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# ANNOTATED BIBLIOGRAPHY ON URBAN DESIGN STORMS

by

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Marsalek (61)

Prepared by the Design Storm Committee

Urban Water Resources Research Council, ASCE

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# PREFACE

One of the goals of the ASCE Urban Water Resources Research Council is dissemination of information in the urban water resources area. To this end a task committee was formed to gather publications relating to the complex and controversial topic of urban design storms. This publication is a result of the efforts of that task committee.

The committee acknowledges the contributions of Stuart G. Walesh in the preparation of the reference list.

This bibliography is dedicated to Murray B. McPherson, whose contributions to the Council are beyond calculation and who was particularly interested in the subject area of this publication.

Design Storm Task Committee:

Jiri Marsalek
Ronald L. Rossmiller
Ben Urbonas
Harry G. Wenzel, Jr., Chairman

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# INTRODUCTION

In May, 1979 a seminar was held at Ecole Polytechnique de Montreal on the subject of the design storm concept as it relates to urban water resources management and design. The seminar was characterized by international participation and demonstrated the variety and complexity of this subject.

In part as an outgrowth of this seminar, a task committee was formed by the ASCE Urban Water Resources Research Council to prepare an annotated bibliography which would summarize significant publications in the area of urban design storms. This publication is a result of that effort. Because the design storm has been used extensively for a long time, it would be impractical to attempt to gather a truly complete list of references. The references cited are limited by the knowledge and judgment of the task committee. Text books are not included and a screening was made of references presenting essentially the same material.

A significant omission from this bibliograph will be the proceedings of a special seminar, "Rainfall as Basis for Urban Run-off Design and Analysis", scheduled for August 24-26, 1983, at the Technical University of Denmark, Copenhagen, Denmark. Although it was decided not to delay the publication of this bibliography to include the proceedings, it will no doubt contain many significant papers.

Because the subject area is broad, an arbitrary classification system was developed. References were placed under one or more of the following classifications:

1. Time Distributions (hyetographs) - Publications which are primarily devoted to the development of temporal distributions of rainfall for design purposes.

2. <u>Procedures and Data</u> – Publications concentrating on the application of design storms and/or presenting related data.

3. <u>Evaluation</u> – Publications devoted to the evaluation or testing of design storms as a useful tool.

4. <u>Alternative Approaches</u> – Publications which discuss or present alternative methods to the traditional design storm approach.

These classifications are listed with each annotation and a subsequent listing of publication numbers by classification is presented.

1. Abraham, C., Lyons, T. C., and Schulze, K.-W.

"Selection of a Design Storm for Use with Simulation Models," Proc. of National Symposium on Urban Hydrology, Hydraulics and Sediment Control, Univ. of Kentucky, 1976, pp. 225-238.

(Classification: 1)

The development of temporal and spatial design storm patterns is presented for the purpose of planning and designing improvements in the combined sewer system of Hamburg, Germany, a system with a drainage area of 8000 hectares. The objective is to retain the statistical properties of the local meteorology in the design storms. First, conventional intensity-duration-frequency and area-depth-frequency analyses are made using rainfall data digitized in 5-min increments.

The statistical model for the temporal pattern incorporated three terms: an average time distribution term for a given event duration; a total depth term related to return period; and a random term. The sequence of rainfall increments is determined using statistical analyses of the ranking indices of the historical data. Finally, a correction factor is applied to the pattern such that the total depth agrees with the results of the intensity-duration-frequency analyses of the historical data.

The model for the spatial pattern is similar to the temporal model. The total rainfall at a given station is taken as the sum of an average spatial term, a uniform depth term related to return period, longitudinal and lateral variability terms and a random term. A correction factor is again applied to produce agreement with the area-depth frequency analysis. A statistical procedure is developed to assign the output of the model to specific stations.

2. Alexander, G. R., Karoly, A., and Scists, A. B.

"Equivalent Distributions with Applications to Rainfall as an Upper Bound to Flood Distributions," Journal of Hydrology, Vol. 9, 1969, Nos. 3, pp. 322-344, and 4, pp. 345-374.

(Classification: 2)

These papers are essentially a presentation and discussion of various probability distributions which have been applied to hydrologic data. They are theoretical and basic; useful as classroom references. However, no direct relationship to design storms appears.

3. Arnell, V.

"Analysis of Rainfall Data for Use in Design of Storm Sewer Systems," In Urban Storm Drainage, Proc. of an International Conference on Urban Storm Drainage, Southampton, 1978, edited by P. R. Helliwell, Pentech, London, 1978, pp. 71-86.

(Classification: 3)

A comparison is made of runoff from a 0.154 $km^2$ urban catchment from two types of rainfall data: design storms developed from intensity-duration-frequency relationships or from measured rainfall data; and measured real-time data or time series generated by statistical methods. A kinematic wave simulation model is used to compute runoff. Three different design storm hyetographs are studied with rainfall durations of 16-40 minutes and return periods from 1/12 to 1.0 years. Comparison of simulated runoff peaks with measured peaks on a frequency plot show that runoff from measured rainfall data produces the best agreement, although differences in peaks from design storm and historical rainfalls are not large.

4. Arnell, V.

"Rainfall Data for the Design of Sewer Pipe Systems," Report Series A: 8, Dept. of Hydraulics, Chalmers University of Technology, Göteborg, Sweden, 1982.

(Classification: 2)

An 18-yr rainfall record is used to derive five synthetic design storms and to select severe actual storms. The following synthetic design storms are produced: a constant-intensity storm determined, for a particular duration, from the I-D-F curves; the Chicago storm; the Sifalda's storm; the Illinois State Water Survey storm; and the (British) Flood Studies Report (FSR) storm. The selection of severe historical storms is accomplished by ranking of storms according to peak intensities of durations from 5 to 30 minutes. For each duration, the top 54 storms are considered.

Both synthetic and actual storms are used to simulate runoff flows at several points in three test catchments. Using the simulated data, runoff peak frequency of occurrence curves are plotted for all points of interest. With the exception of the FSR storm, which yielded excessively high flows, a fairly close agreement between the frequency curves for synthetic and actual storms is found. The validity of such results is limited to systems without surcharge. In practical applications, the synthetic design storms should be used only for pipe sizing. The design storms discussed are not applicable to storage design, studies of combined sewer overflows, design of stormwater pumping stations, and real-time operation of sewer systems and treatment plants.

5. American Society of Civil Engineers

"Design and Construction of Sanitary and Storm Sewers," Manuals and Reports of Engineering Practice No. 37, (WPCF Manual of Practice No. 9), ASCE, New York, N.Y., 1974.

(Classification: 5)

Chapter 4 presents a summary of conventional intensity-duration-frequency analyses with emphasis on applications to the rational method. A design storm hyetograph based on the Chicago method (Keifer and Chu, Ref. 31) is presented but its development is not discussed. This is not a good reference for design storm information beyond the rational method application.

6. Bandyopadhyay, M.

"Synthetic Storm Pattern and Run-off for Gauhati, India," Journal of the Hydraulic Division, ASCE Proc., Vol. 98, No. HY5, May, 1972, pp. 845-857.

