fig. 5), all possible combinations of 1 to n-1 raingauges have been selected to adjust radar rainfall estimates. This avoids biased results.

Thus, in case of n operational raingauges and k adjustment-raingauges (k = 1,..,n-1), the number of combinations of adjustment-raingauges equals:

$$\binom{n}{k} = \frac{n!}{k! * (n-k)!} \tag{11}$$

While k ranges from 1 to n-1, a decreasing number of raingauges is available for verification: n - k.
To avoid the situation that the accuracy statitics (average and standard deviation) become uncomparable by the selected verification procedure, the verification was carried out one by one for the (n-k) raingauges. This implies that the total number of verification combinations becomes equal to

$$\binom{n}{k} * (n-k) \tag{12}$$

Table 5 summarizes the above for 5 to 11 raingauges.

n =	k =	# adjustment combinations	total nr. of combinations	rainfall event
5	1	5	20	2, 3, 4
	2	10	30	
	3	10	20	
	4	5	5	
6	1	6	30	1
	2	15	60	
	3	20	60	
	4	15	30	
	5	6	6	
8	1	8	56	11, 12
	2	28	168	
	3	56	280	
	4	70	280	
	5	56	168	
	6	28	56	
	7	8	8	
9	1	9	72	5
	2	36	252	
	3	84	504	
	4	126	630	
	5	126	504	
	6	84	252	
	7	36	72	
	8	9	9	
10	1	10	90	6, 7, 8, 9, 10
	2	45	360	
	3	120	840	
	4	210	1260	
	5	252	1260	
	6	210	840	
	7	120	360	
	8	45	90	
	9	10	10	
11	1	11	110	13
	2	55	495	
	3	165	1320	
	4	330	2310	
	5	462	2772	
	6	462	2310	
	7	330	1320	
	8	165	495	
	9	55	110	
	10	11	11	

Table 5. *Possible adjustment- and verification combinations. The column "total nr. of combinations" denotes all possibilities on which radar rainfall estimates can be adjusted by k raingauges and verificated by n-k raingauges.*

Each combination of the column "total number of combinations" represents a unique combination of k adjustment-raingauges and 1 verification raingauge. For this a bias error $\overline{P_g\text{-}P_r}$ and a random error $\sigma(Pg\text{-}Pr)$ can be calculated over all time periods. For example, in case of n = 5 and k = 2, 30 values of $\overline{P_g\text{-}P_r}$ and $\sigma(P_g\text{-}P_r)$ can be derived.

These 30 values can be averaged to represent a final measure of accuracy. Meanwhile, the largest and smallest value indicate the spatial variance.

Fig. 6^a - 6^z present the results of the adjustment- and verification calculations as described above. To obtain these results, three additional assumptions have been made which have not been mentioned before:

i. To divide the study-area in a number of sub-areas, the following practical procedure has been used. Calculate the distance of pixel i (i = 1..384) to all raingauges which are used for adjustment. Pixel i is assigned to the raingauge which is located closest to pixel i. The result of this procedure is similar to the Thiessen polygon method.

ii. The radar rainfall estimates at the raingauge locations which were used for verification were not calculated using the weighted averaging procedure as described in paragraph 3.2.1. Instead, the radar value of the pixel in which the raingauge is located is thought to be representative. It appears that this simple procedure does not differ much from the more sophisticated weighted averaging procedure, because a majority of the raingauges is located near the centre of the pixel.

iii. Because of the vertical distance of radar measurements (aloft) and raingauge measurement (earth surface) a lapse time of 7.5 minutes, being half of a 15-minute period, has been introduced to synchronize both types of measurements. While the radarbeam scans 1 - 2 km. aloft and the average raindrop fall velocity equals app. 5 m/s, a lapse time of 7.5 minutes appears be a good estimate.

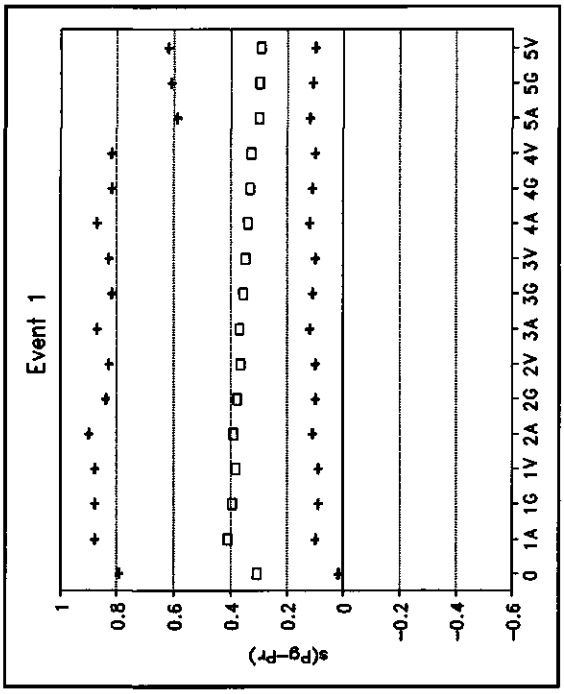

Fig. 6^b

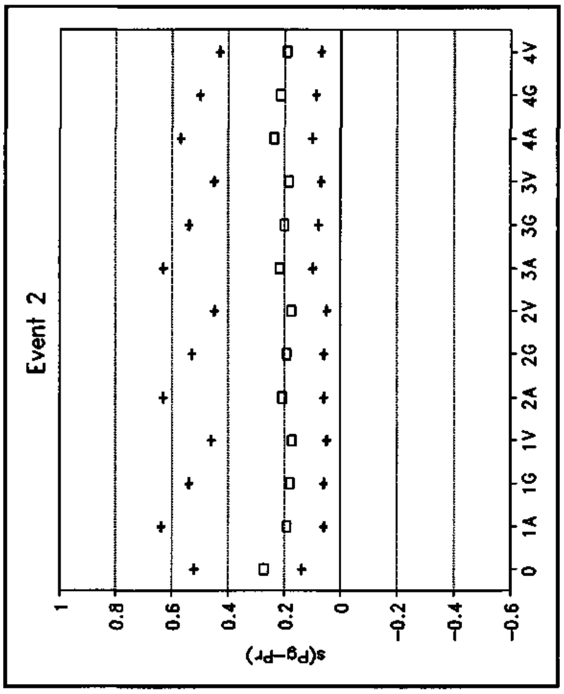

Fig. 6^d

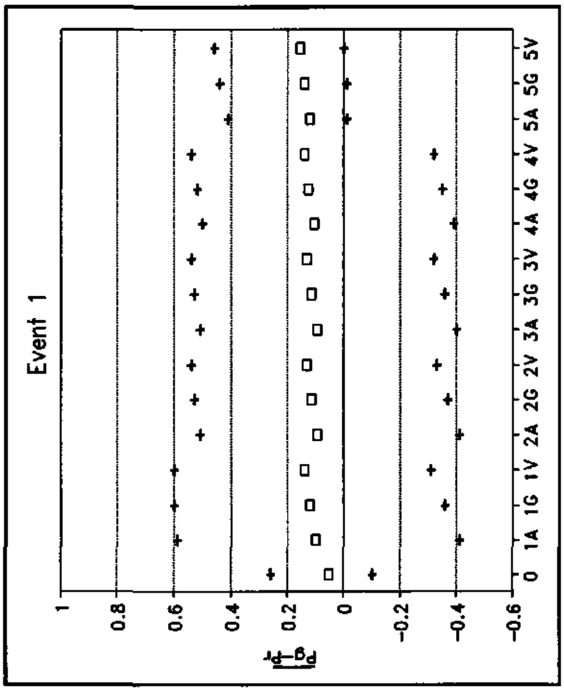

Fig. 6^a

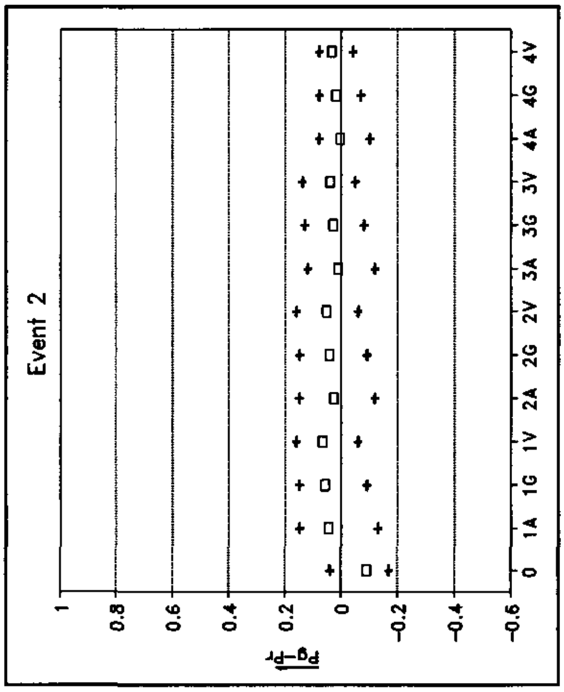

Fig. 6^c

For desription of figures, see page 39.

