Nordic Hydrology, 17, 1986, 65-82

Areal Reduction Factors from Rain Movement

Lars Bengtsson
Div. Hydrology, Uppsala University, Sweden

Janusz Niemczynowicz
Dept. Water Resour. Eng., Lund Inst. Technology, Sweden

The relation between rain movement and areal reduction of rain intensity is investigated. An approach for calculating areal reduction factors from point hyetographs and storm speed is suggested. Very good agreement is found between moving storm derived areal reduction factors and reduction factors determined using a dense net of rain gauges. Moving areal reduction factors calculated for design storms and historical storms are shown not to differ much between different cities in the Nordic countries.

Rainfall Data for Design Purpose

For design of pipes and other constructions in urban sewer networks either design storms or historical storms are used when expected runoff is calculated. The design storm may be an average intensity-duration-frequency storm (*i-d-f*) or a more complex storm developed from the *i-d-f* storm. When historical storms are used, a number of actually observed storms are used as input in an urban runoff model, and statistical analysis is performed on the simulated flows. No matter whether design storms or historical storms are used, point rainfall data is usually taken as areal rainfall data. Although it has long been realized that this procedure results in overestimating the areal rainfall and, if proper runoff model parameters are used, in overestimating storm runoff, it is just recently that systematic studies have been devoted to the relation between areal and point rainfall.

The importance of areal reduction factors (*ARF*) for the design of small drainage structures was considered by Yen and Chow (1980), who suggested that *ARF* should be used if the drainage area is larger than 25 km^2. In Montreal, Nguyen and Rouselle (1981) made observations with a better resolution in space. Studies on spatial and temporal scale relevant for urban problems have been carried out by Niemczynowicz (1982, 1984) in the city of Lund, Sweden. In deriving areal reduction factors he performed the statistical analysis separately on point rainfall and areal rainfall. The areal reduction factor of a storm of a certain return period and a certain duration is simply the areal precipitation value divided by the point precipitation value.

Another factor that has been discussed within urban hydrology is the importance of the movement of raincells on peak flows in sewer pipes. It has been shown by Niemczynowicz (1984) that although peaks are accentuated when rain cells move in downstream direction of a sewer system, these peaks, even for extreme situations, are only increased by about 20%. So far the relation between moving rainstorms and reduction factors has, at least explicitely, not been considered. There should be a relation between rain storm dynamics and areal reduction of rain intensity. The spatial reduction of rainfall intensity, usually expressed by areal reduction factors, depends on the following properties of the rainfall field: 1) limited extension of raincells 2) movement of raincells 3) spacing between raincells and 4) how raincells develop, decay and absorb each other. If a single raincell is considered to move over an area at constant speed without changing shape or character, an exact relation between areal rainfall and storm speed can be determined. Having such a relation, the part of areal reduction factor that depends on extension and movement of raincells can be derived. Since urban areas are limited in areal extension, rainfalls should not be expected to change drastically in intensity when storms move over a city. Areal reduction factors, derived from raincell extention and movement only, here called Moving storm derived Areal Reduction Factors (*M-ARF*) should be comparable to statistically derived ARF.

Whereas *ARF*:s have been determined only for a few cities, and for short time of rainfall duration maybe only for the city of Lund, point rainfall data with short time resolution exists for many places. By simulating observed point rainfalls or design storms to move at a given speed over an area it is possible to determine areal rainfall and *M-ARF* for areas of different extension. Using observed point rainfall and storm velocity calculated from wind velocity observed at the nearest airport, *M-ARF* can be calculated for many cities, thus explaining regional differences and answering the important question of regional validity of areal reduction factors. This idea is tested in this paper. Computed *M-ARF*:s for some Scandinavian cities are given, and in some cases, compared with previously calculated *ARF*:s.

Raincell Structure

Raincells can be subdivided according to their horizontal extension as suggested by Austin and Houze (1982). In large mesoscale areas extending up to 1,000 km^2 there are smaller mesoscale areas, which consist of clusters of convective raincells, each raincell extending over 10-30 km^2. However, recent studies using radar observation techniques, Einfalt and Schilling (1984), and observations using densely spaced gauges, Felgate and Read (1975) and Niemczynowicz and Jönsson (1981), suggest that individual raincells are smaller than stated above.

The basic idea behind the work presented in the present paper is, that areal reduction factors can be determined by letting a storm observed at a fixed point move over an area. A required assumption is that the shape of the hyetograph and its velocity of movement do not change during its passage over the area. In order to check the validity of the assumptions, the shape of rainfall intensity hyetographs along the direction of rain movement should be compared. Data from Lund given by Niemczynowicz and Jönsson (1981) and Niemczynowicz (1984) was chosen for such a comparison. Ten extreme rainfall events are described in details in the works cited above. For two events, hyetographs along the axis of raincell movement are shown in Fig. 1 and Fig. 2. It is seen from the figures that the hyetographs show differences in peak intensity. These differences could have been caused either by growth and decay in intensity of the raincells when they move over the area, or by the fact that the centres of the raincells passed at different distances from the different gauges. Thus, computed areal rainfall depends on which of the hyetographs that is simulated to move over the area. However, it is seen from the figures that the different hyetographs of each event show a similarity in shape, which is seen also for the other eight rainfall events in the study from Lund. This means that although computed areal rainfall depends on the hyetograph that is used for simulation, the areal reduction factor is not very dependent on the choice of hyetograph. This conclusion was confirmed by calculations of *M-ARF*:s for the four hyetographs shown in Fig. 1. Results are shown in Table 1.