(Classification: 1)

This paper describes the development of a synthetic temporal rainfall pattern for Gauhati, India. The method presented by Keifer and Chu, sometimes termed the Chicago method, is used. The intensity duration relationship for a 2-month return period is developed. The ratio of the time of peak intensity to the total duration of the synthetic pattern is determined using 207 rainfall events. The antecedent rainfall approach with a maximum of 150 minutes is used to evaluate this ratio, with a resulting value of 0.4. A discussion of the variation of runoff coefficient with antecedent rainfall duration and percent imperviousness is also presented.

7. Burke, C. B., Rao, A. R., and Gray, D. D.

"Duration and Temporal Distribution of Storms in Urban Drainage Design," Proc. of International Symposium on Urban Storm Runoff, Univ. of Kentucky, 1980, pp. 71-79.

(Classification: 3)

The simulation model ILLUDAS (Illinois Urban Drainage Area Simulator) is utilized to evaluate the sensitivity of peak runoff, time to peak and runoff volume to input parameters and rainfall characteristics. The variables studied include: duration and return period of rainfall; antecedent soil moisture condition; and temporal rainfall distribution.

7. (continued)

The test site for this study is a 121.5 acre residential catchment in West Lafayette, Indiana. Local 10-min rainfall data are used to develop rainfall input. It is concluded that there is a critical rainfall duration which produces a maximum peak runoff for a specific set of input conditions. The duration is a function of physiographic and storm characteristics. It is also shown that first quartile storms (highest intensity in first quarter of the duration) produce the highest peak runoff and that local rainfall data can produce different results than regional rainfall. The sensitivity of runoff peaks and volumes to antecedent soil moisture is demonstrated as well.

8. Chen, C. L.

Urban Storm Runoff Inlet Hydrograph Study - Vol. 4 Synthetic Storms for Design of Urban Highway Drainage Facilities, Utah Water Research Laboratory, Utah State University, Logan, Utah, 1976.

(Classification: 1)

This report presents a procedure for the development of synthetic design storms for small urban highway catchments. The approach is based on the conventional intensity-duration-frequency analysis of local rainfall data. This relationship is described by relating the average intensity to the duration and to three parameters, one of which is related to return period. Expressions for the temporal distribution or hyetograph are developed based on the average intensity relationship. The resulting hyetographs depend on the skewness or time of maximum intensity. This skewness must be independently evaluated and was not found to be correlated to other storm parameters.

A graphical method is presented for evaluating the three intensity-duration-frequency parameters. It was found that by using a standardized form of the parameters, they vary only with the ratio of 1-hour to 24-hour rainfall depth. This ratio is a function of location only and independent of return period.

9. Chien, J. and Sarikelle, S.

"Synthetic Design Hyetograph and Rational Runoff Coefficient," <u>Journal of the Irrigation and Drainage Division-ASCE</u>, Vol. 102, No. IR3, September 1976, pp. 307-315.

(Classification: 1)

9. (continued)

This paper presents a simple method of establishing a synthetic design hyetograph. The method incorporates a rainfall depth-duration-frequency curve based on the rainfall intensity-duration-frequency curves developed by the U.S. Weather Bureau and a typical local storm pattern. The procedure to develop the synthetic design hyetograph involves the following steps: (1) selection of the rainfall intensity-duration curve or the rainfall depth-duration curve for a certain design frequency; (2) determination of the advancement of the storm pattern based on local hyetographical data; (3) selection of the computation time interval; and (4) establishment of the synthetic design hyetograph.

In addition, a method of computing the average runoff coefficient for the Rational Method is developed. This method is predicated on the principle of mass conservation using Horner's field data. Examples are given for the establishment of the synthetic design hyetograph and its application to the determination of the average runoff coefficient.

10. Clark, R. A.

"Temporal and Spatial Variability of Storm Rainfall Patterns and Their Relationship to Operational Hydrologic Forecasting," Fall Annual Meeting of the A.G.U., San Francisco, Dec., 1973.

(Classification: 2)

A crucial requirement in the development of a successful river forecasting scheme is the implementation of a data collection system that will provide reliable rainfall information. Numerous studies in recent years have revealed the highly variable character of rainfall patterns. This variability has been a major difficulty in operational forecasting. Several recently developed data collection and dissemination systems (e.g., GOES, DARDC, D/RADEX and AFOS) are discussed. Errors introduced in estimates of areal average precipitation from fixed networks can lead to serious forecasting errors. Also, forecasts based on observed data can lead to forecasts which escalate. This occurs particularly during extended periods of general rainfall. The problems attendant to the utilization of quantative precipitation forecasts (QPF) in hydrologic forecasting are demonstrated. Unfortunately, QPF's over the years have generally not been made with the high level of required skill. Examples and illustrations of the techniques and systems discussed are presented.

11. Desbordes, M.

"Fondements de l'élaboration d'une pluie de projet urbaine: méthodes d'analyses et application à la station de Montpellier Bel-Air" (Methodology for the definition of urban design storms), La Météorologie, Vol. 6 n° 20-21, June, 1980, pp. 317-326.

(Classification: 1,2)

The sensitivity of a linear reservoir rainfall/runoff model to variations in rainfall input data is studied. The analysis indicates that the simulated runoff peaks depend on the following three parameters of the rainfall input: storm duration (for durations shorter than 4 hours); maximum rainfall depths for durations from 15 to 60 minutes; and the chronological location of these maximum rainfalls. It is also noted that the high-intensity burst could be approximated by a triangular shape, and the rainfall data should be discretized in time intervals of 5 minutes or less.

The rainfall/runoff model was applied to a large number of storms selected from a 50-yr rainfall record from Montpellier, France. The following findings were made: the representative storm duration is 4 hours; the timing of the high-intensity storm segment is uniformly distributed; and, for almost 90% of all storms, the storm segment with the maximum 4-hr rainfall depth also contains the segments with maximum rainfall depths for durations from 15 to 60 minutes.

Finally, a method for developing a probabilistic design storm is proposed. In this method, the distributions of the timing of the high-intensity storm segment and of the maximum rainfall depths corresponding to various durations are derived from local data. For a chosen period, a number of design storms is then developed by random draws from these distributions. Runoff hydrographs are simulated for all these design storms and the simulated runoff peaks are subject to frequency analysis to determine design flows of known return periods.

12. Desbordes, M., Masson, J. M., Raous, P., and Trevisiol, Y.

"Definition of a Design Storm for Region I - Paris-Montsouris," Note LMH 12/81, Laboratory of Mathematical Hydrology, University of Languedoc, Montpellier, France, March, 1981, (In French).

(Classification: 2)

A 30-yr rainfall record is analyzed with regard to frequencies of heavy storms, storm durations, frequencies of high intensities of durations from 15 to 60 minutes, timings of these high-intensity bursts, and the total storm rainfall. Using the derived storm statistics, several types of design storms are proposed.

12. (continued)

The most complex storm proposed is the general simulation design storm model. For a particular project life, one determines the number of heavy storms from the earlier derived Poisson distribution of heavy storms. Individual storms are constructed by random draws from distributions of peak intensities and their timings. The runoff peaks simulated for these events are then subject to frequency analysis to derive design flows of desired return periods. Some simplifications are possible depending on the characteristics of the catchment under design and the simulation model used.

