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Dynamic Properties of Rainfall in Lund

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The shape of a runoff hydrograph depends on the dynamic properties of the rainfall. The possible range of impact of the rainfall movement on runoff generating process can only be judged if the rainfall volocity and direction are known in statistical terms. This paper gives the statistical characteristic of the rainfall movement in the city of Lund. The probability distribution of rainfall velocities and relative frequencies of the rainfall direction are given, based on the analysis of 400 rainfall events observed in the city of Lund. A simple program for determination of the velocities and the directions of storm movement has been developed and tested. Results show that there are two main storm directions in Lund: the first, generally oriented to the East, is prevalent throughout the year except summer; the second, oriented to the North-North-East, occurs primarily during summer months. During summer rainfall velocity is lower and intensity higher than during the rest of the year. Rainfall velocity is lognormally distributed. A strong correlation between wind movement parameters at 700 mb height and storm velocity and direction was observed.

Introduction

It is generally recognized that the shape of a runoff hydrograph depends not only on the catchment characteristics and time distribution of the rainfall pattern, but also on the dynamic properties of the rainfall, such as velocity and direction of the rainfall movement. This statement implies that rainfall movement characteristics should be taken into account when choosing the rainfall input for modeling of runoff. Possible range of impact of the rainfall movement characteristics on runoff generation can only be judged if the rainfall velocity and direction is known in statistical terms. This paper aims at delivering such statistical information for the city of Lund. The probability distribution of rainfall velocities and the relative frequencies of the rainfall directions were studied based on 400 rainfall events observed during a three year period in the city of Lund.

In order to avoid misunderstanding, it is important that the terms »rainfall velocity« and »rainfall direction« are clearly defined. Since in our study, the runoff generating process is in focus, we are interested only in the effects which can be observed on ground. Accordingly, we define rainfall movement as the velocity and direction of the water masses, generated by rainfall, occurring in a sequence on the ground. This means that we are not concerned with a real movement of clouds. For example, stationary clouds generating rainfall in a distinct directionally oriented sequence will produce an effect on the ground which will be considered as a rainfall movement. This definition of rainfall movement clearly implicates the choice of the rainfall tracking method.

For calculations of the storm velocity and direction a special program was developed. Statistical processing of the results was done using generally accepted statistical rules and the MINI-TAB programs.

Data Collection System and Data Base

Twelve automatic tipping-bucket raingauges have been operating in the city of Lund since 1979. All gauges are connected to the registration station via telephone lines. Registration is governed by the same clock assuring absolute time synchronization. The time resolution of the registration is one minute. The volume resolution of the gauges is 0.035 mm per tipping as an average. The average distance between the gauges is 1.3 km and the network covers an area of about 20 sq km. The gauging system and data collection procedure have been described before (Falk et al. 1979, Niemczynowicz et al. 1982). Fig. 1 shows the location of the raingauges in Lund.

The rainfall series from twelve gauges was divided into rainfall events with an arbitrarily chosen interval between events set to 15 minutes. Since our main interest centered on high intensity rainfalls, all events with average intensity below 2 mm/hour during 10 successive minutes were excluded from the data base. Velocity and direction of rainfall movement were calculated for all remaining events when the maximum one minute intensity exceeded 6 mm/hour.

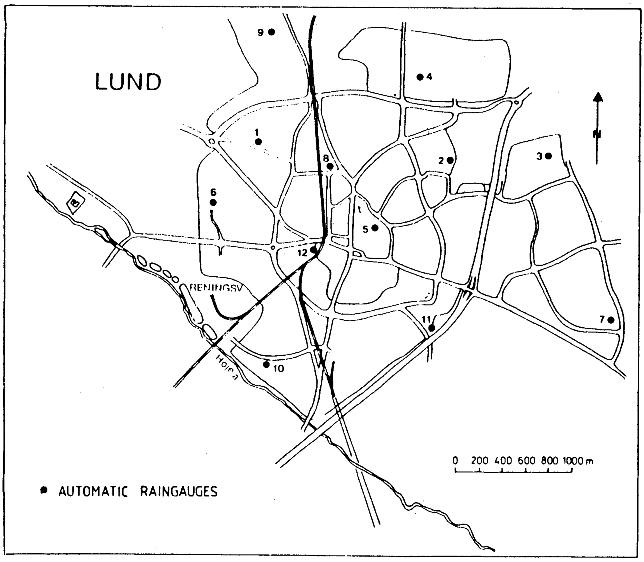


Figure 1. Location of the raingauges in Lund.