In a study on regional distribution of rain intensities Dahlström (1979) described rain intensity as a function of storm duration and return period using the expression

$$i = a\,t_d^{b} \tag{1}$$

where

i – storm intensity,
t_d – storm duration,
a – a coefficient which depends on return period, regional conditions and slightly on storm duration, and
b – another coefficient.

The coefficient b was found to be almost constant, about -0.7, for some different

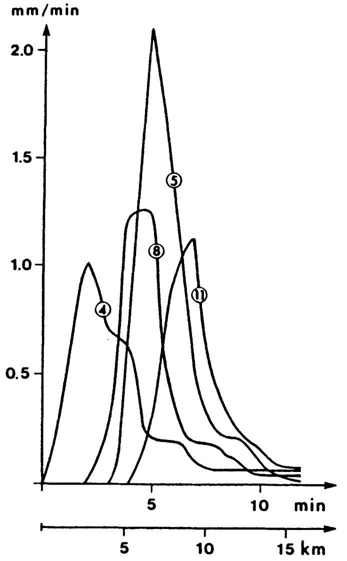

Fig. 1.

Rain intensity observed in four different gauges in Lund situated approximately in the direction of the storm movement. The hyetographs are numbered by the number of the gauges given by Niemczynowicz and Jönsson (1981). Storm speed 22 m/s.

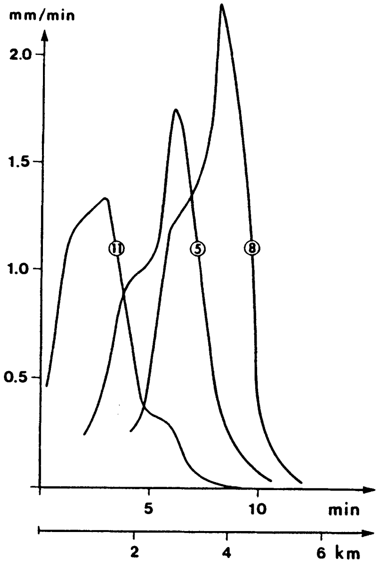

Fig. 2.

As for Fig. 1, but observations in three gauges.

Storm speed 7.7 m/s.

Table 1 – Areal Reduction Factors Calculated from the movement of the four hyetographs shown in Fig. 1.

Hyetograph No.	area (km^2) 5	10	15	20	25
4	0.87	0.81	0.75	0.72	0.69
8	0.85	0.80	0.75	0.72	0.69
9	0.86	0.80	0.75	0.72	0.69
11	0.86	0.79	0.75	0.72	0.69

Swedish cities, different 10-year periods and different return periods. Therefore, the character of convective storms should be rather similar at different Swedish cities. This means that although the absolute frequency of storm generation convection varies over Sweden, the relative frequency of different types of convection is similar at different places.

The Danish Engineering Society had precipitation series from six Danish cities evaluated, DIF Spildvandskomiteen (1974). Formulas for the country as a whole, valid for the summer half-year, were presented in the form of Eq. (1). For return periods within the range 0.2-2 years the coefficient b varied only between 0.70 and 0.73. Deviations for different cities from the country-wide formulas are reduced the longer the precipitation series are, indicating that the deviations are random. Data from Copenhagen given by Statens Vejlaboratorium (1984) confirms that the coefficient b is almost a constant, although this is not explicitely stated in the paper.

Since the coefficient a in Eq. (1) is only slightly dependent on storm duration, the relation between storms of different duration is according to Eq. (1) almost equal for all locations, i.e.

$$\frac{i_2}{i_1} = \left(\frac{t_2}{t_1}\right)^b \tag{2}$$

where

i_1 - storm intensity of duration t_1,
i_2 - storm intensity of duration t_2.

Two frequently used design storms are the Chicago Design Storm, Keifer and Chu (1957), and the Sifalda Design Storm, Sifalda (1973). The location of the peak intensity within the duration t_d is for the Chicago Design Storm described by the ratio between time prior to peak intensity and total time of duration. For some places in Chicago Keifer and Chu found this ratio to be 0.38; for Cincinnati, Ohio, Preul and Papadakis (1973) found the ratio 0.33; for three cities in Czechoslovakia Sifalda (1973) found a ratio of 0.34-0.36. Using data from Göteborg, Sweden, Arnell (1982) found a ratio of 0.35 for return periods exceeding one year. The fact that the ratio is rather constant for different cities gives indications that the convective storm character is similar for the different cities.

Sifalda (1973) evaluated rainfall registrations from three places in Czechoslovakia. He found that for all three places time to peak intensity, duration of period with maximum intensity, and the ratio maximum to average intensity were almost equal for the three cities, again indicating similarity of convective storm character at different places.