A simplified design storm which is referred to as a synthetic design storm is also proposed. In this case, one selects a design storm return period and the corresponding peak intensity of short duration (usually 15 to 30 minutes, depending on the catchment response). Most probable intensities of longer durations are then obtained from the earlier derived distributions and used to construct a symmetrical design hyetograph.

13. Desbordes, M.

"Urban Runoff and Design Storm Modelling," Proc. of the International Conference on Urban Storm Drainage, Univ. of Southampton, April 11-14, 1978, pp 353-361.

(Classification: 1,2)

This reference is essentially the same as #11. Minor differences were detected in numerical values of some regression coefficients.

14. Folland, C. K., and Colgate, M. G.

"Recent and Planned Rainfall Studies in the Meteorological Office with an Application to Urban Drainage Design," Proc. of the International Conference on Urban Storm Drainage, Southampton, 1978, edited by P. R. Helliwell, Pentech, London, 1978, pp. 51-70.

(Classification: 2)

Analyses are presented of short duration rainfall data in the United Kingdom. Data reduction procedures are described which permit rainfall depths and time in 0.01-min and 1-min increments, respectively. Depth-frequency studies for return periods down to 0.1 years are also presented. Duration (less than 2 hours) is not an important variable when data is normalized using the 5-yr return period depth. A discussion of the uncertainty of return period estimates is presented as well as a summary of a study of areal reduction factors.

15. Frederick, R. H. and Tracey, R. J.

"Conditional Probabilities of Intense Rains of Different Durations," <u>Second Conference on Hydrometeorology</u>, Toronto, October 25-27, 1977, pp. 208-213.

(Classification: 2,3)

Published values and maps of precipitation-frequency for a multiplicity of durations and return periods have been available for many years. In all cases values for each duration are derived from observed precipitation values for each duration chosen independently of the precipitation values for any other duration. Despite this independence of data for different durations, it is common practice in hydrologic engineering and design to combine precipitation-frequency values for two or more durations (e.g., short duration for peak flow and longer duration for storage volume) into a common synthetic storm sequence in various methods or models. The objective of this study is to examine the joint occurrence of point precipitation-frequency value events for different durations.

The area selected for this study is the Southeastern United States south of 35°N and from Arkansas and Louisiana eastward. Published hourly precipitation data are available for the period 1948 through 1972. Omitting stations with less than 15 years of data, almost 6,000 station-years of data are available for use. Maximum annual precipitation totals for seven durations (1, 2, 3, 6, 12, 18 and 24 hours) for each station were identified and labeled as independent duration, ID, storms. Next, for each maximum annual storm, the maximum values for each of the other six durations (dependent durations, DD), labeled as rainfalls, either contained within or containing ("surrounding") the maximum annual event were also identified. Statistical analyses were then performed on all 42 ID-DD combinations with the following results.

Assuming that a project, for which one hour is the controlling duration, is designed using the new method, the 24-hr DD rainfalls would be 20 to 40 percent less than those obtained by combining independent 1-hr and 24-hr data (TP-40 values) into a common time sequence. Similar statistics are available for all 42 combinations of ID and DD. While results for durations of less separation are less dramatic, they do show the small probabilities of large storms for different durations coming from the same meteorological event and that a joint frequency based ratio method of obtaining DD rainfalls yields smaller rainfalls, especially at the longer durations.

16. Haan, C. T.

"Urban Runoff Hydrographs-Basic Principles," National Symposium on Urban Hydrology, Hydraulics, and Sediment Control, Lexington, Kentucky, July 26-29, 1976, pp. 349-375.

(Classification: 1)

This paper is one of three mini-courses presented at the symposium. The treatment of hydrology here is largely limited to those parts of the hydrologic cycle of major importance in urban stormwater management. This means that primary emphasis is placed on precipitation, abstractions from precipitation and the runoff process. The treatment begins with a coverage of point rainfall data including depth-duration-frequency curves and storm time-intensity relationships. Next, abstractions from rainfall are discussed. The treatment of runoff begins with a section on terminology and conceptual models. This is followed by hydrodynamic models and unit hydrograph procedures.

The analysis of modern stormwater management systems often requires hydrographs of storm water flow — not just peak flow estimates. Hydrographs in turn require knowledge of the rainfall time-intensity pattern that produced the hydrograph. However, it is difficult to associate a return period with a particular time-intensity pattern. This difficulty of assigning a return period to a total storm or conversely of estimating a rainfall pattern given a return period has led to the development of synthetic storms to which return periods are assigned.

Three methods of synthetic storm development are discussed: storms based on intensity-duration-frequency curves, storm patterns developed by the U.S. Soil Conservation Service and those developed by Huff of the Illinois Water Survey. These synthetic storms have the advantage of being a consistent basis for design but have the distinct disadvantage of an unknown return period (even though they are associated with return periods) and in many cases a very remote possibility of ever happening.

17. Hall, A. G., and Kneen, T. H.

"Design Temporal Patterns of Storm Rainfall in Australia," Institution of Engineers, Hydrology Symposium, Perth, Australia, 1973, pp. 77-85.

(Classification: 2)

Design temporal patterns of durations from 12 minutes to 3 hours are derived for eight Australian cities. These patterns are derived from actual storms of return periods greater than 1-yr, using both the "average variability and the most likely sequence method," and the method based on the median pattern centered on the period of the most intense rainfall. In the first method, the storms are discretized into 6-min periods, the rainfalls in each period are ranked within each storm, and the percentage of the total storm rainfall occurring in the period

17. (continued)

of each rank is calculated. The average rank and the average percentage rainfall for each period is also calculated. To produce the final pattern, the period with the lowest average rank is assigned the average percentage rainfall for the rank 1 period (i.e., the highest), the period with the second lowest average rank is assigned the average percentage rainfall for the rank 2 period, and so on.

The second method used is that proposed by SOGREAH. In this method the median location of the highest rainfall of a given duration within a storm is sought in relation to some standard (longer) durations. The median pattern is then constructed from the median times of occurrence of these falls and the mean amounts of rain in bursts of different durations.

Although both methods produce comparable results, the SOGREAH methods show a tendency to centralize the pattern. For this reason, the average variability method is recommended as a better approach to the derivation of design temporal patterns.

18. Harremoës, P. and Eriksen, M.

"Alternative Application of Rainfall Statistics to Sewer System Design," Proceedings of the Second International Conference on Urban Storm Drainage, Urbana, Illinois, June 14-19, 1981, pp. 365-373.

(Classification: 3)

An evaluation of the conventional design storm approach to storm sewer design is presented using a hypothetical 30mx 2700 m catchment with a single longitudinal pipe with 26 inlets along its length. A 47-yr rainfall record is analyzed using conventional intensity-duration-frequency methods. The record is also screened to identify the 100 extreme events which produce the largest flows within a range of durations. The ILLUDAS model is used to determine the peak flows at each manhole for the 100 events after pipe sizes are determined using the rational method for design for a 5-yr return period. A comparison is made of the return periods of peak flow at each manhole with that of the original design return period. In general, the runoff peaks had higher return periods than the 5-yr design value. The use of commercial pipe sizes is cited as a major reason for this result. It is concluded that the rational method of design using full pipe flow as a criterion is adequate for the catchment.

19. Hogg, W. D.

"Time Distribution of Short Duration Storm Rainfall in Canada," Proceedings of the Canadian Hydrology Symposium: 80-Hydrology of Developed Areas, Toronto, May 1981, Available from the National Research Council of Canada, Ottawa, Ont., 1981, pp. 53-63.

