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Investigation of the Influence of Rainfall Movement on Runoff Hydrograph

Part II – Simulation on Real Catchments in the City of Lund

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Work presented here consists of two parts: the first part, presented before as a separate paper (Niemczynowicz 1984b), described studies performed on conceptual catchment, the second part presented here describes studies made on real catchments in the city of Lund.

The scope of the paper is to use previously calculated statistical characteristics of rainfall movement in Lund for quantitative description of the influence of storm movement on runoff modeled on real catchments in Lund. The relations between rainfall characteristics and the magnitude of directional bias are shown. The special interest in this study is to locate the combination of factors which maximize the effect of directional bias. Finally, by combination of rainfall movement statistics with modeled runoff, the probability distribution of directional bias for differently oriented catchments in Lund is given.

The most important conclusion is that the maximal directional bias observed for real catchments is much smaller than for the conceptual catchment, but still can reach significant values. The maximal bias occurs when the rainfall movement is parallel to direction to conduits and when rain velocity is close to average flow velocity. The highest values of directional bias occur for storms with short durations which give low peak flow discharge without practical importance. Still, the phenomenon of the directional bias can be one of the reasons why frequency of the rainfall does not follow frequency of runoff.

Introduction

In the first part of this work (Niemczynowicz 1984b) the maximal directional bias was defined as follows:

$$\text{MAX DIRECTIONAL BIAS} = \frac{QP\text{DOWN} - QP\text{UP}}{QP\text{UP}} \quad (\%)$$

where: QPDOWN – peak flow for storms moving downstream.
QPUP – peak flow for storms moving upstream.

In order to make comparison with the results from studies on conceptual catchment possible, we will, for the moment, still use this definition in a following text.

The directional bias is greatest if the storm moves with the same velocity as the velocity of water flow down the catchment. Since flow in real catchments consists of both overland and channel flow components, the geometric properties of the land surface and the sewer system will influence the average velocity of flow.

Most previous studies have been performed either in laboratories using rainfall simulators (Yen and Chow 1969, Townson and Ong 1974), or using mathematical runoff models applied to hypothetical drainage areas (for example Surkan 1974). More recent studies about dynamic properties of rainfall have focused primarily on developing methods to calculate the storm velocity and direction from data gathered from dense networks of gauges (Marshal 1975, Shearman 1977, Hindi 1977).

To our knowledge, there are no studies done on the significance of the directional bias for practical applications, such as design of the sewer network. There are also no studies of directional bias made on the basis of statistics of the rainfall movement for real catchments. The reason for this is that a long series of rainfall data from a dense network of gauges with good time synchronisation is necessary for making statistics of rainfall movement. Moreover, the series of good areal rainfall data must be combined with a thorough knowledge of the catchment parameters if the influence of rainfall movement on the runoff hydrograph is to be investigated.

An attempt to quantify the directional bias was done by James and Drake (1983) for the Hamilton, Ontario, urban area. The authors strongly stress that dynamic properties of rainfall influence the shape of the runoff hydrograph, and if one does not account for this effect, an error will be introduced in the modeled runoff. Unfortunately, the Hamilton study was done without convincing statistical support with respect to the storm movement parameters and runoff characteristics. Still, the crucial question of the necessity of including the dynamic properties of the rain into practical rainfall-runoff calculations has not been answered.

The raingauge network of 12 gauges has operated in Lund since 1978 and delivers good quality rainfall data. Three years data was used for deriving statistical areal reduction factors and for statistically describing rainfall movement over the city of Lund. Description of the data collection and processing systems has been given before (Falk et al. 1979, Niemczynowicz and Jönsson 1981, Niemczynowicz 1982). A computer program to determine the velocity and direction of storm movement has been developed and the results have been used for calculating the probability distribution of storm directions, the probability of nonexceedence of storm velocities and the joint probability of storm velocity and direction (Niemczynowicz 1984a).

