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Areal Intensity-Duration-Frequency Curves for Short Term Rainfall Events in Lund

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»Design Storms«, which are usually derived from point intensity-duration-frequency (*i-d-f*) relationships, neither reflect the areal variations of the rainfall pattern nor the dynamics of the moving storms. Design storms derived from point *i-d-f* curves can no longer be accepted as a reasonable rainfall input for simulation of runoff from large urban catchments. One possible way of improving the rainfall input for runoff simulationes is to develop areal *i-d-f* relationships and use them for deriving design storms. The raingauge network operating in Lund for the past four years provided the set of good quality data necessary for developing such relationships. This paper describes the procedure of developing point and areal *i-d-f* relationships and shows the differences between them. Statistically developed factors reducing point values to areal values for areas up to 25 sq.km for different durations and return periods of up to three years are given. Presented relationships will give more realistic design storms in comparison with design storms derived from point *i-d-f* curves. Observed spatial variations of the maximum rainfall intensities in Lund can probably be explained by the city's influence on the rainfall pattern. Orographic effects, earlier observed in Lund, can not be seen from the data used during this study. Since the used data set includes only short term, high intensity rainstorms, it can be concluded that long and low-intensity rainfalls are mainly responsible for orographic effects. This paper is the first part of a major work aiming at developing a stochastic model simulating a time series of the areal rainfall.

Introduction

Intensity-duration-frequency (*i-d-f*) relationships, usually derived from point rainfall measurements, have for a long time been used for synthesizing so-called »design storms«. Simple block rain can easily be derived from *i-d-f* curves for the desired duration and return period and then be used as an input for simulation of runoff occurrences.

Since *i-d-f* curves comprise the statistical properties of a long time series of rainfall data in a comprehensive form, it is easy to believe that rainfall input derived from them has a good statistical justification. As long as the rational method was used, no proof could be found that statistical information taken from point *i-d-f* curves was not always sufficient for design purposes. Later on, when more sophisticated methods of runoff prediction came into common use, it was realised that single block rain not only gives a wrong picture of a hyetograph, but also the wrong rainfall volume (Arnell 1982).

Furthermore, it was soon realised that the rainfall frequency given by intensity-duration relationships did not correspond to the observed runoff frequency (Sieker 1978, Urbonas 1979, James 1981).

During recent years a number of design storms with different shapes have been developed (Keifer at al 1957, Amorocho 1981, Arnell 1982). Some of them tried to reproduce a real shape of observed hyetographs. But these design storms cannot reflect the dynamics of the moving storms and by no means represent areal properties of the rainfall pattern.

The main reason that there is no simple linear relationship between the frequencies of rainfall and runoff is probably the fact that the rainfall frequency comes from point observations, while runoff represents the areal and dynamical properties of the rainfall. In other words, a similar rainfall hyetograph observed by one gauge can give a number of different runoff occurrences, or vice versa.

Convective storms, which are most significant for design purposes, are rather limited in space. Design storms derived from point *i-d-f* curves have no areal dimensions, but are nevertheless used for runoff simulations on catchments of different sizes. We can reduce this idea »ad absurdum« by trying to imagine one single design storm falling simultaneously on thousands of square kilometers. It is obvious that some kind of reduction factors, taking into consideration the areal properties of a rainfall, have to be used, especially while modeling runoff from large catchments.

The comprehensivness and convenience of the statistical information in *i-d-f* curves, make us believe that design storms will stay with us for some time.

One possible way of improving the rainfall input derived from *i-d-f* curves is to develop AREAL INTENSITY-DURATION-FREQUENCY curves. Another way is to develop area-rainfall depth relationships from which factors reducing rainfall from point to areal values can be obtained for different areas, durations and return periods. Those factors can then be used to reduce the design storms from point to areal values.

These solutions are more practical than complete, because neither areal *i-d-f* curves nor areal reduction factors describe the dynamics of the moving storms.

The third and most desirable solution is to develop a statistical model simulating a rainfall series taking into account temporal, spatial and dynamical variations of the rainfall pattern (Bras et al. 1976, Amorocho et al. 1977, Gupta et al. 1979).

The need for reasonable rainfall input for runoff simulations in big cities has caused a number of area-rainfall depth relationships to be developed in different countries (Abraham et al. 1976, Bell 1976, Rodrigues-Iturbe et al. 1974).

One important problem to face is the lack of sufficiently long time series of observations on a dense network with good time synchronisation.