ARF Derived from Storm Speed

For an area that is simply a narrow strip along which a raincell represented by a block rain is moving, areal reduction factors can be analytically related to storm speed and rainfall duration. A block rain of duration t_d moving at speed v extends over a distance

$$L_r = v\, t_d \tag{3}$$

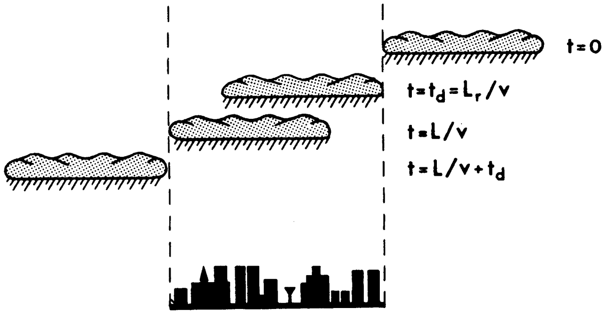

Fig. 3.
Rain cell of extension L_r and duration t_d moving over an area of length L at speed v.

where

L_r – extension of block raincell,
v – storm speed,
t_d – storm duration.

Fig. 3 shows conceptually a rain storm moving over a catchment extending over a distance L. At time $t = 0$ it just begins to rain at the point of the catchment facing the rain front. At $t = t_d = L_r/v$ the entire raincell covers the catchment area under consideration, and it still does at $t = L/v$ but the front of the raincell has now reached the far end of the catchment. From then on until $t = L/v+t_d$ the rain cell moves over the far end point of the catchment. Fraction of the area covered by rain during different periods of the raincell movement is

$$\begin{aligned} \text{covered fraction} &= v\,t/L & 0 < t < t_d \quad &(4a)\\ &= v\,t_d/L = L_r/L & t_d \leq t < L/v \quad &(4b)\\ &= v(t_d+L/v-t)/L & L/v \leq t < L/v + t_d \quad &(4c)\\ &= 0 & t \geq L/v + t_d \quad &(4d) \end{aligned}$$

The covered fraction of the catchment over a period corresponding to the storm duration is determined by integration over that period. After division by the time of duration the areal reduction factor is

$$ARF = \frac{1}{t_d} \int_{t'}^{t'+t_d} (\text{covered fraction})\,dt \qquad (5)$$

where t is so chosen, such that the maximum value is obtained.

For a block rain the areal reduction factor for a narrow strip (or rain extending over unrestricted width) is

$$ARF = L_r/L = v\,t_d/L \qquad \text{if} \quad L_r < 0.5 \qquad (6a)$$

$$ARF = 1 - 0.25\,L/L_r = 1 - 0.25\,L/v\,td \qquad \text{if} \quad L_r \geq 0.5 \qquad (6b)$$

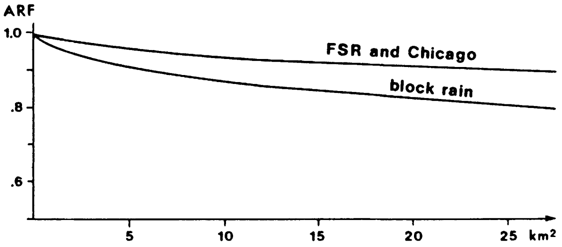

Fig. 4. *M-ARF* for rain storms for Göteborg of one year return period and 10 minutes duration. Infinite raincell width. Storm speed 10 m/s.

Real storms with block rain distribution hardly ever exist. Observed rainfall hyetographs show recession, which is accounted for in other design storms than block rain. Areal reduction factors should depend on the type of storm that is moving over a catchment. In order to find how the choice of design storm influences areal reduction factors, different synthetic storms were simulated to move over a squared catchment. Design storms from Göteborg taken from Arnell (1982) were used. A comparison between computed moving areal reduction factors, when the storm is covering the full width off the area, is shown in Fig. 4. While, for example, the moving areal reduction factor for 20 km^2 is calculated to be 0.90 for Chicago and FSR storms (Flood Studies Report, Natural Environmental Research Council, 1975) when a rain speed of 10 m/s is used, the *M-ARF* for block rain is more pronounced, 0.81. A disadvantage of using other synthetic storms than block rain is that neither the dimension of the raincell nor the relation (Eq. 3) between storm speed, duration and raincell dimension is clearly defined. Still, the definition of raincell dimension given by Eq. (3) is used throughout this paper.

The areal reduction factor of individual real storms and of synthetic storms depends on the rain intensity distribution within the raincell in the direction of the storm movement and transverse to this direction as well. If the storm moves at constant speed, the distribution in the direction of movement is the distribution in time. Transverse to the storm direction the raincell may extend over infinite width, or the rain intensity may have a uniform block distribution or some other lateral distribution. When a lateral block distribution is used, the areal reduction factor as function of catchment area drops very fast to low values with increasing area when the catchment area exceeds the rain cell dimension, as is shown in Fig. 5. This is not in agreement with Niemczynowicz's (1984) investigations. Therefore, another lateral distribution than block distribution must be sought for. However, even the measurements from Lund have a too coarse resolution in space for making it possible to find lateral rain intensity distributions directly from the measured intensities. Instead, one has to assume a certain distribution and when possible compare measured distribution with the theoretical one and always compare measured areal reduction of point precipitation with computed theoretical reduction.