The scope of this paper is to use previously calculated statistical parameters of rainfall movement in Lund for a quantitative description of the influence of storm movement on runoff from several real catchments. Different factors effecting the magnitude of directional bias will be described. We will, first of all, search for the combination of those factors which give the maximum effect on directional bias. Finally, we will combine rainfall movement statistics with the modeled runoff and give the probability distribution of directional bias for different catchments in Lund.

The question of whether the dynamic properties of rainfall must be considered when choosing rainfall input for runoff modeling can only be answered if the range of effect is defined in statistical terms. The presented paper aims to give the necessary basis for answering this question.

Simulation Model

For runoff simulations the Storm Water Management Model (SWMM) was used. SWMM was modified so that the data from 12 gauges could be used as rain input.

The Runoff and Transport Blocks of the SWMM model were run using, at first, simple block rainfalls with intensity and duration following intensity-duration-frequency curves, and later, using observed rainfall events. Both overland flow and conduit flow are calculated by the Runoff and Transport Blocks of SWMM using Manning's equation combined with continuity equation. Surface losses on both impermeable and permeable surfaces are calculated as a specified value of depression storage which is extracted from the rainfall volume at the beginning of the storm, infiltration on permeable surfaces is calculated according to Horton's equation with specified parameters. Rainfall movement was simulated by lagging the uniformly distributed rainfall stepwise over the 12 subcatchments with a time step chosen according to required storm velocity. Downstream and upstream storm movement was simulated by reversing the time sequence of rainfalls occurring on opposite subcatchments.

Drainage System in Lund

The storm water system in Lund can be divided into two major parts: the first, situated in a central part of the town, was built before 1950 and consists of combined sewers; the second part, succesively built during the last 30 years, consists mainly of separated storm water conduits. Between the two parts of the

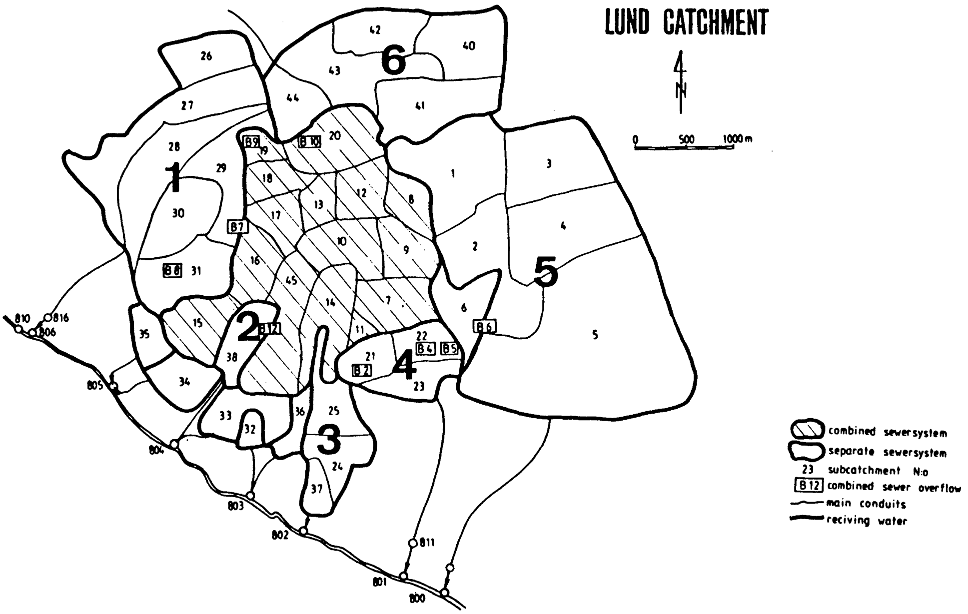


Fig. 1. Segmentation of the Lund catchment.

system there are 9 main overflow structures. Total tributary area of both parts of the system is 529 ha with about 30% imperviousness on the average.

