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# Investigation of the Influence of Rainfall Movement on Runoff Hydrograph

## Part I – Simulation on Conceptual Catchment

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

In this paper we try to find the general shape of the relation between storm movement parameters like storm duration, intensity, velocity and direction, and its influence on peak discharge. This influence is called a "directional bias". Different factors affecting the magnitude of directional bias are described. The relations between rainfall characteristics and the magnitude of the directional bias are shown for a conceptual catchment.

The most important conclusion is that the maximal directional bias can theoretically reach values of several hundred percent, but this can happen only in a catchment with specially designed linear geometry. Maximal directional bias can be expected for storms moving downstream the catchment with velocity equal to the average flow velocity. Maximal directional bias occurs for storms with short duration giving low peak discharge, which are not important for design purposes.

## Introduction

The influence of rainfall movement on the shape of the runoff hydrograph has been recognised for a long time. Rainstorms traveling downstream the catchment along the main direction of conduits produce higher peaks and steeper limbs of the hydrograph than storms moving upstream. In the following text we will call this effect a maximal directional bias and define it as follows:

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

where: $QP$DOWN – peak flow for storms moving downstream,
$QP$UP – peak flow for storms moving upstream.

Motivation for this definition is the fact that we are here interested in a maximal possible effect of the storm movement on the peak discharge. This maximal effect, or the greatest difference between the peaks, will occur when the storm moves in the opposite directions: downstream and upstream. If the peak observed during downstream storm movement is, for example, 10 $m^3/s$ and 5 $m^3/s$ for upstream movement, we will have a maximal directional bias equal to 100% according the definition.

The directional bias is greatest when 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 (for example 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 thorough knowledge of the catchment parameters if the influence of rainfall movement on the runoff hydrograph is to be investigated.

An attemtp 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.

This first part of this work, describes here present studies of directional bias made by simulation of runoff on a conceptual catchment. The second part, presented as a separate paper will describe studies performed on several real catchments in Lund (Niemczynowicz 1984b).

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

## Factors Influencing Peak Discharge

The magnitude of the peak discharge and the directonal bias depends on a number of factors which can be divided into two groups, the first related to rainfall characteristics, and the second related to geometric and hydraulic characteristics of the catchment. All factors in both groups can, theoretically, be variable over a very wide range, but in practice we have to deal only with a limited range of these factors, defined for example, by intensity-duration-frequency (*i-d-f*) relationships or real catchment characteristics.

Dimensional analysis of factors influencing the runoff hydrograph (Yen and Chow 1969, Townson and Ong 1974) shows that non-dimensional, relative peak discharge can be defined as follows:

$$\frac{Qp}{IA} \equiv f\left(\frac{Vr}{I}, \frac{T\,I}{L}, \frac{t}{T}, \frac{B}{L}, \frac{D}{Lc}, Ss, Sc, \frac{K}{L}\right) \qquad (1)$$

where:
*Qp* – peak discharge
*I* – rainfall intensity
*A* – area covered by moving storms during duration *T*
*Vr* – rainfall velocity
*t* – start discharge time
*T* – rainfall duration observed at a point
*B* – width of catchment
*L* – length of catchment
*D* – diam. of conduits
*Lc* – length of conduits
*Ss* – surface slope
*Sc* – conduit slope
*K* – roughness length.

if we neglect terms accounting for temperature, kinematic viscosity and the effect of the distribution of raindrops.

The first 3 terms represent the effect of the momentum, energy and mass inputs of the rainfall, the next 5 terms represent the effect of geometry and topography of the catchment (Yen and Chow 1969). It is obvious that the peak flow discharge depends on storm velocity in relation to flow velocity. But the flow velocity depends on both rainfall and catchment characteristics and changes during one event, thus it can not conveniently be used as an independent parameter. Choosing independent parameters according to Eq. (1), we have a possibility to separate rainfall dependent parameters from catchment dependent parameters, the last ones being constants for one particular catchment.