Triad-Program for Calculation of the Rainfall Velocity and Direction

A simple program called TRIAD, for determination of the velocity and the direction of storm movement has been developed. The algorithm for determination of the velocity vector is a modification of a well known three-point method (e.g. see Hindi et al. 1977). The method requires that some easily recognisable characteristic is present in a rainfall pattern. In our case the maximum intensity during one minute observed at different gauges was used as the characteristic. Knowing the time of occurrence of this peak (called "time to peak") for each gauge, the average velocity vector can be calculated, provided that all peaks denote the same rainfall cell. Time to peak for all gauges and events was chosen manually, directly from the rainfall intensity lists. If only one peak for each raingauge was observed, all time to peak values were accepted. Occurrence of more than one peak during the same event means that more than one raincell passed the network in some sequence. In this case choosing the right combination of time to peak values is crucial for correct estimation of the velocity vectors. In this case the time to peak values were accepted only if they formed a clearly recognisable movement pattern. For events with a great number of peaks it was often difficult to decide which of the time to peak values should be accepted as belonging to the same raincell. In this case a number of combinations of time to peak values were chosen. The final velocity vector was taken from that combination which showed the smallest variation of velocity vectors between all triads of gauges.

If the time to peak values are known for three arbitrarily chosen gauges, a velocity vector V can be calculated

$$V \equiv (v_1, v_2) \tag{1}$$

$$v_1 = \frac{\partial x_1}{\partial t} \tag{2}$$

$$v_2 = \frac{\partial x_2}{\partial t} \tag{3}$$

where (x_1, x_2) are the space coordinates for the gauges and t is the time to peak value. Introducing a three dimensional space, where one axis is the time coordinate and the two others are the ordinary x_1 and x_2 coordinates, a plane can be placed through three points in the space

$$r_1 x_1 + r_2 x_2 + r_3 = t \tag{4}$$

where

$$r_1 = \frac{\partial t}{\partial x_1} = \frac{1}{v_1} \quad , \quad r_2 = \frac{\partial t}{\partial x_2} = \frac{1}{v_2} \tag{5}$$

For each combination of three gauges, three simultaneously linear equations can be established

$$r_1 x_{1i} + r_2 x_{2i} + r_3 = t_i \quad , \quad i = 1,2,3 \tag{6}$$

The system of simultaneous equations was solved by triangulation according to the well-known Crouts method.

The number of systems, m, is equal to the number of combinations of three gauges from a number of gauges in function, n.

$$m \equiv \binom{n}{3} \tag{7}$$

In our case $n = 12$ and $m = 220$ when all gauges are in function. The solution of each of these sets of equations gives a vector R

$$R_j = (r_{1j}, r_{2j}) \tag{8}$$

with a length $||R||_j$

$$||R||_j = \sqrt{r_{1j}^2 + r_{2j}^2} \qquad 1 \le j \le m, \quad j = 1, 2, \ldots m \tag{9}$$

The absolute value of velocity is then V

$$||V||_j \equiv ||R||_j^{-1} \tag{10}$$

A value of the average velocity and direction for the whole area can now be calculated. Velocity for the event was taken as an average value over all combinations of triads of gauges

$$\bar{V} \equiv \frac{1}{m} \sum_{j=1}^{m} ||V||_j \qquad (11)$$

When calculating the average direction we wanted to minimize the influence of the "wrong" vectors i.e. vectors calculated from triads of gauges for which the time to peak value did not belong to the same rainfall cell. Hence, the normalized vectors were used

$$R_j^* = ||R_j||^{-1} R_j = ||V_j|| R_j \qquad (12)$$

The sum of normalized directions

$$R^* = \sum_{j=1}^{m} R_j^* \qquad (13)$$

was finally taken as an average direction of the event. For multi-peak events, a number of average velocities and directions was calculated. Elimination of wrong combinations was done by choosing average vectors with the smallest variation between triads. As a measure of the range of variation, the length of the average vector was taken

$$S = \frac{1}{m} ||R^*|| \qquad (14)$$

The value of S varies between 0, if velocity vectors are equally distributed over the circle, and 1, for the case when all vectors have the same direction. The direction with the smallest S value was taken as final storm direction for the rainfall event.

Performance of the program was checked by comparison of the results with previously calculated storm velocities and directions for extreme rainfall events in Lund (Niemczynowicz at al. 1981) with the Marshal's method (Marshal 1980). A good agreement between two methods was achieved. Further confirmation of the reliability of the results was obtained by correlation of the calculated storm velocities and directions against observed wind velocities and directions.