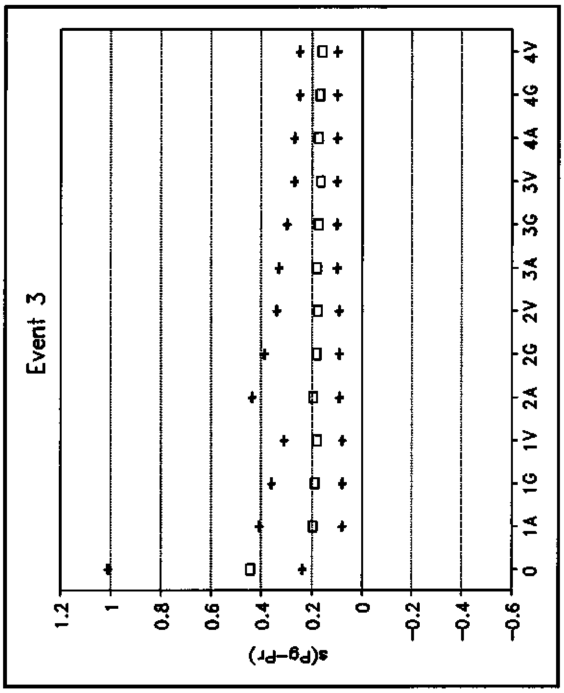

Fig. 6^f

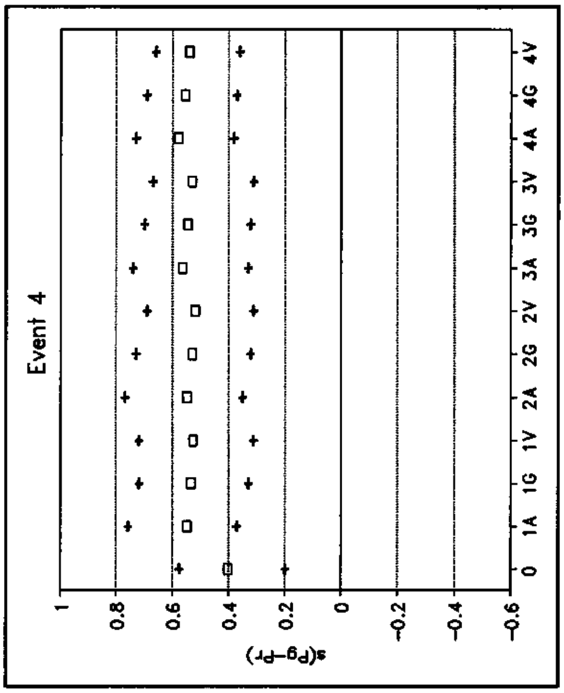

Fig. 6^h

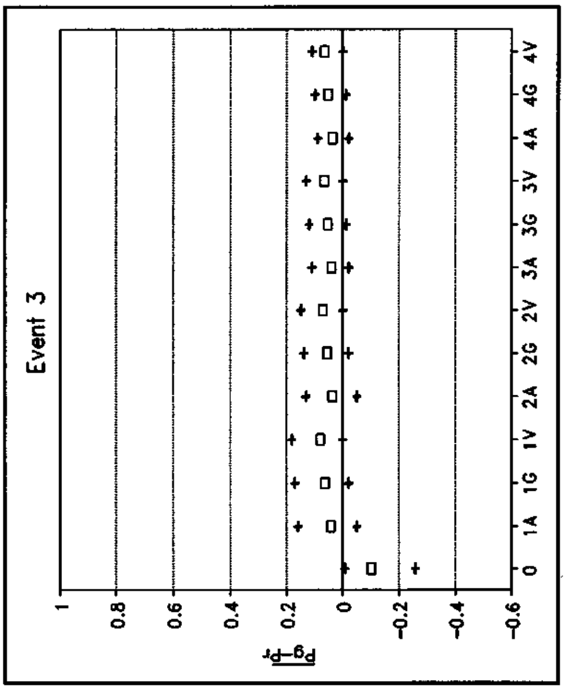

Fig. 6^e

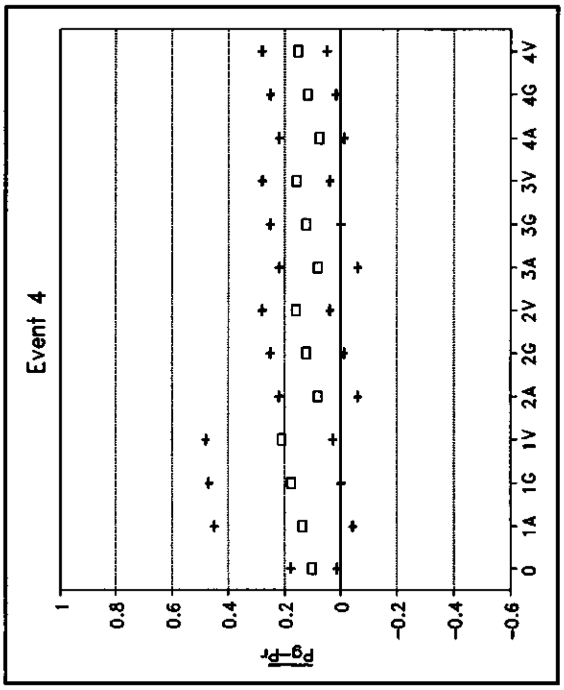

Fig. 6^g

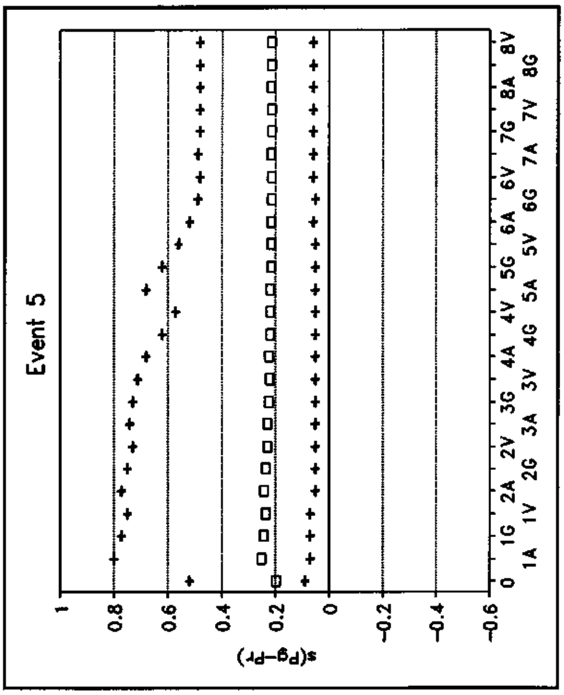

Fig. 6^{j}

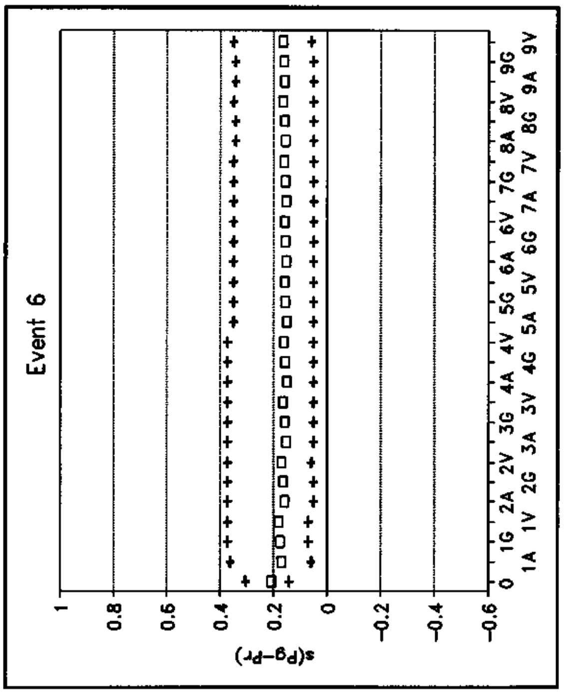

Fig. 6^{l}

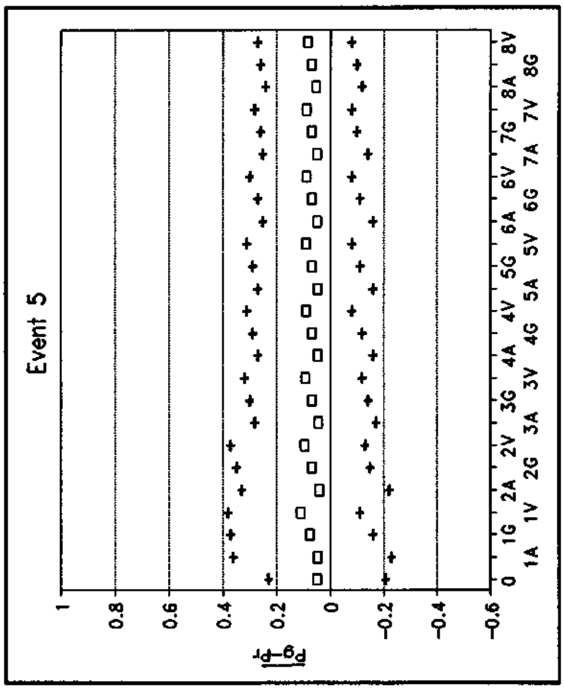

Fig. 6^{i}

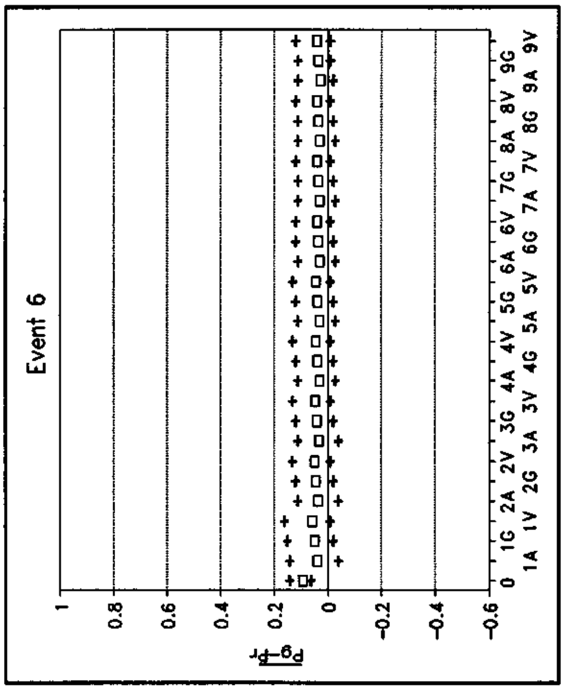

Fig. 6^{k}

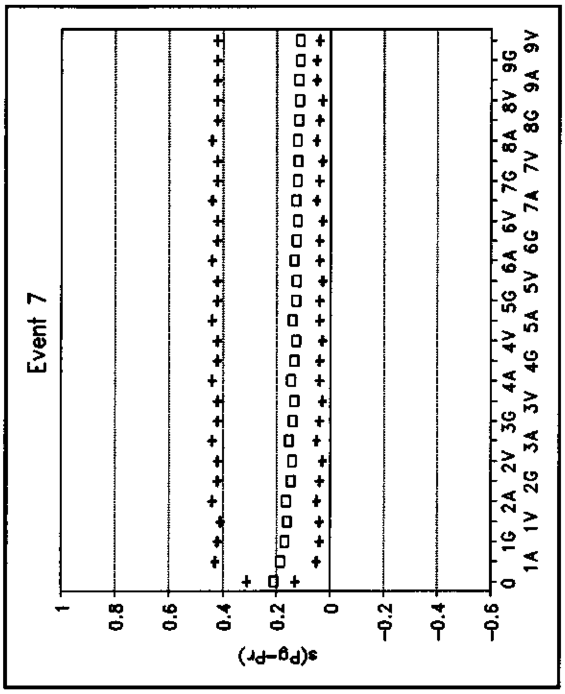

Fig. 6ⁿ

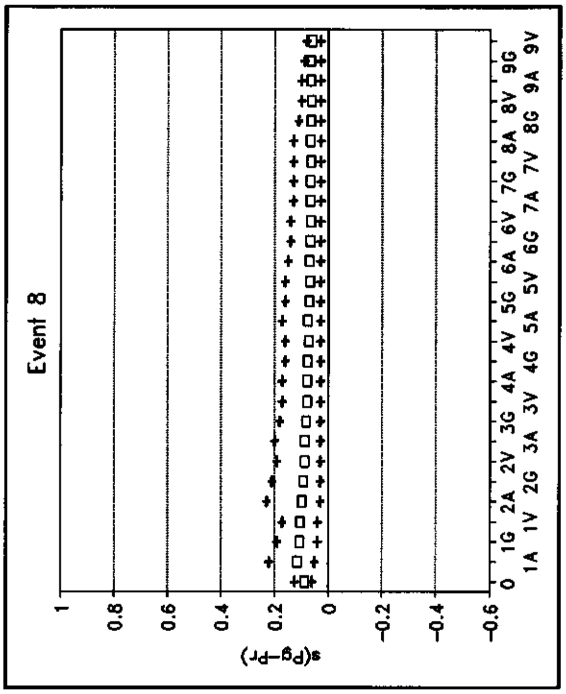

Fig. 6ᵖ

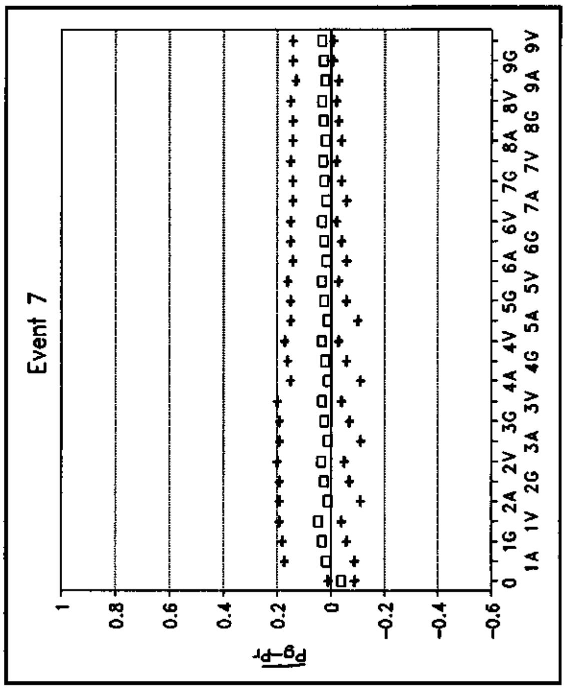

Fig. 6ᵐ

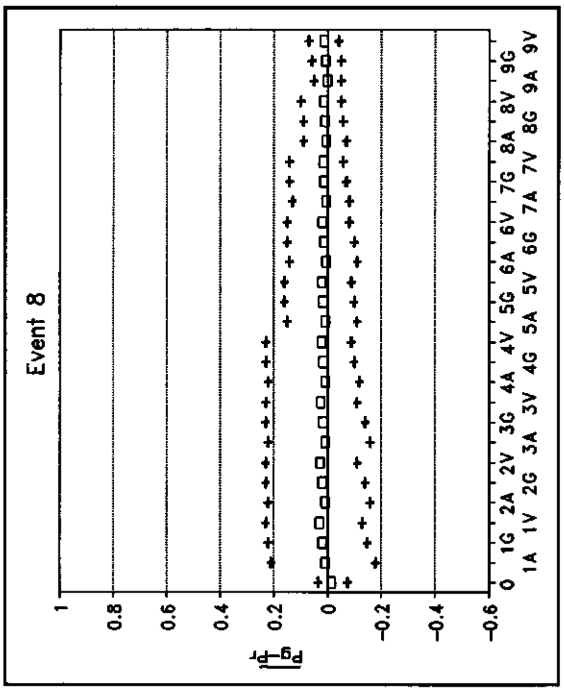

Fig. 6ᵒ

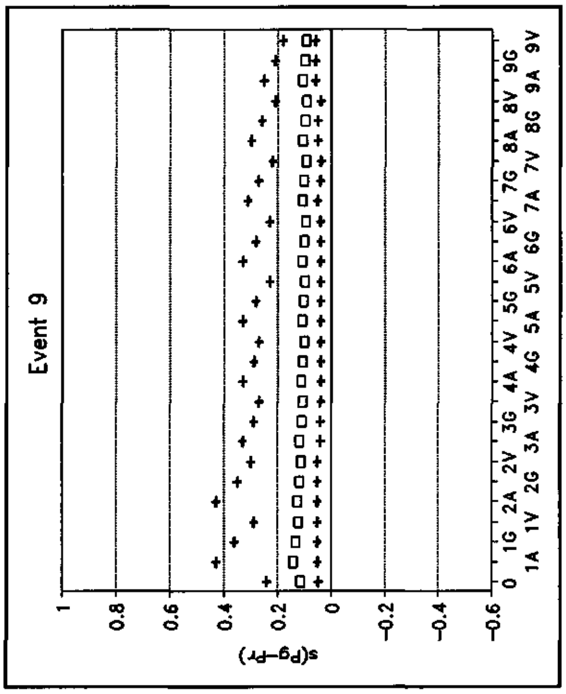

Fig. 6r

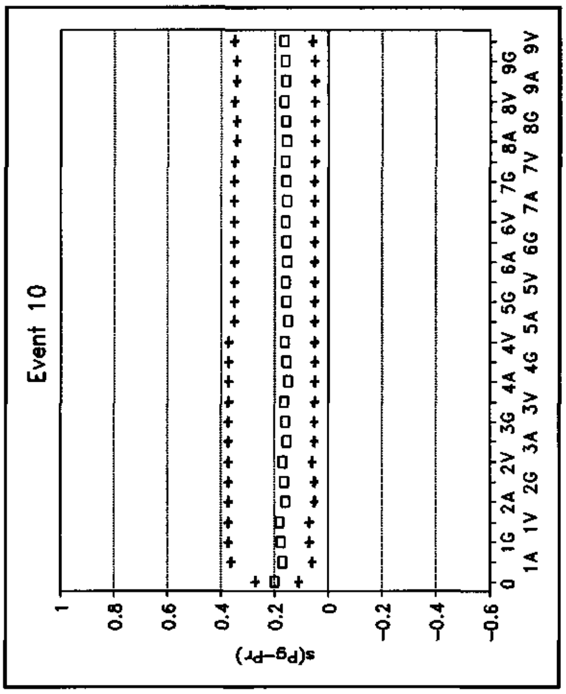

Fig. 6t

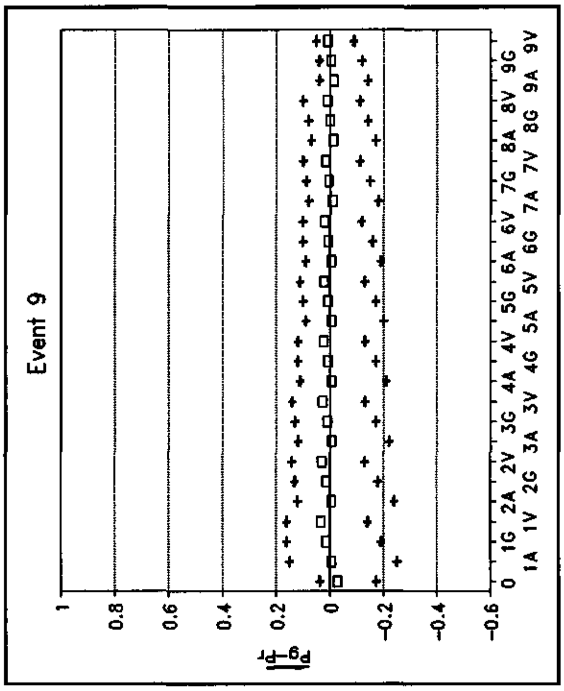

Fig. 6q

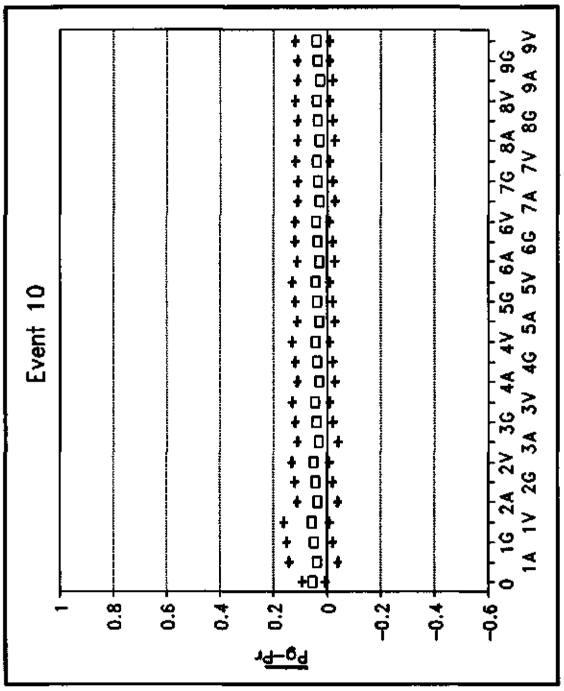

Fig. 6s

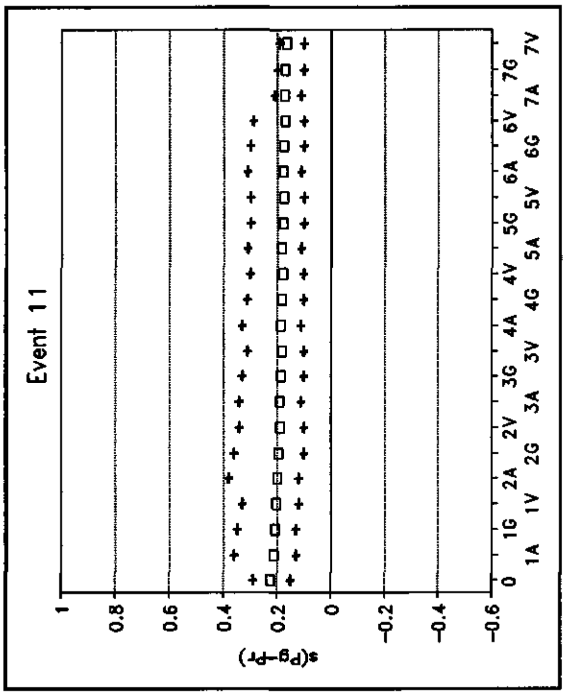

Fig. 6^{v}

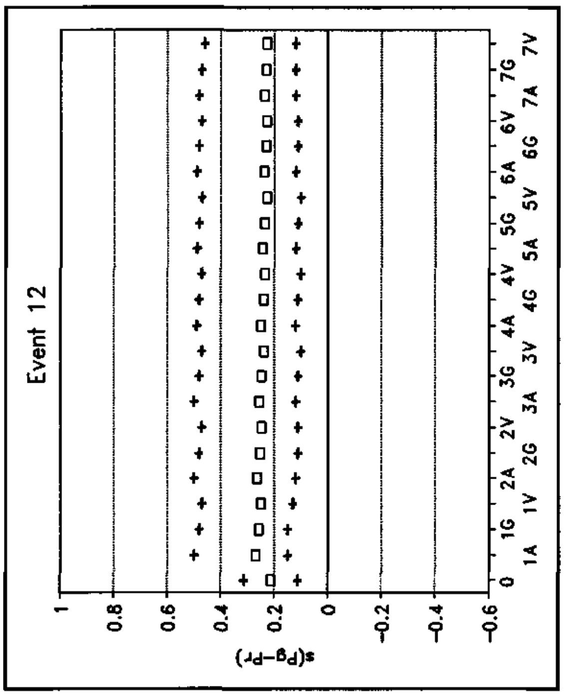

Fig. 6^{x}

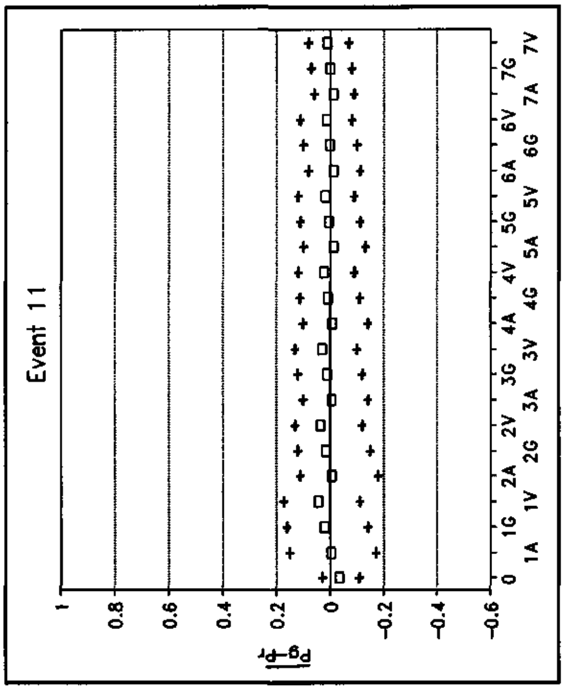

Fig. 6^{u}

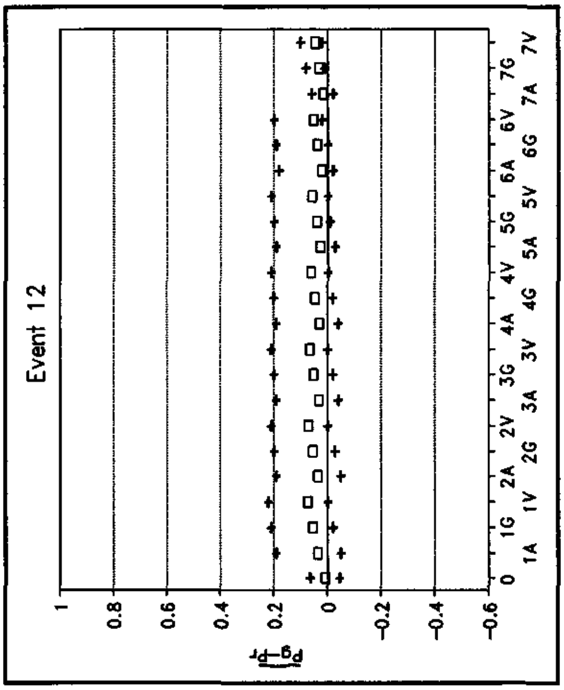

Fig. 6^{w}

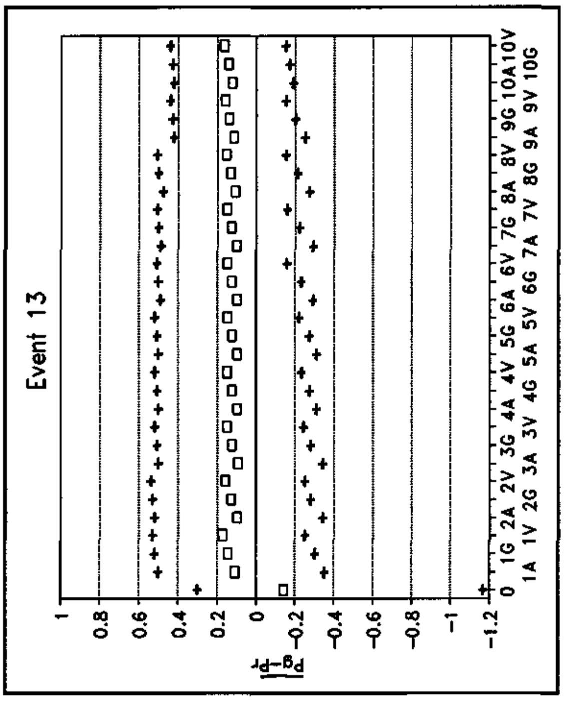

Fig. 6^y

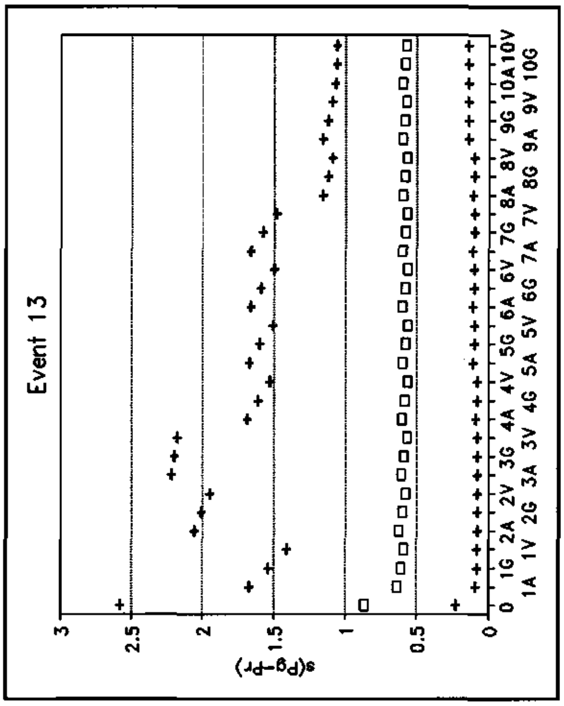

Fig. 6^z

Fig. 6^a - 6^z. *Accuracy of radar rainfall estimates compared to raingauge measurements for thirteen rainfall events. Comparison has been done in an absolute way ($\overline{P_g-P_r}$ [mm/15 min] and $\sigma(P_g-P_r)$ [mm/15 min]). O = unadjusted rainfall estimates. 1A = 1 gauge for adjustment and adjustment factor by arithmetic averaging respectively geometric averaging (G) and volumetric averaging (V). + = extreme values out of the values of the statistics $\overline{P_g-P_r}$ and $\sigma(P_g-P_r)$, □ = average value of the statistics $\overline{P_g-P_r}$ resp. $\sigma(P_g-P_r)$.*

Although in previous parts of this study the $\overline{F}$ and $\sigma(F)$ statistics were also used as measures of accuracy, they are omitted in this section for reasons of interpretation. Especially the $\sigma(F)$ statistic is hard to interprete.

3.3.3 Discussion

Analysis of the results depicted in Fig. 6^a-6^z can be made at best by raising some questions to be answered. The answers should represent the general trend in the results.
A first question is if there is a preference in method for calculating the average adjustment factor by A, G or V. The results reveal systematic lowest average bias values for A and highest for V. The results for the average of the mean standard deviation (= average random error) show the opposite with for most events highest values for method A. As we consider reduction of the bias error the principal goal of adjusting the radar rainfall estimates the conclusion is that arithmetic averaging (A) of individual adjustment factors is most efficient of the three methods. So we omit the G and V results.
A second question can be raised by comparing the unadjusted results (O in figures) with the adjusted results. For a fair comparison the number of combinations used with case O

should be equal to the number of combinations with adjustment. This is only the case if we use n-1 raingauges for adjustment, leaving one raingauge for verification. This is the most rightsided A-case in the figures.

Comparing the mean bias and mean random error results of the 13 events for these two cases show that adjustment is rewarding for most (10 out of 13) events. The reader should note that also adjustment case 1A is an improvement over case O for an ample majority of the 13 events.