At first, we want to clarify the relations between rainfall characteristics and peak discharge. In this case, for the given catchment, Eq. (1) will be reduced to:

$$\frac{Qp}{IA} \equiv f\left(\frac{Vr}{I}, \frac{T\,I}{L}, \frac{t}{T}\right) \tag{2}$$

Obviously, the function *f* will be different for different directions of storm movement in relation to the direction of conduits. Since we are only interested in the situation when directional bias is maximal, we will consider two extreme directions in relation to the main direction of conduits: downstream and upstream direction. We can now split Eq. (2) into two separate equations for these two directions:

$$\frac{Qp\mathrm{up}}{I\,A} \equiv f_1\left(\frac{Vr}{I}, \frac{T\,I}{L}, \frac{t}{T}\right) \tag{3}$$

$$\frac{Qp\mathrm{down}}{I\,A} = f_2\left(\frac{Vr}{I}, \frac{T\,I}{L}, \frac{t}{T}\right) \tag{4}$$

where: *Qp*UP – peak discharge for upstream storm movement,
*Qp*DOWN – peak discharge for downstream storm movement.

Because, for the moment we are not interested in time pattern of the runoff hydrograph and *L* is a constant, we can relate the relative peak discharge for both downstream and upstream storm movement only to relative storm velocity *Vr/I* and plot this relationship using storm duration *T* as a curve parameter. With this relationship, the peak flow for both downstream and upstream storm movement can be calculated for any combination of storm movement parameters. The relative peak discharge relates to rainfall intensity and duration by different functions. It would be very difficult to derive these relations from observed rainfall events, because the intensity and duration cannot be clearly defined. Therefore, at first we used the rainfall with constant intensity during its duration ("block rains").

## Conceptual Catchment and Runoff Simulation Model

In order to minimize the costs of computer runs we chose to investigate the general form of the relations on a simple, conceptual catchment with geometric and hydraulic parameters similar to respective parameters for the real catchment in Lund. The conceptual catchment consists of 12 subcatchments with a total area of 50 ha and 30% imperviousness each. Subcatchments are connected to each other by 12 identical conduits, each with a length of 460 m, a diameter of 2.0 m and slope of 0.004 (see Fig. 1). The geometry of the conceptual catchment seems to be simple in comparison with real catchments, but if we want to simulate the runoff process in a realistic way, the simulation model must account for important physical processes which influence the shape of runoff hydrograph. Therefore, the Storm Water Management Model (SWMM) was used for simulations. SWMM

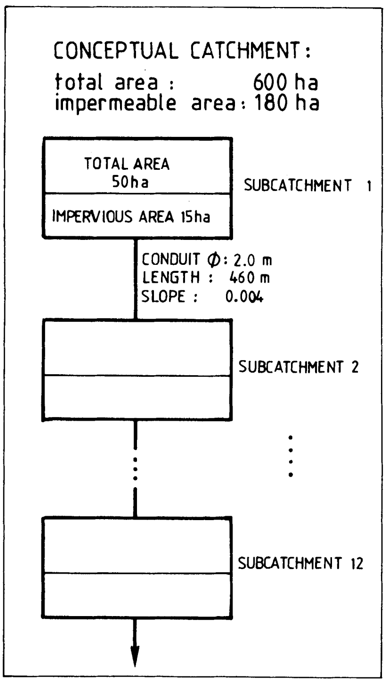


Fig. 1. Schematic representation of conceptual catchment used for developing the relationships between peak discharge and storm movement parameters.

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 block rain input with intensities between 5 and 100 mm/h, and durations between 2 and 100 minutes. 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 with 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 in opposite subcatchments.

## Relationship between Relative Storm Velocity and Relative Peak Discharge

Results of about 100 SWMM runs were used for plotting the relations between relative peak discharge and relative storm velocity for downstream and upstream storm movement. These plots are shown in Figs. 2 and 3. Simulation runs were performed with storm velocity of 2 m/s, 4 m/s and 8 m/s. Each simulation was run twice with storm direction downstream and upstream. Rain input consisted of simple block rainfalls with constant intensity $I$ during duration $T$.