(Classification: 1,2)

The paper examines the time distribution of actual 1- and 12-hr rain events at 35 locations across Canada. The rainfall events are selected according to predetermined intensity criteria. Mass curves with various probabilities of occurrence are presented for specific locations and further used to produce rainfall distributions for various regions of Canada. Differences in the distributions between regions are substantial, ranging to 30%. The observed distributions are stratified according to whether the region has a maritime or continental type climate. The possibility of the 1- and 12-hr distributions being dependent on the intensity of rainfall (i.e., the storm return period) is examined, however no such relationship has been found.

20. Huff, F. A., and Neill, J. C.

"Rainfall Relations on Small Areas in Illinois," Bulletin 44, Illinois State Water Survey, Champaign, Illinois, 1957.

(Classification: 2)

This report presents a statistical analysis of Illinois rainfall for durations of 1 to 10 days on both an annual and seasonal basis. The data base consists of a 40-yr record from 39 stations in addition to U.S. Weather Bureau cooperative station data.

The state is divided into four sections of similar precipitation characteristics, with frequency analyses performed for each section. Data are fit to various frequency distributions using several techniques. Results are presented in terms of areal averages for the four sections due to the sensitivity of isohyetal patterns to sampling variation.

21. Huff, F. A.

"Time Distribution of Rainfall in Heavy Storms," Water Resources Research, Vol. 3, No. 4, 1967, pp. 1007-1019.

(Classification: 1)

This paper presents the much quoted statistical analyses of the time distribution of heavy storms which were measured using a 49-raingage network on a 400 $mi^2$ area in east central Illinois for an 11-yr period.

21. (continued)

The basic data are reduced to 3-min rainfall increments for independent events with durations grouped into periods of less than 12 hours, 12-24 hours and over 24 hours and into areas of 50, 100, 200, and 400 sq miles. It was found that many of the storms are characterized by a relatively short period of heavy rainfall within the total event duration. This reduces the effect of duration and area, and the time distributions are therefore classified into four groups depending on whether the heaviest rainfall occurs in the first, second, third, or fourth quarter of the duration. For each quartile a series of dimensionless cumulative depth vs. time curves are presented with probability level as the parameter, where the probability level corresponds to the percentage of storms which would have a time distribution different than the corresponding curve. A table of areal connections for the median curve is presented for the first quartile storms.

Other characteristics such as burst frequency, relationship between quartile and type of rain, quartile and duration, storm shape and orientation are discussed as well.

22. Irish, J. L.

"Rainfall Temporal Patterns for Design Floods," Discussion, Jour. of Hydraulics Div., ASCE Proc., Vol. 101, No. HY12, December, 1975, pp. 1545-1547

(Classification: 2)

This discussion paper examines the assumption made in the original paper that "by considering median or mean values of parameters affecting the generation of a flood, the frequency of the derived flood should be approximately equal to the frequency of the design rainfall." It is noted that in the case of hydrologic variables, there is usually a considerable difference between the mean and the median and, consequently, the interchangeable use of both characteristics should not be recommended. Furthermore, rare runoff events result from the conjunction of a relatively rare rainfall and worse-than-usual combination of other parameters affecting flood generation. Design methods should reflect this by using rainfalls in conjunction with other parameters and by taking values more favourable to a large flood than the mean or median.

Two other observations can be made from the data in the original paper. Different temporal patterns may operate for very intense storms, whereas average variability patterns may apply to less intense storms. Noting the high probability of the antecedent precipitation exceeding the median value, it appears unlikely that a transformation from rainfall to runoff will preserve the average recurrence interval of rainfall.

23. James, W., and Drake, J. J.

"Kinematic Design Storms Incorporating Spatial and Time Averaging," Proceedings Stormwater Management Model Users Group Meeting of June 19-20, 1980, U.S.E.P.A., Athens, GA., December 1980, pp. 133-149.

(Classification: 2,3)

The paper explores the use of a numerical storm model as a pre-processor for a detailed urban runoff model. The proposed storm model generates hyetographs for each subcatchment, thus simulating the spatial and temporal growth and decay of a system of storm cells as they move across an urban catchment system.

Traditionally, design storms were and continue to be developed from statistical analysis of point rainfall records that include all types of rainstorms. This methodology was originally appropriate for flood predictions based on the rational formula. The resultant rain distributions, however, are unlike any type of observed rain storm. This synthetic temporal distribution is typically applied uniformly across the catchment and flow hydrographs are consequently also unlike observed runoff hydrographs.

Large static cells of uniform rainfall intensity are rare even in prolonged frontal events. Convective cells tend to be circular with a circular rainfall intensity pattern. Rain cells tend to be elliptical, aligned sub-parallel to the front and moving sub-parallel to it. Rainfall is typically most intense near the leading edge of the cell. Fast moving storms produce very rapid point-intensity-duration changes. Statistics of the size and distribution of rain cells can be obtained most readily from weather radar studies. The storm model simulates these storm characteristics.

24. James, W., and Shtifter, Z.

"Implications of Storm Dynamics in Design Storm Inputs," Proceedings of Stormwater and Water Quality Modelling and SWMM User's Group Meeting, U.S.E.P.A., September, 1981.

(Classification: 3)

In this paper the authors point out that design storms are supposed to represent a statistical characterization of input hyetographs for rainfall/runoff models. However, the non-linear aspects such as antecedent dry-days, and the mismatch of the time-scales involved in typical design applications argue against the continued use of the design storm concept. They also contend that the evolution of runoff quality models, recent advances in continuous rainfall/runoff modelling and emerging computer hardware costs should hasten the obsolescence of design storms.

24. (continued)

Stormwater management in urban areas typically involve subcatchments with short characteristic response times, for which the authors claim, short sharp rain events are appropriate. Such rain storms are always associated with distinct meso-scale motion over the ground. Expected synoptic characteristics of such rain cells are discussed in the paper and comparisons are drawn with the Chicago storm. A storm model is also evolved. The model is applied to an urban catchment using historical data and compared with standard design storm methodology. Comparisons of synthesized and observed runoff, BOD5 and settleable solids indicate gross errors inherent in current design storm methodology. The authors conclude with their opinion that it is time to drop the design storm concept for stormwater management practice.

25. Jens, S. W.

Design of Urban Highway Drainage - The State of the Art, FHWA-TS-79-225, U.S. Dept. of Transportation, Federal Highway Administration, Washington, D.C., 1979.

(Classification: 2)

Chapter 2 of this report contains a summary of information pertaining to synthetic design storms useful on highway drainage design. A summary of sources of National Weather Service Precipitation data is presented. The procedure for the development of intensity-duration-frequency curves is summarized and examples are provided. A discussion of several methods for developing temporal rainfall patterns is given with a particular emphasis on an explanation of the work by Chen (ref. 8).

26. Johansen, L., and Harremoës, P.

"The Use of Historical Storms for Urban Drainage Design," Proc. International Symposium on Urban Storm Runoff, University of Kentucky, Lexington, KY., July 23-26, 1979, pp. 61-70.

