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Extreme Rainfall Events in Lund 1979-1980

Janusz Niemczynowicz and Olle Jonsson

University of Lund, Sweden

All raingauge measurements give only one-point values. Since the practical applications of rain data always deal with areal measures, the knowledge of areal distribution of rain is very important for correct evaluation of the rain volumes. Two types of rainfall input data are generally used: design rainfall hyetographs and long historical rainfall records. The third type of input data has to be recognized: the observed single rainfall event, during which the consequences such as runoff, flooding or pollution loads have been observed and recorded. Good areal characterization of such single event is necessary if the results are to be generalized.

In the paper a set of extreme rainfall events observed in Lund during a period of two years is presented. Point and areal intensities are presented for ten extreme events. Storm centered Areal Reduction Factors (AFR-s) calculated for different durations are also presented. Size, shape and movement of the raincells is discussed in the context of the meteorological background observed.

Introduction

All raingauge measurements give one-point values. The raingauge represents only its own funnel area and all areal estimates of rainfall volumes or rainfall depth are more or less erroneous. The practical applications of rain data always deal with areal measures, and thus the knowledge of the areal distribution of rain is very important for correct evaluation of rain volumes (Bell 1976). This fact is generally accepted but not much has been done to use correct, areal measures of rainfall in practical applications. Perhaps the reason is that just one-point rainfall statistics is complicated enough and, besides, the areal statistics, according to general belief, will not be so much different from one-point statistics for very long time series.

During the last decade a great explosion of mathematical modeling of rainfall-runoff relations, especially in urban areas, has been observed. Very often the need to solve practical problems forces us to use in modeling, not only statistically calculated design storms, but also the real, historic rainfall events. Use of historic records is suitable for solving many urban water problems such as studies of volumes of combined sewer overflows, flooding, pollution control and etc. (Colyer 1978).

Two types of rainfall input data are generally used: design rainfall hyetographs and long historical rainfall records (Marsalek 1978, Arnell 1978, Johansen 1979).

The third type of rainfall input data should be recognized: the observed single rainfall event during which the consequences such as runoff, flooding or pollution loads have been observed and recorded. This particular rainfall event can be used for modeling in order to simulate measures which can be taken to prevent against observed, negative consequences. For example, if flooding was observed during one particular rainfall event, this event can be used in simulation of a retention basin which would prevent flooding. In such a simulation it is essential to know rainfall areal distribution in order to be sure that right rainfall volume is used. The return period for such an event is usually unknown or can only be roughly estimated by comparison with intensity-duration curves if such are available. The single event hyetographs have been used for simulations of changes in the urban water system and assessment of its consequences in terms of storm water shock loads and volume of combined sewer overflows (Hogland et al. 1980).

It has been recognized before, that the use of historical storms needs more local field data than the use of design storms (Sieker 1978, Colyer 1978). But if a single storm is used for simulation of the runoff hydrograph and the results are to be generalized in statistical terms, good charaterization of the spatial properties of the event is necessary. Not only the depth and volume of the areal rainfall is needed but also the shape, size and movement of raincells and knowledge of how these properties depend on the specific meteorological situation.

Unfortunately, there are only a few measurements of short term rainfall in urban areas with a good spatial and time resolution. Only such measurements can be used to make a description of the raincell characteristics and movement possible. Of course, radar measurements would give the best spatial characterization of a rainfall event.

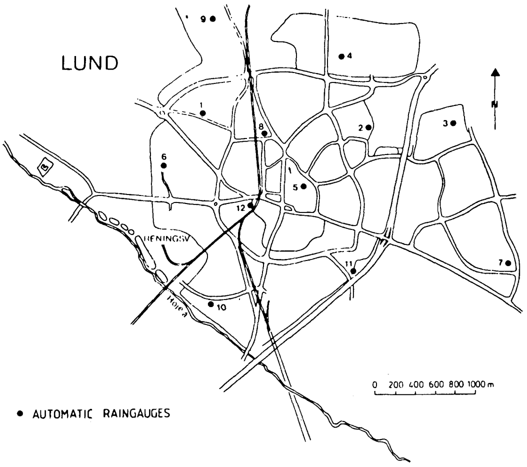


Fig. 1. Location of the raingauges in Lund.