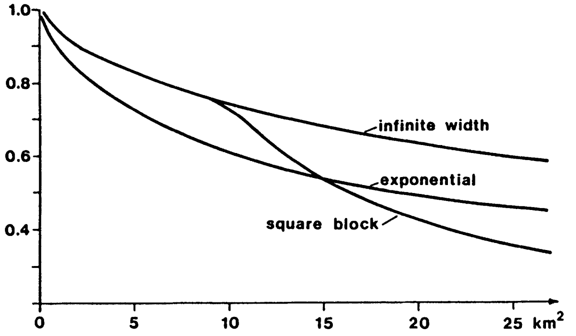

Fig. 5. *M-ARF* for block rain of 10 min duration assuming different intensity distributions transverse to the storm movement: infinite width, square block distribution, exponential intensity distribution with r = 0.7. Storm speed 5 m/s.

A reasonable lateral intensity distribution may have the form of a decay function from the centre of the raincell. A fictive but still reasonable approach is to assume an exponential lateral distribution,

$$i = i_c e^{-ky} \tag{7}$$

where

i – rain intensity with index c at centre position, i.e. maximum rain intensity of a cross section,

y – lateral distance from this centre, and

k – a distribution coefficient.

When areal reduction factors computed using exponential lateral intensity distribution and block distribution are compared, as in Fig. 5, it is found that the former gives higher *ARF* (less reduction of areal rainfall relative point rainfall) for large areas and lower *ARF* (more reduction) for small areas than a block width distribution does.

The lateral distribution coefficient, k, should depend on raincell dimension. It may be related to the ratio, r, between intensity at half cell width from centre and intensity at storm centre

$$r = i_{0.5}/i_c \tag{8a}$$

which gives

$$k = 2 \ln(1/r)/L_r \tag{8b}$$

where

$i_{0.5}$ – rain intensity at 0.5 L_r from storm centre and

L_r – rain cell dimension.

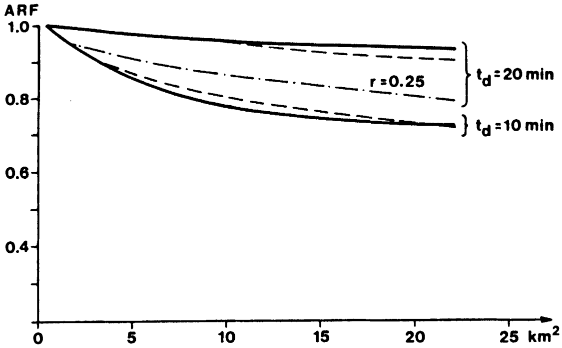

Fig. 6. Observed *ARF* (solid lines) and *M-ARF* determined for lateral distribution ratio r=0.5 (broken lines) for 10 min duration (two lower graphs) of event 1 of the storm events presented by Niemczynowicz and Jönsson (1981), and for 20 min duration (three upper graphs) also *M-ARF* with $r=0.25$, i.e. k in Eq. (7) kept at the same value as for the 10 min. storm, as indicated on the graph.

Since neither an infinite width of raincell, nor a lateral block distribution are physically reasonable, further calculations of reduction factors are made using the assumption of exponential lateral distribution. The choice of lateral distribution affects computed *M-ARF* very much. For the Lund data the ratio between intensity at half cell width from centre and intensity at storm centre is about 0.5. The good correspondence between observed and computed reduction factors is illustrated in Fig. 6. *M-ARF* of a storm event was computed using data from one gauge and compared to observed *ARF* centred around the gauge, showing maximum catch. Best fit for the 10-minute storm was found for the ratio $r = 0.5$, which corresponds to a distribution coefficient of 0.21 km^{-1}. Usually, as shown in Fig. 6, computed *M-ARF* agrees better with "centred" *ARF* for different storm durations if r is kept constant for all durations than if the distribution coefficient k is kept constant.

Knowing the storm speed and assuming a lateral rain intensity distribution, moving storm derived reduction and areal precipitation can be computed from point hyetographs. The point hyetographs can represent real storms or synthetic storms. To compare observed and computed areal precipitation the observed point hyetograph No. 8 of Fig. 1 is used as an example. The point hyetograph was simulated to move at the observed rain speed. The observed point hyetograph, the corresponding 3 minute block rain, areal precipitation computed by moving the point hyetograph, areal precipitation from 9 gauges, and areal precipitation computed by moving the block rain are compared in Fig. 7. The three areal graphs follow each other very closely. The conclusion can be drawn that the areal precipitation calculated by moving observed hyetographs and block rains is a good approximation of real areal precipitation observed in many gauges.

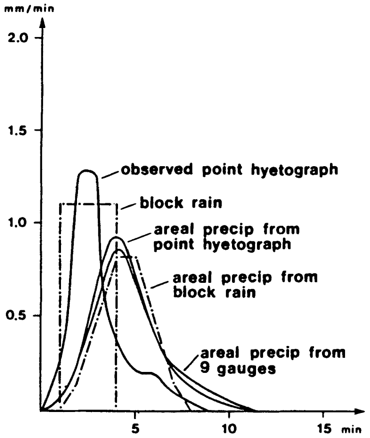

Fig. 7.
Comparison between point hyetographs and areal precipitation derived by different approaches using hyetograph No. 8 of Fig. 1.

Observations of Storm Speed

The storm speed has a strong influence on the moving areal reduction factor. Lower the storm speed more pronounced is the areal reduction with the same point hyetograph. In their work from Lund, Niemczynowicz and Dahlblom (1984) found that most storm velocities were in the range 5-15 m/s. Only 3.5 % of the storms moved with a higher speed than 22.5 m/s. It seems that the average storm speed of intense storms is just below 10 m/s.