The raingauge network installed in Lund in 1978 covers approximately a 25 square kilometre area with 12 gauges. More than three years of registered data are assumed to be sufficient to produce reasonably good statistics for short term rainfall. This paper describes point and areal *i-d-f* curves derived for the city of Lund. Presented areal relationships will give more realistic design storms in comparison with design storms derived from point relationships. The question of validity of the presented relationships outside the city of Lund is beyond the scope of this work.

This paper is the first part of a major work aiming at developing a statistical model for simulation of the areal time series of the rainfall.

The Gauging System and Data Processing

Twelve automatic tipping-bucket gauges were installed in Lund in 1978 to cover an area of approximately 25 sq. km. The depth resolution of the gauges is 0.035 mm per tipping, the time resolution of registration is one minute. All gauges are connected via open telephone lines to the receiving station in the laboratory of the department. Since all gauges are governed by the same clock, the absolute time synchronisation is achieved. Fig. 1 shows the situation of the raingauges in Lund. The gauging system and the data collecting procedure have been described before (Falk et al. 1979, Niemczynowicz at al. 1981) Collected data were processed according to the flow chart shown in Fig. 2.

The rainfall series from all twelve gauges were divided into rainfall events with an arbitrarily chosen interval between the events set to 40 minutes. Since the main goal of this study is to compare the point rainfall statistics with the areal rainfall statistics for short term rainfalls, all events with low intensity were taken out of the data base. The criterion chosen was that all events with rainfall depth less than 0.35 mm observed during ten successive minutes were excluded from data base. If any of the gauges exceeded the criterion, data from all other gauges were accepted for the same period of time. It was found that this procedure only eliminated rainfall events with a very uniform temporal and spatial distribution. All data

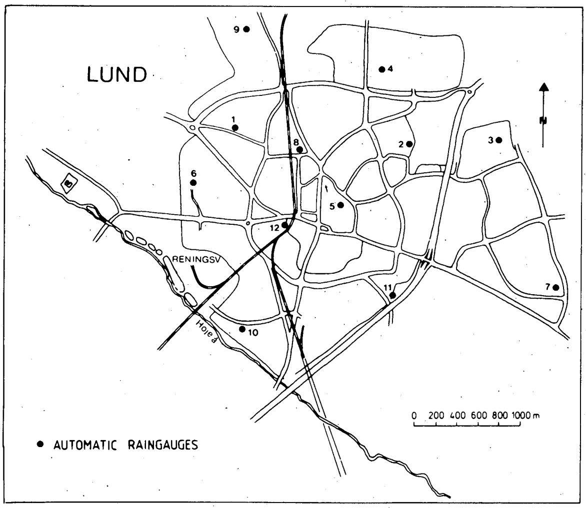

Fig. 1.
Location of the raingauges in Lund.

suspected to be wrong and all events with less than eight gauges operating were taken away from the data base. This data base, originally consisting of about 130 thousands lines was reduced to 20 thousand lines which made file operations much easier. A total of 588 rainfall events were finaly included into the data base.

Malfunction of the gauges was observed or suspected about 15% of the time on the average for the 12 gauges. Gauge No. 1 was the worst with malfunctions during 38% of the time, gauges Nos. 2,3 and 8 were functioning all the time. Most of the malfunctions were caused by broken telephone lines.

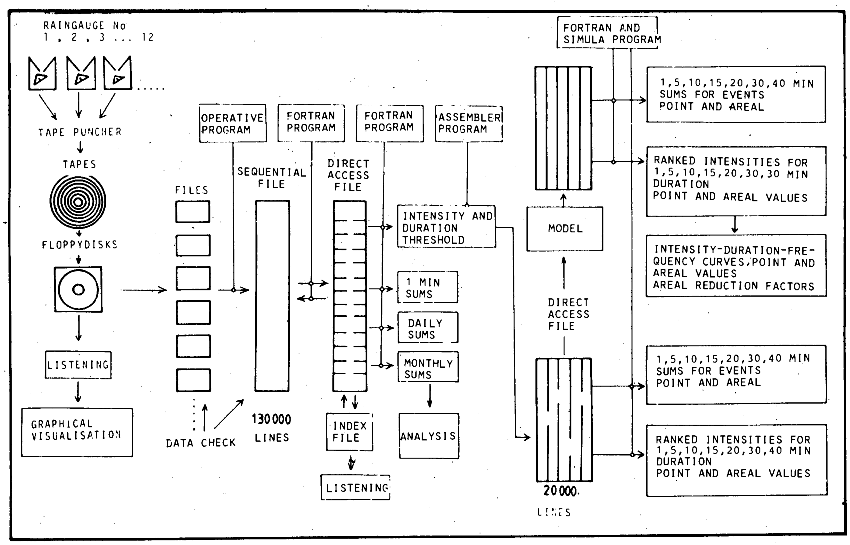

Fig. 2. Flow chart for rainfall data processing.