Measurements of Short Term Rainfall in Lund

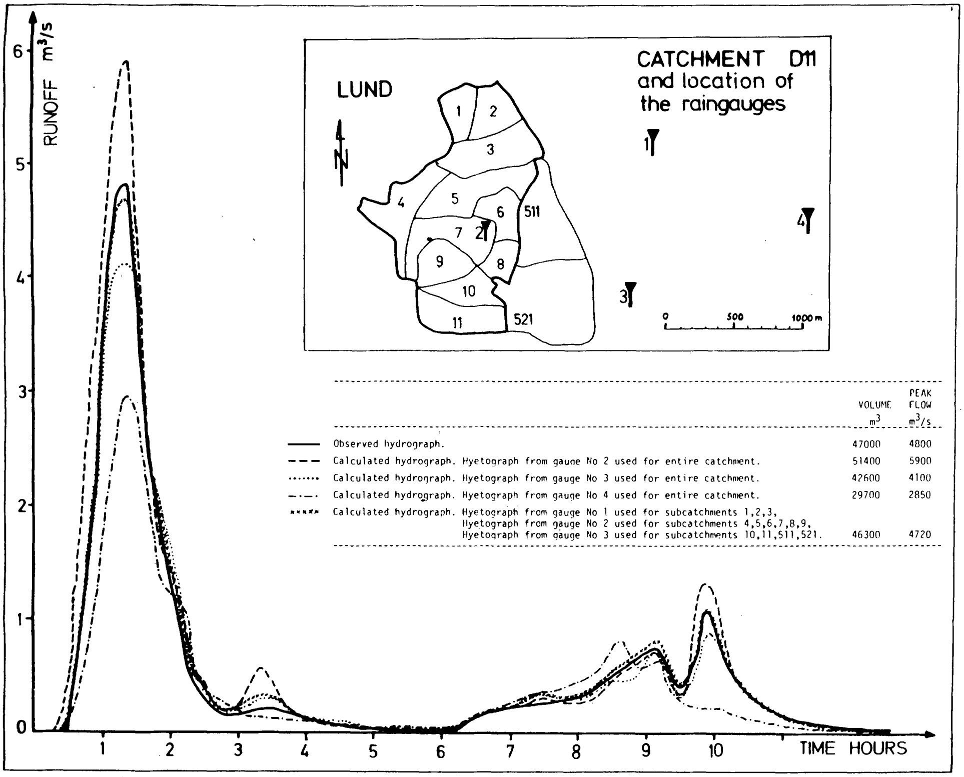
In 1978 an extensive study of short term rainfall intensities started in Lund. Twelve automatic tipping-bucket gauges were installed to cover an area of approximately 20 sq. km in central Lund. The depth resolution of the gauges is 0.035 mm per tipping, the time resolution of registration is 1 min. Fig. 1 shows the situation of the raingauges in Lund.

The gauging system and data processing procedure have been described before (Falk et al. 1979). The aim of the project is to study the short-term areal rainfall intensities within a single city in connection with the specific meteorological situation. The size, shape and movement of the raincells is investigated for individual events.

In another project in Lund, running parallel to this one, the runoff and the quality of storm water from five catchments in the city, the volume and quality of combined sewer overflows are registered (Hogland et al. 1979 an 1980). Observed extreme rainfall events were used for simulation of changes in water management in the city and the assessment of the results of these changes. It has been shown that using only one-point hyetographs introduces a very serious error in simulation of the runoff (Falk et al. 1980). Fig. 2 shows the SWMM-simulated runoff hydrographs from a 3 sq. km catchment in Lund using different rainfall inputs.