Storm Velocity and Direction for 400 Rainfall Events

Average velocity of storms in the city of Lund is 10.35 m/s based on calculations made for 400 rainfall events observed during a 3-year period. Fig. 2 gives relative frequencies and Fig. 3 shows a probability of nonexceedance of rainfall velocities. Two parameter lognormal distribution fits well to the observed points. $X2$-test gives a value $X2 = 9.82$, $r = 0.997$.

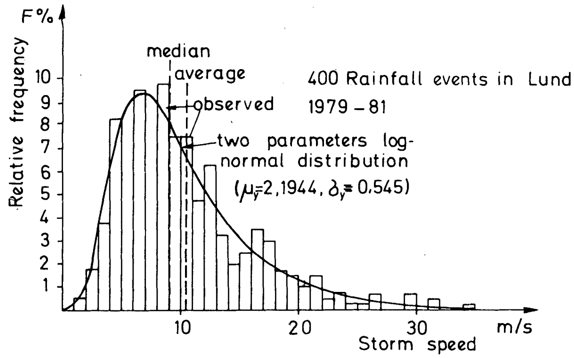


Fig. 2.
Relative frequency of storm velocity(based on 400 events)

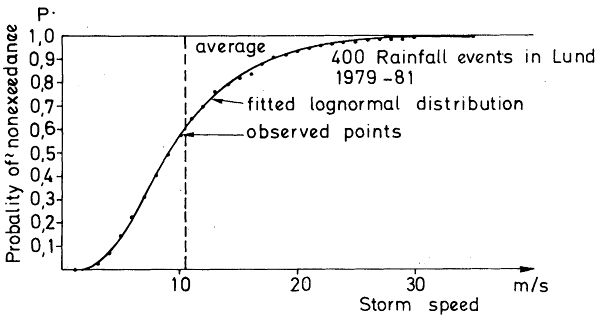


Fig. 3.
Probability of nonexceedence for storm velocity (based on 400 events).

Average direction of storm movement, defined as the sum of normalized vectors, is 72 degrees counted clockwise from the North. Relative frequency of storm directions in 20 degree sectors is shown in Fig. 4. Fig. 5 shows the relative frequency of rainfall direction in sectors with varying width. Note that two main directions of rainfall movement can be distinguished: the first towards South-East, and the second towards North-North-East. Rainfalls moving to South-West were very seldomly observed.

Table 1 - Relative frequencies of storm velocity and direction (%)

Storm direction degrees	Storm Velocity 0.0–5.4	5.5–12.4	12.5–17.4	17.5–22.4	m/s 22.5–27.4	27.5	All
0-45	3.5	8.5	4.8	1.8	0.8	0.3	19.5
46-90	2.8	5.5	5.3	3.0	1.0	0.8	18.3
91-135	3.3	9.0	4.3	2.8	1.3	0.8	21.2
136-180	2.5	8.3	1.8	1.8	0.3	–	14.5
181-225	2.0	2.5	1.0	–	–	–	5.5
226-270	0.8	1.8	0.3	0.3	–	–	3.0
271-315	1.8	0.3	1.3	–	0.3	0.3	6.5
316-360	2.5	4.8	2.3	1.5	–	0.5	11.5
All	19.0	43.3	20.7	11.0	3.5	2.5	100.0

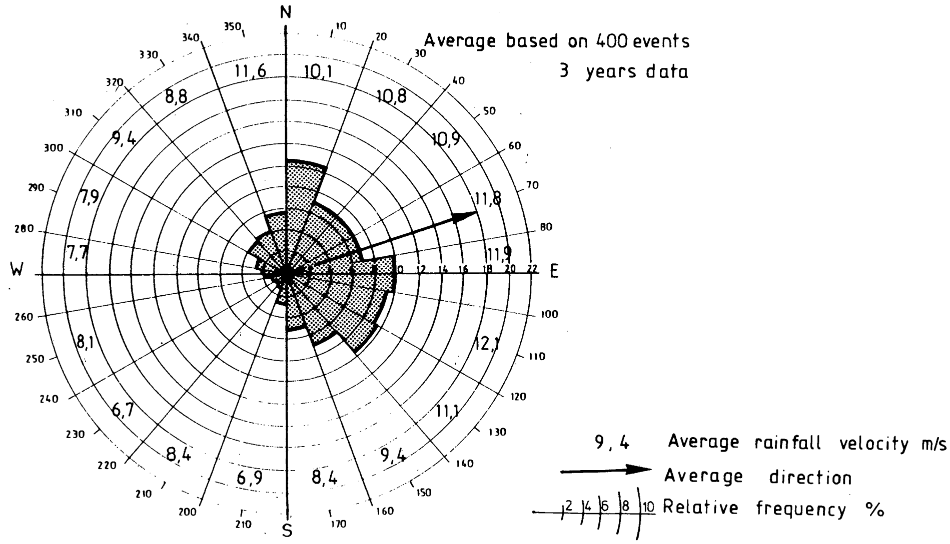


Fig. 4. Relative frequency of storm direction (based on 400 events).