There is not a good correspondance between storm speed and wind velocity observed at close to ground level. However, many researchers (e.g. Shearman 1977, Marshall 1980) have found a good correlation between storm speed and wind velocity at 600-700 mb. For 158 storm events at Sturup Airport, Sweden, Niemczynowicz (1984) found that the average wind velocity was 12.5 m/s with a standard deviation of 6.2 m/s. The regression formula, which gave the best fit to observed storm speed, is

$$v = 2.64 + 0.583\, v_{600} \qquad (9)$$

where

v – storm speed and
v_{600} – wind speed at 600 mb (m/s)

From a correlation such as Eq. (9) storm speed can be determined from wind observations from airports, and statistics of storm speed can be evaluated on large data sets. Three years of data (1982-83-84) from eight meteorological stations in Sweden and from Oslo, Norway have been used for statistical analysis. Rainy days were defined as days when the precipitation was at least 1 mm. Since convective

Table 2 – Wind speed statistics (m/s) at 600 mb height during days of at least 1 mm precipitation, 1982-84 May-Sept., and storm speed determined from the regression Eq (9).

met. stn	No events	Observed mean	st.dev	Log-Normal mean	st.dev	storm speed
Luleå	189	12.85	6.38	2.42	0.54	10.13
Östersund	106	12.80	7.95	2.36	0.64	10.10
Sundsvall	224	11.84	5.31	2.35	0.53	9.54
Visby	205	14.27	6.58	2.54	0.50	10.96
Stockholm	200	12.06	5.88	2.36	0.55	9.67
Karlsborg	35	13.14	6.74	2.44	0.55	10.30
Oslo	306	11.77	6.22	2.28	*)0.68	9.50
Göteborg	252	14.01	6.33	2.52	0.52	10.81
Lund	158	12.47	6.23	2.39	0.54	9.91
mean		12.77				10.09

*) Only data from 1984 has been fitted to Log-Normal distribution.

storms usually occur during summer, only data from May through September was used. As shown in Table 2, the average wind speed at 600 mb for the nine different places only varied between 11.8 m/s (Oslo) and 14.3 m/s (Visby). The standard deviation of the wind speed was about 6 m/s for all the stations. The two parameters in the log-normal distribution was found to be very similar for the different stations with a mean of 2.4 and a standard deviation of 0.53, except for the "mountainous" places Östersund and Oslo for which the standard deviation was higher.

When the mean wind speed at 600 mb for each of the meteorological stations is inserted into Eq. (9) the mean storm speed for the different places is found to vary only between 9.5 and 11.0 m/s. Since it previously in the paper has been argued that the areal reduction factor, due to the similarity shape of point hyetographs, is mainly dependent on storm speed, it seems that *ARF*:s should be very similar all over Sweden.

Comparison between Observed ARF and M-ARF Derived from Synthetic Storms

Using a network of gauges extending over the city of Lund, Niemczynowicz (1984) determined *ARF* for storms of different durations and return periods. These reduction factors are considered as "true" values. *M-ARF* estimated from the moving storm approach can be compared to the "true" *ARF*. In doing so, a block rain given by the *i-d-f* and also a Chicago design storm were simulated to move at a

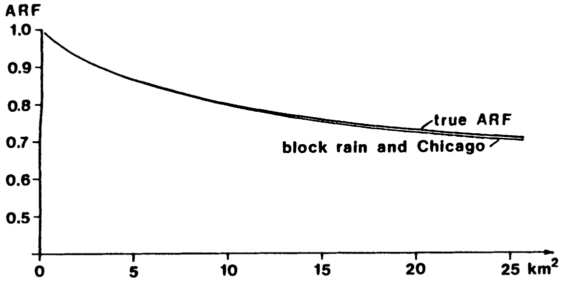

Fig. 8. Areal Reduction Factors of design storms for the city of Lund, Sweden, as derived for block rain storm and Chicago storm moving at 10 m/s having an exponential intensity distribution transverse to the direction of movement with half value of the storm centre intensity at half cell dimension distance from the centre. Comparison is made with "true" ARF determined from observations in twelve gauges over three years. Time of storm duration 10 minutes.

speed of 10 m/s. The assumed rain intensity distribution transverse to the storm was exponential. Computed areal reduction as function of area is shown in Figs. 8-9.

When comparison is made between actually observed *ARF* and *M-ARF* computed for synthetic storms, it is seen that the agreement is perfect for storms of 10 min duration, and for storms of longer duration better for block rain than Chicago storm. However, if the Chicago design storm is assumed to move at 7 m/s, the computed *ARF*:s for rain storms of 20 and 30 minutes duration are even closer to the "true" values than what is calculated using block rain moving at 10 m/s. It may be noted from observations that *ARF* has been found to depend on return period. This is obtained by simulating rain movement of Chicago design storm, but not for block rain, unless the storm speed or lateral rain intensity distribution is varied with return period.