One interesting question arises: would the error decrease if the statistical point rainfall is used instead of statistical areal rainfall? In other words: will point rainfall frequency be the same as areal rainfall frequency?

In small catchments in Southern Sweden the short summer storms are consi-



		VOLUME m^3	PEAK FLOW m^3/s
——	Observed hydrograph.	47000	4800
– – –	Calculated hydrograph. Hyetograph from gauge No 2 used for entire catchment.	51400	5900
·······	Calculated hydrograph. Hyetograph from gauge No 3 used for entire catchment.	42600	4100
–·–·	Calculated hydrograph. Hyetograph from gauge No 4 used for entire catchment.	29700	2850
×××××	Calculated hydrograph. Hyetograph from gauge No 1 used for subcatchments 1,2,3, Hyetograph from gauge No 2 used for subcatchments 4,5,6,7,8,9, Hyetograph from gauge No 3 used for subcatchments 10,11,511,521.	46300	4720

Fig. 2. SWMM-simulated runoff hydrographs using different rainfall inputs.

dered to be most important from the point of view of design and pollution problems. Rainfall durations of some 10-30 min with high intensities cause the most serious flooding problems, combined sewer overflows and result in shock loads to receiving waters. In the engineering practice 10 min, 1 mm/min block rainfall is still used as a design storm.

In the paper a set of extreme rainfall events observed in Lund during a period of two years is presented. The observation period started in June 1978 and ended in September 1980.

The arbitrary criterion for selection of the events was set at a maximum 10 min average intensity observed for any of the 12 gauges. 10 rainfalls with highest 10 min average intensity observed in one of the gauges were chosen from 2 years observation data.

Point and areal intensities are presented for 10 events. Storm centered Areal Reduction Factors (ARF) are calculated for 10 events and all gauges in service. Size, shape and movement of the raincells is discussed within the context of observed meteorological background.

Rainfall Intensities

The maximum 1 min intensity observed during the period of two years was 2.31 mm/min as a point value (event No. 2) and 1.37 mm/min as an areal value for 10 sq.km area (event No. 1).

The maximum 10 min intensity is 1.07 mm/min as a point value and 0.94 mm/min as an areal value (event No. 1.). The areal intensities were calculated by Thiessens polygon method expanding outward from the gauge with maximum point intensity. Table 1 lists observed point and areal rainfall intensities for different time periods.

Table 1 – Observed rainfall intensities. (mm/min)

Event		1 min duration			10 min duration			20 minduration		
No	Date	point value	10 km value	20 km value	point value	10 km² value	20 km² value	point value	10 km² value	20 km² value
1	800823	1.59	1.37	0.66	1.07	0.94	0.36	0.79	0.64	0.37
2	800709	2.31	0.60	0.30	1.00	0.56	0.23	0.63	0.40	0.23
3	800713	1.75	0.68	0.48	0.98	0.57	0.34	0.67	0.47	0.34
4	800823	2.25	0.70	0.34	0.95	0.54	0.20	0.52	0.34	0.20
5	790524	1.47	0.58	0.37	0.70	0.40	0.19	0.43	0.27	0.19
6	790921	1.12	0.33	0.18	0.57	0.21	0.16	0.30	0.16	0.10
7	800822	2.11	1.20	0.71	0.57	0.42	0.25	0.47	0.31	0.25
8	800706	1.13	0.55	0.22	0.54	0.39	0.08	0.38	0.26	0.08
9	790625	1.24	0.78	0.51	0.51	0.38	0.15	0.26	0.20	0.14
10	800709	1.10	0.37	0.18	0.49	0.24	0.07	0.28	0.17	0.07

Fig. 3 shows the intensity-duration curves for 10 events with point values, 10 km^2 values and 20 km^2 values. Each line in the point value diagram represent values calculated for the same gauge, but different lines in the diagram are derived from different gauges. For comparison the synthetic intensity-duration curves with return period of 0.5, 1, 2, 5 and 10 years are shown in point value diagram. There are no original intensity-duration curves available for the region of Lund. The curves shown were calculated using a »Z« factor (Dahlstrom 1978) which make such calculations possible for any point in Sweden.