Since the influence of storm movement on runoff depends on joint effects of storm velocity and direction, it is interesting to know the relative frequency of storm velocity; on different directions. Table 1 gives the relative frequencies of storm velocity and direction in velocity and direction classes. It can be noticed that there is a distinct maximum of relative frequency around storm velocities 5.5 – 12.4 m/s and storm direction towards East and South-East.

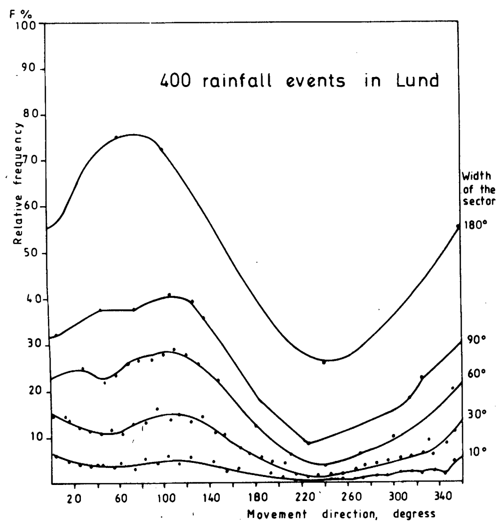


Fig. 5.
Relative frequency of storm direction in sectors with varying width (based on 400 events).

Relation Between Storm Movement and Storm Intensity

The entire data base was divided into six classes, based on a maximum 5-minutes rainfall intensity. Table 2 shows the average velocities and directions in the whole data base and in the intensity classes. Fig. 6 shows relative frequency of movement direction in the six intensity classes. It can be noticed from Table 2 and from Fig. 6 that there is a dependency between the rainfall movement and rainfall intensity. The one way analysis of variance performed on rainfall velocity versus rainfall intensity shows that the relation is significant on the 95 % probability level. The regression equation is

$Y = 11.0–2.30\ X$, where Y is storm velocity in m/s and X is 5-min max intensity, $r = 0.323$

Although the relation is weak, the regression equation and Table 2 indicate that high intensity storms may have a low velocity and low intensity storms have usually high velocities. This rather unexpected conclusion can probably be explained by the specific climatic conditions in the Southern part of Sweden. High intensity storms usually occur during summer when wind velocities are low. Strong winds, which can be observed on the ground level during high intensive rainfalls such as thunderstorms, are probably generated by the storm itself and have no relation to wind velocities at high altitudes which govern the storm movement. It will be shown later that wind velocities on the ground level are very little correlated to storm velocities.

Lognormal distribution also fits well to the rainfall velocities in intensity classes. The parameters of lognormal distribution are shown in Table 2 where μ_y and δ_y are the mean and standard deviation of the natural logarithms of x = storm velocity m/s. Probability of nonexceedance for storm velocity in intensity classes varies

Table 2 – Rainfall movement parameters for different rainfall maximum intensity classes.

5-min MAX intens. classes mm/min	Number of events	Rainfall Velocity Average m/s	St. dev.	Median m/s	μ_y	δ_y	Rainfall direction degree from N
0.00-2.36	400	10.35	5.65	9.03	2.194	0.545	71
0.00-0.10	89	11.03	5.60	9.87	2.284	0.490	62
0.11-0.16	99	10.52	5.94	9.32	2.196	0.576	85
0.17-0.26	91	10.96	6.29	9.08	2.240	0.575	78
0.27-0.45	52	9.19	4.17	8.37	2.125	0.432	76
0.45-0.74	39	9.86	5.19	8.77	2.140	0.578	34
0.75-2.36	30	8.53	5.22	6.51	1.975	0.595	21

according to shown parameters for lognormal distribution. From Fig. 6 it can be seen that the main direction of rainfall movement for high intensity rainfalls is oriented to the North-North-East.