Some scatter of observation points can be noticed on both plots. The reason for scatter is that rainfall intensity involved in terms on the axis of the plot is not exactly defined for all runs. We assume that there is no runoff from permeable surfaces, the assumption which is often valid for real catchments. But here, some runoff from permeable surfaces can occur during runs with high rainfall intensity and long duration. Resulting contribution area $A$ is slightly different between runs with and without runoff from permeable surfaces. Also effective rainfall intensity on permeable surfaces is not the same as that for impermeable surfaces. Storm duration, used as a curve parameter, was adjusted for the time of filling up the depression storage, but even this parameter is not defined exactly, because the model produce runoff directly, without extracting depression storage, on 25% of all impermeable surfaces. Therefore, the plots of relationship between relative storm velocity and relative peak discharge shown in Figs. 2 and 3 can be only used as a rough approximation of this relationship. Further refinement of the accuracy of the relation is not worth trying, because it is only valid for one particular catchment.

In spite of the inaccuracies mentioned above, both plots show a clear picture of relationship.

The relationships shown in Figs. 2 and 3 are only valid for our particular

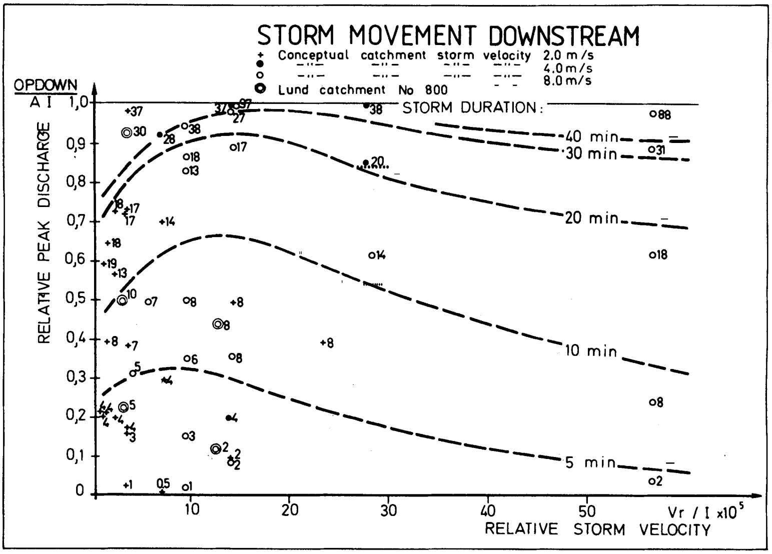


Fig. 2. Relation between relative peak discharge and relative storm velocity for downstream storm movement.

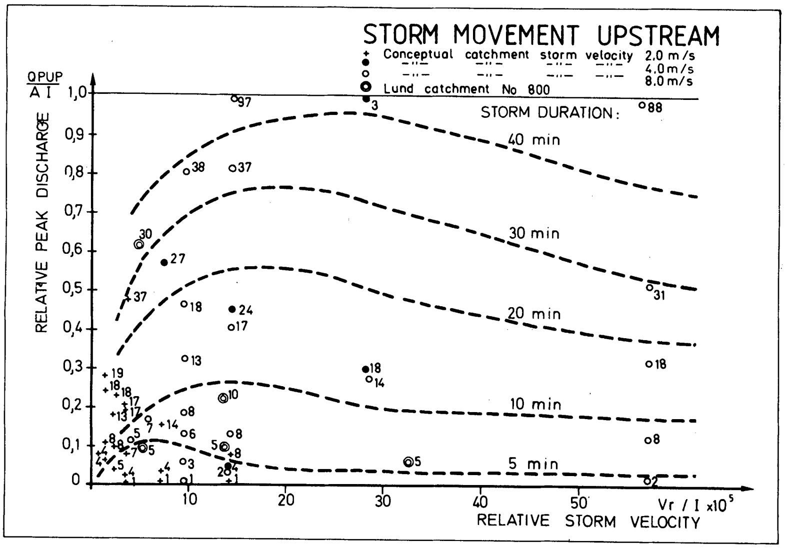


Fig. 3. Relation between relative peak discharge and relative storm velocity for upstream storm movement.

catchment, but since the parameters chosen for this conceptual catchment are similar to those of the real catchment, we can expect that the general shape of the relations will also be similar. For comparison, points obtained from runs on a real catchment in Lund are shown in Figs. 2 and 3. These points fit quite well. From both graphs, the peak flow for downstream and upstream storm movement can be calculated for any combination of storm parameters.