Fig. 3 shows that all rainfall intensities decline with increasing duration and area. It can be noticed that high intensity rainfalls were rather well represented during two years of observations because 4 of 10 observed events are situated above a 2-year return period curve. This can be explained by the fact that different lines does not represent the same raingauge, while synthetic intensity-duration curves are based on only one gauge. Event No. 1 has a return period of some-

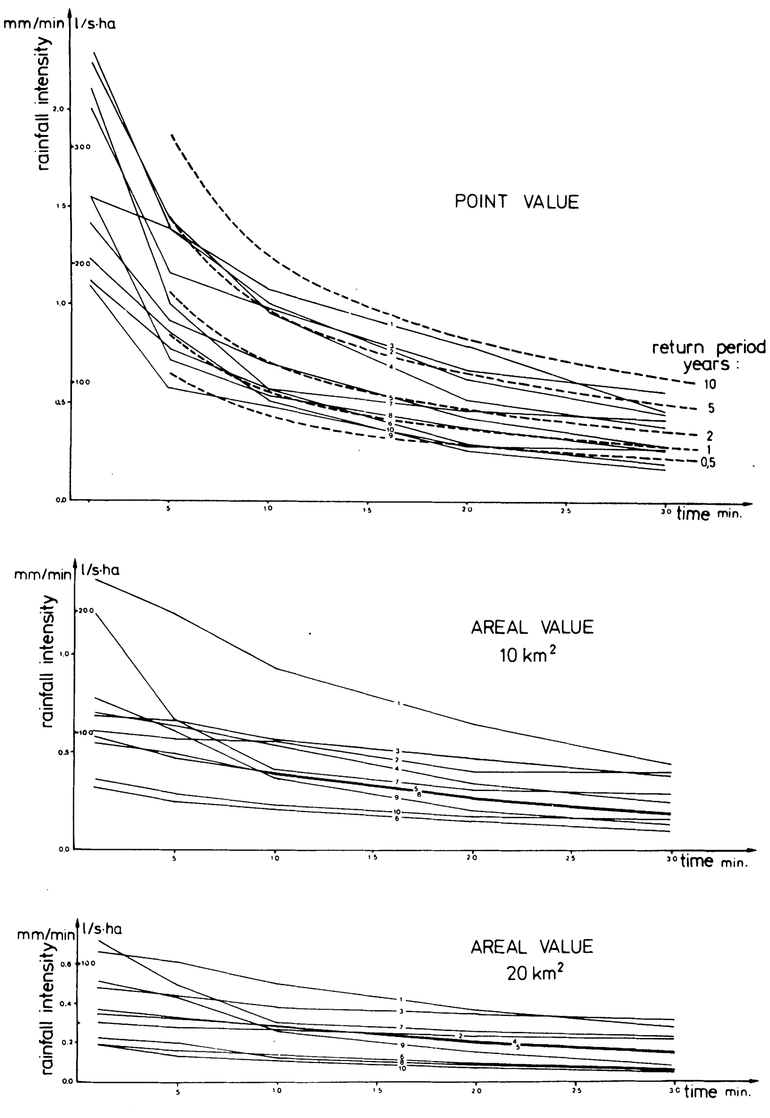


Fig. 3. Intensity-duration curves for 10 extreme rainfall events in Lund.

where between 5 and 10 years. From the diagram Fig. 3 it can also be noticed that intensity-duration curves for observed events do not follow the synthetic curves smoothly with any return period. For example event No. 1 has a return period of about 7 years regarding it as a 10 min average value, but only 4 years return period as 30 min average value. It can also be noticed that rainfall volumes observed during this type of storm definitely depend on the size of the area.

