Institutionen för vattenbyggnad
Chalmers Tekniska Högskola

Department of Hydraulics
Chalmers University of Technology

ISSN 0348 - 1069

Analysis of rainfall data for use in design of storm sewer systems

Viktor Arnell

Report
Series B:11

Göteborg 1978

22-c-14

Institutionen för vattenbyggnad
Chalmers Tekniska Högskola

Department of Hydraulics
Chalmers University of Technology

ANALYSIS OF RAINFALL DATA FOR USE IN DESIGN OF STORM SEWER SYSTEMS

Viktor Arnell

Paper presented at the
International Conference on
Urban Storm Drainage
11-14 April 1978, in Southampton, England

Report Göteborg 1978
Series B:11

Adress: Institutionen för vattenbyggnad
Chalmers Tekniska Högskola
Fack
S-402 20 Göteborg 5, Sweden

Telefon: 031/81 01 00

CONTENT

ANALYSIS OF RAINFALL DATA FOR USE IN DESIGN OF STORM SEWER SYSTEMS

Viktor Arnell

Department of Hydraulics, Chalmers University of Technology, Fack, S-402 20 Göteborg, Sweden.

ABSTRACT

The paper describes a comparison of calculated storm water discharges with two kinds of rainfall data: design rainfalls developed from intensity-duration-frequency relationships or from measured rainfall data and real measured time series of rainfalls or time series generated by statistical methods. These two rainfall approaches have been compared by simulation of the runoff by a runoff model for a 0.154 km² catchment area, Bergsjön, in Göteborg, Sweden. Data from two years of rainfall-runoff measurements have been analysed. Different types of design rainfalls have been derived and the 40 heaviest real rainfalls have been selected for simulations. The statistical analysis of the simulated peak flows shows that the real rainfalls give the best results. The conclusion is that the use of design rainfalls give a more uneven dimensioning of storm sewer systems. With real rainfalls it is possible to make a design from a statistical point of view and to find out what happens at discharges with frequencies lower than the design frequency.

INTRODUCTION

The need for precipitation data is dependent not only on the problem studied but also on the design method used. For example you need different kinds of precipitation data for the design of a detention storage than for the design of a single pipe. But you also need different rain data if you use the so-called rational method than if you use a more detailed design method.

The rational method used for design of storm sewer systems is defined as (Arnell & Lyngfelt, 1975 b):

$$Q\ (T) = \varphi \cdot i_m\ (T,t) \cdot A \qquad (1)$$

Q (T) is the calculated runoff with return period T, i_m (T,t) is the average rain intensity with return period T and durationtion t, and A is the area of the catchment. φ is a non-dimensioned runoff coefficient which defines the relationship between the statistical distribution functions for the peak flow Q (T) and the rain intensity I (T,t),(Schaake, Geyer & Knapp, 1967). The assumption is made that the runoff coefficient is independent of the recurrence interval, and therefore the only statistical analysis you need is the one you obtain through the intensity-duration curves. The peak flows are assumed to have the same frequency as the rainfalls. The use of intensity-duration-frequency relationships is connected with the use of the rational method and gives for this method enough statistical information of the rainfall. The definition above of the runoff coefficient also implies that it is not possible to calculate the runoff for single real rainfall events with the rational method.

During the last few years new and more detailed design methods have begun to come into use. Examples of such methods are ILLUDAS, (Terstriep & Stall, 1974), SWMM, (Storm Water Management Model, 1971), RRL-method, (Watkins, 1962), and the CTH-model, (Arnell & Lyngfelt, 1975 a). With these methods it is possible to simulate the runoff for real rainfall events. This means that you can apply the statistical analysis to the calculated runoffs instead of to the rainfalls. Since the runoff is the interesting design parameter, this method is more attractive.

Detailed design methods require a different type of precipitation data from that of the rational method. Input is here a series of rain intensity values describing the variation in time of the rainfall. When designing a storm water system, you can choose between different kinds of precipitation data:

- design rainfalls developed from intensity-duration-frequency relationships or from measured rainfall data
- real measured time series of rainfalls or time series generated by statistical methods.

A design rainfall is usually an average value of many rainfalls and is developed for a certain designing recurrence interval. The simulated design flows are assumed to have the same recurrence interval. Most of the design rainfalls are in one way or another connected with the intensity-duration curves.

Real measured time series of rainfalls can also be used. This means that you apply the statistical analysis to the simulated flows to find the design flow. Since volumes and time lapse vary considerably for different rainfalls, you do not need to make the rough simplifications and assumptions, which you must do when using design rainfalls developed from intensity-duration curves, (Mc Pherson, 1977), (Johansen & Harremoës, 1975). Another advantage of real rainfalls is that you receive information about what is happening with flows larger than the design flow.

Two types of precipitation data are described in the following, design rainfalls and historical rainfall data. These different rainfall data have been compared by simulation of the peak flows for a runoff area in Göteborg, Sweden.

DESIGN RAINFALLS DEVELOPED FROM INTENSITY-DURATION-FREQUENCY RELATIONSHIPS OR FROM MEASURED RAINFALL DATA

Analysis of intensity-duration-frequency curves (I-D-F-curves)

Since many of the design storms have been developed from I-D-F-curves, the following explanations may be helpful.

The I-D-F-curves are the results of a statistical analysis of single independent rainfalls. The independence is usually defined as a minimum time distance between the rainfalls. This time distance should be connected with the analysed flow problem and will therefore vary depending on, for example, if it is a pipe or a detention storage that is to be designed.