The third question considers the number of raingauges for adjustment. Is the statistical result improving if the number of adjustment raingauges increases? Again, we compare the mean bias and mean random error results of the 13 events for the case 1A and the case A with n-2 adjustment raingauges. Both cases provide the same number of verification combinations for each event. It can be seen that for a small majority of the events (7 out of 13) the result slightly improves, in case more raingauges are used for adjustment. Concerning the comparison of the mean random error of case 1A and case A with n-2 adjustment raingauges for 13 events, again an improvement of the results (9 out of 13 events) can be seen when more raingauges are used for adjustment.

From a hydrological point of view, it is interesting to know the radar over- or underestimation in terms of depth of rainfall. For this, the amount of rainfall per time period, averaged over all operational raingauges and all time periods, has been calculated. Table 6 lists the result.

Event	Average depth of rainfall [mm]	Number of time periods	Rainfall intensity [mm/15 min.].
1	5.40	20	0.27
2	2.70	22	0.12
3	5.97	32	0.19
4	48.93	93	0.53
5	15.20	43	0.35
6	20.72	80	0.26
7	4.70	28	0.17
8	3.95	33	0.12
9	7.14	31	0.23
10	8.44	49	0.17
11	23.28	75	0.31
12	11.92	59	0.20
13	10.00	28	0.36

Table 6. Rainfall per event. Depth of rainfall is an average over all operational gauges. Rainfall intensity is an average over all operational raingauges and time periods.

Combining the information from Table 6 and Fig. 6^a - 6^z it can be concluded that radar estimates the rainfall amount very well in case of events 6, 7, 8, 9, 10 and 13. In these events the mean bias error is very close to zero. The mean bias error during the other events appears to be larger. For example:

event 2:

(P_g) = 0.12 mm/15 min. (Table 6)
$(P_g\text{-}P_r)$= 0.04 mm/15 min. (Fig. 6^c, case 1A)

$\Rightarrow (P_r) = 0.12 - 0.04 = 0.08$ mm/15 min.
When it is assumed that raingauge measurements represent the ground truth, the radar underestimates:

$2.70 - (0.08 * 22) = 0.94$ mm.

event 4:

(P_g) = 0.53 mm/15 min. (Table 6)
$(P_g\text{-}P_r)$= 0.14 mm/15 min. (Fig. 6^g, case 1A)

$\Rightarrow (P_r) = 0.53 - 0.14 = 0.39$ mm/15 min.
When it is assumed that raingauge measurements represent the ground truth, the radar underestimates:

$48.93 - (0.39 * 93) = 12.66$ mm.

Although radar estimates are relatively better during event 4 (0.14/0.53 = 26% underestimation) as compared to event 2 (0.04/0.12 = 33% underestimation), from a hydrological perspective radar performs much better during event 2.

Regarding the random error, it can be concluded that only events 1 and 13 deal with an average of $\sigma(P_g\text{-}P_r)$ larger than 0.2. Concerning event 13, this can be explained by the appearance of anaprop. The meteorological situation of event 1 is unknown (Table 3).
For the other events, the average of $\sigma(P_g\text{-}P_r)$ varies from 0.10 to 0.20. No relation of the random error with either the rainfall intensity or the meteorological situation can be found.

To obtain the results as presented in Fig. 6^a - 6^z, radar rainfall estimates have been adjusted by every possible combination of a certain number of raingauges. Some combinations of gauges will provide better results than others. The accuracy of adjusted radar rainfall estimates might further improve when a procedure would be introduced, which would decide per time period which combination of raingauges provides the best adjusted radar rainfall estimates per time period.