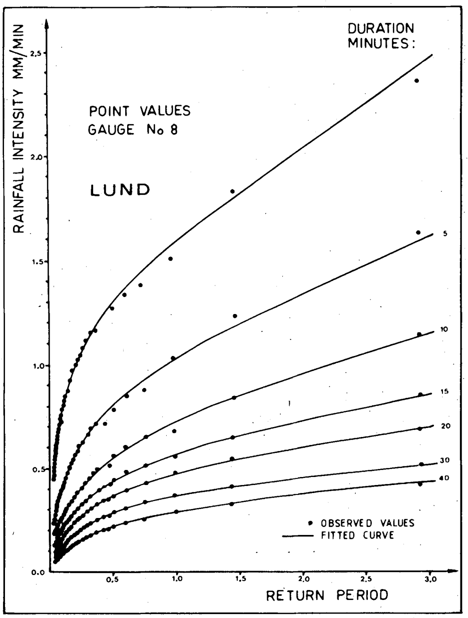

Fig. 3. Intensity-return period diagram for gauge No. 8.

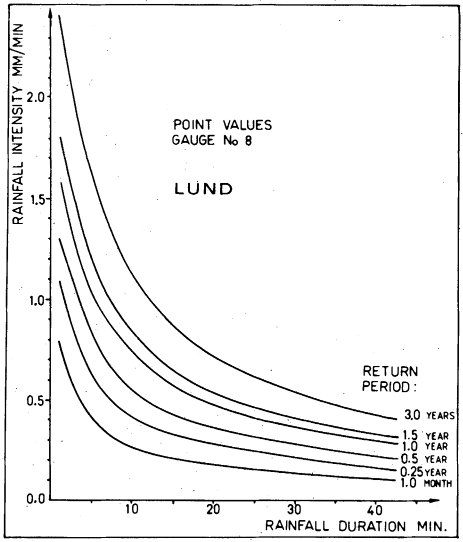

Fig. 4. Intensity-duration-frequency relationships for gauge No. 8.

Point Intensity-Duration-Frequency Relationships

Point *i-d-f* curves were developed separately for all 12 gauges in Lund. The one hundred maximum values of rainfall intensity were found for durations of 1,5, 10, 15, 20, 30, and 40 minutes. Intensities for each duration were then ranked and listed for each gauge. The return period for each intensity and duration was calculated by dividing the total time of operation of the gauge by the rank number. Descending maximum intensities were then plotted on a linear scale against return periods for each duration and gauge.

A smoothed curve can be drawn manually or by fitting some mathematical distribution function. Several investigators have found that the Log-Pearson type III distribution function fits well with the maximum rainfall intensity data (Arnell 1982). Since our main interest is the differences between point and areal rainfall, no other distribution functions were tested during this study. A Log-Pearson distribution function was fitted to the observation points by method of moments according to the computer program given by Kite (1977).

Fig. 3 shows an example of the intensity-return period diagram with observed and fitted distribution function for one of the gauges. Values from the fitted distribution curves were then rearranged and the usual form of intensity-duration -frequency curves were drawn as shown in Fig. 4. The described procedure was followed for the 12 gauges and resulted in 12 complete *i-d-f* curves, each of them representing a point value. The mean point-value *i-d-f* curve was finally calculated by averaging the values for all durations and return periods. Fig. 5 shows the mean point-value intensity-duration-frequency curves. The values of maximum average intensities, for different durations and return periods estimated by the Log-Pearson Type III distribution function are shown in Tabel 4.

Spatial Variations of Rainfall Intensity

Tabel 1 gives the range of differences in maximum intensities observed between 12 gauges in Lund. The highest, the lowest, average values and standard deviations between 12 gauges are given for different durations.

The differences between the highest and the lowest values and standard deviations decrease quickly for shorter return periods. Obviously, extreme intensity values are the most unevenly distributed in space. The highest values of intensity occur persistently in gauges Nos. 2,3,4,5 and 12 which are situated in the central part of the town and to the north-east which is in the most prevailing wind direction. The lowest intensity values are typical for gauges Nos. 9, 1, 11, and 6, situated outside of the town. This effect can perhaps be explained by the influence of the city on precipitation.