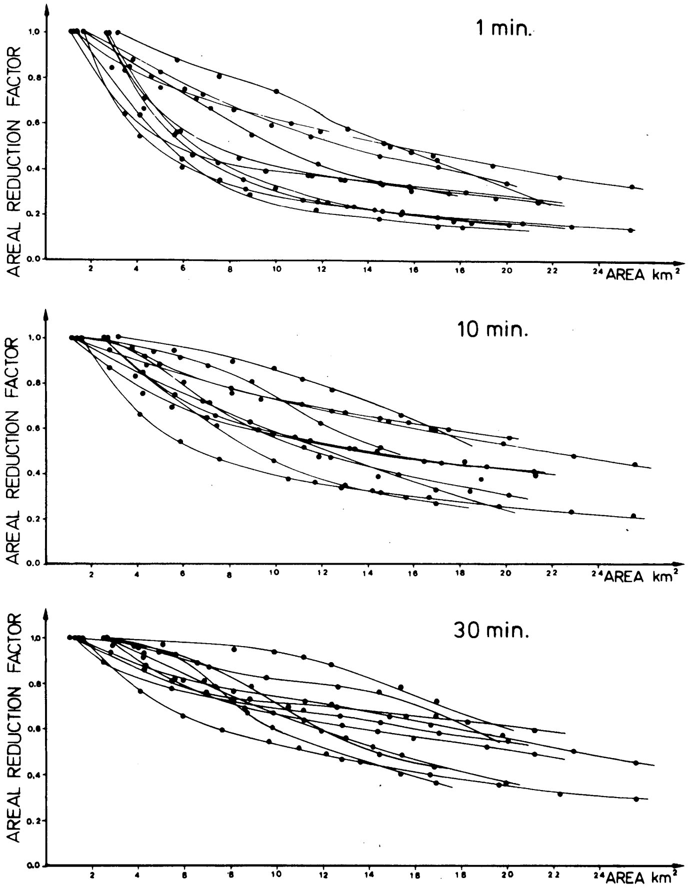


Fig. 4. Areal Reduction Factors for 10 extreme rainfall events in Lund.

Areal Reduction Factor

In order to show how the areal rainfall intensity decreases with increasing area, the storm centered areal reduction factors (ARF-s), for individual rainfall events, have been calculated. ARF-s represent the ratio between the maximum areal rainfall within the storm zone for the given area and duration, and the maximum point rainfall within the same storm zone and the same duration (Bell 1976). Calculations started for each event from the area represented by the gauge with the highest rainfall. The areas represented by gauges were determined by the Thiessen polygon method. Fig. 4 shows ARF-s calculated for all 10 rainfall events and different time periods.

Storm centered ARF-s are nothing more than a description of the areal properties of the individual storms. They tell nothing about the rainfall frequency distribution for a given area. Such a description can not be generalized to other storms as the area with the highest storm varies from event to event and the location of this area can not be predicted. As seen from Fig. 4, ARF-s decline differently for different events.

The fixed area ARF-s has been recognized as more useful for practical applications, being more statistical in character, as they represent the ratio between areal and point rainfall with the same return period (Bell 1976, Rodriguez et al. 1974). Having calculated statistically fixed area ARF-s would make possible construction of the areal intensity-duration curves with different return periods from one point intensity duration-curves.

24-hours fixed area ARF-s have been derived from 14 years data on 9 areas of 1,000 sq.km each in the United Kingdom and from 10 to 15 years data on an area of 3,000 sq.km in the United States (Bell 1976, Rodriguez 1974).

From the urban hydrology point of view, it would be interesting to derive fixed area ARF-s, or which is equivalent, to derive areal intensity-duration curves for much shorter rainfall durations and smaller area sizes which could be relevant for practical problems within city areas. Fixed area ARF-s will show much less variation between events than shown in Fig. 4 storm centered ARF-s, because fixed area ARF-s are not directly related to any individual recorded storm, but originate in rainfall statistics (Bell 1976). Hopefully, the continuation of measurements in Lund witll provide the necessary long record of data.