In section 3.2 the radar rainfall adjustment methods ONE and AVG were introduced. In section 3.3 other adjustment methods were introduced, based on different assumptions and considering a variable number of raingauges for adjustment.
It is interesting to compare the results of the methods D/ONE/15 and 1A. Both methods use space-time interpolated radar rainfall estimates, adjustment by one raingauge (if possible the same gauge) and arithmetical averaging of individual adjustment factors.

Method D/ONE/15 only uses pixels in which raingauges are located for computing an average adjustment factor. Method 1A, however, takes all radarpixels into account where the individual adjustment factors are within a given range of values. Table 7 shows the results.

	Adjustment method D/ONE/15			Adjustment method 1A		
Rainfall event	Adj. gauge	$\overline{P_g-P_r}$	$\sigma(P_g-P_r)$	Adj. gauge	$\overline{P_g-P_r}$	$\sigma(P_g-P_r)$
1	W2	0.0092	0.45	W2	0.10 (-)	0.49 (-)
2	W2	-0.056	0.56	W2	-0.0075 (+)	0.35 (+)
3	W2	-0.049	0.33	W2	0.0051 (+)	0.23 (+)
4	W2	0.045	0.46	W2	0.10 (-)	0.52 (-)
5	W2	0.034	0.30	O2	0.043 (-)	0.34 (-)
6	W2	0.0090	0.26	O2	-0.012 (-)	0.21 (+)
7	W2	-0.072	0.29	O2	-0.026 (+)	0.19 (+)
8	SE	0.0070	0.095	SE	0.017 (-)	0.10 (-)
9	SE	-0.070	0.20	SE	-0.024 (+)	N.A.
10	SE	-0.016	0.19	SE	0.043 (-)	0.20 (-)
11	SE	-0.0090	0.26	SE	-0.015 (-)	0.21 (+)
12	SE	-0.013	0.20	SE	0.019 (-)	0.24 (-)
13	SE	-0.014	1.15	SE	0.16 (-)	0.69 (+)

Table 7. Comparison of adjustment method D/ONE/15 and 1A in terms of $\overline{P_g-P_r}$ *[mm/15 min] and* $\sigma(P_g-P_r)$ *[mm/15 min]. (+) = method 1A performs better than D/ONE/15, (-) = method 1A performs worse than D/ONE/15. N.A.= not available.*

It appears that only in a minority of the events (4 out of 13) method 1A results in a smaller bias error than method D/ONE/15. Concerning the random error $\sigma(P_g-P_r)$, it can be seen that the accuracy improved for 6 out of 12 events.

At first glance, it appears that method 1A does not improve the accuracy of radar rainfall estimates. However, after close inspection it can be seen that the deterioration of the bias error for method 1A is relatively small, whereas the improvement of the random error for this method is significant.

It seems that method 1A is rewarding with respect to reduction of the random error. This is especially true in case of special meteorological situations, such as the occurence of anaprop during event 13.

3.3.4 Influence of adjustment domain boundary values on the accuracy of radar rainfall estimates

The boundary values R_{low} and R_{up} determine the size of the domain in which an individual adjustment factor is used for calculating an average adjustment factor (section 3.3.1). As already is mentioned, the values of R_{low} and R_{up} are arbitrary. The results presented in previous section 3.3.2 were obtained using $R_{low} = 0.33$ and $R_{up} = 3$. To investigate the effect of R_{low} and R_{up} on the accuracy of adjusted radar rainfall estimates, the next options have been tried:

	Option 1	Option 2
R_{low}	0.5	0.2
R_{up}	2.0	10.0

Table 8. Variation in R_{low} and R_{up} values.

Collier [1986] obtained good results by relaxing the limits according to option 2.
In this study, option 2 did not improve the accuracy of radar rainfall estimates. Option 1, i.e. tighten the limits to 0.5 and 2, showed a small increase in the accuracy of radar rainfall estimates. This relatively small increase of the accuracy does not change the overall conclusions. For this reason, no graphical results obtained by applying option 1 are shown.