A strong local variation of rainfall depth in Lund explained as an orographic effect was reported before (Niemczynowicz et al. 1981). Comparisons of the rainfall sums from our data base given in Tabel 2 show no clear picture of such an effect.

The orographic effect was found by analysis of a complete time series of a rainfall and our data base includes only short-term, high intensity rainstorms. It can be concluded indirectly that most of the altitude differences in rainfall sums are created during long and low-intensive rainfall events.

Tabel 1 – Maximum rainfall intensities observed in 12 gauges in Lund during a three year period. (The figure in parenthesis is the gauge No.)

Maximum intensity mm/min	Duration in minutes						
	1	5	10	15	20	30	40
Highest value	3.19(7)	1.98(2)	1.36(3)	1.00(2)	0.84(3)	0.62(3)	0.55(4)
Lowest value	1.31(9)	1.08(11)	0.86(9)	0.64(9)	0.51(9)	0.40(9)	0.37(9)
Average 12 gauges	2.20	1.61	1.20	0.93	0.76	0.57	0.47
Standard deviation	0.61	0.51	0.43	0.34	0.26	0.18	0.15

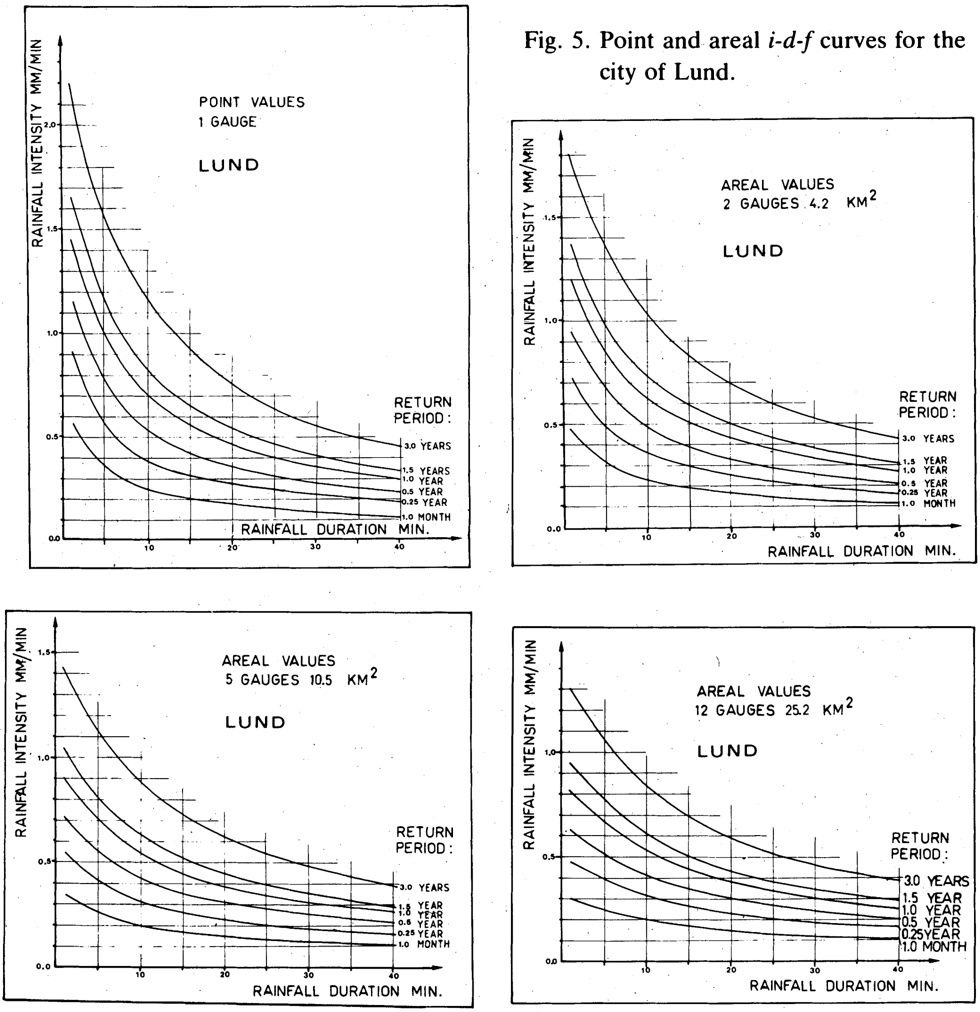

Fig. 5. Point and areal *i-d-f* curves for the city of Lund.