Size, Shape and Movement of the Raincells

In order to describe the characteristics of the raincell some arbitrary definitions have to be made. As the limits of the raincell are not sharply defined, the borderline has to be established in some way. On the other hand, in order to make a comparison between the cells possible, the limits of the raincells for different events must be selected in the same way for all events.

If the network of gauges is sufficiently dense, i.e. the distance between two gauges is small compared to the size of the raincell it is reasonable to expect that the gauges within the same raincell will have a high correlation coefficient between its hyetographs with no time lag introduced. If the time lag is introduced, the correlation factor between gauges will be higher in the direction of raincell movement compared with other directions.

Estimation of the drift of storm across the network is made by a correlation analysis technique (Marshall 1980). One minute isohyetal plots (not shown) indicate that the pattern of rainfall at adjacent gauges is often similar, but there is a time lag from one gauge to the next one. The apparent consistency of these lags suggests that they represent the drift of the rainstorm over the area covered by the gauge network.

A procedure for estimating the velocity and direction of the drift of the raincells was incorporated into a computer program. The procedure is based on the sample cross-correlation between all pairwise combinations of gauges. Supposing spatial stationarity the cross-correlation between gauges i and j is a function of the lag and the relative distance between gauges i and j

$$R(i,j,T) = \frac{\mathrm{Cov}\,(x(i,t),\ x(j,t+T))}{D(x(i))\ D(x(j))}$$

where

$x(i, t)$ – the rainfall intensity at gauge i and time t,
$D(x(i))$ – the standard deviation of gauge i,
($R(i, j, T)$ – the correlation between gauges i and j, and gauge j is lagged T min.

The calculations will produce correlations at $N(N\text{-}1)$ points, where N is the number of gauges in service.

Fig. 5 shows the example of correlation diagram with isolines drawn for correlation coefficients 0.5, 0.6, and 0.7. The »COLOR« system was used for contour

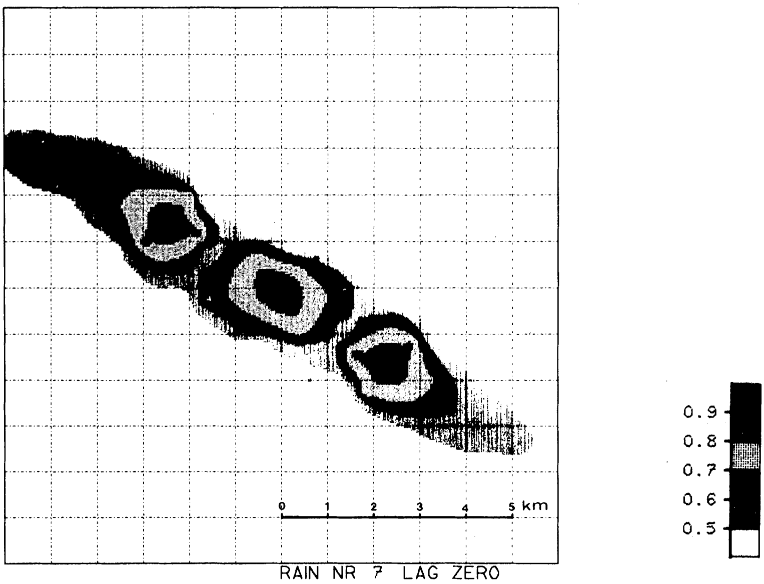


Fig. 5. An example of a correlation diagram.

map plotting (Jern 1980).

In order to produce correlation values in a regular gridnet and to smooth out errors, a moving averages procedure in two dimensions was applied. Values within a circle with a radius of 500 m where averaged with equal weight and the result was assigned to the centre of the circle. Then the circle was moved in steps of 500 m. and the procedure repeated until the grid was filled. NORMAP (Nordbeck 1973) library routines were used to produce isaritmic maps.

In the way described above, a number of graphs were obtained where the areas limited by 0.7 correlation isoline moved in the direction of the raincell movement. The speed and direction of movement of the raincells was then calculated by observation of how the centre of gravity of the area, limited by 0.7 correlation isoline, moves.