The total area of Lund can be divided into 6 main subcatchments with a separated sewage system, and one area with a combined system (Fig. 1). Fig. 2 shows the schematic representation of the sewage system. Since the whole area of the city of Lund slopes to the South-West, most of the conduits are oriented in this direction and drain to the small river Höje. One exception is subcatchment No. 6 (see Fig. 1), which is situated in the North part of the town and is oriented to the North-East.

Previously, during the so called "Lund-project", runoff from the stormwater system in Lund was measured at 5 outlets, collecting stormwater from about 90% of the total area of the city over a period of 17 months (Hogland and Niemczynowicz 1979, 1980). The whole area of the city was mapped and all parameters needed for runoff simulation were collected. Thorough calibration of the Storm Water Management Model on 5 catchments with separated system was performed.

For the purpose of the present study, the total area of the 5 separated catchments and of the combined part of the system was matched together so that one run of SWMM simulates runoff from the whole city, excluding subcatchment No. 6. Simulated runoff hydrographs are listed at the stormwater outlets, numbered in the scheme (Fig. 2), No. 800 to 816 and at the outlet from the combined system, No. 906.

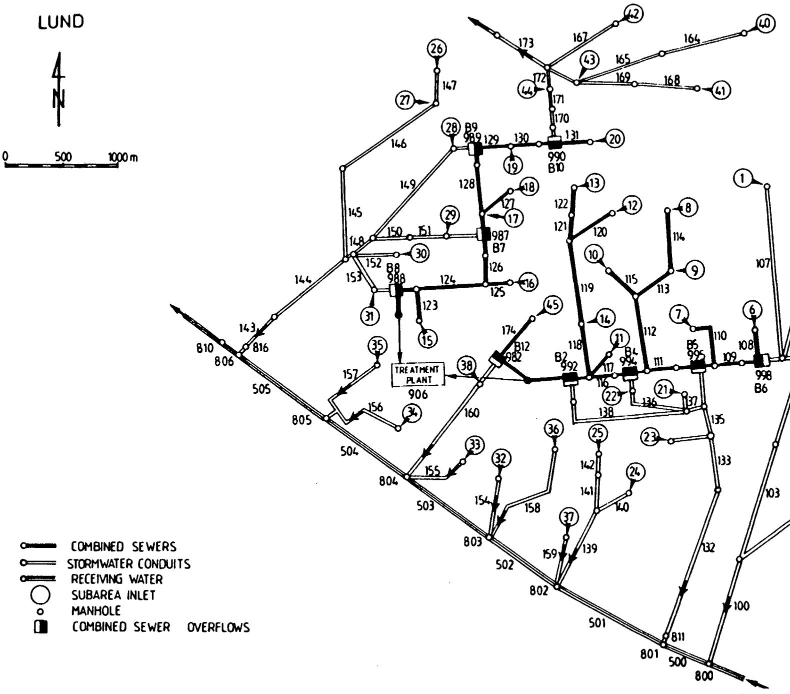


Fig. 2. Schematic representation of the sewage system in Lund.

Different catchments in Lund have a different geometry of conduits. The greatest directional bias can be expected on the long catchment with conduits going straight along the long axis of the catchment. Catchment No. 5, draining into outlet No. 800, is the longest and has rather straight conduits. This catchment shows the greatest directional bias. Other catchments are also generally oriented to the South-West, but several smaller conduits occur at right angles to this direction. Directional bias for these catchments is always smaller than for catchment No. 5.

Catchment No. 3 shows reversed directional bias, where storms moving downstream give a smaller peak discharge than storms moving upstream. This amazing effect can be explained by the geometric properties of the conduit system. There are two main conduits draining the catchment, one short and flat and the other longer and steeper. The runoff from the upstream part of the catchment appears first at the outlet while runoff from the downstream part comes later. This causes the reversal in directional bias. All mentioned irregularities of geometry of the conduits reduce the effect of directional bias. To locate situations giving maximal directional bias we will primarily look at catchment No. 5 draining to outlet No. 800.