For each rainfall event you evaluate maximum rain volumes for different durations. The volumes for the different rain events with a certain duration are ranked, and the statistical distribution function is evaluated. This gives one function for each duration. For specified frequencies you draw curves showing the average rain intensity as a function of duration. This is the intensity-duration-frequency curves (Figure 1). Each curve con-

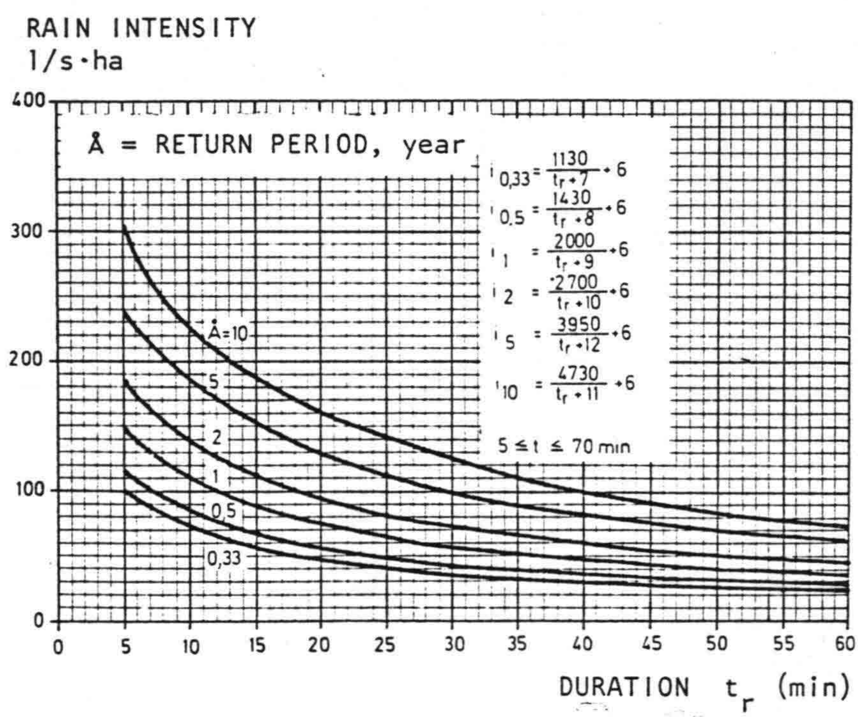

Figure 1. Intensity-duration-frequency curves for Göteborg 1926 - 1971. (VAV, 1976).

tains data from several rain events since the different durations have been treated separated from each other. This means that a design storm developed from an I-D-F-curve will contain data from several real rainfalls, (Mc Pherson, 1977). The return period for the design rainfall must therefore be longer than for different parts of the I-D-F-curve.

The rain volume given by the I-D-F-curves represents only a part of the total volume of the real rainfall. The volume prior to and the one after the studied duration are not included in the analysis. Especially the rain volume prior to the studied duration influences the design of detention storages, (Mc Pherson, 1977). Table 1 shows the rain volume for different durations in comparison with the total volume for a precipitation station in Göteborg.

Table 1. The rain volumes for different durations in comparison with the total rain volume at Lundby, Göteborg, 1926-1955. Average values for rainfalls with a return period exceeding two years, (Arnell, 1974).

Duration	Rain volume corresponding to the duration	Total rain volume	Percent of the total rain volume
min	mm	mm	%
10	10,7	20,0	54
20	15,2	23,9	64
30	17,6	24,4	72
40	19,3	26,7	72
50	20,5	26,7	77
60	21,2	30,2	70
70	22,2	30,4	73

Design rainfalls developed from intensity-duration-frequency relationships

The characteristics of most of the design rainfalls developed from I-D-F-curves are such that the average intensities for different durations follow an I-D-F-curve. The easiest way of developing a design rainfall is to assume that the peak intensity is located in the middle of the rain and distribute the rest of the rain symmetrically around the peak (see Thorndal, 1971 and Figure 2).

Keifer & Chu (1957) presented a design rainfall developed from the mathematical expression for the I-D-F-curves, for example