(Classification: 4)

This paper recommends the use of historical storms rather than synthesized storms for urban drainage design. A simple, though laborious, procedure is described to identify which of the historic storms should be used for design purposes at various locations within a watershed and for various recurrence intervals. Three hypothetical and one real watershed are used in the study. Once the historic storms which produce the maximum peak rates of runoff are identified, these few storms are then used in a more sophisticated computer model as the design storms to design the drainage system.

26. (continued)

Forty years of observations were available in histogram form for 1,114 storms with durations less than one hour at the town of Gentofte near Copenhagen, Denmark. Hydrographs are simulated from all 1,114 historical storms by a simplified transformation, and those storms to be used as design storms are evaluated statistically from the ranked runoff peaks. The design storms for selected points in the drainage system are chosen from those storms which, for a given recurrence interval, give a runoff peak deviating from the theoretical by less than a fixed percent (five percent in this study).

27. Keers, J. F.

"Rainfall Criteria for Urban Drainage Design," Meteorological Magazine, 106, 1977, pp. 117-126.

(Classification: 2)

An evaluation is made of those aspects of rainfall which are important for the economic design of urban storm sewer systems. These include the mean rainfall intensity for specified duration and return period, the temporal storm pattern, and the spatial distribution.

The rainfall depth, for a specified return period and duration (typically equal to the time of concentration at the point under design), is the most important single rainfall factor for design purposes. The temporal storm pattern is affected by the rainfall type, the speed of movement of the rainfall system across the point or area, and the local development and decay of rainfall intensity. The sharpness of the storm profile is also affected by the storm duration. The spatial variation of rainfall over a drainage area is dealt with statistically by applying an areal reduction factor. Numerical values of this factor are given for various catchment areas and rainfall durations.

Finally, the movement of rainfall system may be significant in an advanced design. This is particularly the case if the speed and direction of the storm movement are comparable to those of the flow in sewers.

28. Keers, J. F., and Wescott, P.

A Computer-based Model for Design Rainfall in the United Kingdom. Meterological Office, Scientific Paper No. 36, Her Majesty's Stationery Office, London, 1977.

(Classification: 2)

28. (continued)

The paper describes a computer model suitable for determining design rainfall in the United Kingdom. The model is generally based on the techniques recommended in the Flood Studies Report (ref. 39). In particular, the model provides the following types of data: rainfalls for various durations and return periods; maximum precipitation; areal reduction factors; and storm profiles.

Using the mapped values of 5-yr, 60- min, and 2-day rainfalls, 5-yr rainfalls for other durations are interpolated or extrapolated by means of empirical formulae. Such rainfalls are then used to produce rainfall data for other return periods.

The maximum precipitation is derived, using a physically-based approach, for 11 durations from 1 minute to 25 days for various ranges of average annual precipitation.

The areal reduction factor is defined as a function of the catchment area and the rainfall duration. Areal reduction factors are presented for durations from 0.1 to 50 hours and areas from 1 to 10,000 $km^2$.

Finally, the model also produces 50- and 75-percentile summer (May to October) or winter (November to April) storm profiles for any specified duration. The return period of the storm profile is equated with the return period of the total rainfall in the central one third of the total storm duration. The rainfall intensities for each minute of the design storm are computed using tabular data describing the particular percentile profile.

29. Keifer, C. J., and Chu, H. H.

"Synthetic Storm Pattern for Drainage Design," Journal of the Hydraulics Division, ASCE, Vol. 83, No. HY4, August, 1957.

(Classification: 1)

The purpose of this paper is to present the development of a synthetic storm pattern for use in the Chicago hydrograph method of storm sewer design. The three most important characteristics affecting the peak runoff rate for a specific period or duration are as follows: (1) volume of water falling within the maximum period, (2) amount of antecedent rainfall, and (3) location of the peak rainfall intensity. The chronological location of the peak periods of rainfall with reference to the total storm period and the amount of antecedent precipitation immediately preceding the maximum period of any duration is derived from the statistical average of rainfall records. The importance of this antecedent rainfall in affecting the peak of the runoff hydrographs is illustrated.

29. (continued)

The volume of water falling within the maximum period is taken from the U.S. Weather Bureau rainfall intensity-duration curve for the selected design frequency. Within the maximum period of any rainfall, the duration $t_d$ can be split up into that part occurring before the most intense moment (designated as "r") and that part after the most intense moment (designated as "1-r"). Based on rainfall records from four widely scattered stations in the Chicago area, the value of "r" was determined to be 3/8. Using this value, equations are derived for rainfall intensities both before and after the peak intensity value. The synthetic storm pattern plotted according to these equations satisfies the three characteristics discussed before and therefore can be used as the design storm pattern for the hydrograph method of storm sewer design in the Chicago area.

30. Konrad, T. G.

"Statistical Models of Summer Rainshowers Derived from Fine-Scale Radar Observations," Journal of Applied Meteorology, Vol. 77, 1978, pp. 171-188.

(Classification: 2)

This paper discusses a study concerning the statistical modeling of rain-cell characteristics based on high-resolution radar measurements of the cell sturcture. The fine-scale three-dimensional structure of summer rainshowers in the mid-Atlantic region has been analyzed leading to statistical descriptions of the rain cells in terms of a variety of physical cell parameters. Core reflectivity profiles contour area and altitude extent of the cells have been generated along with the frequency of occurrence for various storm classes and categories. Rain cell classes and categories are based on the reflectivity levels at essentially ground level. Cell population which include all the cells observed are also treated. The mean and median core reflectivity profiles are essentially constant up to altitudes of 4-6 km and then fall off with increasing altitude and follow an orderly progression with cell category. The area of the reflectivity contours about the core value is found to follow an exponential relationship.

The statistical descriptions of the rain cells for the mid-Atlantic region are compared to those from previous investigators at other geographical locations. In terms of core reflectivity profiles, the data for the various locations are rather similar. Significant differences, however, are evident in the altitude extent. Finally, simplified models of rain cells based on the statistical descriptions are developed for the different rain categories as a function of frequency of occurrence.

31. Larsen, T.

"Real Rainfall Time Series for Storm Sewer Design," Proceedings of the Second International Conference on Urban Storm Drainage, Urbana, Illinois, June 14-19, 1981, pp. 358-364.

(Classification: 4)

This paper describes the use of an historical rainfall record as input to a simulation model of an urban catchment with detention storage. The objective is to illustrate the use of the rainfall time series as an alternative to the conventional design storm when volume as well as discharge is a design parameter.

The continuous rainfall record is screened to include only summer rainfalls greater than 3 mm. A 3-hr dry period is used to define independent events.

An autoregressive moving average (ARMA) model involving the catchment outflow at the previous time step is used to compute inflow from the catchment into a detention reservoir. This is coupled to the continuity equation for the reservoir to predict outflow. The output is then analyzed and expressed in terms of frequency of overflow volume, overflow duration, peak flow, and maximum reservoir water level. The application to a 28.9 ha catchment in Copenhagen, Denmark is illustrated.

32. Lowing, M. J.

"Prediction of the Runoff Hydrograph from a Design Storm," Proc. of Flood Studies Conference by Thomas Telford, Ltd., London, England for ICE, 1975.

(Classification: 2)

The paper concentrates on the estimation of a maximum design flood hydrograph. Earlier methods of estimation are reviewed and compared. The paper draws attention to the anomalous rainfalls implied which sometimes approach world maxima. Results are presented to illustrate these points.