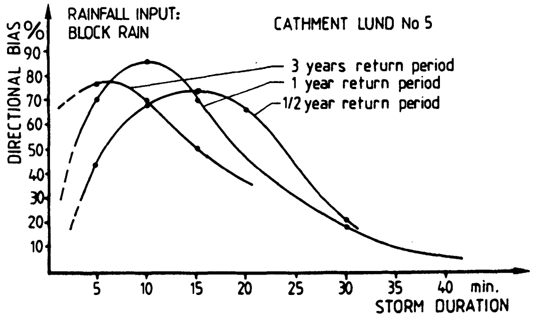


Fig. 3.

Relationship between rainfall duration and directional bias for "block rain" with different return periods. Catchment No. 5 in Lund. Storm velocity 4.2 m/s.

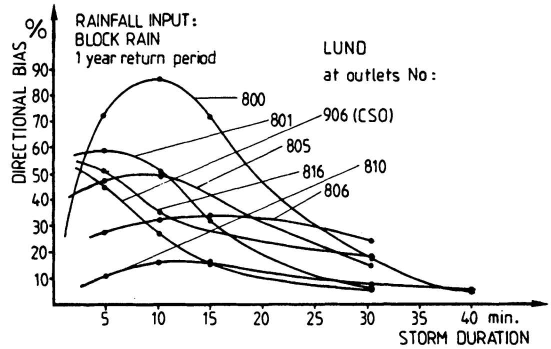


Fig. 4.

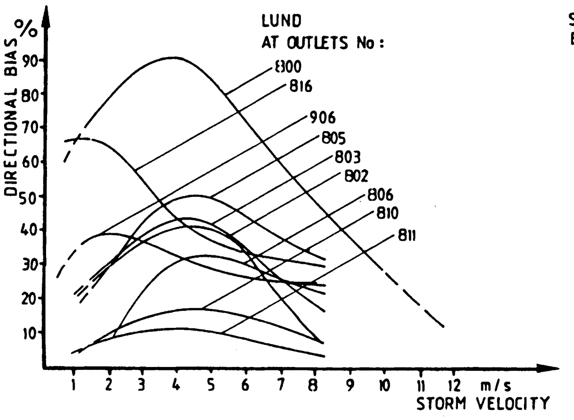
Relationship between rainfall duration and directional bias for "block rain" with one year return period. Different catchments in Lund. Storm velocity 4.2 m/s.

Directional Bias Simulated Using Block Rainfalls

According to conclusions drawn from studies performed on the conceptual catchment, maximal directional bias will be expected for storm velocity equal to average flow velocity and for storm durations of about 10-15 minutes if the rainfall intensity is chosen according to *i-d-f* relationship. A number of runs performed with "block rainfall" as input confirm this conclusion.

Fig. 3 shows the relation between rainfall duration and the directional bias simulated on catchment No. 5 for rainfalls of 1/2, 1 and 3 years return period. Maximal directional bias of 88% is observed for rainfall with duration of about 10 minutes and one year return period. 10 minutes duration is approximately equal to ⅓ of the time of concentration for catchment No. 5. The relation does not show the characteristic shape observed for the conceptual catchment because the average storm velocity used in simulations does not usually match average flow velocity. Flow velocity varies significantly with flow discharge, which in turn depends on the magnitude of the rainfall input. Flow velocity varies also in different parts of the catchment. Therefore, the relationship has a mixed character, involving elements from cases of storm velocity that are under and over the velocity of flow.

Fig. 4 shows the directional bias as a function of rainfall duration for different catchments in Lund. Catchment No. 5 shows maximal directional bias.



STORM INPUT:
BLOCK RAIN 10 min. duration, 1 year return period

Fig. 5. Relationship between storm velocity and directional bias on Lund catchment No. 5.