## Relationship between Storm Duration and Directional Bias

Maximal directional bias can be expected if the storm velocity is equal to the flow velocity in a conduit. However, the flow velocity in a conduit is a function of flow discharge and changes during runoff event and between events. Therefore, the storm velocity was compared with approximate of average flow velocity being equal to full-conduit flow. Due to the shape of the relation between flow velocity and discharge for a given conduit, the error in estimation of average velocity is small if the flow does not decrease below ⅓ of the full-conduit flow. Rain input for simulation runs was chosen so that this condition was fulfilled. The average flow velocity for the conceptual catchment was about 3 m/s. Simulation runs were performed with storm velocity of 2 m/s, 4 m/s and 8 m/s.

Now we can rearrange the observation points and show the relation between the directional bias and the storm duration for different storm intensities and for any particular storm velocity. Fig. 4 shows this relationship for storm velocity of 2 m/s (under the average flow velocity) and Fig 5, for storm velocity of 8 m/s (above the average flow velocity).

Figs. 4 and 5 show that the relationship is rather complicated and that the shape of the relationship changes drastically if the storm velocity changes. If the storm velocity is approximately equal to the average flow velocity (Fig. 4), the directional bias increases when the rainfall intensity decreases for all durations. The maximal bias for all intensities occurs, when the duration is short, of the order of 3-10 minutes. These cases, however, are of small practical importance because the discharge is relatively small. The maximal simulated bias was about 500% for rainfall intensity 10 mm/h and duration 5 minutes.

If the storm velocity is higher than average flow velocity (Fig. 5), the relationship has an opposite sequence: low intensitites generally give smaller maximal bias than high intensities. Maximal bias occurs at different durations for different intensities. In this case, the maximal bias of about 180% was simulated for rainfall intensity of 50 mm/h and 5 minutes duration. It is worth noticing that, as expected, the magnitude of directional bias decreases as the storm velocity increases above the average flow velocity.

It is also worth noticing that the directional bias tends to zero if the rainfall duration approaches a certain value. The value of duration when the bias is equal

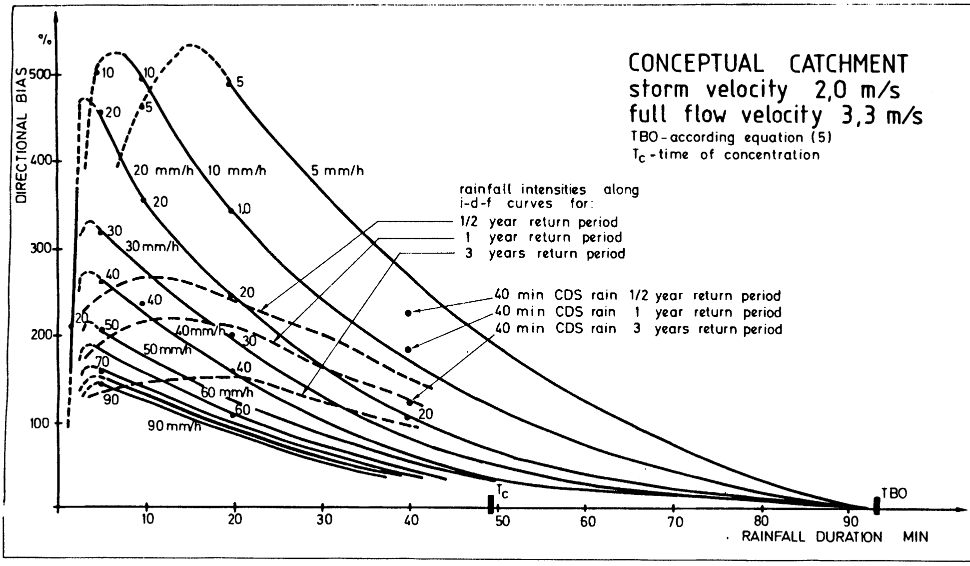


Fig. 4. Relationship between storm duration and directional bias for storm velocity of 2 m/s.