33. James F. MacLaren, Ltd.

"A Comparison of Historical and Theoretical Design Storms for the City of Edmonton," A report to the City of Edmonton, Edmonton, Alberta, May, 1979.

(Classification: 3)

Frequency curves of runoff peaks simulated for the Chicago-type design storms and selected historical storms are compared for a drainage district in Edmonton, Alberta. Runoff simulations are somewhat simplified by deleting some elements from the drainage system and by replacing sewer pipes with open channels (gutters) to avoid surcharging. A considerable amount of storage is introduced to "smooth out" the high-intensity peak of the Chicago-type design storm.

The Chicago-type design storms are derived from the locally available Intensity-Duration-Frequency curves. Historical storms are selected from intermittent precipitation records (41 years from a period of 54 years). The "peakiness" of design and historical storms is compared. It was found that 90% of all historical storms are less "peaky" than the Chicago-type design storm.

Under the conditions modelled, the Chicago-type design storms and historical storms produce similar runoff peak frequency curves for the entire drainage district (10.68 $km^2$) as well as for smaller parts of the district (as small as 0.06 $km^2$). In view of the abstract nature of the synthetic design storms, it may be desirable to use selected historical storms in lieu of synthetic storms for the analysis of relief sewer alternatives.

34. James F. MacLaren, Ltd.

"Report on Design Storm Selection," A report to the City of Winnipeg, Winnipeg, Manitoba, May, 1978.

(Classification: 3)

A drainage district in the City of Winnipeg, Manitoba is selected for a comparative study of runoff peaks simulated for historical and synthetic design storms. In these simulations, the district of 4.14 $km^2$ is described by a number of subcatchments varying in size from 0.004 $km^2$ to 0.93 $km^2$ and sewer pipes are replaced by rectangular open channels. Runoff peaks are simulated for both design and historical storms. The design storms of the Chicago type are derived from the intensity-duration-frequency (I-D-F) curves available for the area. The historical storms are selected from an intermittent rainfall record (23 years out of 36 years) on the basis of maximum hourly rainfalls. The return periods of these hourly rainfalls are evaluated for the 23 historical storms selected, and the largest return period is only 10 years. For the range of return periods studied, good agreement between the runoff peaks simulated for the historical and the design storms has been found.

35. Marsalek, J.

"Synthesized and Historic Design Storms for Urban Drainage Design," Proceedings of the International Conference on Urban Storm Drainage, University of Southampton, England, April, 1978, pp. 87-99.

(Classification: 2,3)

Runoff peaks simulated for historical storms and two types of synthetic design storms are compared for a small catchment with fast response. For identical return periods, both design storms produce higher runoff peaks than the historical storms. The overestimation is particularly significant for the Chicago-type design storm applied with a short time step (1 to 2 minutes). The runoff peaks simulated for the second design storm, which was based on the maximum hourly rainfall and the predominant average temporal pattern, only slightly exceed the runoff peaks simulated for historical storms. It is noted that the second design storm did not contain maximum rainfall depths for durations other than one hour. However, the Chicago-type design storm contains the maximum rainfall depths for all the durations shorter than the total storm duration. As an alternative to synthetic design storms, the use of historical design storms is proposed.

36. Marsalek, J.

"Research on the Design Storm Concept," ASCE Urban Water Resources Research Program, Technical Memorandum No. 33, September 1978.

(Classification: 2,3,4)

A comparative application of historical and synthetic design storms to various aspects of drainage design is examined on several small urban catchments. The design aspects considered include runoff peaks in drainage systems with and without detention facilities, runoff volumes, and runoff pollution loadings. In terms of runoff peaks, the design storms employed produce higher simulated peaks than the historical storms. Particularly large peaks are obtained for the Chicago-type design storm applied with short time steps. The second design storm, which is based on the maximum hourly rainfall and a predominant temporal pattern, produces simulated runoff peaks only slightly higher than those obtained for the historical storms.

In drainage systems with detention facilities, runoff volumes also need to be considered. The design storms produce runoff volumes widely varying from those obtained for historical storms. It is observed that the detention storage changes the return periods of outflow peaks to a varying degree, depending on the storage characteristics and the rainfall depth and its distribution. It is concluded that, for the conditions studied, simple design storms could not approximate the volume, timing and multiple-peak nature of actual hyetographs affecting the storage design.

36. (continued)

Finally, the applicability of simple design storms in runoff quality considerations is investigated. Two observed storms with similar rainfall intensities and durations, which produce almost identical observed runoff hydrographs, produce substantially different pollutographs. The usefulness of simple design storms is therefore questioned, and the use of historical rainfall records for various aspects of drainage design is recommended.

37. McPherson, M. B.

"The Design Storm Concept," Addendum 2 to Urban Runoff Control Planning, ASCE Urban Water Resources Research Council, New York, June 1977, pp. 100-118.

(Classification: 4)

An attempt is made herein to indicate how precipitation data can best be employed in planning and design of stormwater facilities under emerging imperatives. The only way an event frequency can be determined is by referring to a reasonably large series of prior events. However, it is first necessary to review concepts that have been used for decades, to show why they are not suited for investigating performance, either expected or experienced. These now outmoded concepts originated in connection with the sizing of conduits.

Because the sizing, deployment and operation of detention storage facilities is determined by the time patterns and amounts of rainfalls selected, the use of actual precipitation records is greatly preferred. Several examples are given which give a clear indication of why synthetic storms can be a liability in detention storage evaluations. In one test it was found that storage sized to contain either 90 or 95 percent of the total runoff volume resulting from the synthetic storm would be capable instead of containing only about 60 or 80 percent, respectively, of the total runoff volume based on a long-term precipitation record.

In conclusion, current storm drainage analysis procedures too often emphasize the use of a synthetic storm, which is a device for facilitating analysis but at the expense of reliability. For small projects such an approach is useful and can be appropriate in helping to define marginal costs among alternatives, but may be acceptable only when gross differences in levels of protection from flooding or pollution are sought. However, for more important projects, local officials should make reference to actual rainfall histories for the planning, design and operation of new facilities. This recommendation is particularly appropriate where detention storage is involved, and even more so when detention storage is interconnected as in schemes for reduction of combined sewer overflows.

38. McPherson, M. B.

"Synthetic Storm Pattern for Drainage Design," Discussion, Journal of the Hydraulics Division, ASCE, Vol. 84, No. HY1, February, 1958, pp. 1558, 49-57.

(Classification: 1,4)

This paper is a discussion of the paper by Keifer and Chu (paper no. 29 in this review of the literature). McPherson commends the authors for their new approach but holds several major reservations insofar as the efficacy of the described synthetic storm is concerned. These reservations involve the following three considerations: (1) use of published rainfall intensity-duration-frequency curves, (2) use of a computed "r" value (see paper no 29), and (3) use of a synthetic storm rather than actual historic storms. These three aspects are discussed in the following paragraphs in McPherson's words.

"Intensity-duration-frequency curves are derived for each duration by taking maximum excessive rainfalls, regardless of where the critical duration occurs in each record, and arranging intensities by rank for statistical analysis. In this way the various durations of a frequency curve represent a series of unrelated values from a variety of storms; a frequency curve thus gives intensities on the average, which are for a rarer occurrence than indicated. The use of frequency-curve data for drainage design, by any method, thus becomes highly empirical..."