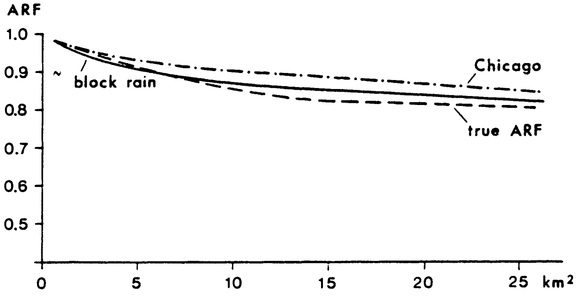

Fig. 9. As for Fig. 8 for time of duration 20 minutes. Chicago storm moving at 7 m/s follows "true ARF" so closely that it is not shown.

M-ARF Computed for Individual Rain Storms

The ten storms presented by Niemczynowicz and Jönsson (1981) discussed previously were used for computing areal reduction with the suggested approach, i.e. using observations from one gauge and storm speed. In order to investigate the sensitivity of the choice of gauge, computations were performed for three different gauges. Examples of computed *M-ARF* for different rainfall duration are shown in Tables 3-4. For individual storms *M-ARF* depends somewhat on the choice of rain gauge, but for average values the storm speed approach does not seem to depend on from which gauge data is used. Moving storm derived *ARF* for the ten storms for 1 gauge and averaged for 3 and 12 gauges in Lund are compared in Table 5. The *ARF* statistically derived by Niemczynowicz (1984) from a large data material is also shown. The agreement between moving areal reduction factors derived from a single gauge or averaged from many gauges and statistically derived *ARF* is very

Table 3 – Moving Areal Reduction Factor for ten individual storm events in Lund. Storm duration 10 minutes. Catchment area 20 km^2.

event No	1	2	3	4	5	6	7	8	9	10	mean
moving gauge 1	0.72	0.65	0.60	0.80	0.62	0.73	0.87	0.68	0.98	0.64	0.74
moving gauge 2	0.72	0.58	0.60	0.83	0.66	0.74	0.88	0.86	0.90	0.65	0.74
moving gauge 3	0.72	0.60	0.57	0.80	0.65	0.86	0.83	0.68	0.90	0.63	0.73

Table 4 – Moving Areal Reduction Factor for ten individual storm events in Lund. Storm duration 20 minutes. Catchment area 20 km^2.

event No	1	2	3	4	5	6	7	8	9	10	mean
moving gauge 1	0.88	0.76	0.77	0.89	0.84	0.94	0.90	0.88	0.95	0.77	0.86
moving gauge 2	0.88	0.81	0.87	0.91	0.76	0.92	0.90	0.78	0.95	0.79	0.85
moving gauge 3	0.86	0.81	0.80	0.93	0.83	0.92	0.87	0.84	0.95	0.79	0.86

Table 5 – Average Areal Reduction Factors of ten intense storms in Lund for an area of 20 km^2.

duration (min)	moving storm gauge 1	moving storm 3 gauges	moving storm 12 gauges	"true value" 0.5 year return period
10	0.74	0.74	0.76	0.78
20	0.86	0.86	0.85	0.85
30	0.91	0.92	0.90	0.88
40	0.92	0.93	0.91	0.91

Table 6 – Areal Reduction Factor determined with the moving storm approach (first value) applied to ten extreme storm events in Lund, and "true" *ARF* of 0.5 year return period given by Niemczynowicz (1984) (value after the slash).

duration	area (km^2)				
(min)	5	10	15	20	25
10	0.87/0.89	0.81/0.82	0.77/0.79	0.74/0.78	0.72/0.77
20	0.93/0.93	0.90/0.88	0.88/0.86	0.86/0.85	0.84/0.85
30	0.96/0.95	0.94/0.91	0.93/0.89	0.92/0.89	0.91/0.88
40	0.96/0.95	0.95/0.93	0.94/0.92	0.93/0.91	0.92/0.90

good. It seems that *M-ARF* can well be determined from only one point hyetograph, and that *M-ARF* well describes the true reduction of areal precipitation.

In Table 6 a summarizing comparison is made between statistically derived *ARF*:s and *M-ARF*:s derived from the moving storm approach. The agreement is very good, even for large areas. It should be possible to derive *ARF* for any place where rain data from one gauge and storm speed are available.

M-ARF for Design Storms for some Swedish Cities

Given design storms for different cities and storm speeds, areal reduction factors can be derived for different cities. When comparison was made between observed *ARF* and moving storm derived *ARF* for Lund, best agreement was found for block rain with storm speed 10 m/s and Chicago design storm with storm speed 7-10 m/s. Moving storm derived reduction factors using block rain moving at 10 m/s are identical for all cities showing no regional differences. However, *i-d-f* storms from different Swedish cities, as given in the design manual, Höganäs Avloppshandbok (1975), show somewhat different character. For example, for storms of two year return period the intensity ratio between storms of 30 and 10 minutes' duration is about 0.48 for Lund and Helsingborg; 0.51 for Uppsala and Malmö; 0.54 for Stockholm and Göteborg; and 0.62 for Norrköping and Borås. Therefore, a synthetic design storm is less peaked in Norrköping and Borås than in the other cities. Hence, the areal reduction too, should be less pronounced.