$$i_m = \frac{a}{t+b} + c \qquad (2)$$

i_m = average rain intensity during the time t

t = duration

a,b,c = constants

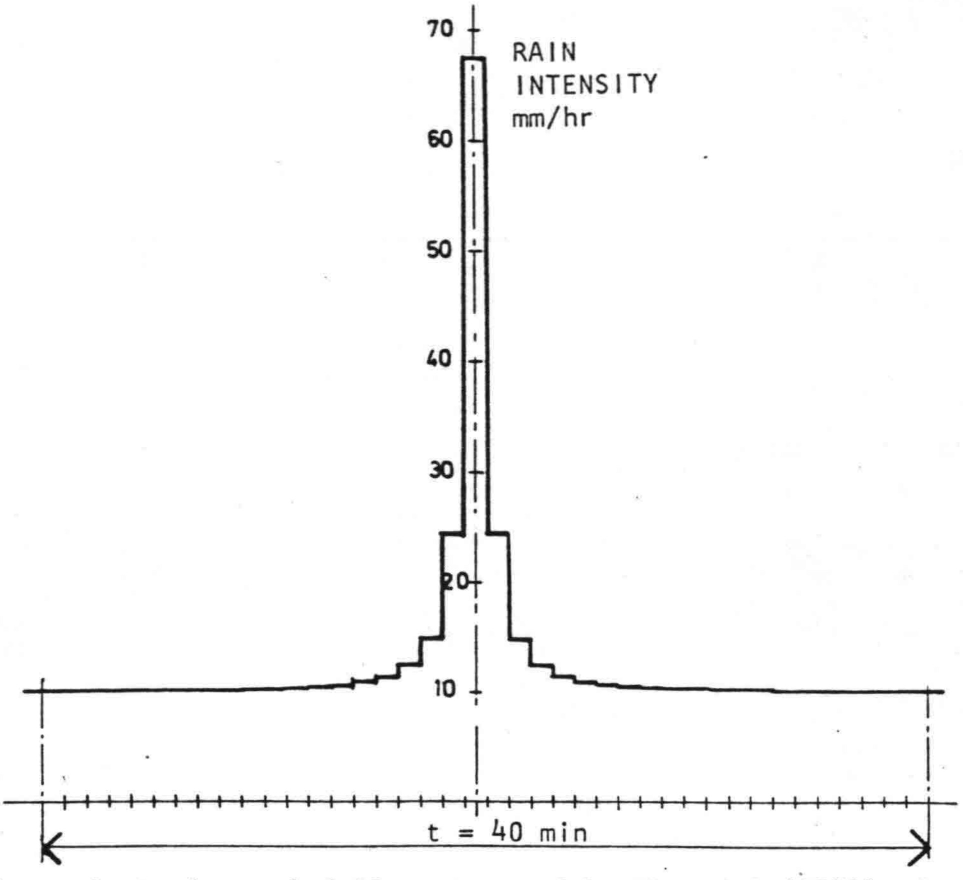

Figure 2. Design rainfall, suggested by Thorndal (1971), derived from intensity-duration-frequency relationship for Bergsjön 1973-1974. Recurrence interval 1/2 year.

From this equation it is possible to develop two expressions describing the variation in rain intensity prior to and after the peak intensity:

$$i = \frac{a \cdot b}{\left(\frac{t_f}{r} + b\right)^2} + c \qquad \text{(prior)} \qquad (3)$$

$$i = \frac{a \cdot b}{\left(\frac{t_e}{1-r} + b\right)^2} + c \qquad \text{(after)} \qquad (4)$$

i = instantaneous rain intensity

t_f = time counted from peak intensity towards the start of rainfall

t_e = time counted from peak intensity towards the end of rainfall

r = the relationship between the time prior to peak intensity (t_f^{max}) and the total duration (t).

$r = t_f^{max}/t$; $1-r = t_e^{max}/t$

The location of the peak intensity within the rainfall is evaluated in one of two ways. One is to study the location of the peak intensity within the duration t for the real rainfalls. The other way is to determine how much of the total rain volume has been registered prior to the peak intensity. Precipitation data for Chicago (Keifer & Chu, 1957), Cincinnati, (Preul & Papadakis, 1973), India, (Bandyopadhyay, 1972) and Czechoslovakia, (Sifalda, 1973) show that between 13/40 and 16/40 of the total rain

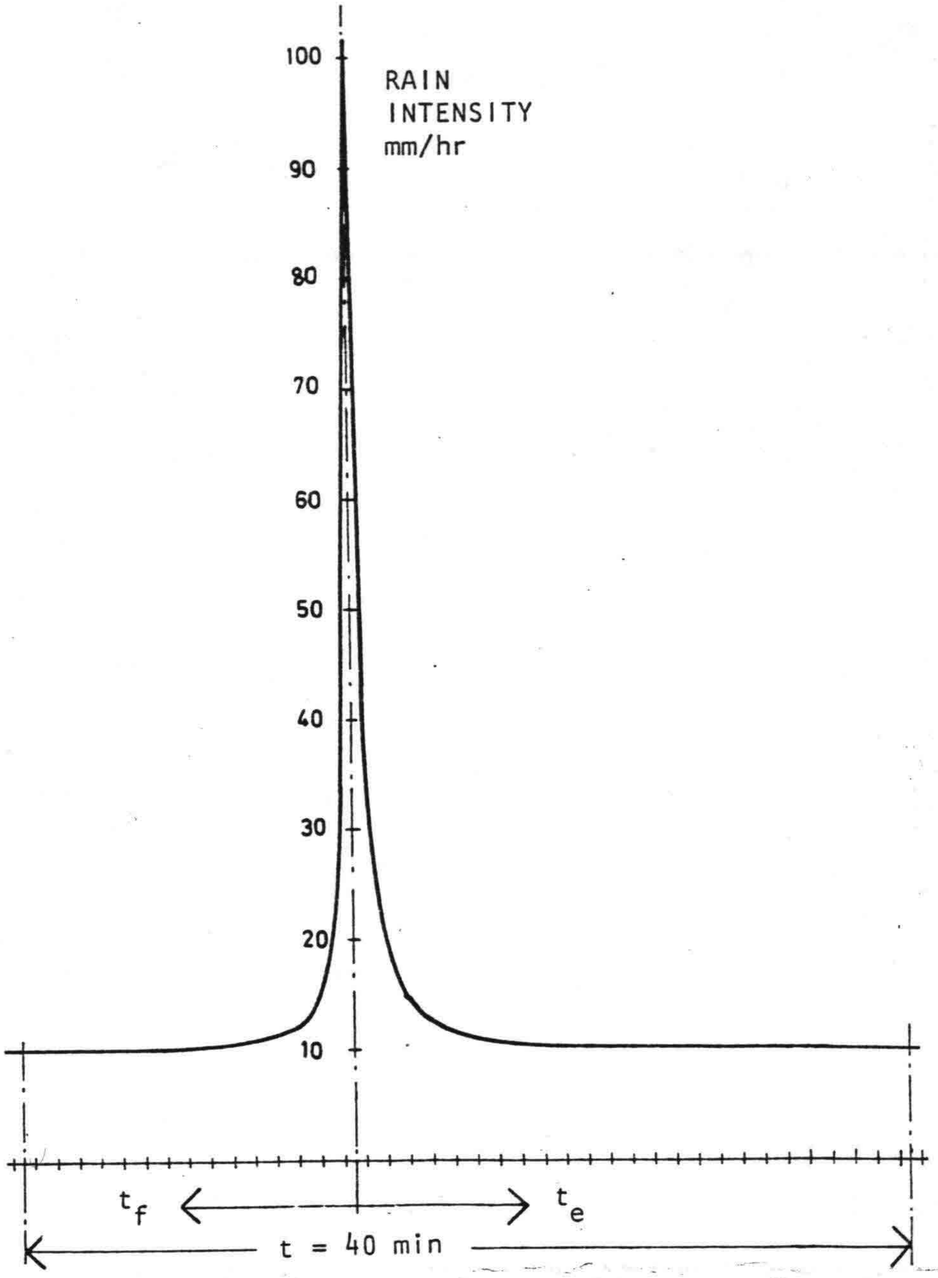

Figure 3. Design rainfall, suggested by Keifer & Chu (1957), derived from intensity-duration-frequency relationship for Bergsjön 1973-1974. Recurrence interval 1/2 year.

volume during a rainfall is registered prior to the peak intensity. The design rainfall is thus given an oblique distribution according to Figure 3.