4 USE OF RADAR RAINFALL DATA FOR HYDROLOGICAL PURPOSES: A CASE STUDY

4.1 Introduction

In chapter 1 the objectives of the CEC-project were defined. While the first two objectives were examined in the previous chapters, this last chapter deals with the third: evaluation of the accuracy of radar derived rainfall amounts for hydrological purposes, in particular the use of radar derived rainfall amounts as input for a precipitation-runoff model of a regional sewer system of urban locations.

Since precipitation can be considered to be the input of the hydrological system, it is important to obtain more detailed information about the spatial and temporal variability of precipitation. In this chapter radar rainfall estimates will be used as input in the waterbalance model NAMRAP. This model describes the transformation process of rainfall and waste water to discharge at the central outlet and at local overflow structures.

In the previous chapters, the accuracy of radar rainfall estimates has been verified in comparison with raingauge measurements. An additional approach to quantify the accuracy of radar rainfall estimates is by comparing simulated model outflow, using radar data as model input, with measured outflow. This method can only be used as an indication of accuracy, since both the actual system and the NAMRAP model can drain water by means of overflows. Overflows, which have not been measured, may occur in case of large rainfall intensities when the sewer storage capacity is exceeded.

In 1987 a study has been carried out aimed to investigate the possibility of reducing the hydraulic design capacity of a sewage purification plant, exploiting the spatial variability of raingauge measured rainfall. Financial support for this study was provided by the STORA (Stichting Toegepast Onderzoek Reiniging Afvalwater = Foundation of applied research of waste water purification) and therefore this study will further be referred to as the STORA-project. The STORA-project was carried out at the Department of Water Resources of Wageningen Agricultural University. It included the development of the waterbalance model NAMRAP (Witter et al, 1989).

In addition to the STORA-project, in which raingauges are used to estimate rainfall, radar rainfall estimates can be used as model input as well. Radar can refine the rainfall input by its higher spatial resolution. This may affect the number of sewer overflows and the outlet discharge in the model.

4.2 NAMRAP

4.2.1 Introduction

In the study-area West-Brabant, approximately 30 urban locations (villages and towns) possess a sewer system, which injects waste water into a regional pressure pipe system. This system transports sewage and rainfall water to a purification plant. Fig. 7 shows the geographical locations of the urban areas, while Fig. 8 is a schematization of the complete sewage transportation system.

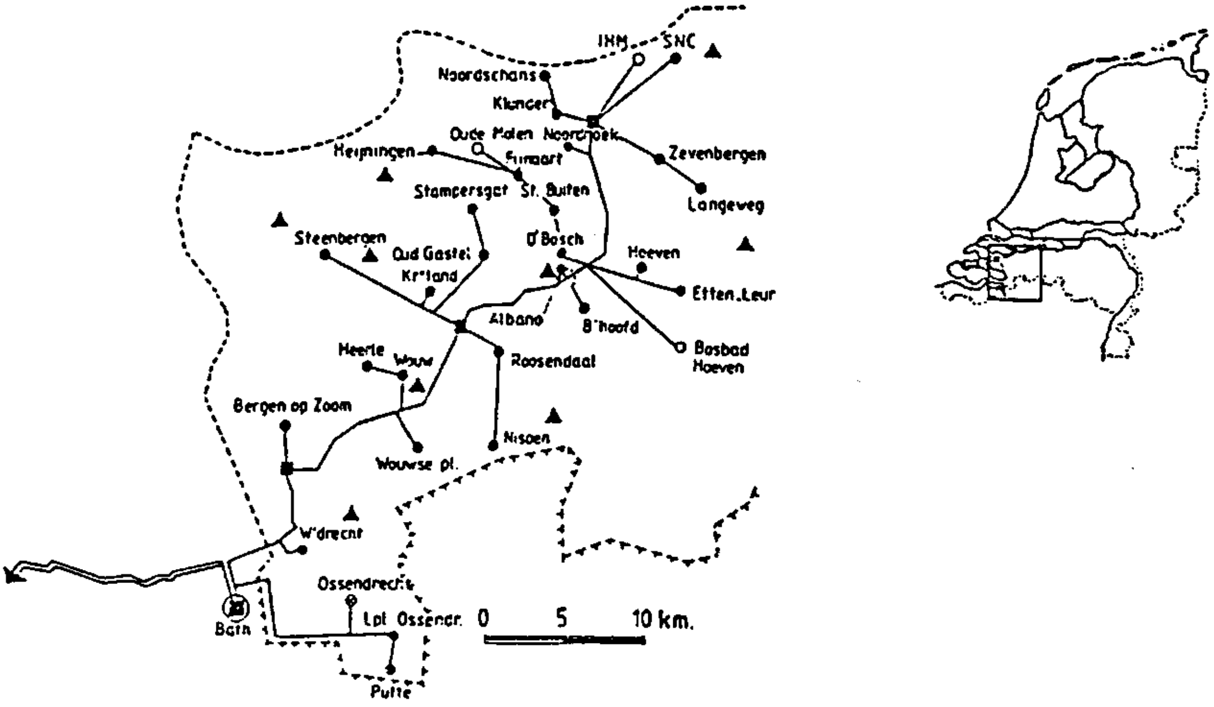

Fig. 7 Geographical locations of the urban areas connected to the regional pressure pipe system.
⦿ = regional purification plant, • = combined system, ○ = separated system, ▲ = raingauge,
—— = sewer system.

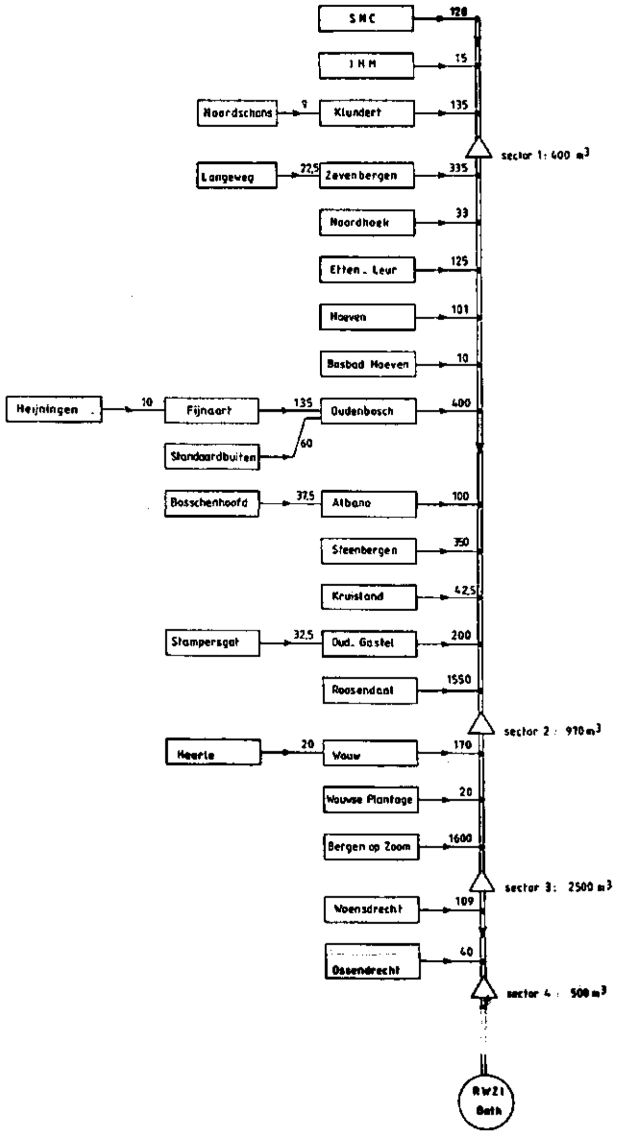

Fig. 8 Schematization of the sewage transportation system, with injecting pump capacities [m^3/30 min]. Situation 1983/1984. Δ *= storage in pressure pipe system,* ▭→ *= urban area with pump capacity [m^3/30min]*,* ═ *= pressure pipe system with pumping engine.*

** For this study, the pump capacity has been divided by 2 to obtain the capacity per 15 min. [m^3/15min].*

The transportation system has been mathematically described in terms of a simple distributed waterbalance model with input (rainfall and average dry weather sewage), storage and output (overflows and outflow at the purification plant). For a detailed description of the model, including the calibration of its parameters, the reader is referred to STORA [1987].

In order to be able to run NAMRAP one needs to know the impervious surface area, the sewage flux and the storage capacity of the sewer system associated with each urban area. Finally, the capacity and regimes of the pumps need to be known.

The NAMRAP model was originally designed for calculations on a 30-minute basis. Since the rainfall data for the CEC-project are 15-minute values, NAMRAP has been adjusted for calculations on a 15-minute basis.

4.2.2 Model structure

NAMRAP is designed to model the waterbalance of a system of 27 urban areas (Fig. 8), representing the situation of 1983/1984. Most of the areas (25) have a combined sewer system. These systems transport both sewage and rainfall water to the regional pressure pipe system. Two areas have separated systems, which only deliver dry weather sewage to the pressure pipe system.
During the period from 1983/1984 to 1988/1989 the following changes have been made in terms of extra connected areas to the pressure transportation system:

i. Moerdijk Dorp (separated system, sewage ≈ 456 m^3/d) and Tanco Dongen (constant effluent ≈ 1440 m^3/d) have been connected to IHM. Instead of remodelling NAMRAP, it is assumed that the fluxes of the two new areas are added to the flux of IHM (700 + 456 + 1440 = 2596 m^3/d). The effect of this assumption on model outflow simulations has been verified by changing the sewage for this composed area from 700 to 2596 m^3/d. Hardly any changes in outflow were found.
ii. During the STORA-project, Bosbad Hoeven was reported to be a separated system. According to more recent information Bosbad Hoeven is a combined system, but this has not been changed for the CEC-project. The introduced error is negligible, because the impervious area of Bosbad Hoeven (0.5 ha) represents only 0.04 % of the total impervious area.

The impervious area of each location has been updated according to the situation 1988/1989.

Concerning the sewage flux, no updated information was available to adjust it for the situation 1988/1989. Therefore the sewage flux per location has been adjusted proportionally to the change of impervious surface area.

Appendix 5 depicts the KERN.DAT inputfile, in which the above described parameters for each location are stated. This file also contains discharge coefficients, pump regimes, pump capacities and storage capacities of the regional transportation system. These factors remain the same as for the STORA-project [STORA, 1987].

The military encampment of 'Ossendrecht' is located 6 kilometres from Woensdrecht, but lies outside the area of radar pixels studied here. It is assumed that the radar derived rainfall of Woensdrecht is also valid for 'Ossendrecht'.

4.2.3 Rainfall input

The selected area of radar pixels comprises 16 * 24 pixels of 2 * 2 km. To each urban location one pixel has been assigned, except for Roosendaal and Bergen op Zoom for which the radar rainfall estimate is the average value of 4 pixels.

To examine the required accuracy of radar derived rainfall amounts for this particular hydrological purpose, several sets of rainfall estimates have been selected as input for NAMRAP:

i. Radar rainfall estimates, calculated according to the space-time interpolation method (using a displacement vector to calculate radar rainfall amounts) without adjustment.
ii. Raingauge estimates by Thiessen polygons, using all operational raingauges.
iii. Radar rainfall estimates, calculated according to the space-time interpolation method, adjusted by one raingauge. The adjustment procedure has been described in paragraph 3.3.1.
iv. Radar rainfall estimates (calculated according to the space-time interpolation method), adjusted by n - 1 raingauges. n is the number of operational raingauges per event (appendix 3).

With respect to iii. and iv., it is possible to compute several rainfall inputfiles, because adjustment can be done using an other (set of) raingauge(s). Since the impervious areas are located in the western part of the radarfield (16 * 24 pixels), only adjustment raingauges which are located in the western part of the radar field have been used.