Relation Between Storm Movement and the Season of the Year

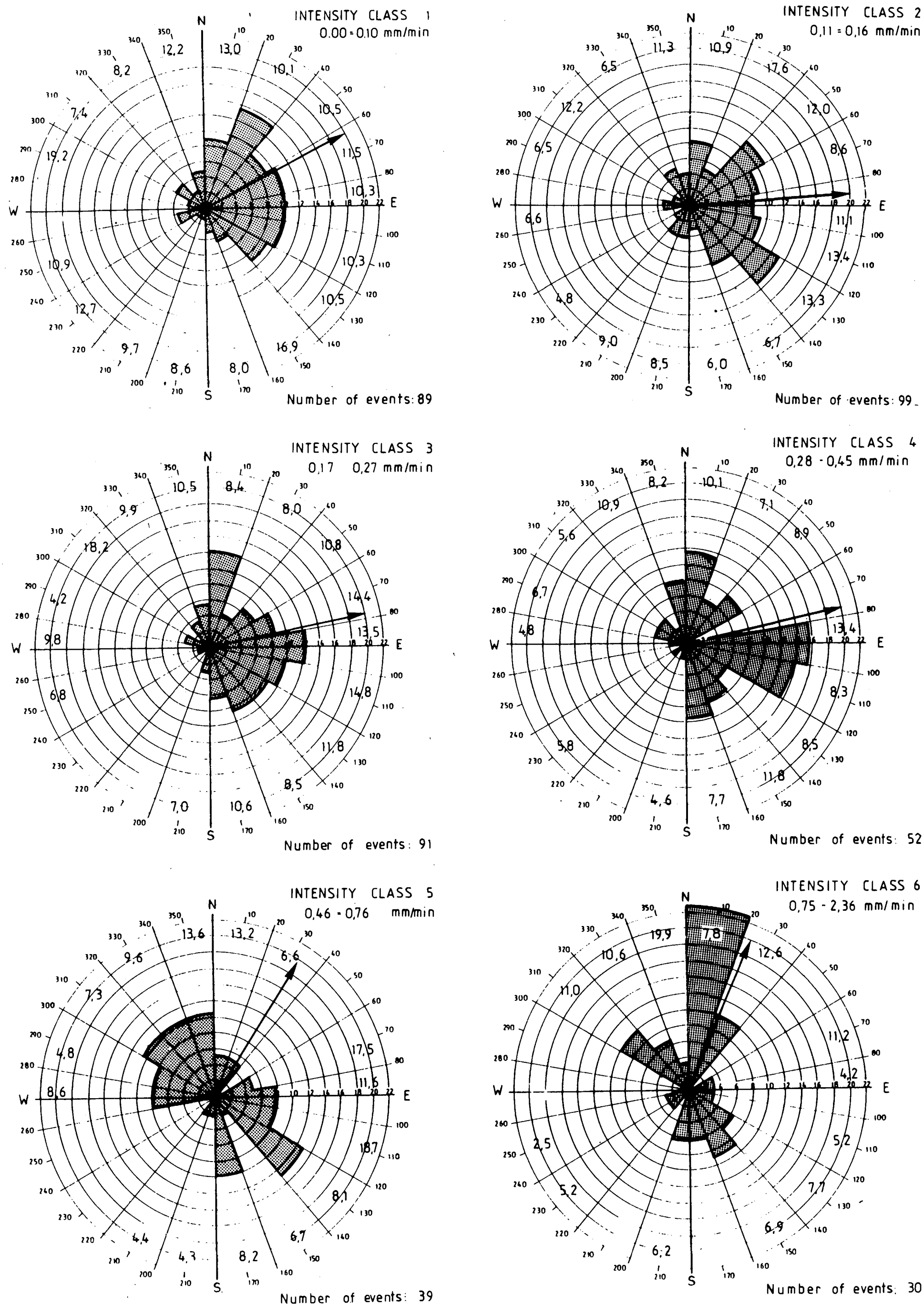
The whole data base was divided into 4 classes with respect to the season of the year. Table 3 shows the average velocities and directions of the storm movement in 4 time classes. Fig. 7 shows the relative frequencies of storm direction in time classes. From Table 3 and the figures, the general pattern of the relation can be seen. The conclusions from section 4 can be confirmed: low storm velocities occur most often during summer months. Analysis of variance performed on storm velocity versus the month number show that the relation is significant at the 99 % probability level. Storm velocities in time classes were also found to be lognormally distributed; Table 3 gives the parameters.

The storm movement during the summer months is mainly oriented to the North-North-East, during the rest of the year the main direction of movement is to the East.