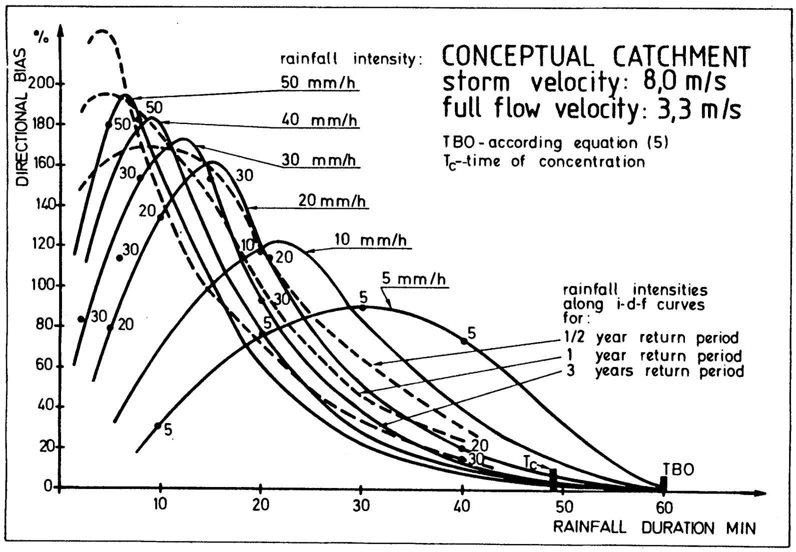


Fig. 5. Relationship between storm duration and directional bias for storm velocity of 8 m/s.

to zero ($TBO$) depends on the time of concentration for the catchment ($Tc$), storm velocity ($Vr$) and the length of the catchment ($LA$) in the following way:

$$TBO = Tc + \frac{LA}{Vr} \quad (5)$$

Eq. (5) simply says that there will be no difference in a peak flow for down- and upstream storm movement if the storm duration is sufficiently long for steady-state conditions to develop in both cases.

We can also calculate the width of the storm band ($LRO$) (or the diameter of a storm cell in real cases), necessary for occurrence of the above described conditions:

$$LRO = LA + Tc\ Vr \quad (6)$$

In this case, $TBO$ equals 93 minutes for a storm velocity of 2 m/s and 60 minutes for a storm velocity of 8 m/s, assuming the same value of $Tc$ equal to 49 minutes in both cases.

The width of the storm band $LRO$ would be 11,160 m for 2 m/s and 28,800 m for 8 m/s storm velocity. Such large dimensions are more typical for so-called Small Mesoscale Areas (Austin and Houze 1972) than for single rainfall cells. Therefore, we can conclude that conditions necessary for directional bias equalling zero never occur in practice.

## Directional Bias Simulated for Rainfalls along the Intensity-Duration-Frequency Curves

In order to connect the directional bias values to a return period we can follow the relationship along the *i-d-f* curves. For storm velocity equal to average flow velocity (Fig. 4), the lines along the *i-d-f* curves have a distinct maximum for durations longer than those of the observed absolute maximum of directional bias. Maximal bias occurs for rainfall durations varying between 1/5 and 1/3 of the time of concentration if the rainfall intensity is chosen along respective *i-d-f* curves. It is worth noticing that the sequence of curves describing the directional bias along the *i-d-f* curves is "favorable" from a practical point of view; storms with a longer return period have a lower bias than storms with a short return period. In other words, maximal directional bias will occur for small rainfall events which do not cause any problems. The same sequence was observed using the so-called Chicago design storm (CDS-storm, Keifer and Chu 1957) as rainfall input (see Fig. 4).

Respective relationships for storm velocities greater than flow velocity (Fig. 5), have an opposite sequence; directional bias is highest for rainfalls with a long return period. Rainfall duration for maximal bias varies between 1/10 and 1/6 of the time of concentration. Table 1 shows the maximal directional bias for different storm velocities and return periods.