Design rainfalls developed from measured rainfall data

By evaluating "typical" heavy rainfalls, you can develop design rainfalls directly from measured rainfall data. These rainfalls are rather some sort of average rainfalls than design rainfalls developed in a statistical way.

Sifalda (1973) has described a design rainfall of this type developed from data for some places in Czechoslovakia (Figure 4). The rainfall is an average rainfall for those rains, where the average rain intensity for at least one duration exceeds the I-D-F-curve with a recurrence interval of one year. The design rainfall is connected with the I-D-F-curves by part 2 for which the average intensity-duration is chosen from the curves. The average total duration of all rainfalls in the investigation was 30-35 minutes. This means that the duration of the main rainfall, part 2, on the average was only about 8 minutes. Since the rain includes the parts prior to and after the main part 2, the total volume is better described than for the design storms developed directly from the I-D-F-curves.

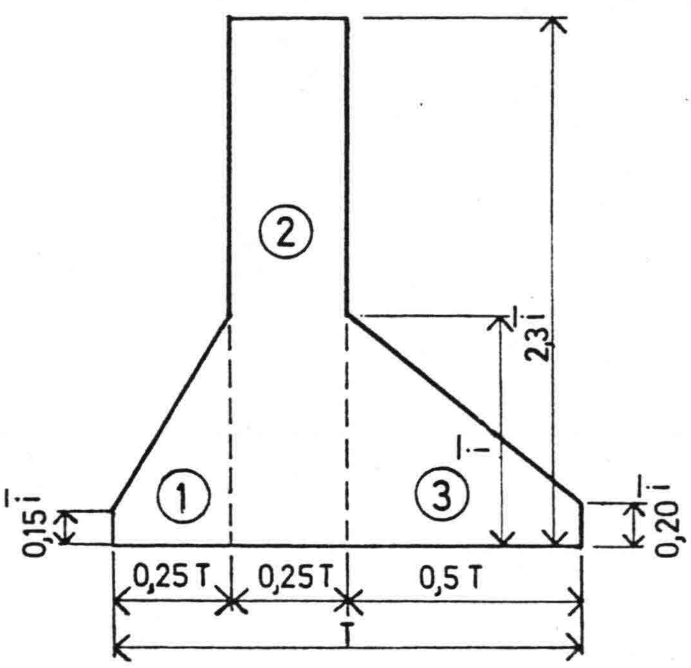

Figure 4. Design rainfall suggested by Sifalda (1973). Intensity-duration for part 2 is obtained from intensity-duration-frequency curves.

For the RRL-method in England a rainfall determined as an average of a number of heavy rainfalls is used, (Natural Environment Research Council, 1975). The rainfalls were divided into four quartiles according to the shape of the rainfalls. The shape was classified from rainfalls with pronounced peaks to more uniform rainfalls. The results are presented in tables and curves; one example is shown in Figure 5. The shapes of the curves were found to be independent of the total duration of the rainfall and the return period. Average intensity (volume) and duration for the total rainfall are given by the I-D-F-curves.

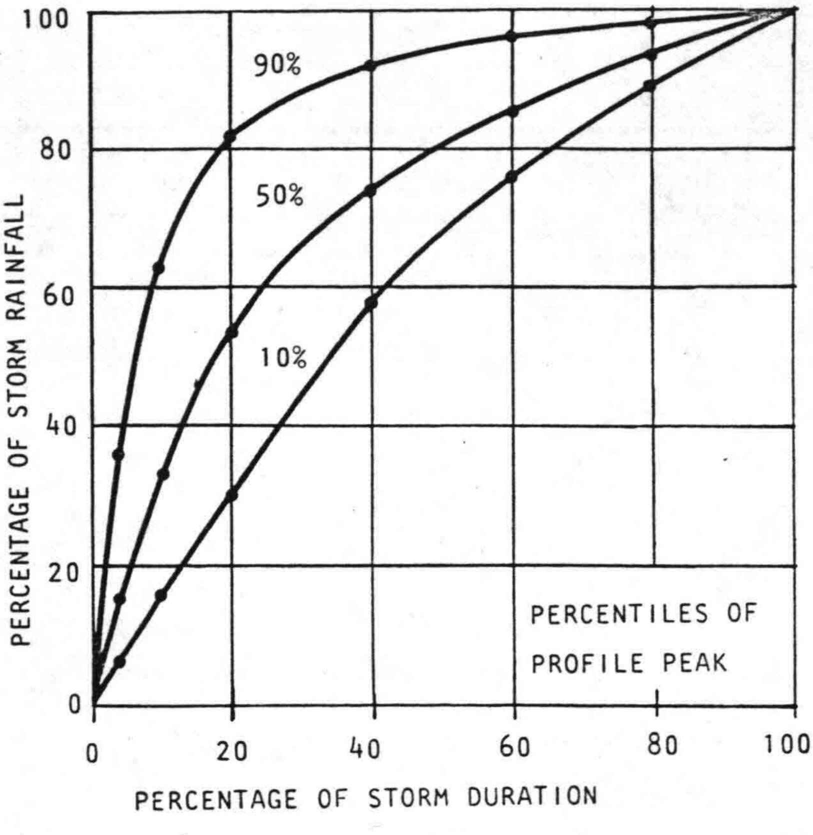

Figure 5. Cumulative percentage rainfall in England (May to October) as a function of rainfall duration. The duration, expressed as percent of the total duration, is centered around the peak intensity. The 90%-curve means that 10% of the rainfalls are more peaked than that curve. (Natural Environment Research Council, 1975).