Wind data were available at Sturup airport, 17 km SSE of Lund and at Kastrup airport, 20 km W of Lund. At Sturup, wind data denote records of wind velocity and direction at ground level, made every 6 hours starting at 0100 hrs. Kastrup data consist of wind velocity and direction registered at 800 mb, 700 mb and 600 mb height, appr. corresponding to altitudes 1,200 m. 2,200 m. and 4,500 m above sea level, registered every 6 hours starting at 0000 hrs. Wind parameters corresponding to rainfall events in the data base were chosen as data nearest in time to the available wind record. A total of 158 rainfall events with corresponding wind data from the period between May and September were analysed. Table 4 compares average rainfall and wind movement parameters and demonstrates that the wind velocity at all measured altitudes exceeds the rainfall velocity. There is good agreement between wind directions and rainfall movement. Wind velocities at all

Table 3 – Rainfall movement parameters for different seasons of the year.

Period month	Number of events	Rainfall Velocity Average m/s	St. dev.	Median m/s	μ_y	δ_y	Rainfall direction degree from N	Rainfall intensity aver. mm/min	st. dev.
12-01-02	14	12.21	7.73	10.78	2.321	0.637	81	0.15	0.096
03-04-05	51	10.51	5.27	9.99	2.224	0.532	27	0.22	0.204
06-07-08	207	9.25	5.05	8.03	2.096	0.506	76	0.35	0.337
09-10-11	128	11.85	6.10	10.54	2.327	0.574	88	0.23	0.253



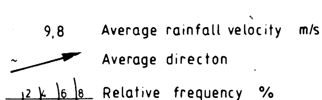
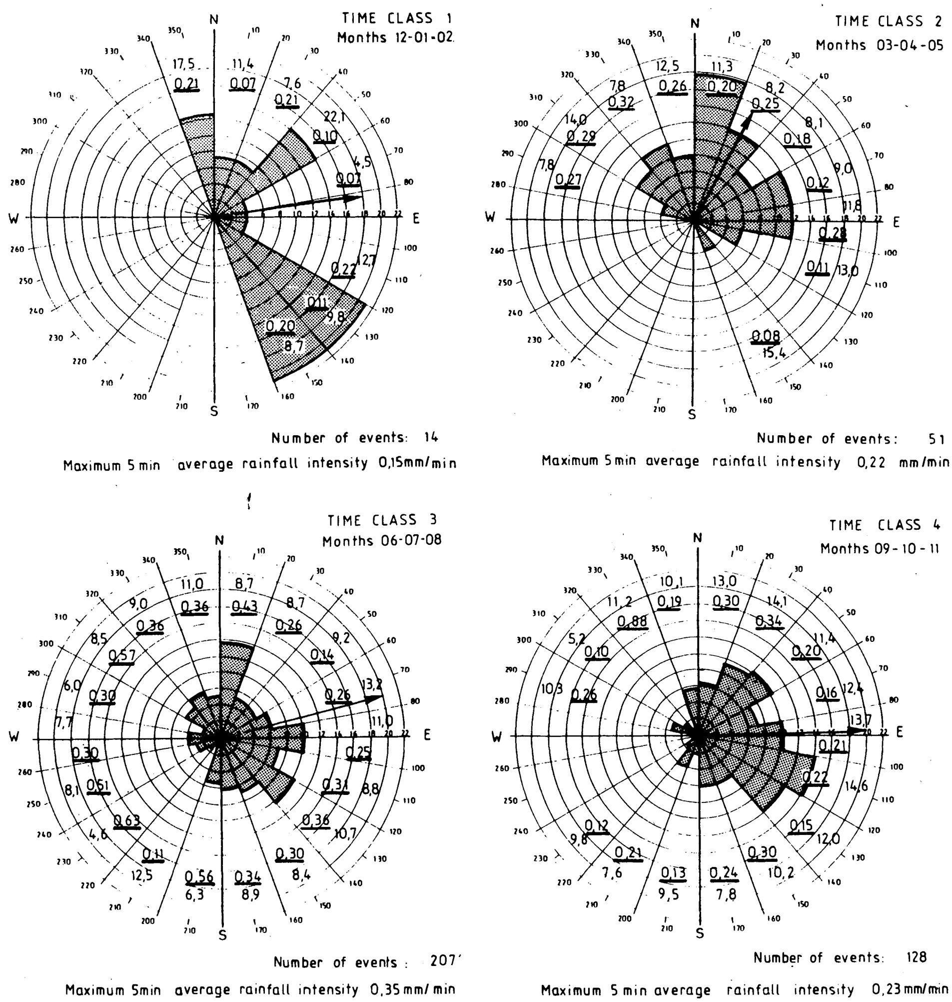


Fig. 6. Relative frequency of storm direction in intensity classes.