"From the above data there does not appear to be any outright correlation between an "r" calculated on the basis of an antecedent time and on the basis of an antecedent mass. In the opinion of the writer, the values 0.386 and 0.376 of "r" are characteristics of the specific sample used and their nearness in magnitude should be considered fortuitous...Although the writer (i.e., McPherson) has used the method of the authors in determining the value of "r" from mass antecedent rainfall, he can find no basis or reason given by the authors (i.e., Keifer and Chu) to justify the assumption that the antecedent portion of their synthetic hyetograph should have the same trend or shape as the part after the peak."

"...Although evaluation and allocation of the factors involved in the overland flow method of surface routing would become much more complicated, why could not actual storms be used in a computer program? Using the same storm pattern for both branch sewers and main sewers seems to be somewhat inconsistent. Perhaps design could be based upon the routing of several moderately infrequent storm patterns, in which different storms might well be critical for different sewers in the system. It is recognized that a basis for selecting the proper storms presents a formidable stumbling block. However, the method of storm evaluation proposed by the authors retains too many of the fallacies and empiricisms inherent in the "rational" method to recommend its principle for general use by others."

39. Natural Environment Research Council

"Flood Studies Report, Vol.2 - Meteorological Studies," Natural Environment Research Council, London, 1975.

(Classification: 2)

A description of a new design storm which is characterized by its duration, the total rainfall depth, and a series of symmetrical temporal patterns is given. The storm duration should be taken as 2-3 times the time of concentration, which is defined as the travel time from the most remote contributing point to the point of interest. The corresponding rainfall depth is obtained from the intensity-duration-frequency (I-D-F) curves. This depth is then distributed in time using given standard distributions which were developed for this purpose from actual data. The standard distributions are characterized by the probability of the profile sharpness. For general applications, the distribution characterized by the 50 percentile of profile peak (i.e., 50% of all rainfall profiles are less sharp) is recommended.

40. Normand, D., Recoura, J., and Rene, R.

"Etude statistique des hyetogrammes types," (A Statistical Study of Design Storms), Ministere de l'Equipement, Rapport SOGREAH No. R10653, 1970.

(Classification: 2)

Four rainfall records are discretized into individual events, and the data sets obtained for discrete events are subjected to statistical analysis. Such an analysis includes computations of correlations between maximum mean intensities of selected durations, correlations between return periods of maximum mean intensities of selected durations, and timing of the maximum mean intensities of selected durations during storm events. Using the results of such analyses, a 10-yr design storm characterized by a 30-min maximum mean intensity is developed. The 10-yr, 30-min maximum intensity is determined from the intensity-duration-frequency (I-D-F) curve. From a graph of return period correlations, the return periods corresponding to the 10-yr, 30-min maximum intensity are determined for durations of 5, 15, 60, 120 and 240 minutes. These return periods vary from 3.6 to 8.7 years. For the above durations and the associated return periods, the corresponding rainfall intensities are derived from the I-D-F curves. Finally, a storm pattern with centered peak intensities of the selected durations is produced.

41. Oren, K., Sirum, J., and Balmer, P.

"Evaluation of the Base Rainfall Method in Urban Drainage Simulations," Proc. Nordic Hydrological Conference, 1978, edited by M. Melanen, Report No. 10, Helsinki University of Technology, Helsinki, 1978, pp. 2-10.

(Classification: 2)

The method of base rainfalls, which is applicable in planning as well as in some design simulations, is evaluated for a particular problem. The base rainfalls are derived as follows: the rainfall record is broken into individual events; each event hyetograph is replaced by an equivalent block hyetograph; the equivalent block hyetographs are classified according to the intensity and duration; and each classification group is then represented by a mean base rainfall of a known return period. Because of the extensive averaging involved, the method is not particularly useful for studies of runoff peaks, but it may be applied to other aspects of drainage design. In the study described, the base rainfalls are used to simulate the annual overflow volume for a hypothetical area served by combined sewers. For two alternatives studied, the simulations with base rainfalls produce the annual overflow volume within 10% of that simulated for the actual rainfall record. The use of base rainfalls reduces the computer costs by 90% compared to those needed for the simulation with the actual rainfall record. It is concluded that these savings outweigh the minor loss of accuracy. Even larger benefits could be realized in more complex drainage systems with numerous control alternatives.

42. Packman, J. C., and Kidd, C.H.R.

"A Logical Approach to the Design Storm Concept," Water Resources Research, Vol. 16, No. 6, December, 1980, pp. 994-1000.

(Classification: 3)

Flood estimation using isolated event simulation models requires selection of a suitable combination of design storm and antecedent conditions. Current practice in storm drainage design is to adopt arbitrarily a storm duration, profile, and catchment wetness and to assume that the return periods of rainfall depth and flood peak are equal. This paper describes how sensitivity analysis may be used to examine the relationship between rainfall and flood return periods and, thereby, to determine systematically a suitable set of design inputs which give a peak runoff of the required return period. This process permits this particular model to be used with confidence in design as well as in simulation.

The paper outlines the form of the sensitivity analysis used in developing the Wallingford model for storm sewer design. This analysis determines the antecedent conditions and design storm that consistently give flows which match an observed flood frequency distribution. The study uses historic rainfall events to perform

42. (continued)

the sensitivity analysis. A 98-yr record applicable to southeastern England and a 34-yr record applicable to southwestern England were available.

Four inputs are needed to the Wallingford model: rainfall depth and duration, profile (time distribution of rainfall during the storm), and an antecedent condition index. Because design discharges are required at each point within the sewer network, the model considers a range of storm durations (15, 30, 60 and 120 minutes), choosing the design duration as that duration which gives the largest peak. Depth is defined for each of the standard durations from local depth-duration-frequency relationships. Profiles have been published for use in the United Kingdom and the 50 percent summer profile was found to be the most appropriate. A detailed sensitivity analysis is used to define a relationship between the antecedent condition index and average annual rainfall.

43. Padmanabhan, G., and Delleur, J. W.

"An Alternative to the Design Storm Approach for Urban Stormwater Management," Proc. of an International Symposium on Urban Hydrology, Hydraulics and Sediment Control, Lexington, Kentucky, July 27-29, 1982, pp. 267-274.

(Classification: 4)

There is an increasing need for comprehensive planning for urban stormwater management with respect to quantity and quality. The "design storm" concept has a number of disadvantages: watershed characteristics are not considered; return periods of runoff (and of pollutant loads) are assumed to be the same as that of rainfall; sequences of rain events are not considered; and it is deficient for the economic analysis of alternate designs.

The conjunctive use of STORM and ILLUDAS is proposed as an alternative to the design storm approach. STORM provides the information on runoff events, overflows and pollution loads while ILLUDAS may be used for the detailed computation of the conveyance system. ILLUDAS is also sensitive to different locations of detention basins. These complementary characteristics are useful in the economic analysis of alternate drainage systems.

The methodology is applied to two watersheds in West Lafayette, Indiana, for the probabilistic analysis and for the study of alternatives for the control of stormwater. The output of STORM is used for further statistical analyses. The proposed method makes use of continuous simulation of runoff quantity and quality in the context of the drainage system with its characteristics and is therefore more meaningful than isolated storms. It is a practical alternative to the "design storm" approach.