4.2.4 Model output

Initially, 13 rainfall events were selected. Five out of 13 events contain missing periods (Table 1). Values of rainfall estimates for the missing time periods have been computed by linear interpolation, because NAMRAP needs rainfall input files without discontinuities. For event 3, no outflow has been measured by the Water Authority West-Brabant and therefore event 3 has not been taken into account for the NAMRAP calculations.

For all outflow simulations of 12 rainfall events, the following statistics were computed:

Outflow = total volume of outflow $[m^3]$
Overflow = total volume of overflow $[m^3]$
MBE/AVG = the mean bias error divided by the average measured outflow per 15 minutes [-]
RMSE' = root mean square error $[m^3/15\ min]$, corrected for the bias error. RMSE'can be derived from RMSE and MBE: $RMSE' = \sqrt{(RMSE^2 - MBE^2)}$.
RMSE'/STD = ratio of corrected root mean square error and the standard deviation of the measured outflows [-]

The results of outflow simulations, in terms of statistics, are shown in Table 9.

Event		Measured	Radar	Rgauges	-- Radar adjusted	with 1 gauge --			----- Radar adjusted with n-1 gauges ------				
1	Sum	61344	76339	59720	71958	58177			60699	53203	53392	52616	
	Overflow		136	0	121	0			0	0	0	0	
	MBE		294.0	-31.9	208.1	-62.1			-12.7	-159.6	-155.9	-171.1	
	MBE/AVG		0.24	-0.03	0.17	-0.05			-0.01	-0.13	-0.13	-0.14	
	RMSE'		409.7	268.0	312.1	214.6			213.2	298.2	309.6	302.4	
	RMSE'/STD		0.73	0.48	0.56	0.38			0.38	0.53	0.55	0.54	
2	Sum	128600	97664	57016	58420	46774	53569		53138	57596	58236	57836	
	Overflow		19094	0	0	0	0		0	0	0	0	
	MBE		-412.5	-954.5	-935.7	-1091.0	-1000.4		-1006.2	-946.7	-938.2	-943.5	
	MBE/AVG		-0.24	-0.56	-0.55	-0.64	-0.58		-0.59	-0.55	-0.55	-0.55	
	RMSE'		385.7	452.2	459.7	530.0	551.4		497.3	523.2	507.5	518.5	
	RMSE'/STD		0.84	0.99	1.01	1.16	1.21		1.09	1.14	1.11	1.13	
4	Sum	322920	267711	275494	267968	283495	270232		279977	275200	273719		
	Overflow		337739	406472	291519	468904	355128		428040	433845	428802		
	MBE		-475.9	-408.8	-473.7	-339.9	-454.2		-370.2	-411.4	-424.1		
	MBE/AVG		-0.17	-0.15	-0.17	-0.12	-0.16		-0.13	-0.15	-0.15		
	RMSE'		451.4	340.2	478.3	318.0	473.9		349.7	396.4	408.7		
	RMSE'/STD		0.88	0.66	0.93	0.62	0.92		0.68	0.77	0.80		
5	Sum	188176	152477	176323	148010	168099	164930	17535	176020	175806	174793	175977	
	Overflow		2952	11955	7660	9937	3509	822	7059	5717	6048	7083	
	MBE		-457.7	-152.0	-514.9	-257.4	-298.0	-164.	-155.8	-158.6	-171.6	-156.4	
	MBE/AVG		-0.19	-0.06	-0.21	-0.11	-0.12	-0.0	-0.06	-0.07	-0.07	-0.06	
	RMSE'		447.2	256.9	453.6	373.3	366.6	279.	259.7	260.5	266.7	260.1	
	RMSE'/STD		0.89	0.51	0.90	0.74	0.73	0.5	0.52	0.52	0.53	0.52	
6	Sum	149561	107027	158613	164336	141943	144071	12576	149272	147863	148261	149272	
	Overflow		899	251127	45160	30676	18616	684	17737	18023	17596	17737	
	MBE		-467.4	99.5	162.4	-83.7	-60.3	-261.	-3.2	-18.7	-14.3	-3.2	
	MBE/AVG		-0.28	0.06	0.10	-0.05	-0.04	-0.1	-0.00	-0.01	-0.01	-0.00	
	RMSE'		379.9	489.2	592.5	469.5	547.4	550.	498.2	502.9	511.5	498.2	
	RMSE'/STD		1.31	1.69	2.05	1.62	1.89	1.9	1.72	1.74	1.77	1.72	
7	Sum	138076	99902	86591	103712	81430	93176	9506	89239	88779	89508	89239	
	Overflow		316	0	0	0	387	41	0	0	12	0	
	MBE		-469.2	-605.0	-430.3	-657.7	-537.8	-518.	-578.0	-582.7	-575.2	-578.0	
	MBE/AVG		-0.27	-0.34	-0.24	-0.37	-0.30	-0.2	-0.33	-0.33	-0.32	-0.33	
	RMSE'		720.4	467.6	572.2	543.4	765.0	714.	534.9	534.1	537.1	534.9	
	RMSE'/STD		2.97	1.93	2.36	2.24	3.15	2.9	2.20	2.20	2.21	2.20	
8	Sum	92324	74853	71887	64756	64842	91108	9528	71231	71528	71315	71231	
	Overflow		86	0	0	0	423	51	51	51	51	51	
	MBE		-329.6	-385.6	-897.5	-518.5	-22.9	55.	-398.0	-392.4	-396.4	-398.0	
	MBE/AVG		-0.19	-0.22	-0.52	-0.30	-0.01	0.0	-0.23	-0.23	-0.23	-0.23	
	RMSE'		490.8	470.4	374.7	446.8	514.3	549.	475.4	478.5	477.6	475.4	
	RMSE'/STD		2.13	2.04	1.62	1.94	2.23	2.3	2.06	2.07	2.07	2.06	
9	Sum	81862	90376	90175	97891	94865	84861	8501	91565	92596	91229	91565	
	Overflow		869	66	2646	1251	0		0	0	0	0	
	MBE		146.8	143.3	276.4	224.2	51.7	54.	167.3	185.1	161.5	167.3	
	MBE/AVG		0.10	0.10	0.20	0.16	0.04	0.0	0.12	0.13	0.11	0.12	
	RMSE'		561.0	595.5	595.1	583.8	571.4	550.	603.4	599.3	607.0	603.4	
	RMSE'/STD		1.63	1.73	1.73	1.69	1.66	1.6	1.75	1.74	1.76	1.75	
10	Sum	102790	83051	110609	100042	95921	99052	9610	102770	103538	102951	102770	
	Overflow		0	225	0	15	60	2	100	100	100	100	
	MBE		-274.1	108.6	-38.2	-95.4	-51.9	-92.	-0.3	10.4	2.2	-0.3	
	MBE/AVG		-0.19	0.08	-0.03	-0.07	-0.04	-0.0	-0.00	0.01	0.00	-0.00	
	RMSE'		580.8	463.8	406.4	460.3	496.4	519.	440.1	435.9	437.2	440.1	
	RMSE'/STD		1.02	0.82	0.71	0.81	0.87	0.9	0.77	0.77	0.77	0.77	
11	Sum	213120	253982	246405	245283	248731	254813		246830	247992	246982	246830	
	Overflow		92957	62041	117672	114391	133237		84161	89161	86768	84161	
	MBE		374.9	305.4	295.1	326.7	382.5		309.3	319.9	310.7	309.3	
	MBE/AVG		0.19	0.16	0.15	0.17	0.20		0.16	0.16	0.16	0.16	
	RMSE'		248.3	292.4	313.5	294.6	260.6		318.9	307.0	319.3	318.9	
	RMSE'/STD		0.54	0.64	0.68	0.64	0.57		0.70	0.67	0.70	0.70	
12	Sum	136358	181297	175871	169999	173051	185124		174309	174929	174342	175648	174309
	Overflow		3664	11211	6785	29364	50393		25098	27976	25493	25875	25098
	MBE		493.8	434.2	369.7	403.2	535.9		417.0	423.9	417.4	431.8	417.0
	MBE/AVG		0.33	0.29	0.25	0.27	0.36		0.28	0.28	0.28	0.29	0.28
	RMSE'		493.7	538.7	565.2	550.8	490.3		518.1	534.5	518.3	511.7	518.1
	RMSE'/STD		1.86	2.03	2.13	2.08	1.85		1.95	2.02	1.96	1.93	1.95
13	Sum	79356	119482	104525	110186	98746	85938	11353	104981	104981	104969	106652	
	Overflow		308579	17900	56759	645	360	4430	25871	25871	25871	26071	
	MBE		680.1	426.6	522.5	328.6	111.6	579.	434.3	434.3	434.1	462.6	
	MBE/AVG		0.51	0.32	0.39	0.24	0.08	0.4	0.32	0.32	0.32	0.34	
	RMSE'		488.7	429.4	579.7	383.2	276.5	453.	398.9	398.9	398.7	402.9	
	RMSE'/STD		0.72	0.64	0.86	0.57	0.41	0.6	0.59	0.59	0.59	0.60	

Table 9. *Statistical results of outflow simulations of 7 rainfall events, and 6 to 8 rainfall estimation methods per event.*

The statistics in Table 9 are calculated over a certain number of time periods. The first period is the period in which the simulated outflows from different rainfall inputfiles within an event start to differ. For most events this is one time period after the onset of rainfall. The last period is set to the end of the rainfall event plus 10 hours. A period of 10 hours is supposed to be the drainage time of the sewage transportation system [STORA, 1987].

After simulations with NAMRAP, the outflow hydrographs [G.M.T.] have been translated 1, 2 or 3 of hours to match the measured outflow hydrographs [L.S.T.]. Moving simulated outflow in time by a number of hours has been neccessary to correct for the time lag caused by different time registration standards. Unfortunately the number of hours which had to be added was found to be inconsistent (appendix 6).

4.3 Discussion

In order to clarify the meaning of the statistics presented in Table 9, some graphs of simulated outflow versus measured outflow are shown (Fig. 9^a - 9^f).