Table 2 – Rainfall sums for 12 gauges in Lund for the period 78 12 84 – 81 11 25

Raingauge No	Rainfall Sum (mm)	Raingauge No	Rainfall Sum (mm)
1	1113	7	1143
2	1205	8	1253
3	1146	9	1077
4	1172	10	1125
5	1145	11	1134
6	1113	12	1144

Areal Intensity-Duration-Frequency Relationships

In order to extrapolate rainfall data from point measurements to areal values, specific areas were associated to all gauges. The influence that different methods of extrapolating point values to areal means have on the accuracy of areal estimation was investigated by Gottshalk and Jutman (1982). Results show that the magnitude of error is to a small extent influenced by the method of extrapolation. For simplicity of calculations, the method of Thiessen polygons was chosen for this study. Tabel 3 lists the areas associated with 12 gauges.

Due to periodical malfunction, the gauges represented slightly different periods of observations. In order to develop areal relationships, mean rainfall values from a number of gauges had to be treated simultaneously. In order to avoid shortening to total length of the record by averaging the observation period for all gauges, a special routine for reproducing the missing values was developed. The average weighted values from the three nearest functioning gauges were inserted in place of the missing values for each minute of the data base. After this procedure, new point *i-d-f* relationships were developed for all 12 gauges. No significant changes in results were observed after this procedure. All further calculations were performed on the same data base with reproduced missing values.

Areal *i-d-f* curves were developed by making calculations on mean weighted values from combinations of the gauges. Each combination consists of 12 groups of gauges. In each combination, the same gauge is represented the same number of times.

For example, a mean-value *i-d-f* curve representing an area of two gauges was developed as follows: mean value of rainfall intensity for each minute in the data base was calculated for the arbitrarily chosen group of two gauges. Intensity-duration-frequency relationships were then developed for this group. The next group of two gauges was chosen and new relationships were developed. Calculations proceeded until 12 groups of gauges were treated. This resulted in 12 different, complete intensity-duration-frequency relationships representing different areas of pairs of gauges. Finally, the mean-value relationship was calculated representing the mean area of 12 pairs of gauges.

The same procedure of calculating was carried out for the groups consisting of

Table 3 – Areas associated with raingauges in Lund

Gauge No	Area Sq.Km	Gauge No	Area Sq.Km	Gauge No	Area Sq.Km
1	1.56	5	1.48	9	1.65
2	1.82	6	2.11	10	2.80
3	2.92	7	2.57	11	2.91
4	2.52	8	1.44	12	1.56

3, 4, 5, 6, 8, 10 and 12 gauges.

Intensity-duration-frequency curves for point value, and the 4, 10, and 25 sq.km values are shown in Fig. 5. The point and areal mean-values of the maximum intensity for different durations and return periods fitted to log-Pearson Type III distribution function are shown in Table 4.

Areal Variations of Rainfall Intensity

By rearranging the values from point and areal *i-d-f* relationships the statistical areal reduction factors were developed for different durations and return periods. Factors for 3.0, 1.5, 1.0, and 0.5 years return periods are shown in Fig. 6 with duration as a curve parameter. Fig. 7 shows areal reduction factors with return period as a curve parameter. It is interesting to notice that statistically derived areal reduction factors not only depend on duration, but also on the return period, which was questioned before (Bell 1976). Table 5 lists the statistical areal reduction factors for different durations and return periods.

Conclusions

Areal *i-d-f* relationships give rainfall values different from point *i-d-f* relationships. Areal rainfall intensity values are lower for all durations and return periods.

If point *i-d-f* curves were used for deriving design storms, an error in average rainfall intensity and rainfall volume will be introduced for simulation of runoff from real catchments.

The magnitude of error depends on duration, return period and the size of the catchment.

The most significant differences between point and areal rainfall values can be found for short durations and long return periods.

Factors reducing point rainfall values to areal values are given in this paper. The presented relationships will give more realistic design storms in comparison with such storms derived from point *i-d-f* curves.

Acknowledgements

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Table 4 – Point and areal mean-values of the maximum rainfall intensity for different durations and return periods fitted to observation points by log-Perason Type III distribution function (mm/min).