To test how much *M-ARF*:s differ for design storms from different cities, the moving storm approach was tested on design storms of two year return period for Lund and Borås, and computed *ARF*:s were compared. The Chicago storm was assumed to move at the average storm speed found from regression using wind speed at 600 mb (Table 2). For Borås the storm speed from Göteborg Airport (Landvetter) was used. The computations showed only small differences in *ARF*:s for the two cities. The difference is largest for storms of short duration, but as shown in Fig. 10 even for storms of 10 min duration *M-ARF* for Borås is less than

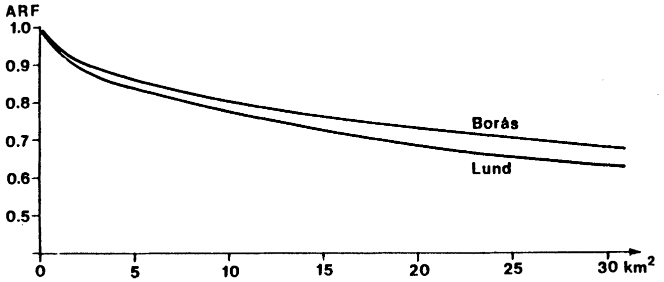

Fig. 10. Areal Reduction Factors of design storm of two year duration and 10 minutes duration in Lund and Borås assuming exponential lateral intensity distribution.

0.05 higher than the corresponding value for Lund up to an area of 30 km^2. Lund and Borås were chosen for comparison of *M-ARF,* since the difference between *ARF* for these two cities should be higher than between any other cities mentioned in this section. Borås is the place for which the ratio of 30 min rain intensity to 10 min rain intensity is the highest (less pronounced peak) and the wind speed is very close to the highest (cf. Göteborg Table 2), which means that *M-ARF* should be high. Data from Lund shows the lowest 30 to 10 min rain intensity ratio (pronounced peak) and almost the lowest wind speed, indicating *M-ARF* to be low. Since *M-ARF*:s for Lund and Borås are very close, there is no reason to believe that *ARF*:s should differ much for different Swedish cities.

M-ARF for Observed Storms

Areal precipitation is better determined from observed storms than from design storms. Consequently, moving areal reduction factors are best determined from statistics performed on simultaneous rain and wind measurements. In order to test the regional influence on areal reduction of point rainfall *M-ARF*:s were determined for storm events (about 10 for each city) observed in the Swedish cities Linköping, Göteborg, Stockholm and Lund and from Oslo, Norway. From each city, point hyetographs from one gauge and storm speed calculated from observed 600 mb wind speed were used for computing *M-ARF.* The computations are summarized in Tables 7-9. For storm duration 20 minutes and especially 30 minutes, *M-ARF*:s for the five cities follow each other closely, which is illustrated in Fig. 11, but for 10 min duration the range of *M-ARF* exceeds 0.1 for an area of 10 km^2 and is 0.17 for 25 km^2. The areal reduction for Stockholm (especially) and Linköping is more pronounced than for the other three cities. However, the rain intensity data from Stockholm and Linköping might be less accurate since the observations were made on a routine basis and not as in Lund, Göteborg and Oslo for research purpose.

Table 7 – Moving Areal Reduction Factor of one year return period computed from storm observations as fuction of catchment area. Storm duration 10 min.

city	area (km^2) 5	10	15	20	25
Linköping	0.80	0.73	0.67	0.63	0.60
Göteborg	0.83	0.76	0.73	0.70	0.66
Stockholm	0.78	0.70	0.63	0.59	0.55
Lund	0.87	0.81	0.77	0.74	0.72
Oslo	0.87	0.82	0.77	0.73	0.72

Table 8 – Moving Areal Reduction Factor of one year return period computed from storm observations as function of catchment area. Storm duration 20 min.

city	area (km^2) 5	10	15	20	25
Linköping	0.90	0.84	0.81	0.78	0.76
Göteborg	0.92	0.88	0.85	0.83	0.81
Stockholm	0.89	0.85	0.81	0.78	0.75
Lund	0.93	0.90	0.88	0.86	0.84
Oslo	0.92	0.89	0.87	0.84	0.82

Table 9 – Moving Areal Reduction Factor for one year return period computed from storm observations as fuction of catchment area. Storm duration 30 min.

city	area (km^2) 5	10	15	20	25
Linköping	0.94	0.91	0.89	0.88	0.86
Göteborg	0.96	0.93	0.91	0.90	0.89
Stockholm	0.93	0.90	0.88	0.86	0.85
Lund	0.96	0.94	0.93	0.92	0.91
Oslo	0.95	0.92	0.88	0.85	0.84

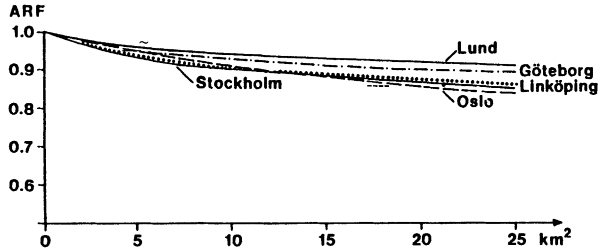

Fig. 11. Moving Areal Reduction Factor of one year return period computed from storm observations as function of catchment area. Storm duration 20 min.

Conclusions

According to the present investigation convective storms seem to have similar character over Sweden. Storm speed and parameters that describe the shape of synthetic hyetographs are almost equal for different places. Therefore, areal reduction factors are very much the same for different Scandinavian cities. There is a relation between areal reduction of point rainfall and storm movement. From the information about rain intensity at a point and storm speed, areal precipitation can be determined, and moving storm derived areal reduction factors. If historical storm data is not available, *M-ARF* can be estimated from synthetic design storms.