Table 1 – Maximal directional bias simulated on the conceptual catchment for storms following intensity-duration-frequency curves.

| Storm Input | Storm durat. min. | Storm intens. mm/min. | Return period years | Maximal bias % | Time max bias / time concentr. |
|---|---|---|---|---|---|
| | | STORM VELOCITY 2.0 m/s | | | |
| Block rain | 12 | 28.8 | 1/2 | 265 | 0.24 |
| Block rain | 15 | 33.0 | 1 | 207 | 0.31 |
| Block rain | 18 | 47.5 | 3 | 142 | 0.37 |
| | | STORM VELOCITY 4.0 m/s | | | |
| Block rain | 12 | 28.8 | 1/2 | 200 | 0.24 |
| Block rain | 12 | 37.8 | 1 | 195 | 0.24 |
| Block rain | 11 | 77.2 | 3 | 187 | 0.22 |
| | | STORM VELOCITY 8.0 m/s | | | |
| Block rain | 12 | 28.8 | 1/2 | 164 | 0.24 |
| Block rain | 8 | 48.9 | 1 | 180 | 0.16 |
| Block rain | 6 | 88.2 | 3 | 192 | 0.13 |
| | | STORM VELOCITY 2.0 m/s | | | |
| CDS-storm* | 40 | | 1/2 | 222 | |
| CDS-storm* | 40 | | 1 | 182 | |
| CDS-storm* | 40 | | 3 | 120 | |

* Chicago Design Storm (Keifer and Chu 1957)

## Directional Bias Versus Conduit Slope

All values presented in Table 1 are obviously valid only for our particular catchment. As can be seen from Eq. (1), flow discharge depends also on geometric and hydraulic parameters of the catchment and sewer network. Investigation of the influence of all included parameters would require a great number of runs. Instead, we assumed that our real catchments in Lund would react in a way similar to the conceptual catchment since the parameters chosen are similar. Only one parameter, which intuitively feels very important, the slope of conduit was tested.

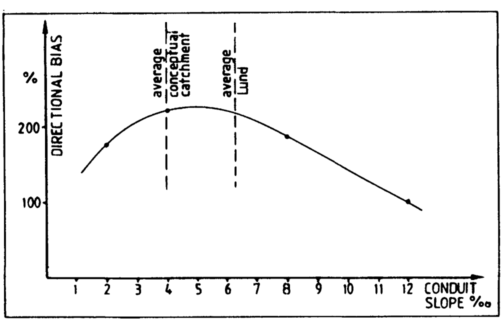


Fig. 6.
Conduit slope versus directional bias for 1-year "block rain" with 15 min. duration.

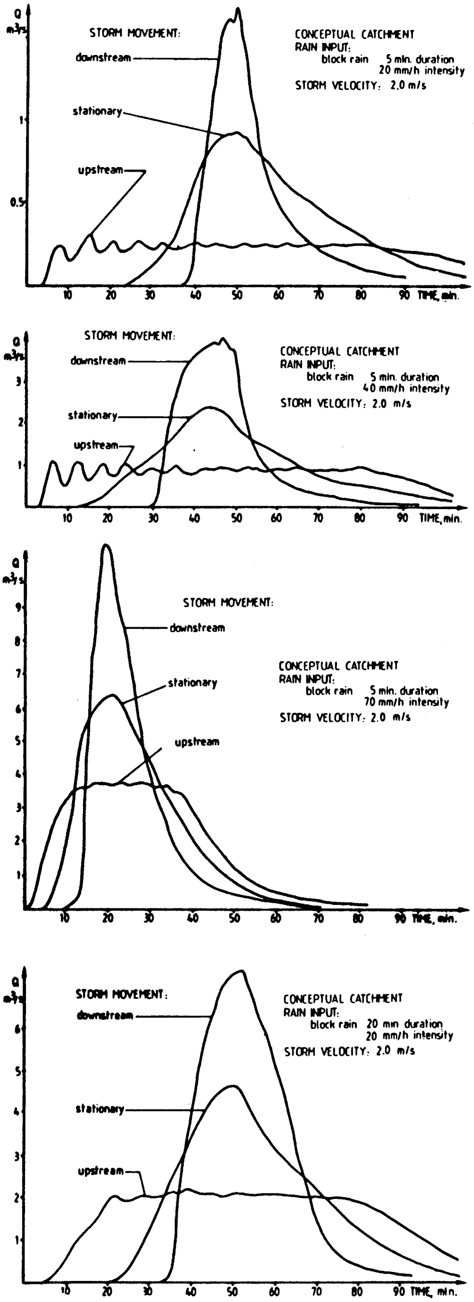


Fig. 7. Runoff hydrographs for down- and upstream storm movement. Conceptual catchment.