A similar investigation has been done by Huff (1967). The resulting design storm is used in the ILLUDAS model, (Terstriep & Stall, 1974). Huff found that the peak intensity usually is located in the first quarter of the duration and therefore recommended a curve according to Figure 6. In Huff's study the rainfalls were divided into time increments of 30 minutes, and only rainfalls with a long total duration were studied. Consequently, it is difficult to judge if the result is valid for shorter durations.

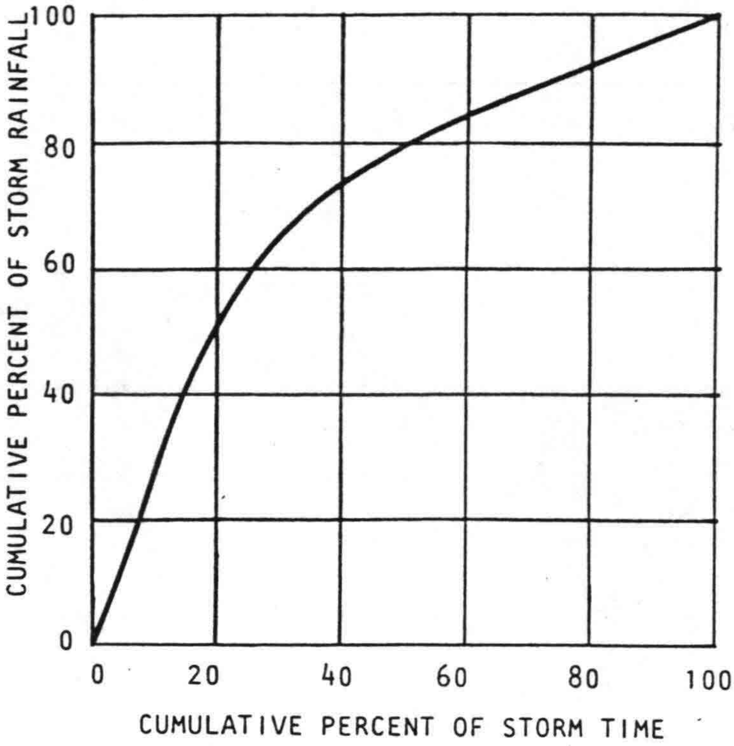

Figure 6. Design rainfall used in the ILLUDAS-model. (Terstriep & Stall, 1974).

Other design rainfalls developed directly from measured rain data have been presented by Holland (1967) and Young (1973).

USE OF REAL MEASURED TIME SERIES OF RAINFALLS

Runoff simulations for real measured rainfalls make it possible to apply the statistical analysis to the simulated flows and thereby find the design flow. With this procedure the rainfall and the runoff do not need to have the same statistical characteristics. It is more attractive to make the statistical analysis on the flow since it is the interesting design parameter.

To minimize the costs, you should select the interesting rainfalls for analysis. The number of rainfalls needed equals the number you need to evaluate the statistical distribution function for flows with interesting recurrence intervals. It should be possible to select a suitable group of rainfalls by means of some method.

Johansen & Harremoës (1975) have suggested the use of a simple runoff model to select the most interesting rainfalls. They propose that you use the time-area-method for developing a unit hydrograph for selected design points in the sewer system. Then you calculate the runoff for all rainfalls by this simple method and make the statistical analysis. The rainfalls corresponding to and close to the design frequencies are selected for more accurate simulation with a detailed design model.

Another method is based on the selection of rainfalls with certain characteristics, for example all rains with a volume exceeding some values. When designing a sewer system for peak flows, you can evaluate the times of concentration for the interesting points in the pipe system. This can be done by means of a design model and a rainfall with constant rain intensity. Knowing the times of concentration, you can, for all rainfalls, calculate maximum average rain intensities for the corresponding durations. After ranking these intensities in magnitude, you can select a group of rainfalls giving runoffs with frequencies around the design frequency. This group of rainfalls is then used in the real design.

The latter method has the advantage that you can once and for all list the rainfalls for different durations. When designing a system, you just calculate the time of concentration and choose the group of rainfalls with corresponding duration and desired frequency. The reliability of the method is probably depending on the size of the runoff area and the structure of the sewer system.

Another advantage of using historical rainfalls is that you obtain information about what is going to happen for flows larger than the design flow.

TEST OF RUNOFF SIMULATIONS WITH DIFFERENT TYPES OF PRECIPITATION DATA

Some of the rainfall approaches have been tested on the catchment called Bergsjön in Göteborg. This is a 0.154 km^2 large residential area with multi-family houses. The imperviousness is 38%. The structure of the storm sewer system is tree type, and the longest distance from one inlet to the outlet is 800 m. The slopes of surfaces and pipes are rather steep. Additional details of the catchment can be found in Arnell & Lyngfelt (1975 b).

For the Bergsjön area we have evaluated rainfall-runoff data for the period 1973-1974, (Arnell & Lyngfelt, 1975 b). The test described in this paper has been carried out using data on peak flows, runoff volumes, rain volumes, and average rain intensities for 1,2,3,6,9,12,15, and 20 minutes' duration. The 40 largest peak flows and average intensities have been statistically analysed and intensity-duration-frequency curves derived (see Figure 7). The curves are described by the following equation:

$$i_m = \frac{a}{t+b} + c \tag{5}$$

where i_m is the average rain intensity (mm/hr) for the duration t (min) and a, b, and c are constants.