Fig. 5 shows the relationship between storm velocity and directional bias for rainfall with 10 minutes duration and 1 year return period. The maximal directional bias is observed around a storm velocity of 4 m/s which is approximatively equal to the average, weighted full-flow velocity for all conduits along catchment No. 5.

Directional Bias Simulated Using Observed Rainfall Events

Now we know the range of values of maximal bias which can be expected for several catchments in Lund, when block rain is used as input. The next question which we will try to answer is which order of magnitude of directional bias can be expected for real, observed rainfall events. Rainfall data registered from 12 gauges in Lund contain the information about rainfall movement. Rainfall velocity and direction has been calculated before for 400 rainfall events (Niemczynowicz 1984a). From this material we have chosen a number of events where the direction of rainfall movement was close to parallel with the main direction of conduits on catchment No. 5. Hyetographs for 12 gauges were assigned to the nearest subareas within the city of Lund and SWMM was run in order to calculate the runoff hydrograph for observed, natural storm movement direction. The opposite storm movement direction was then simulated by reversing the time sequence for each hyetograph. Figs. 6 and 7 show examples of runoff hydrographs, simulated with observed rainfall events as input, with natural and reversed direction of storm movement.

Table 1 lists the values of directional bias simulated for Lund catchment No. 5.

It can be seen from Figs. 6 and 7 and Table 1 that directional bias observed for real storms is generally smaller than that of design storms. This effect was obviously expected, because design storms were chosen so that the directional bias would be maximized. Observed storms, on the other hand, were never com-

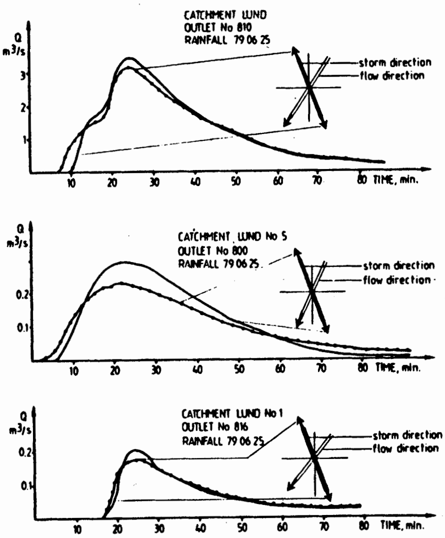


Fig. 6. SWMM – simulated runoff hydrographs for observed rainfall event. Rain 79.06.25.