M-ARF:s calculated for Lund agree very well with areal reduction factors determined from observations in a dense net of rain gauges. Since convective storms are of similar character at all places in Sweden, *M-ARF* calculated by the moving storm approach described in this paper should for any place rather well represent the true areal reduction.

Moving storm derived reduction factors agree well with true areal reduction factors. These *M-ARF*:s have about the same values all over Sweden. Hence, *ARF*:s should be region independent. This means that the measured and statistically derived areal reduction factors for Lund can be used for other Scandinavian cities.

Acknowledgement

Access to precipitation data from other cities than Lund was provided free of charge through the generosity of Viktor Arnell VIAC – Linköping, Knut Bennerstedt, Nils O. Langgård Norwegian Meteorological Inst., Johan Larsson VBB – Stockholm, Sven Lyngfelt Dep. Hydraulics – CTH, Rolf Skretterberg NVE – Oslo, to whom we express our sincere thanks.

References

Arnell, V. (1982) Rainfall data for the design of sewer pipe systems, Chalmers Univ., Göteborg, Sweden, Rep. Ser. A:8, ISSN 0348-1050, 214 pp.

Austin, P. M., and Houze, R. A. (1972) Analysis of the structure of precipitation patterns in New England, *J. Applied Meteor., Vol. 11,* pp. 926-934.

Dahlström, B. (1979) Regional Distribution of Rainfall Intensity – A Climatic Analysis, Swedish Council Building Research, Rep. R18:1979, Stockholm (in Swedish).

Danish Engineering Society, DIF Spildevandskomiteen (1974) Evaluation of precipitation series, publ. No. 16, Teknisk Forlag, Copenhagen (in Danish).

Einfalt, Th., and Schilling, W. (1984) SSCOUT – a storm tracking procedure for a microcomputer, Proc. Third Int. Conf. Urban Storm Drainage, pp. 353-361, Göteborg, Sweden.

Felgate, D.G., and Read, D.G. (1975) Correlation analysis of the cellular structure of storms observed by raingauges, *J. Hydrology, Vol. 24,* pp. 191-300.

Höganäs AB Avloppshandbok (1972) Berlingska boktryckeriet, Lund, Sweden, issue 1975.

Keifer, C.J., and Chu, H.H. (1957) Synthetic Storm Pattern for Drainage Design, *J. Hydraulics Div., ASCE, Vol. 83* (4), pp. 1332-1-1332-25.

Marshall, R.J. (1980) The estimation and distribution of storm movement and storm structure, using a correlation analysis technique and rain gauge data, *J. Hydrology, Vol. 48,* pp. 19-39.

Nguyen, V.T.V., and Rouselle, J. (1981) A stochastic model for the time distribution of hourly rainfall depth, *Water Resour. Res., Vol. 17,* pp. 399-409.

Natural Environment Council (1975) Flood Studies Report, Vol. 2, Meteorological Studies, Natural Environment Research Council, London.

Niemczynowicz, J. (1982) Areal Intensity-Duration-Frequency Curves for short term rainfall events in Lund, *Nordic Hydrology, Vol. 13,* pp. 193-204.

Niemczynowicz, J. (1984) An investigation of the areal and dynamic properties of rainfall and its influence on runoff generating processes, Dep. Water Resour. Eng., Univ. Lund, Sweden, Rep. 1005, 215 pp.

Niemczynowicz, J., and Dahlblom, P. (1984) Dynamic properties of rainfall in Lund, *Nordic Hydrology, Vol. 15,* pp. 9-24.

Niemczynowicz, J., and Jönsson; O. (1981) Extreme rainfall events in Lund 1979-1980, *Nordic Hydrology, Vol. 12,* pp. 129-142.

Preul, H., and Papadakis, C.N. (1973) Development of Design Storm Hyetographs for Cincinnati, Ohio, Water Resour. Bull., Vol. 9, pp. 291-300.

Shearman, R.J. (1977) The speed and direction of movement of storm rainfall patterns, Meteor. Office, Bracknell, Birkshire, UK, Rep. UDC 551.513.43, 53 pp.

Sifalda, V. (1973) Entwickling eines Berechnungsregens für die Bemessung von Kanalnetzen, GWF-WASSER/ABWASSER 114, H9, pp. 435-440.

Statens Vejlaboratorium (1984) Rain an runoff measurements from Bispeengsbuen and Holbaekmotorvejen, Staten Vejlab. not 164, Vejdirektoratet, Copenhagen (in Danish).

Yen, B.G., and Chow, V.T. (1980) Design Hyetographs for small drainage structures, *J. Hydraulics Div., ASCE, Vol. 106,* pp. 1055-1076.

First received: 31 October, 1985
Revised version received: 4 February, 1986

Address:

Lars Bengtsson,
Div. Hydrology,
Uppsala University,
Västra Ågatan 24,
S-752 20 Uppsala, Sweden.

Janusz Niemczynowicz,
Dep. Water Resources Engineering,
Lund Inst. Technology/Univ. Lund,
Box 118,
S-221 00 Lund, Sweden.