Fig. 6 shows diagrams of correlation coefficients for all rainfall events. The isolines shown represent correlations with a time lag zero. Movement of the raincells is indicated by a thick line drawn through centers of gravity of 0.7 area in diagrams with a consecutively increasing time lag.

Table 2 lists the speed, size and direction of movement of the rainfall cells for 10 rainfall events. Also direction of wind observed at Sturup (17 km SSE of Lund) and in Copenhagen is shown.

Table 2 – Size, speed and direction of movement of the rainfall cells during 10 extreme rainfall events.

	Rainfall cell			Wind	
Event No	Speed m/s	Direction (clockwise from N) Degree	Size km	(observed at Sturup)	(observed in Copenhagen) Degree
1	11.2	147	2.0	SE	155
2	7.0	319	2.9	WNW	123
3	7.0	330	3.0	NNE	60
4	14.6	146	2.3	SE	155
5	8.2	324	2.8	WSW	355
6	15.0	85	2.3	ENE	70
7	22.2	148	3.6	E	125
8	9.2	330	2.8	NNE	3
9	25.0	5	7.6	ENE	5
10	9.0	335	2.2	WNW	303

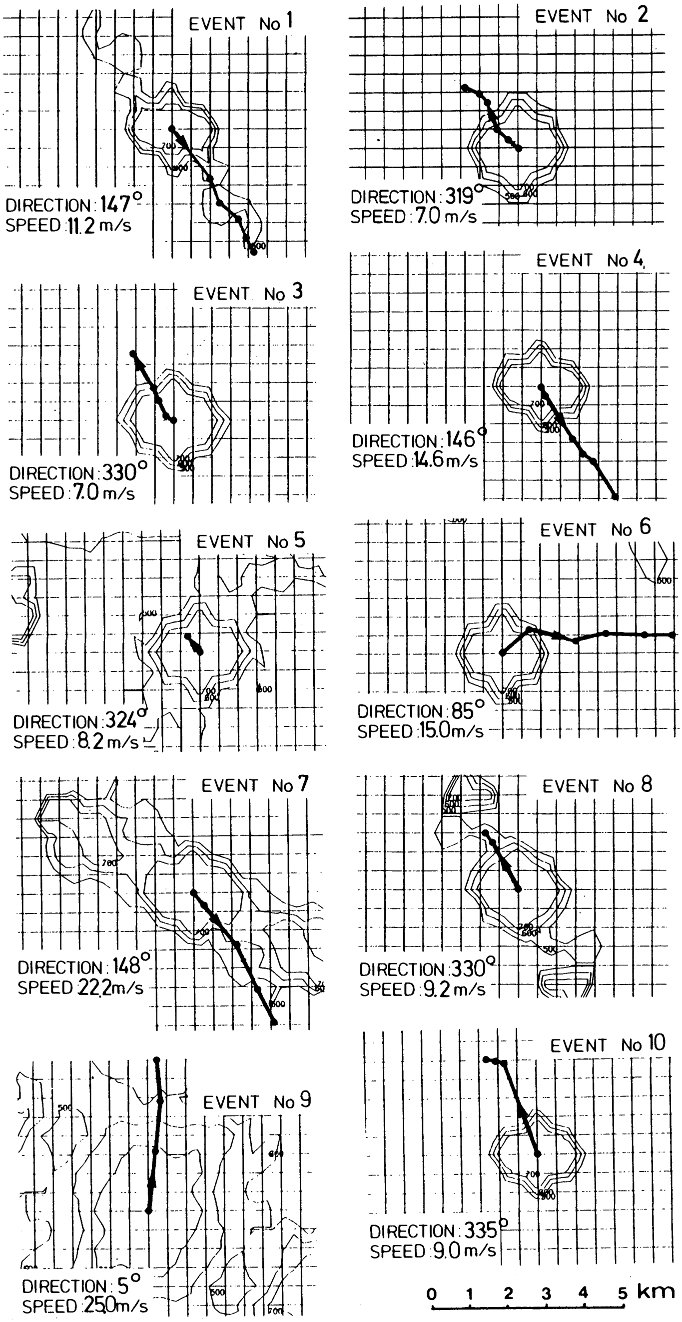


Fig. 6. Correlation diagrams showing shape, size and movement of rainfall cells.