Return Period	Duration in Minutes 1	5	10	15	20	30	40
	Point value (area 2.1 sq km 1 gauge)						
3.0 years	2.19	1.55	1.17	0.92	0.74	0.55	0.45
1.5 year	1.64	1.11	0.82	0.64	0.53	0.40	0.32
1.0 year	1.44	0.96	0.70	0.55	0.45	0.34	0.28
0.5 year	1.14	0.74	0.53	0.42	0.35	0.27	0.22
0.25 year	0.89	0.53	0.39	0.31	0.26	0.22	0.17
1.0 month	0.56	0.33	0.24	0.19	0.16	0.13	0.11
	Areal value (area 4.2 sq km 2 gauges)						
3.0 years	1.80	1.35	1.04	0.83	0.68	0.52	0.42
1.5 year	1.35	0.98	0.74	0.59	0.49	0.37	0.31
1.0 year	1.18	0.85	0.63	0.51	0.42	0.32	0.27
0.5 year	0.94	0.65	0.48	0.39	0.33	0.25	0.21
0.25 year	0.72	0.48	0.36	0.30	0.24	0.20	0.16
1.0 month	0.46	0.30	0.22	0.18	0.16	0.13	0.11
	Areal value (area 6.3 sq km 3 gauges)						
3.0 years	1.67	1.29	1.00	0.80	0.66	0.51	0.41
1.5 year	1.22	0.92	0.70	0.57	0.47	0.37	0.30
1.0 year	1.06	0.79	0.60	0.49	0.41	0.32	0.26
0.5 year	0.83	0.61	0.46	0.38	0.32	0.25	0.21
0.25 year	0.64	0.42	0.35	0.30	0.24	0.20	0.15
1.0 month	0.41	0.28	0.21	0.18	0.15	0.12	0.10
	Areal value (area 8.4 sq km 4 gauges)						
3.0 years	1.53	1.22	0.97	0.77	0.64	0.49	0.40
1.5 year	1.12	0.87	0.68	0.55	0.46	0.36	0.29
1.0 year	0.98	0.75	0.58	0.48	0.40	0.31	0.26
0.5 year	0.77	0.58	0.44	0.37	0.31	0.24	0.20
0.25 year	0.57	0.42	0.33	0.27	0.24	0.20	0.15
1.0 month	0.38	0.27	0.21	0.17	0.15	0.12	0.10
	Areal value (area 16.8 sq km 8 gauges)						
3.0 years	1.34	1.08	0.85	0.70	0.59	0.46	0.38
1.5 year	0.98	0.78	0.62	0.51	0.43	0.34	0.28
1.0 year	0.86	0.68	0.54	0.44	0.38	0.30	0.25
0.5 year	0.67	0.53	0.42	0.35	0.30	0.24	0.20
0.25 year	0.57	0.41	0.32	0.27	0.22	0.20	0.15
1.0 month	0.32	0.25	0.20	0.17	0.15	0.12	0.10
	Areal value (area 21.0 sq km 10 gauges)						
3.0 years	1.31	1.06	0.84	0.69	0.58	0.46	0.38
1.5 year	0.95	0.77	0.61	0.50	0.43	0.34	0.28
1.0 year	0.83	0.67	0.53	0.44	0.37	0.30	0.25
0.5 year	0.64	0.52	0.41	0.34	0.29	0.24	0.20
0.25 year	0.56	0.40	0.32	0.26	0.22	0.19	0.15
1.0 month	0.30	0.24	0.20	0.17	0.15	0.12	0.10
	Areal value (area 25.2 sq km 12 gauges)						
3.0 years	1.30	1.05	0.84	0.69	0.58	0.45	0.37
1.5 year	0.94	0.76	0.61	0.50	0.42	0.34	0.28
1.0 year	0.81	0.66	0.52	0.43	0.37	0.30	0.24
0.5 year	0.63	0.52	0.41	0.34	0.29	0.23	0.19
0.25 year	0.47	0.38	0.31	0.25	0.23	0.18	0.15
1.0 month	0.29	0.24	0.19	0.16	0.14	0.12	0.10

Table 5 – Statistical areal reduction factors. (Areal rainfall intensities can be obtained by taking given percentages of point values).