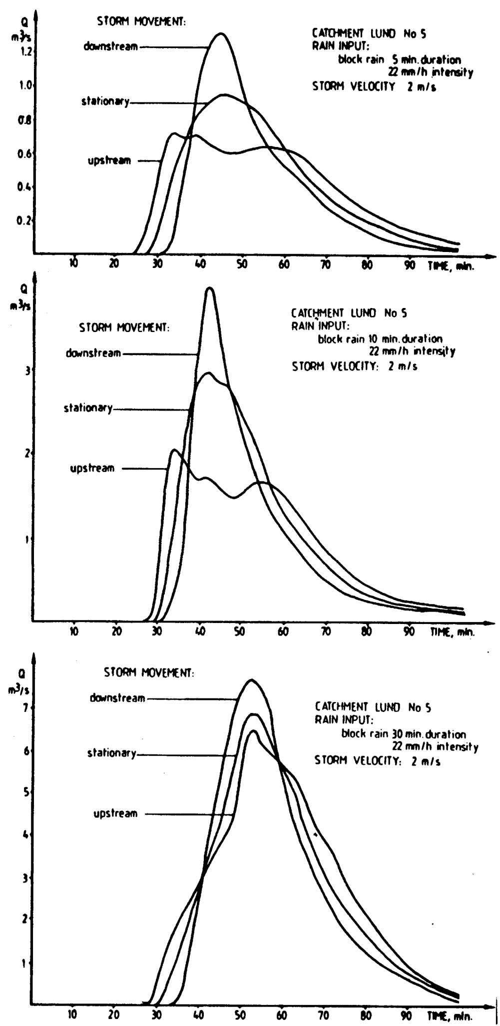


Fig. 8. Runoff hydrographs for down- and upstream storm movement. Lund catchment.

Fig. 6, which describes the relationship between conduit slope and the directional bias, shows that for block rain with a return period of 1 year and a duration of 15 minutes, there is a maximum corresponding to conduit slopes on the conceptual catchment and on the catchments in Lund.

Figs. 7 and 8 give some examples of runoff hydrographs for downstream and upstream storm movement for cases in which the observed directional bias was large. Hydrographs for stationary storms are included for comparison.

## Summarizing Conclusions

Now we can draw some summarizing conclusions which will apply for real catchments with a range of parameters similar to the conceptual catchment:

1) The maximal directional bias can be expected for storms moving downstream the catchment with velocity equal to the average flow velocity.

2) The maximal directional bias can reach values of several hundred percent, but this occurs for storms with short duration and has no practical importance.

3) For rainfalls with intensities and durations following the *i-d-f* curves, the maximal directional bias will occur at a duration related to the time of concentration. This duration can be roughly estimated at 1/5 to 1/3 of the time of concentration for the catchment.

4) For storms with velocity under the average flow velocity the maximal directional bias decreases with increasing return period. For storms with velocity above the average flow velocity, the maximal directional bias increases with increasing return period.

5) Typical slopes of conduits occurring in Lund are within the range of slopes which cause the maximal directional bias.

6) Maximal directional bias for real catchments will probably be lower than simulated for the conceptual catchment. Simple, linear geometry of the conceptual catchment was designed to maximize the directional bias.

7) Relations between storm duration and intensity versus directional bias for the real catchments will probably be more complex since the geometry of real catchments is more complicated than that of the conceptual catchment.

8) Plots of the relative peak discharge versus relative storm velocity (defined in Part II) for downstream and uppstream storm movement are useful tools for approximative calculation of the directional bias for any combination of storm characteristics.

Now, knowing the approximative shape of the relation between the storm characteristics and the directional bias, we can examine the real catchments in Lund and check our conclusions with a smaller number of computer runs. Part II of this work, presented as a separate paper (Niemczynowicz 1984b) will give the results of the studies.

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