Meteorological Context of the Extreme Rainfall Events

Two general rain producing mechanisms are usually distinguished: macro-scale mechanisms such as cyclones and anticyclones which express themselves in great horizontal and vertical transport and exchange of air-masses, and the meso-scale mechanisms. The later produce meso'scale raining units (or convective cells) and usually appear as passing showers in the rear of extra-tropical cyclones or as local Cumulonimbus clouds inland, or occur around certain kinds of cold fronts and in tropical cyclones (Bergeron 78).

The average yearly precipitation in Lund amounts to about 650 mm. The major part of this amount falls during the late summer and autumn in connection with the passage of frontal zones. The frontal rainfalls are usually of many hours duration and relatively low intensity. These rainfalls are not interesting for urban hydrologists in southern Sweden.

It has been previously observed that even these frontal cloud-systems often show »granulated« and partly convective structure of precipitation pattern (Bergeron 1978). These »partly convective« storms were also observed in Lund with short, high intensity periods overlapping long periods of low intensity. But the most important rain systems producing all the 10 storms presented are meso-scale units often expressing themselves with thunderstorms.

The most typical situation when the convective storms occur in Lund is after the passage of a cold front, especially if the low pressure area is to the north and the air masses move from south to north. Such a situation caused rainfall events Nos. 2,3,8 and 9.

The other typical situation for the occurrence of convective rainfalls is when no frontal structures are in the area and a westerly wind brings wet air masses which rise in convective mechanisms and Cumulonimbus clouds form. This situation occurred during rainfall events Nos. 1,4,6 and 7. During rainfall No. 5 the convective movement has occurred as a result of vertical air mass transport in the rear of a warm front before a rapidly approaching cold front from the south-east and during winds from the south. Rainfall No. 10 is one of the many showers that day in connection with a cold front which passed the Lund area from south to north. To sum up it can be stated that the most dangerous situation in terms of high intensity rainfalls occurs in Lund in connection with cold fronts and south winds.

Conclusions

Serious errors in single-event hydrograph simulations can be introduced if the one-point rainfall input is used instead of areal rainfall input.

If the historical single-events are to be used in simulation, especially in urban hydrology applications, the knowledge of real rainfall volume is very important.

A true areal rainfall spatial distribution is never really known. It must be substituted by hyetographs from all gauges available within the area allocated to correspoding subcatchments.

Observations in Lund suggest that the reasonable density of gauges is one gauge per 2 or 3 sq.km.

Derived in Lund storm centered Areal Reduction Factors confirm the conclusion that areal intensities for short-term, high-intensity rainfalls, decrease with the increasing size of the area.

These ARF-s should not be used for areal reduction of intensity-duration curves, because a significant uncertainty would be introduced by ARF-s variation.

In order to take into account the spatial rainfall variation, the areal intensity-duration curves or the area centered ARF-s, based on a long time series of observations in a dense network of gauges, must be derived.

Such areal intensity-duration curves, based on areal statistics of rainfall could be used for choosing a »design storm«.

The size of the raincells observed in Lund during 10 extreme rainfall events, defined as an area within 0.7 correlation isoline, varies between 2.0 and 7.6 sq.km.

The speed of the raincells observed in Lund varies between 7.0 and 25.0 m/s.

The direction of movement of the raincells is generally in good agreement with wind direction observed at the ground level.

The most intense convective rainfall events occur in Lund in connection with the passage of a cold front and winds from South.

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Address:
Department of Water Resources
Engineering,
Lund Institute of Technology/
University of Lund,
Fack 725,
S-220 07 Lund,
Sweden.