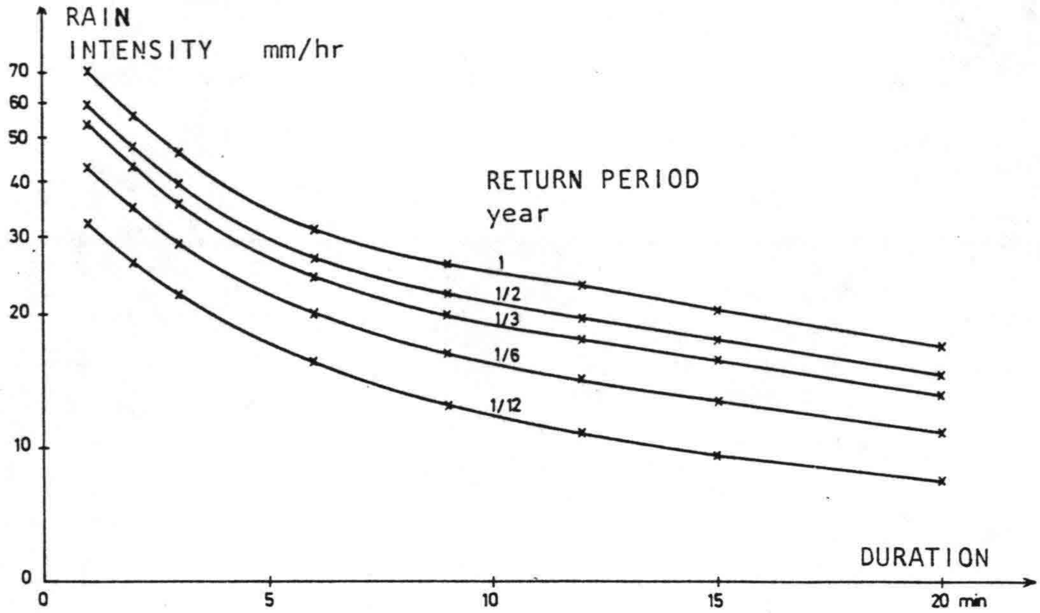

Figure 7. Intensity-duration-frequency curves for Bergsjön 1973-1974.

From the I-D-F-curves design rainfalls according to Thorndal (1971), Keifer & Chu (1957), and Sifalda (1973) have been evaluated for return periods of 1/12, 1/2 and 1/1 years (see Figures 2, 3 and 4). For the Sifalda rainfall you also have to choose duration since the central part of that rain is obtained from the I-D-F-curves. In order to find the maximum peak flows, we have tested the durations of 4, 6, 8, and 10 minutes for the central part giving a total rainfall duration of 16, 24, 32, and 40 minutes.

Maximum average rainfalls with a duration of 3, 4, 6, 8, and 10 minutes have also been used to simulate peak flows. All these rainfalls have been used as input in a detailed runoff model (see Figure 9).

The runoff model (Arnell & Lyngfelt, 1975 a), is divided into five parts: infiltration, surface depression storage, overland flow, gutter flow, and pipe flow. The overland flow and pipe flow are described by kinematic wave theory. The model's capability of reproducing the statistical distribution function for the 40 largest peak flows is shown by simulation of the runoff from the rainfalls corresponding to those peak flows (see Figure 9). For all historical storms and for all of the design storms but the maximum average rainfalls the surface depression storage is chosen to be 0.8 mm for paved areas and 0.3 mm for the roofs. For the maximum average rainfalls the storage is set at zero because these rainfalls have no rainfall prior to the main rainfall.

Time of concentration for the Bergsjön area has been determined by simulation of the runoff for a constant rain intensity of 25 mm/hr preceded by a rainfall of 3 mm/hr (see Figure 8).

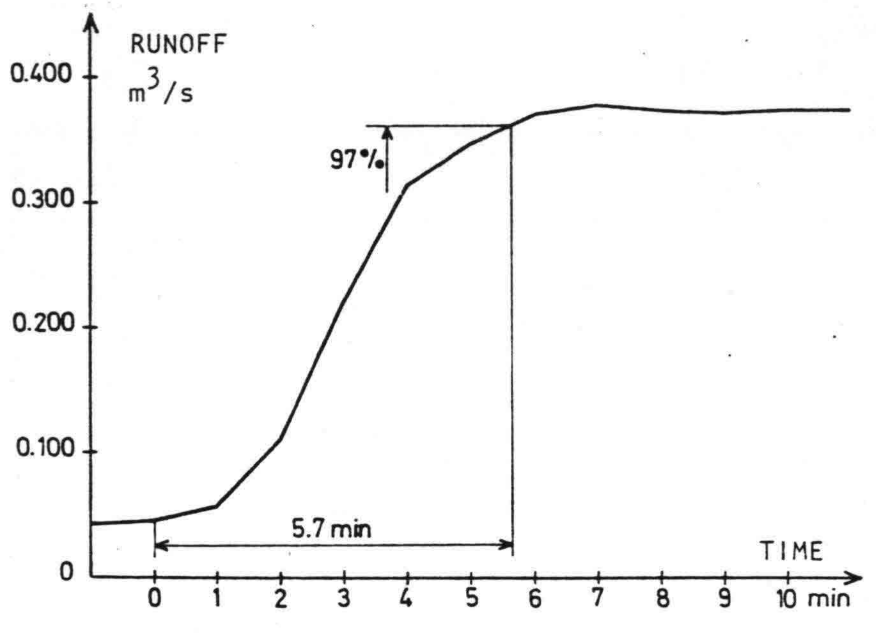

Figure 8. Runoff from Bergsjön for a constant rainfall of 25 mm/hr preceded by a rainfall of 3 mm/hr.

97% of the asymptotic flow value has been chosen as the point of time for evaluating the time of concentration (see Izzard, 1946).This time was found to be six minutes. The 40 biggest rainfalls were selected from the list of average rain intensities with six minutes' duration. These historical rainfalls are used for runoff simulations, and the result is compared with the results from the simulations for the design storms (see Figure 9).

RESULTS AND DISCUSSION

The results of all simulations are presented in Figure 9. The figure shows the real distribution function for the measured peak flows and the calculated peak flows of different kinds of rainfall data.