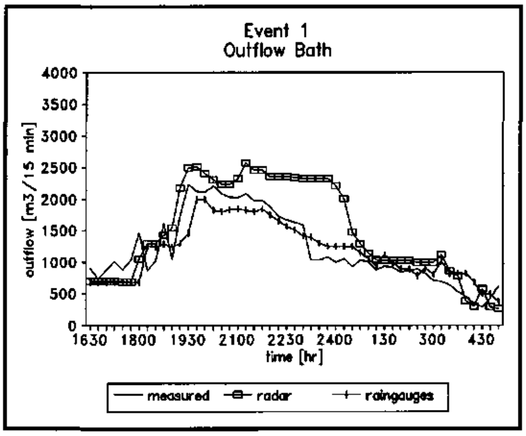
Event 1
Outflow Bath

Fig. 9^a

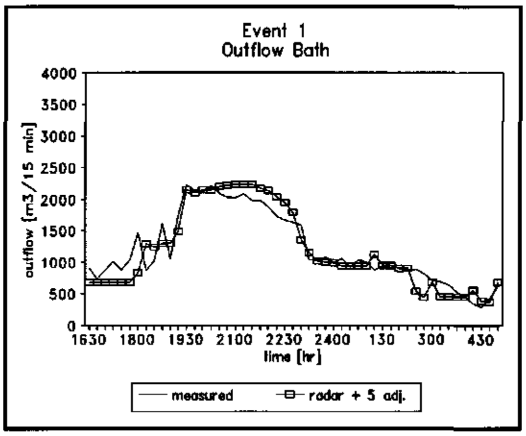
Event 1
Outflow Bath

Fig. 9^b

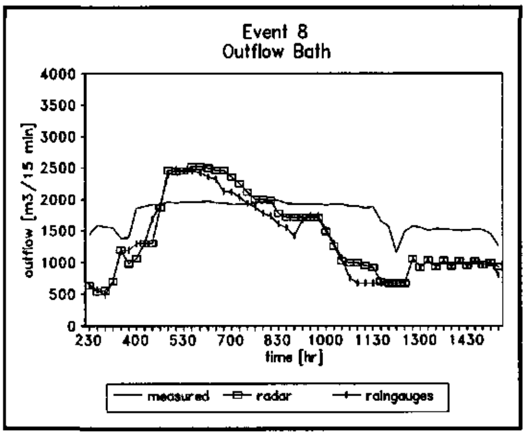
Event 8
Outflow Bath

Fig. 9^c

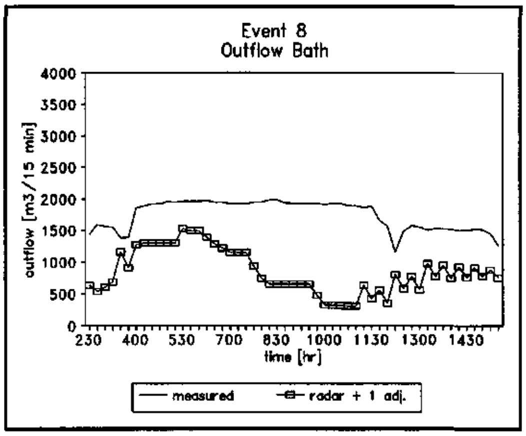
Event 8
Outflow Bath

Fig. 9^d

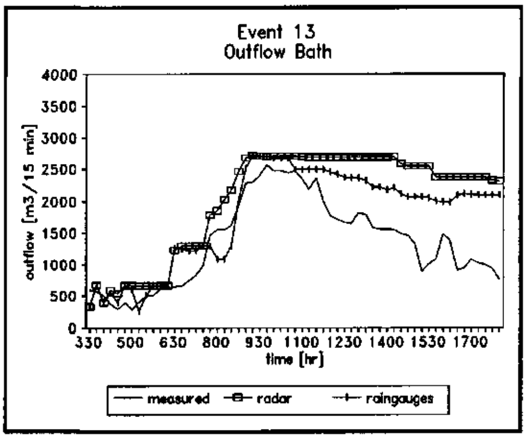

Fig. 9^e

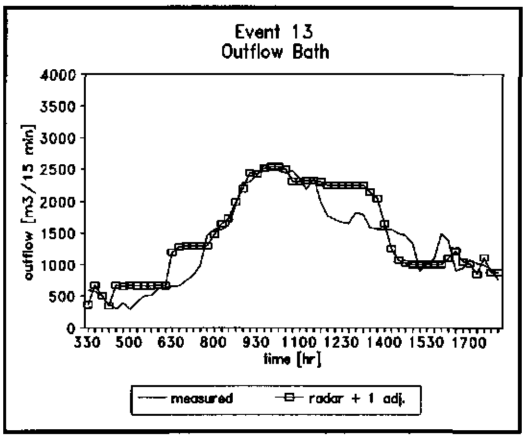

Fig. 9^f

Fig. 9^a - 9^f. *Simulated outflow hydrographs of rainfall events 1, 8 and 13. Rainfall input is unadjusted radar estimates, raingauges measurements and radar estimates adjusted by raingauge(s).*

The outflow depicted in Fig. 9^b is the best simulated outflow (see also Table 9). On the other hand, Fig. 9^d shows a worse simulated outflow result. Fig. 9^e and 9^f show outflow simulations associated with a rainfall event for which the radar data were contaminated by anomalous propogation (anaprop). It can be seen that the total volume of overflow, using unadjusted radar estimated rainfall as input, is extremely large (308579 m^3). When using one raingauge to adjust radar rainfall estimates, the outflow simulation can be improved (Fig. 9^f).

The total input volumes [m^3] of rainfall per rainfall estimation method have been calculated. This is especially interesting for 4 out of 12 events (7, 8, 11 and 12), for which the simulated outflow does not match well the measured outflow.
Below the input volume of rainfall is depicted for event 8 (corresponding to Fig. 9^c and 9^d).

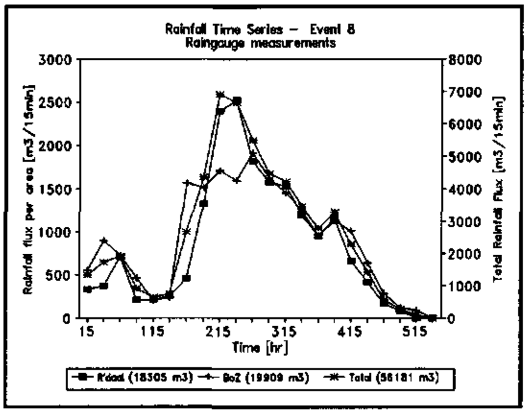

Fig. 10^a

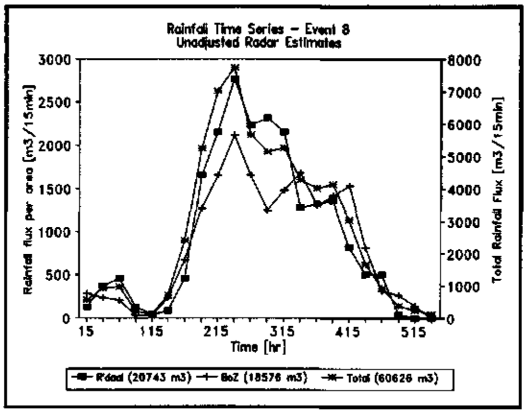

Fig. 10^b

Fig. 10^a and 10^b. Input volume of rainfall for NAMRAP during event 8. R'daal = rainfall input volume for the area of Roosendaal. BoZ = Bergen op Zoom and Total = Total rainfall input volume for all impervious areas.

While comparing input (Fig. 10) and output (Fig. 9^c, 9^d) of the system for event 8, it can be seen that the measured outflow remains almost constant and reacts only slightly on changes in rainfall input volume. Apperently NAMRAP cannot model this almost constant outflow. Also for events 7, 11 and 12, this phenomenon occurs and causes large deviations between measurements and outflow simulations.
The Water Authority West-Brabant has been consulted about the outflow measurements during these four events, but no clear explanation about this phenomenon could be given.

The results denoted in Table 9 also show that choosing a different adjustment raingauge can lead to different outflow simulation results. Apparently, the location of the adjustment raingauge greatly influences the accuracy of the adjusted radar rainfall estimates and subsequently the accuracy of the outflow simulation results. For (n - 1) adjustment raingauges it can be concluded that changing adjustment raingauges in sets of 8 raingauges or more, hardly influences the magnitude of the radar rainfall estimates and thus the accuracy of the simulated outflows.

To obtain conclusions from Table 9, ranking numbers have been associated with the statistics MBE/AVG and RMSE'/STD. With respect to both statistics, the best values - and subsequently the lowest ranking numbers- are the ones closest to zero. The ranking numbers, ranging from 1 to 6, are associated with:

- unadjusted radar rainfall estimates.
- raingauge measurements interpolated using Thiessen polygons.
- <u>best</u> result of adjusted radar rainfall estimates using 1 adjustment raingauge.
- <u>best</u> result of adjusted radar rainfall estimates using n - 1 adjustment raingauges.
- <u>worst</u> result of adjusted radar rainfall estimates using 1 adjustment raingauge.
- <u>worst</u> result of adjusted radar rainfall estimates using n - 1 adjustment raingauges.

To decide which type of rainfall input provides the best simulation results, the ranking numbers were averaged over both statistics MBE/AVG and RMSE'/STD as well as over

12 events. With this, both statistics as well as the rainfall events, are assumed to be of equal importance.

It appears that for 12 rainfall events, raingauges (avg. rankingnr. = 3.00) can provide more accurate rainfall estimates for hydrological purposes than radar (avg. = 4.02), in case no adjustment of radar by raingauges is considered.

When adjustment of radar rainfall estimates by one raingauge is considered, it appears that adjusted radar estimates can both improve and deteriorate the simulation results depending the choice made by chance. The simulation results do improve (avg. = 1.85) when the right adjustment raingauge is chosen. However, when a non-representative raingauge (location) is chosen to adjust (avg. = 5.50), all other considered rainfall estimation methods perform better.
Simulations with radar rainfall estimates adjusted by (n - 1) raingauges, are found not to be the best result (avg. = 2.65) nor the worst result (avg. = 3.98) in terms of outflow accuracy. This rainfall estimation method compensates the disadvantage of adjusting radar estimates by non-representative raingauge locations with the advantage of adjusting radar estimates by representative raingauges (locations). As such, it is the best compromise and thus the most reliable approach.

As already said the simulated outflow hydrographs of events 7, 8, 11 and 12 are very bad fits of the measured outflow hydrographs. The conclusions described in this paragraph, based on 12 rainfall events, still remain the same when events 7, 8, 11 and 12 are excluded from the set of rainfall events.

It can be seen in Table 9 that the total volume of overflow is in most cases a minor part of the outflow volume within a rainfall event. The volume of overflow is only substantial during event 12 and 13. The extremely large overflow volume during event 13 for the case of rainfall estimation method 'radar' is probably due to anaprop, which can cause a large overestimation of rainfall by radar.
It is not possible to draw conclusions with respect to simulated volumes of overflow, because the total volume of overflow has not been measured during rainfall events. However, the fact that overflows show to be a minor part of the waterbalance in the selected events strengthen the earlier discussion of the results of Table 9.

5 CONCLUSIONS & RECOMMENDATIONS

Conclusions

- The accuracy of radar rainfall estimates as compared to raingauge measurements has been determined in an absolute and a relative way. It is found that the absolute comparison is more transparent and especially for hydrological purposes more valuable. The relative statistic can fluctuate heavily and is therefore hard to interprete.

- Forward extrapolated radar rainfall estimates, adjusted by using either one raingauge (method ONE) or all operational raingauges (method AVG), may result in an increase of the bias- and random error. Especially for method ONE, the location of the raingauge appears to influence the accuracy of adjusted radar rainfall estimates heavily. Adjustment method AVG smoothes the effect of an individual raingauge.

- Radar rainfall estimates calculated according to the space-time interpolation method (using a displacement vector) provide more accurate results than the forward extrapolated radar rainfall estimates. This is especially true when adjustment of radar rainfall estimates is applied. Further conclusions are based on results of the space-time interpolation method.

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

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

- Meteorological circumstances causing high reflectivities as a result of bright band or anomalous propagation does not significantly comtaminate the accuracy of radar rainfall estimates, except for rainfall event 13. However, the effect of anomalous propagation on the accuracy was again found to be less severe for radar rainfall estimates calculated according to the space-time interpolation method, as compared to forward extrapolated radar rainfall estimates.

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

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

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

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

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

- It can be concluded from the results in chapters 3 and 4 that adjusted radar rainfall estimates using all operational raingauges minus 1 (chapter 4) or 2 (chapter 3) provide the most reliable radar rainfall estimates compared to all other rainfall estimation methods considered. This method compensates the disadvantage of adjusting radar rainfall estimates at 'non-representative' raingauge locations with the advantage of adjusting radar rainfall estimates at 'representative' raingauge locations. As such, it is the best compromise and thus the most reliable approach. If it would be possible to know which adjustment raingauge performs best, then adjusted radar rainfall estimates using one adjustment raingauge probably provide the most accurate rainfall estimates.

Recommendations

- It is found that the accuracy of adjusted radar rainfall estimates using one adjustment gauge strongly depends on which raingauge is chosen for adjustment. Moreover it appears, especially in chapter 4, that adjusted radar rainfall estimates adjusted with the best performing single raingauge are more accurate than adjusted radar rainfall estimates adjusted according to any other considered adjustment method. Therefore, it is recommended to develop a model which decides per time period which raingauge is used for adjustment. In fact a cross-validation procedure is applied to all operational raingauges for each time period. This concept is likely to improve the accuracy of the radar rainfall estimates.

- Decreasing both the spatial and temporal scale of radar rainfall estimates probably yields more accurate radar data.

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APPENDICES

Appendix 1.