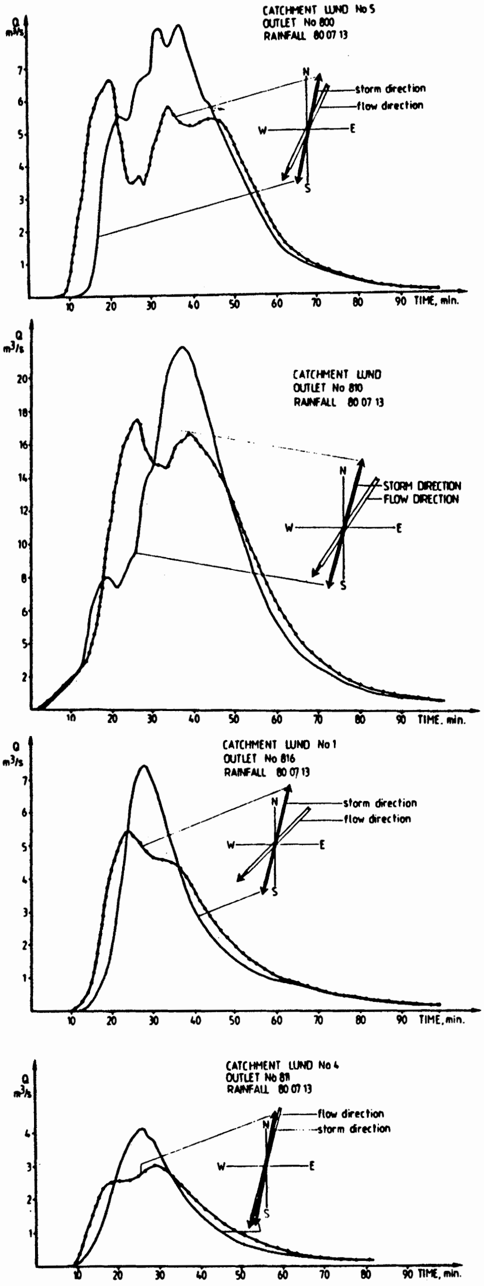


Fig. 7. SWMM – simulated runoff hydrographs for observed rainfall event. Rain 80.07.13.

Table 1 – Directional bias values for different rainfall input simulated for Lund catchment No. 5.

Storm Input	Storm veloc. m/s	Storm durat. min.	Storm. intens. mm/h	Return period years	Maximal bias %	Tmax bias T conc.
Block rain	4.0	5	44.4	1/2	43	
Block rain	4.0	10	31.8	1/2	68	
Block rain	4.0	15	25.2	1/2	72	0.43
Block rain	4.0	20	21.0	1/2	65	
Block rain	4.0	30	16.2	1/2	22	
Block rain	4.0	5	57.6	1	70	
Block rain	4.0	10	42.0	1	88	0.29
Block rain	4.0	15	33.0	1	70	
Block rain	4.0	30	20.4	1	18	
Block rain	4.0	5	93.0	3	78	0.20
Block rain	4.0	10	70.2	3	67	
Block rain	4.0	15	55.2	3	50	
Block rain	1.5	10	42.0	1	80	0.29
Block rain	2.0	10	42.0	1	73	
Block rain	8.0	10	42.0	1	43	
Rain 790625	19.0				28	
Rain 800713	4.0				33	
Rain 800823	5.2				18	
Rain 800824	5.2				25	
Rain 800822	8.0				30	
Rain 800706	1.8				21	
Rain 800709	8.8				8	

pletely parallel to the conduits, and their duration and intensity were not necessarily close to that which gives maximal bias. Velocity of most rainfall events was higher than flow velocity in conduits. Still, significant values of directional bias were simulated for real catchments and observed rainfall events.

Probability Distribution of Directional Bias for the City of Lund

Now we know the magnitude of possible directional bias which can be expected for the catchments in Lund. Maximal bias will occur only if rainfall with certain specific duration and intensity moves with a certain velocity exactly parallel to the direction of conduits.

There is a certain probability that storms move with this velocity and direction. Therefore, knowing the direction of conduits for any catchment in Lund we can

Table 2 – Joint probability of storm movement direction and velocity for the city of Lund.

Storm direction degrees	STORM VELOCITY m/s 0.0-5.4	5.5-12.4	12.5-17.4	17.5-22.4	22.5-27.4	≥ 27.5	All
00- 45	0.035	0.085	0.048	0.018	0.008	0.003	0.195
45- 90	0.028	0.055	0.053	0.030	0.010	0.008	0.183
91-135	0.033	0.090	0.043	0.028	0.013	0.008	0.212
136-180	0.025	0.083	0.018	0.018	0.003	–	0.145
181-225	0.020	0.025	0.010	–	–	–	0.055
226-270	0.008	0.018	0.003	0.003	–	–	0.030
271-315	0.018	0.030	0.013	–	0.003	0.003	0.065
316-360	0.025	0.048	0.023	0.015	–	0.005	0.115
All	0.190	0.433	0.207	0.110	0.035	0.025	1.000

derive the probability of exceedence of the certain directional bias value for this catchment. The necessary statistics about rainfall movement parameters for the city of Lund have been derived previously by analysis of storm direction and velocity calculated for 400 rainfall events (Niemczynowicz 1984a).

Table 2 shows the joint probability of storm direction and velocity for the city of Lund.