Return Period	Duration in minutes 1	5	10	20	30	40
	Area 4.2 sq km 2 gauges					
3.0 years	82.0	87.3	89.1	92.3	94.2	94.4
1.5 year	82.1	88.0	90.1	93.0	94.4	94.7
1.0 year	82.0	88.3	90.6	93.2	94.5	95.4
0.5 year	82.1	89.0	91.5	94.0	95.1	95.9
0.25 year	82.4	90.2	92.8	95.0	95.9	96.8
1.0 month	82.9	91.3	94.5	96.3	96.9	97.2
	Area 8.4 sq km 4 gauges					
3.0 years	69.7	78.8	82.5	86.4	89.2	90.1
1.5 year	68.5	78.5	82.6	87.5	90.1	91.0
1.0 year	68.0	74.5	83.1	87.9	90.7	91.8
0.5 year	67.5	78.6	83.9	89.1	91.4	92.7
0.25 year	67.6	79.0	85.1	90.8	93.0	93.8
1.0 month	68.0	81.1	87.3	92.6	93.8	94.4
	Area 16.8 sq km 8 gauges					
3.0 years	61.3	69.5	73.1	79.0	84.3	85.2
1.5 year	59.7	70.6	75.6	81.7	86.6	87.3
1.0 year	59.2	71.7	76.7	83.0	87.5	88.6
0.5 year	58.4	71.8	78.8	85.1	89.1	90.4
0.25 year	58.1	72.3	80.2	87.3	90.3	92.0
1.0 month	57.2	75.1	84.0	90.8	93.0	93.5
	Area 21.0 sq km 10 gauges					
3.0 years	59.6	68.2	72.2	78.0	83.6	84.5
1.5 year	57.9	69.3	74.7	81.0	85.8	86.7
1.0 year	57.2	69.8	75.8	82.2	86.6	88.2
0.5 year	56.2	70.6	77.9	84.5	88.3	89.9
0.25 year	55.2	71.3	80.4	86.4	89.7	91.8
1.0 month	54.7	73.6	83.1	90.2	92.2	93.5
	Area 25.2 sq km 12 gauges					
3.0 years	59.0	67.6	71.9	77.6	83.6	84.1
1.5 year	57.1	68.8	74.4	80.8	85.8	86.7
1.0 year	56.4	69.3	75.5	81.9	86.6	87.9
0.5 year	55.2	70.2	77.3	84 5	88.3	89.9
0.25 year	54.4	71.3	79.8	86.9	90.1	91.2
1.0 month	53.4	73.0	82.7	90.2	92.2	93.5

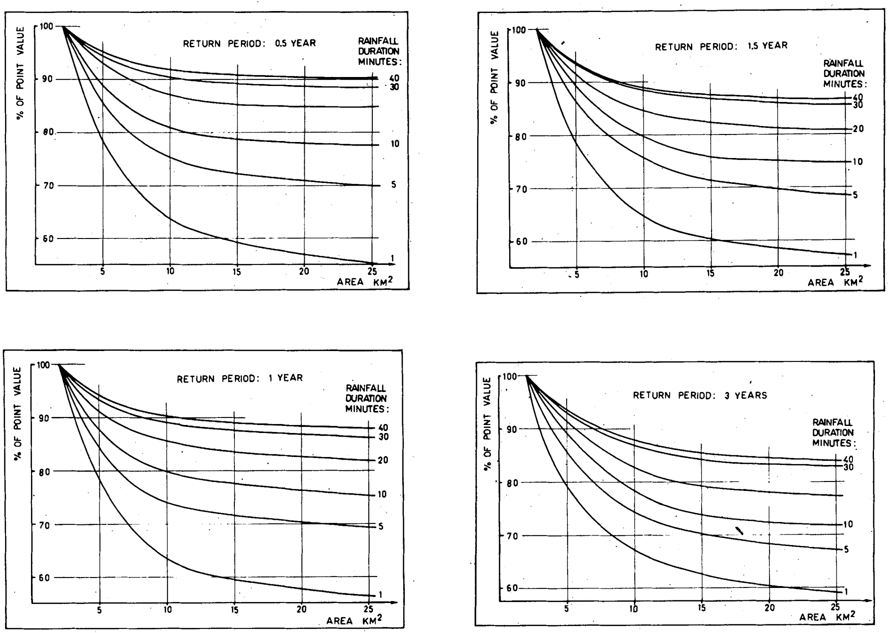

Fig. 6. Statistical areal reduction factors.