7,6 Average rainfall velocity m/s

<u>7,6</u> Max. 5 min average rainfall intensity mm/min

Average direction

2 4 6 Relative frequency %

Fig. 7. Relative frequency of storm direction in time classes.

altitudes are lognormally distributed; parameters of distribution are shown in Table 4. Fig. 8 shows the relative frequency and probability of nonexceedence of wind velocity at 600 mb height.

Correlation coefficients between rainfall and wind movement parameters are given in Table 5. In order to avoid discrepancy due to circularity of directions, 360 degrees were added to the smaller value of two to be correlated when the difference was greater then 180 degrees.

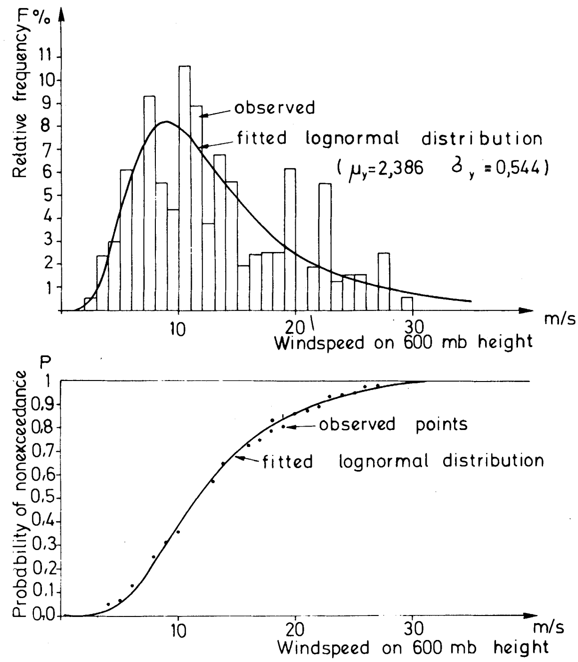


Fig. 8.
Relative frequency and probability of nonexceedence for wind velocity (based on 158 events).

Table 4 – Comparison of rainfall and wind movement parameters (Based on 158 rainfall events)

	Rainfall Velocity m/s	Wind Velocity m/s				Rainfall Direction	Wind Direction Degrees from North			
		ground level	800 mb	700 mb	600 mb		ground level	800 mb	700 mb	600 mb
AVERAGE	9.89	5.81	10.92	11.58	12.47	65	60	66	58	59
ST.DEV.	5.61	2.89	5.39	5.32	6.23					
MEDIAN	8.67	6.00	11.00	11.00	11.00					
μ_y	2.15	1.59	2.26	2.32	2.39					
δ_y	0.54	0.65	0.54	0.55	0.54					

Table 5 shows that, in general, there is good correlation between storm and wind movement parameters with the exception of storm velocity and wind velocity at ground level. The storm velocity correlates best to wind velocity at higest altitude, 600 mb height. The best correlation for storm direction is observed with wind direction at 700 mb height. Similar relations have been observed before by several researchers (Shearman 1977, Marshall 1980) Fig. 9 shows the relation between rainfall velocity and wind velocity at 600 mb height. For comparison, Fig. 10

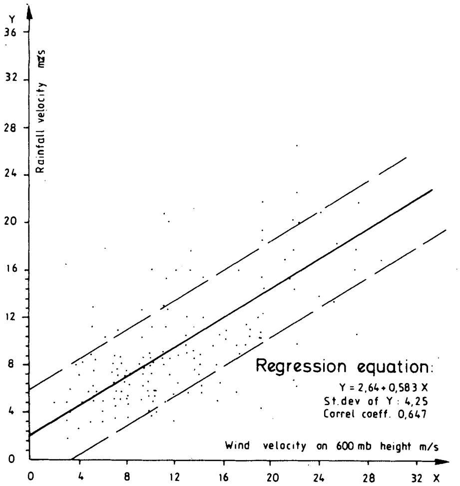


Fig. 9. 600 mb wind velocity versus storm velocity.

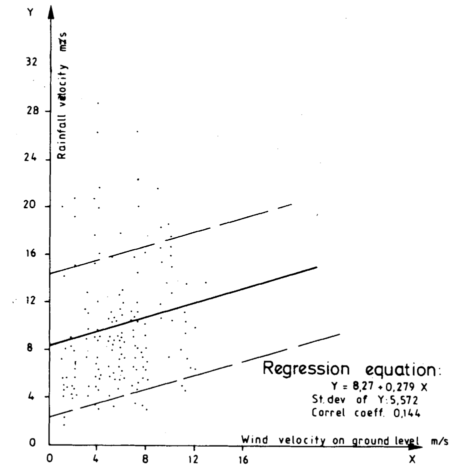


Fig. 10. Ground level wind versus storm velocity.

shows the same relation for wind velocity at the ground level. It can be clearly seen that there is practically no relation between storm and wind velocity at ground level.