According to the definition in Part I, the directional bias value describes the difference in peak flow between storms moving down and upstream. In relation to stationary storms, the peak flow can be higher or lower if we use moving rainfall as input. Here we are interested in cases when the peak flow exceeds the value observed using stationary storms. Because in most applications, usual rainfall input for runoff modeling is a stationary storm, we will here consider only the cases when the peak flow can be higher than that for stationary storms. We therefore define the directional bias in relation to stationary storms as follows:

$$\mathrm{BIAS} = \frac{Q P\mathrm{DOWN} - Q P\mathrm{STATIONARY}}{Q P\mathrm{STATIONARY}} \quad (\%)$$

where: QPDOWN – peak flow for storms moving downstream.
QPSTATIONARY – peak flow for stationary storms.

We assume that the stationary storms give the same peak flow as storms moving at a right angle to the direction of conduits. The observed maximal directional bias of 88% in relation to upstream storm movement will be equal 31% in relation to stationary storms.

We assume also that the directional bias for storm movement directions between parallel and right angle to the conduit direction will decrease form maximal value according to the cosine function:

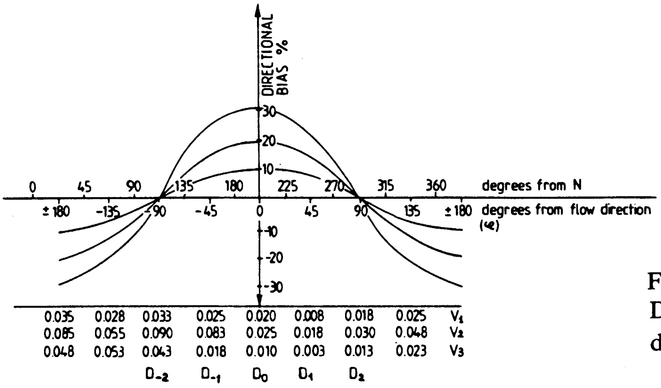


Fig. 8.
Directional bias on different directions

$$BIAS(\rho) = MAXBIAS \quad \cos \rho$$

where:

BIAS – directional bias for storm movement directions not parallel to the conduit direction

MAXBIAS– maximal directional bias, observed for storm movement direction parallel to the conduit direction,

– an angle between the storm movement direction and the conduit direction.

Fig. 8 shows the distribution of directional bias on different directions and lists the relative probabilities of storm velocity (*V*) and direction (*D*).

Now we can calculate the values of directional bias for each sector of storm movement direction and each storm velocity interval listed in Table 2. By summation of probabilities for positive bias values exceeding 0, 10, and 20%, the exceedence probabilities for directional bias on differently oriented catchments have been calculated.

We define probabilities shown in Table 2 as follows:

$P(Vi, Dj)$ where: Vi is a velocity interval with $i = 1,2,3$

$V1 = [\ 0.0,\ \ 5.4]$ m/s
$V2 = [\ 5.5,\ 12.4]$ m/s
$V3 = [12.5,\ 17.4]$ m/2

Dj is a 45 degree sector with $j = -2, -1,0,1,2$

$D\text{-}2 = [-112.5,\ -67.5]$ degrees
$D\text{-}1 = [\ -67.4,\ -22.5]$ degrees
$D\ 0 = [\ -22.4,\ \ 22.4]$ degrees
$D\ 1 = [\ \ 22.5,\ \ 67.4]$ degrees
$D\ 2 = [\ \ 67.5,\ 112.5]$ degrees

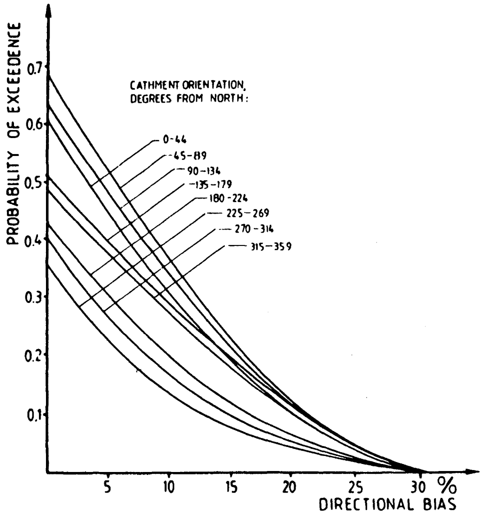


Fig. 9. Probabilities that the directional bias exceeds the value given by the abscissa.