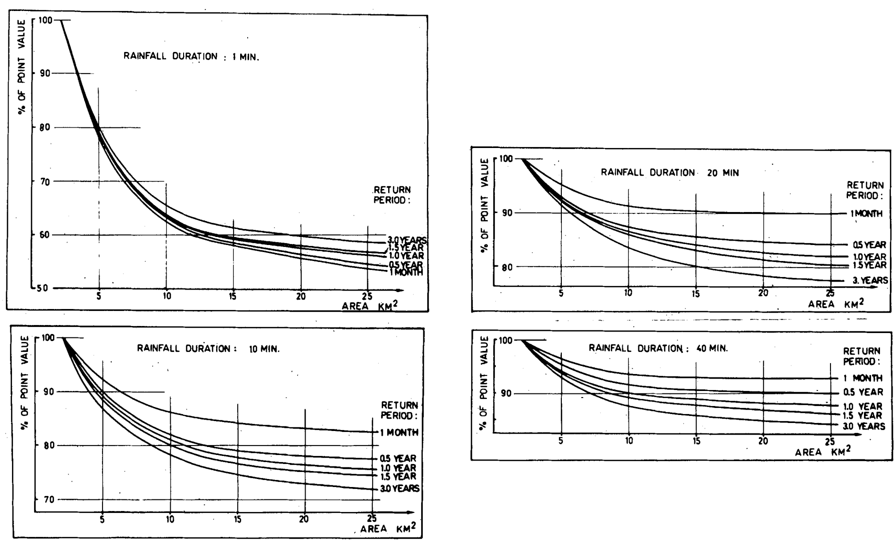

Fig. 7. Statistical areal reduction factors.

References

Abracham, C., Lyons, T. C., and Schulze, K., W. (1976) Selection of a Design Storm for Use With Simulation Models. National Symposium on Urban Hydrology, Hydroulics and Sediment Control, Univ. of Kentucky, July.

Amorocho, J., and Wu, B. (1977) Mathematical Models for the Simulation of Cyclonic Storm Sequences and Precipitation Fields. *Journal of Hydrology, 32.*

Amorocho, J. (1981) Stochastic Modeling og Precipitation in Space and Time. International Symposium on Rainfall-Runoff Modeling Mississippi State Univ., May.

Arnell, W. (1982) Rainfall Data for the Design of Sewer Pipe Systems. Chalmers Institute of Technology, Report series A:8, Göteborg.

Bell, F., C. (1976) The Areal Reduction Factors in Rainfall Frequency Estimation. Institute of Hydrology, Wallingford, U.K. Report No. 39, December.

Bras, R., L., and Rodriguez-Iturbe, I. (1976) Rainfall Network Design for Runoff Prediction. *Water Resources Research, Vol. 12,* No. 6.

Falk, J., Jönsson, O., and Niemczynowicz, J. (1979) Measurements of Rainfall Intensities in Lund. Lund Institute of Technology, Department of Water Resources Engineering, Report No. 3023.

Gottshalk, L., and Jutman, T. (1982) Calculation of Areal Means of Meteorologic Variables for Watersheds. Nordiske Hydrologiske Konferanse, Förde.

Gupta, V., K., and Waymire, E., C. (1979) A Stochastic Kinematic Study of Subsynoptic Space-Time Rainfall. *Water Resources Research Vol. 15,* No. 3.

James, W. (1981) Kinematic Design Storm Incorporating Spatial and Time Averaging. Second International Conference on Urban Storm Drainage, Univ. of Illinois, Urbana.

Keifer, C., U., and Chu, H., H. (1957) Synthetic Storm Pattern for Drainage Design. *Journal of the Hydraulics Div., ASCE, Vol. 83,* No Hy 4.

Kite, G., W. (1977) Frequency and Risk Analysis in Hydrology. Water Resources Publications, Fort Collins, Colorado.

Niemczynowicz, J., and Jonsson, O. (1981) Extreme Rainfall Events in Lund 1979-1980. *Nordic Hydrology, Vol. 12.*

Rodriguez-Iturbe, I., and Mejia, J., M. (1974) On the Transformation of Point Rainfall to Areal Rainfall. *Water Resources Research, Vol. 10,* No. 4.

Sieker, F. (1977) Statistical Simulation Model Based on Analysis of Variance. 3-rd International Hydrological Symposium, Fort Collins.

Sieker, F. (1978) Investigation of the Accuracy of the Postulate »Total Rainfall Frequency Equal Flood Peak Frequency«. International Conference on Urban Storm Drainage, Univ. of Southampton.

Urbonas, B., (1979) Reliability of Design Storms in Modeling. International Symposium on Urban Storm Runoff, Univ. of Kentucky.

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