Additionally, in Table 4, the correlation coefficients between wind speed and maximum 5-minutes rainfall are shown. The observed correlation is weak, but the minus sign indicates that the same relation as observed between storm velocity and max intensity of the storms is also valid for the relation between wind velocity and max intensity of the storms. Table 6 gives the significance levels for the relations between wind and rainfall movement parameters. Fig. 11 shows the relation between storm and wind direction at 700 mb height.

Table 5 – Correlation coefficients for wind and storm movement parameters (Based on 158 events)

	Wind Speed				Wind Direction			
	ground level	800 mb	700 mb	600 mb	ground level	800 mb	700 mb	600 mb
Storm velocity	0.144	0.611	0.647					
Storm direction					0.856	0.914	0.932	0.923
5-min max intensity	–0.301	–0.283	–0.205	–0.140				

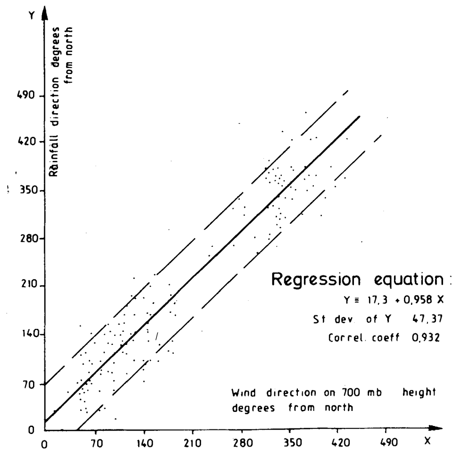


Fig. 11. 700 mb wind direction versus storm direction (based on 158 events).

Table 6 – Significance levels for relations between storm and wind movement parameters.

	MONTH No	STORM VELOCITY	STORM DIRECTION	STORM MAX INTENS.	WIND VELOCITY GROUND LEVEL	WIND VELOCITY 700 mb	WIND DIRECTION GROUND LEVEL	WIND DIRECTION 700 mb
STORM VELOCITY	**							
STORM DIRECTION		**						
STORM MAX INT.	***	*	O					
WIND VEL. GROUND	***	*	***	***				
WIND VEL. 700 mb	***	***	*	***	***			
WIND DIR. GROUND		*	***	***	***	*		
WIND DIR. 700 mb		***	***	***	***	***	***	

where : *** - significance on 99.9 % probability level,
** - significance on 99.0 % probability level,
* - significalce on 95.0 % probability level,
O - not significant.

Conclusions

1) Observed good correlations between storm and wind movement parameters indicate that the used simple method of computation storm velocities and directions is sufficiently good for practical applications. Since this method calculates the storm velocity on the basis of the time to peak values it is possible that obtained velocities might be underestimated. If we assume that observed wind velocities at the 800 mb height should be equal to the storm speed on the average, then we can estimate the average error to be about 10 %.

2) 700 mb wind is a very good indicator of storm movement. Most airports measure wind at this level. Airport wind data can be used for rough estimation of storm movement parameters.

3) Storm velocity and wind velocity at different levels are lognormally distributed.

4) Two main directions of rainfall movement can be clearly distinguished: the first, prevalent for most of the year except summer, is oriented to the East and South-East. Rainfalls moving in this direction have mainly average or low intensity and high velocity. The second main direction of storm movement is oriented to the North-North-East. Storms moving in this direction occur mainly during the summer months, have high intensities and low velocities.

5) Obtained results have clear practical implications. Analysis of storm velocities indicates that the rainfall events with high intensities, which are most adequate for various practical applications, may have low velocities.

These velocities however, are on the average much higher than usually occurring velocities of water flow in sewers. Thus the "worst" situation, when the storm velocity equals the velocity of flow, has a low probability of occurrence. Probabilities of nonexceedance of storm velocities are given in this paper. Relative frequences of storm movement direction, reported here can be used to judge the probability of "worst" events when the main direction of sewers in the catchment coincides with the most probable direction of the storm movement. Catchments with general orientation of sewers to the North-North-East can expect that this "worst" event may happen.

6) Further investigations, presently being performed, will quantify the impact of rainfall movement on the runoff generating process. This question is crucial with respect to the necessity of taking into account the dynamic properties of the rain when choosing rainfall input for simulation of runoff. The range of storm movement parameters given in this paper is a necessary basis for answering this question.

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