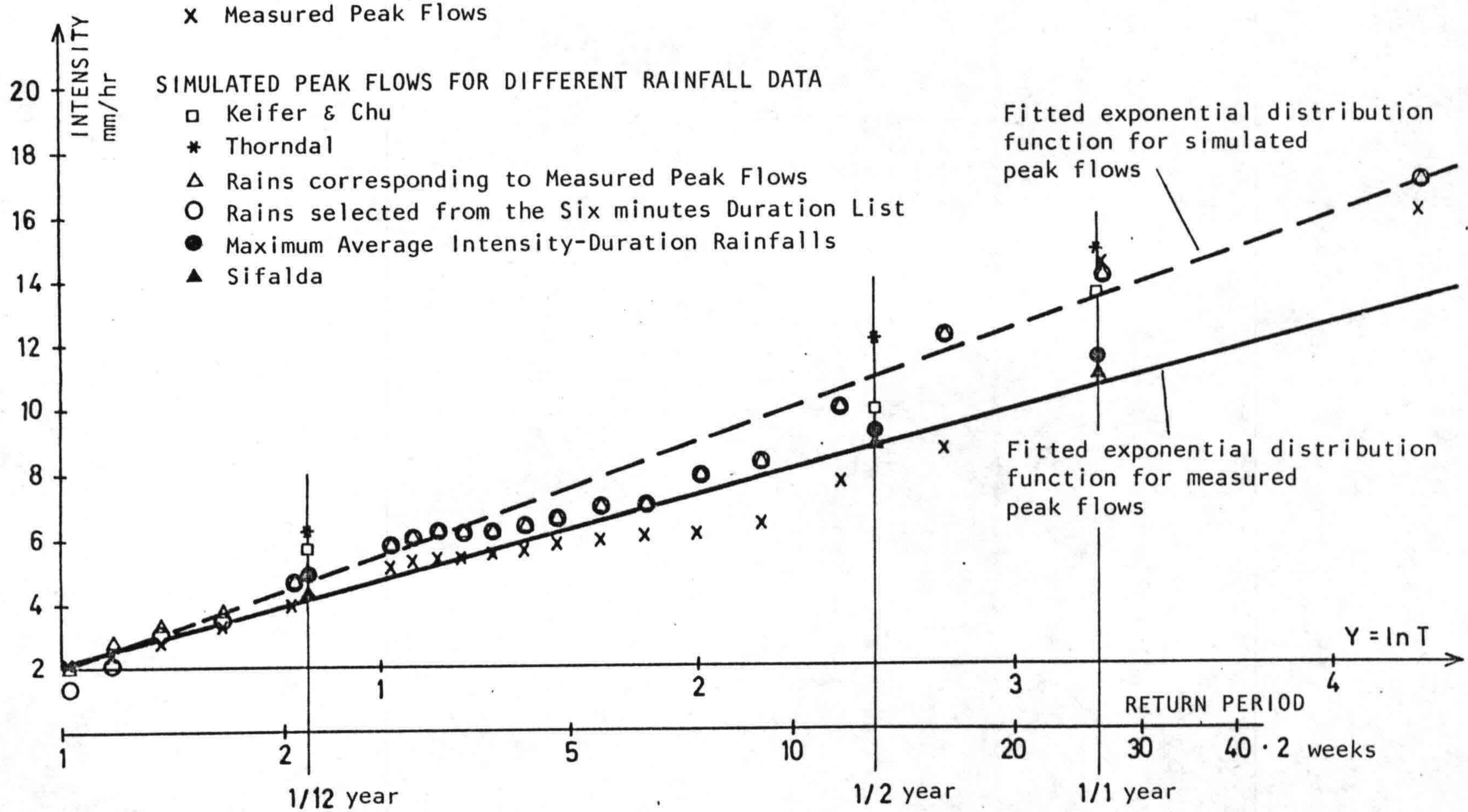

Figure 9. Results of simulation of the peak flows from Bergsjön 1973-1974 with different types of rainfall data.

The runoff model slightly overestimates the peak flows because of the difficulties in determining the areas supporting the runoff. The model is not calibrated. Input data are chosen after mapping and from the literature.

The distribution function for peak flows corresponding to the rainfalls selected from the six minutes' duration list coincide nearly exactly with the simulated distribution function for the real peak flows, except for recurrence intervals shorter than one month.

Calculated peak flows for different design rainfalls should be close to the distribution function simulated by the model (see Figure 9). Peak flows corresponding to rainfalls suggested by Thorndal and Keifer & Chu are close to or slightly larger than the distribution function, especially for the return period of 1/12 year.

Design storms presented by Sifalda and simple average-duration rainfalls give too small peak flows for return periods of 1/2 and 1/1 year. They are so close to each other because of the choice of the maximum surface depression storage. For the simple average rainfalls the storage values are set at zero. These design rainfalls are probably too great a simplification of reality. We have to remember that they were developed for use in the rational method.

CONCLUSIONS AND FUTURE WORK

This study does not indicate large differences in simulated peak flows between design storms and historical rainfall data. Simple average intensity-duration rainfalls and storms according to Sifalda may give slightly too small peak flows. However, this is a study applied to only one area and an area with a tree type pipe system. This means that the lag-time for different subareas is about the same. Marsalek (1977) compared design storms according to Keifer & Chu and historical storms. He found that the Keifer & Chu storms gave much larger peak flows. The explanation to this can probably be found in the characteristics of the runoff area.

Further studies are now being carried out on larger areas and areas with varying structure of the storm sewer system.

The use of historical storms makes it possible to carry out a good statistical analysis of simulated flows and is therefore much more attractive. The work is now mainly focused on how to analyse and use historical rainfall data when designing different storm sewer systems.

In practical engineering work the use of design storms is simple and makes the analysis cheaper. Even if the use of historical storms is more attractive from a statistical point of view, it can be worth-while trying to improve the design storms by means of a detailed runoff model and real measured rainfall data.