List of rainfall events for the NWO-project.

date: yymmdd; P_g:range of measured raingauge rainfall amounts; m_{loc}: number of different operational raingauge locations; m_G: number of operational gauges; WW: weather code: 0:cloudiness less than 4/8, 6: widespread rainfall, 8: showers, 9: thunderstorm; RC: radar code: O: nothing special, D: circular discontinuity, B: bright band, A: anaprop, X: unknown; melting: estimated height of melting hydrometeors ([km].

date	P_G	m_{loc}	m_G	WW	RC	melting
880303	6- 8	1	5	6	B	0.4
880306	10-13	1	5	6;8	B	0.8
880315	6- 8	1	4	6;8	O	1.0→2.0
880323	10-12	1	4	6;8	O	1.5
880325	10-12	1	4	6	B	1.2
880604	4- 8	1	4	8.	X	1.6
880723	7- 8	3	7	9	O	3.9
880728	6	3	6	6	O	2.1→3.0
880810	6-22	3	6	8	O	4.0
880820	2- 9	3	5	8	O	
880821	27-41	3	5	8	O	2.3
880901	5- 6	3	5		X	2.7
880904		3	5	0	A	
880905		3	5	0	A	
880912	2-13	5	8		X	2.3→1.9
880914	1- 6	5	8		X	2.0
880923	4- 8	5	7	6;8	O	3.8→2.0
880924	24-61	5	7	6+8	O	2.0→2.8
880925	4-20	5	7	6+8	O	2.8→3.3
881020	11-23	9	13	6+8	O	2.5
881129		10	14	0	A	
881130	7-16	10	14	6	D	1.4→2.1
881201	7-20	10	14	8;6	O	2.1→1.6
881204	9-15	10	14	8;6	B	1.1
881209	5- 9	10	14	6+8;6	B	1.0→1.8
881218	5- 9	10	10	6;6+8	O	0.7→2.1
890217		10	10	0	A	
890219	7-11	10	10	6;6+8	B	2.6→1.7
890301	7-12	10	10	6	B;O	1.0
890302	7-10	10	10	6;6+8	B	1.2
890307	18-23	8	8	8;6+8	O;D	2.2→0.9
890308	2- 6	8	8	6+8	B	0.7
890316	11-18	8	8	6;6+8;8	D	1.1
890324	5- 9	8	8	6+8	B	1.0→1.8→1.2
890414	11-23	13	15	6+8;8	O	1.8→1.2
890608	0- 8	14	15	8	O	1.5
890627	5-14	13	15	8	O	3.2→1.8
890628	1-11	13	15	8	O	1.8→2.4
890629	7-10	14	16	8	O	2.4
890701	4-25	14	16	8	O	2.8
890723	3-17	13	14	8	D+A	3.4

Appendix 2.

Storm travel directions (ϕ) and speeds to initiate displacement vector calculations.

Event	ϕ [degrees]	Speed [km/h]
1	295	60
2	340	40
3	260	85
4	275	60
5	145	4
6	220	25
7	275	40
8	330	75
9	300	110
10	250	90
11	215	20
12	200	20
13	205	30

Appendix 3.

Event	W0	W1	W2	W3	O2	BN	DI	BR	SE	ST	WE	WW	WD	CH	TA	RV	DU	ND
1	o		x	o		x	x	x	x	x								
2	o		x	o		x	x	x		x								
3	o		x	o		x	x		x	x								
4	o		x	o		x	x		x	x								
5		o	o	o	x	x	x	x	x	x		x	x	x				
6		o	o	o	x	x	x	x	x	x	x	x	x	x				
7		o	o	o	x	x	x	x	x	x	x	x	x	x				
8					x	x	x	x	x	x	x	x	x	x				
9					x	x	x	x	x	x	x	x	x	x				
10					x	x	x	x	x	x	x	x	x	x				
11					x	x	x	x	x		x		x	x				
12					x	x	x	x	x		x		x	x				
13					x	x	x		x	x	x	x	x	x	x	x		x

Raingauge:

W0 W1 W2,
W3 O2 : Zevenbergen
BN : Baarle-Nassau
DI : Dintelsas
BR : Breda
SE : Seppe
ST : Steenbergen
WE : Wernhout

WW : Wouw
WD : Woensdrecht
CH : Chaam
TA : Ter Aalst
RV : Raamsdonkveer
DU : Dussen
ND : Nieuwendijk

x, o : Operational raingauges per rainfall event.
o : This raingauge is temporarily removed from the set of operational raingauges during the calculations in section 3.3.
Note : ND is located outside the radarquadrant.

Appendix 4.

Rainfall event 1.
One adjustment raingauge (ST).
Arithmetically averaging of indivudual adjustment factors to compute an average adjustment factor A.
0 : $P_r = 0$
< : $P_g/P_r < R_{low}$
= : $R_{low} \leq P_g/P_r \geq R_{up}$
> : $P_g/P_r > R_{up}$

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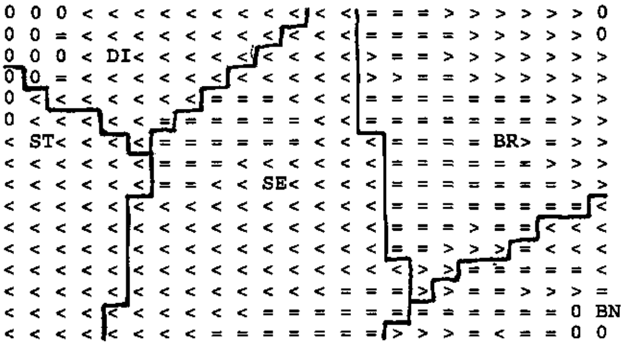
--->

Rainfall event 1.
Five adjustment raingauges (BN, DI, BR, SE and ST).
Arithmetically averaging of indivudual adjustment factors per sub-area to compute an average adjustment factor A.

$0 : P_r = 0$
$< : P_g/P_r < R_{low}$
$= : R_{low} \leq P_g/P_r \geq R_{up}$
$> : P_g/P_r > R_{up}$

1415.00



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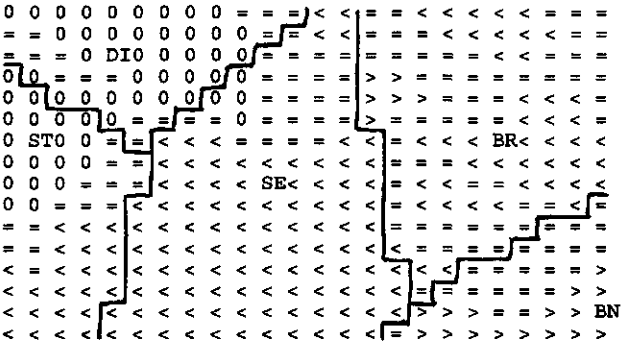

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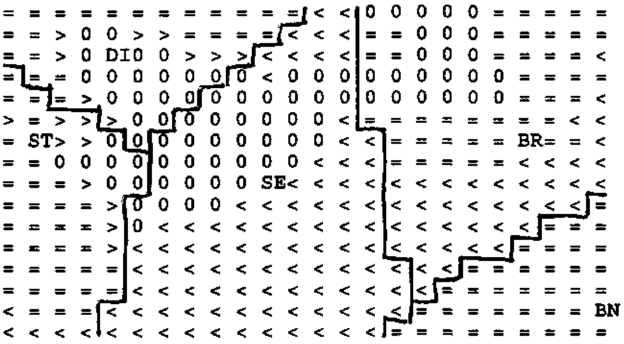

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Appendix 5.

The inputfile KERN.DAT is a file in which specific parameters per impervious area are denoted. The reader is referred to [STORA, 1987] for a detailed description of the contents of KERN.DAT.

```
      6.85      1.44     32.30      4.40     79.70      6.90
      8.80     33.60      2.10     27.30     14.80     62.00
     12.20     28.00     70.00     11.60      7.50     41.70
    413.20     10.50     23.00      4.80    289.80      3.20
      4.50
    240.00    128.00   2461.00    345.00   6608.00    610.00
   1700.00   2355.00    154.00   1870.00   1262.00   4390.00
   1098.00   2730.00   5502.00   1130.00    766.00   3553.00
  25531.00    600.00   1851.00    381.00  19587.00    224.00
    315.00
   8214.00     58.00   1242.00    202.78   2827.00    388.00
   1603.00   1350.00     76.00   1040.00    461.00   2573.00
    304.50    686.00   1871.00    446.00    453.00   1586.00
  13595.50    445.70    974.00     84.00  14557.00    128.00
    840.00
      1.00      1.28      1.28      0.90      1.00      1.10
      1.00      0.78      1.06      1.06      1.07      1.00
      0.97      0.97      1.12      1.45      1.01      1.01
      1.12      1.11      1.11      1.00      1.06      1.00
      1.00
    400.00    970.00   2500.00    500.00  99999.00
      1.00         1         1         1
   6154.00
      0.89         0         2         2
      4.50
      0.89         2         6         1
     47.50     67.50   2320.00         2
      1.00         0         2         2
     11.25
      1.05         3         6         1
     96.25    167.50   4500.00         4
      0.99         4         4         1
      5.50     11.00     16.50    585.00    460.00
      2.00         5         2         1
     62.50
      0.73         6         3         1
     20.00     50.50   1400.00
      0.92         0         2         3
      5.00
      0.92         0         6         2
     27.50     67.50   1600.00         9
      1.01         0         2         2
     30.00
      0.66         7         7         1
     75.00    145.00    200.00   3900.00   3600.00        10        11
      0.60         0         2         2
     18.75
      0.60         8         5         1
     50.00        13
      1.15         9         4         1
     90.00    107.50    175.00   4000.00   3500.00
      0.74        10         2         1
     21.25
      0.51         0         2         2
     16.25
      0.51        11         6         1
     65.00    100.00   1800.00        17
      0.90        12         9         1
    350.00    600.00    775.00  23100.00  22295.00  19460.00  17850.00   9240.00
      1.43         0         2         2
     10.00
      1.43        13         5         1
     85.00        20
      1.00        14         3         1
      5.00     10.00    300.00
      0.86        15         8         1
    420.00    685.00    800.00  17875.00  15125.00  12650.00
      1.00        16         2         1
     41.25
      1.00        17         2         1
     20.00
   2596.00
    490.00
```

Appendix 6.

Time lag in simulation results versus measured results caused by different time registration standards.

Raingauge measurements of raingauges in the WBR-area have been stored by the Water Authority West-Brabant and the Department of Water Resources, Wageningen Agricultural University for research purposes during the NWO-project. The raingauge measurements of the Water Authority West-Brabant are reported to be registrated in Winter time. After 1991, the Water Authority changed the time registration to Local Standard Time [L.S.T.], i.e. Summer time and Winter time. The time registration used during the NWO-project is reported to be U.T.C.

The table below denotes the comparison and correction of the time registration standards of the raingauge measurements.

	Difference[1]: [hr]	Difference after correction[2] [hr]:	Required difference[3] [hr]:
Rainfall events during winter time:			
5	1	1	1
6	1	1	1*
7	1	1	1*
8	1	1	1
9	1	1	1
10	1	1	1
11	3	3	1*
12	1	1	1
Rainfall events during summer time:			
1	2	3	2
2	2	3	1*
3	2	3	-
4	2	3	3
13	1	2	3

Ad 1. Difference in registration between rainfall stored by the Water Authority West-Brabant and during the NWO-project.

Ad 2. Difference in registration after correction of events during summer time

Ad 3. Based on outflow simulations, this column denotes the number of hours which have to be added in order to match the simulated outflow hydrographs with measured outflow hydrographs.

* For these events the required difference is not as evident as for the other events, but the number of hours translation seems to be the best possible solution.

\- For event 3, outflow measurements have not been recorded and thus no comparison can be done in terms of required number of 'translation hours'.

The different time standards are interconnected through the following general rule:
12.00 U.T.C. = 12.00 G.M.T. = 13.00 Winter time = 14.00 Summer time