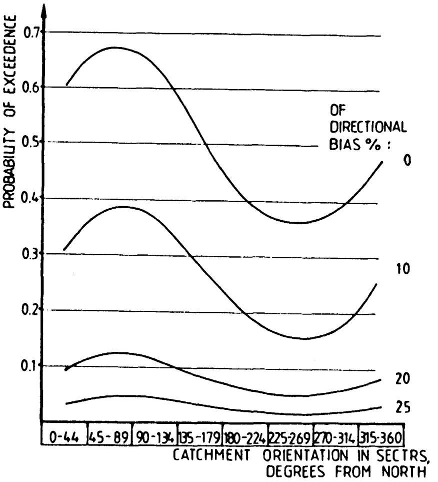


Fig. 10.

Probabilities that certain values of the directional bias will be exceeded on differently oriented catchments.

Calculation of exceedence probabilities was done by the following summations:

$$P(\text{BIAS} > 0) = \sum_{i=1}^{3} \sum_{j=-2}^{2} P(Vi, Dj)$$

$$P(\text{BIAS} > 10) = \sum_{i=1}^{2} \sum_{j=-1}^{1} P(Vi, Dj)$$

$$P(\text{BIAS} > 20) = \sum_{j=-1}^{1} P(Vi, Dj)$$

$P(\text{BIAS} > 30) = 0$ (according to definition of MAXBIAS)

By rotating the coordinate system for conduit direction, the summation was repeated for 8 catchment orientations. Fig. 9 shows the exceedence probabilities for directional bias on differently oriented catchments with directional sectors as a curve parameter. Fig. 10 shows the same values with directional bias as a curve parameter. From Figs. 9 and 10 and Table 2 it can be seen that catchments oriented to the North-East (45-90 degrees sector) have the highest probability of high directional bias. This is a reasonable expectation, since summer storms with high intensity, short duration and low velocity often come from this direction.

Conclusions

1) The influence of storm movement on runoff hydrographs has been proved and the magnitude of the influence has been quantified and presented in statistical terms.
2) The maximal directional bias can theoretically reach values of several hundred percent. This can only be shown on conceptual catchments, with specially designed geometry, for storms with short duration and is without practical importance.
3) The maximal directional bias shown for real catchments is much smaller than for the conceptual catchment, but can still reach a significant value. Maximal directional bias simulated for the Lund catchment is 88 percent in relation to upstream storm movement, or 31 percent in relation to stationary storms following intensity-duration-frequency curves. For catchment No. 5 in Lund the maximal bias was observed for a rainfall duration of 10 minutes and a return period of 1 year.
4) The maximal directional bias occurs for rainfalls with velocities equal to the average full-flow velocity, weighted for all conduits along the catchment. The average full-flow velocity on Lund catchments is much smaller than the average storm velocity. Rainfalls with velocities equal to this velocity have a small probability of occurrence.
5) For rainfalls with intensities following the intensity-duration-frequency relaitonships, maximal directional bias will occur at durations approximately equal to 1/5 to 1/3 of the contration time for the catchment. (Concentration time observed for full flow in conduits).
6) Long catchments with straight conduits oriented parallel to the long axis of the catchment will show higher directional bias than catchments with a more complicated geometry of sewers.
7) The magnitude of occurrence probability for directional bias values shown in Figs. 9 and 10 suggests that the error in simulated runoff peak discharge caused by using stationary storms as input, will not be very important from a practical point of view. Still, the phenomenon of directional bias can be one of the reasons why the frequency of rainfall does not follow the frequency of runoff.

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