A long time series of rainfall data is necessary to make it possible to evaluate results and write manuals to be used in engineering design work. In collaboration with the Swedish Meteorological and Hydrological Institute, a 30 year series of measurements for a rainfall station in Göteborg is being analysed. These data will be used in future work.

REFERENCES

Arnell, V. (1974) Intensity-Duration-Frequency Relationships for Heavy Rainfalls in Göteborg during the 45 Year Period 1926-1971. Chalmers University of Technology, Urban Geohydrology Research Group, Göteborg, Report No 5. In Swedish.

Arnell, V., Lyngfelt, S. (1975 a) Rainfall-Runoff Model for Simulation of Storm Water Runoff in Urban Areas. Chalmers University of Technology, Urban Geohydrology Research Group, Göteborg, Report No 12. In Swedish.

Arnell, V., Lyngfelt, S. (1975 b) Rainfall-Runoff Measurements at Bergsjön, Göteborg 1973-1974. Chalmers University of Technology, Urban Geohydrology Research Group, Göteborg, Report No 13. In Swedish.

Bandyopadhyay, M. (1972) Synthetic Storm Pattern and Runoff for Gauhati, India. Journal of the Hydraulics Division ASCE, Vol 98, No HY5, Proc Paper 8887, pp 845-857.

Holland, D. J. (1967) The Cardington Rainfall Experiment. The Meteorological Magazine, Vol 96, No 1140.

Huff, F. A. (1967) Time Distribution of Rainfall in Heavy Storms. Water Resources Research, Vol 3, No 4, pp 1007-1019.

Izzard, C. F. (1946) Hydraulics of Runoff from Developed Surfaces. Proceedings, 26th Annual meeting, Highway Research Board, Vol 26, 1946.

Johansen, L., Harremoës, P. (1975) Selection of Rain Event for Design of Sewer Systems. Nordic Symposium on "Quantitative Urban Hydrology" in Sarpsborg, Norge, 1975. The Norwegian Committee for the International Hydrological Decade. Oslo. In Danish.

Keifer, C. J., Chu, H. H. (1957) Synthetic Storm Pattern for Drainage Design. Journals of the Hydraulics div., ASCE, Vol 83, No HY4, Aug 1957. Discussion by Mc Pherson in Vol 84, No HY1, 1958.

Marsalek, J. (1977) Runoff Control on Urbanizing Catchments. Symposium on the "Effects of Urbanization and Industrialization on the Hydrological Regime and on Water Quality" in Amsterdam, Oct 1977. IAHS-AISH Publication No 123.

Mc Pherson, M. B. (1977) The Design Storm Concept. Institute on Storm Water Detention Design, University of Wisconsin, Madison, Wisconsin.

Natural Environment Research Council, London (1975) Flood Studies Report. Vol 1 - Hydrological Studies. Vol 2 - Meteorological Studies.

Preul, H., Papadakis, C. N. (1973) Development of Design Storm Hyetographs for Cincinnati, Ohio. Water Resources Bulletin, Vol 9, No 2.

Schaake, J. C., Geyer, J. C., Knapp, J. W. (1967) Experimental Examination of the Rational Method. Journal of the Hydraulics Division, ASCE, Vol 93, No HY6.

Sifalda, V. (1973) Entwicklung eines Berechnungsregens für die Bemessung von Kanalnetzen. Gwf - Wasser/Abwasser 114 (1973) H9.

Storm Water Management Model (1971) Volume 1 - Final Report. Environmental Protection Agency (EPA), Water Quality Office, Washington D. C. Water Pollution Control Research Series, 11024DOC07/71.

Terstriep, M., Stall, J. B. (1974) The Illinois Urban Drainage Area Simulator. Illinois State Water Survey. Urbana, Illionis, Bulletin 58.

Thorndal, U. (1971) Precipitation Hydrographs. Stads og havneingeniøren, Köpenhamn, No 7. In Danish.

VAV, Swedish Water and Sewage Works Association (1976) Manual for Design of Sewer Pipes. VAV, Stockholm, Publication P 28. In Swedish.

Watkins, L. H. (1962) The Design of Urban Sewer Systems. Dept. of Scientific and Industrial Research, London. Road Research Technical Papers No 55.

Young, C. P. (1973) Estimated Rainfall for Drainage Calculation in the United Kingdom. Transport and Road Research Laboratory TRRL, Crowthorne, England, Report LR 595.

Institutionen för Vattenbyggnad
CHALMERS TEKNISKA HÖGSKOLA

Report Series B

1. Bergdahl, L.: Beräkning av vågkrafter. 1977.

2. Arnell, V.: Studier av amerikansk dagvattenteknik. 1977.

3. Sellgren, A.: Hydraulic Hoisting of Crushed Ores. A feasibility study and pilot-plant investigation on coarse iron ore transportation by centrifugal pumps. 1977.

4. Ringesten, B.: Energi ur havsströmmar. 1977.

5. Sjöberg, A. och Asp, Th.: Brukar-anvisning för ROUTE-S. En matematisk modell för beräkning av icke-stationära flöden i floder och kanaler vid strömmande tillstånd. 1977.

6. Annual Report 76/77.

7. Bergdahl, L. och Wernersson, L.: Calculated and Expected Thermal Ice Pressures in Five Swedish Lakes. 1977.

8. Göransson, C-G. och Svensson, T.: Drogue Tracking - Measuring Principles and Data Handling.

9. Göransson, C-G.: Mathematical Model of Sewage Discharge into confined, stratified Basins - Especially Fjords.

10. Arnell, V. och Lyngfelt, S.: Beräkning av dagvatten-avrinning från urbana områden. 1978

11. Arnell, V.: Analysis of Rainfall Data for Use in Design of Storm Sewer Systems. 1978.

12. Sjöberg, A.: On Models to be used in Sweden for Detailed Design and Analysis of Storm Drainage Systems. 1978.