44. Patry, G., and McPherson, M. B.

The Design Storm Concept, Urban Water Resources Research Group, Dept. of Civil Eng., Ecole Polytechnique De Montreal, Report EP80-R-8-GREMU-79/02, December 1979.

(Classification: 1,2,4)

The contents of these proceedings are summarized by Walesh in "Summary - Seminar on the Design Storm Concept" which is paper no. 59 of this review. Walesh's remarks are an excellent summary of the seminar.

45. Pilgrim, D. H., and Cordery, I.

"Rainfall Temporal Patterns for Design Floods," Journal of the Hydraulics Division, ASCE, Vol. 101, No. HY1, January, 1975, pp. 81-95.

(Classification: 1,3)

The rainfalls used in the practical estimation of design floods are generally based on frequency-duration relationships derived from recorded intense bursts of rainfall of various durations rather than from complete storms. These recorded intense bursts are therefore used in the derivation of the temporal patterns. The method produces patterns that incorporate average variability of intense rainfall and also the most likely sequence of intensities. Use of these patterns should minimize the introduction of joint probabilities into the design flood model and aid in estimation of a flood with the same frequency as the design rainfall. The method provides patterns with average or typical variations in intensity, in contrast to simple averaging which is shown to be generally unlikely to yield satisfactory patterns. Frequency distributions of rainfall during various periods immediately antecedent to the recorded intense bursts are also derived, and these antecedent rainfalls in flood estimation are considered.

The basic premise adopted in the paper is that if median or average values of all other parameters are used, the frequency of the derived flood should be approximately equal to the frequency of the design rainfall. The methodology is therefore aimed at producing from the recorded intense bursts of a given duration, a temporal pattern with average variation of intensities within the design burst, and the most likely sequence of these varying intensities.

The method is tested with rainfall data observed at Sidney, Australia, and temporal patterns for use in practical design at this location are derived covering 16 durations from 10 minutes to 24 hours. These Sydney data are also used to illustrate an approach that considers the implications for design flood estimation of the rainfalls occurring before the intense bursts used in developing frequency relationships.

46. Preul, H. C., and Papadakis, C. N.

"Development of Design Storm Hyetographs for Cincinnati, Ohio," Water Resources Bulletin, AWRA, Vol. 9, No. 2, April, 1973, pp. 291-300.

(Classification: 1)

A synthetic storm rainfall hyetograph for a 1-yr design frequency is derived from the 1-yr intensity-duration curve developed for Cincinnati, Ohio. Detailed rainfall data for a 3-yr period were collected from three raingages encompassing the Bloody Run Sewer Watershed, an urban drainage area of 2,380 acres in Cincinnati, Ohio. The advancement of the synthetic storm pattern is obtained from an analysis of the antecedent precipitation immediately preceding the maximum period of three selected durations. Only rains which produced excessive runoff at least for some duration are considered.

The same approach can be used for other design frequencies. The purpose of this study is to provide synthetic storm hyetographs to be used as input in deterministic mathematical models simulating urban storm water runoff for the design, analysis and possible surcharge prediction of sewer systems.

The procedure used in this study involved establishing the rainfall intensity-duration curve for a selected design frequency for a particular location and then deriving the corresponding storm pattern using a method first proposed by Keifer and Chu (paper no. 29 in this review of the literature).

47. Raman, V., and Bandhyopadhyay, M.

"Frequency Analysis of Rainfall Intensities for Calcutta," Journal of the Sanitary Engineering Division, ASCE Proc., Vol. 95, No. SA6, June, 1969, pp. 1013-1030.

(Classification: 2)

This paper discusses procedure used to reduce rainfall data to duration-frequency-intensity for Calcutta, India. The authors derive three equations relating intensity to frequency or reoccurrence and duration. The authors also use graphical plotting methods of analysis.

48. SCS, Technical Release No. 55

"Urban Hydrology for Small Watersheds, January, 1976.

(Classification: 1)

48. (continued)

This technical release was prepared by hydraulic engineers from the SCS Engineering and Watershed Planning Unit (E&WP), Upper Darby, PA., and the Central Technical Unit, Hyattsville, MD. Valuable contributions were received from the Engineering Division, Washington, D.C., E&WP Units at Lincoln, NE, Portland, OR, and Fort Worth, TX, and from various state hydrologists and engineers.

Technical Release 55 is presented as a guide for field personnel in estimating the effects of land use changes and structural measures on hydraulic and hydrologic parameters, runoff volume, and peak rates of discharge. Field engineers are cautioned that some of the proposed methods are in the formative state and thus have not been fully tested. The results should be compared with other available methods, and engineering judgment should be used in arriving at a final estimate. Careful consideration should be given to the scope and importance of the job when deciding on a particular procedure. It is not intended that all procedures fit all situations that arise. As more data become available it is expected that the procedures described in this technical release will be revised. (This publication offers very little information on design storms, their distribution or their validity).

49. Sieker, F.

"Investigation of the Accuracy of the Postulate 'Total Rainfall Frequency Equal Flood Peak Frequency,'" Proceedings of International Conference on Urban Storm Drainage, Univ. of Southampton, April 11-14, 1978, pp. 31-41.

(Classification: 3)

This paper compares the peak outflow frequency response for historical rainfall to the response for a series of design storms on a 54 hectare residential catchment. Rainfall-runoff data for a 2-yr period are used to correlate total rainfall and duration to runoff depth and also to develop an average 5-min unit hydrograph. A simulation model based on a single linear reservoir is used to simulate the peak outflows. A depth-duration-frequency analysis for 24 years of rainfall data from a nearby raingage is performed, from which constant intensity design storms are determined.

The annual maximum series of simulated outflow peaks from the 24-yr rainfall records are used to develop a historical frequency response. Design storms of various frequencies and intensities are also processed through the simulation model. It was found that, for return periods greater than 1 year, the historical peaks are higher than the design storm peaks from the same return period, with the difference increasing with return period.

50. Sieker, F.

"Simulation of Design - Storms with Probable Distributions in Time and Space for Storm Drainage Systems," Inst. Für Wasserwirtschaft, Tech. Univ., Hannover, Ger., Prog. Water Technology, Vol. 9, No. 3, 1977, pp. 509-519.

(Classification: 2)

In this paper, the author claims that in the case of hydraulic computation of storm draiange systems the postulate: "Frequency of Rain is Equal to Frequency of Discharge" is established. In order to ensure this postulate, design storms with probable distributions in time and space need to be used. A method used to obtain such a design storm is described. The procedure is based on the statistical method of variance analysis. The probable distribution in time is simulated by a model of twofold variance analysis, and the probable distribution in space represents statistical regularities which can be interpreted in regard to their physical sense. The probable distributions are given by the arithmetic addition of those terms. The application of the method is illustrated by examples.

51. Sieker, F.

"Verfahren zur Ermittlung eines Berechnungsregens mit ortlich und zeitlich ungleichmassiger Verteilung," (Method for the Determination of a Design Storm with Disproportionate Distribution in Space and Time), Wasserwirtshaft, Vol. 65, No. 11, 1975, pp. 293-296.

(Classification: 2)

The paper describes the development of a statisitical model for design storms. Model parameters are derived by a multi-variate analysis of variance of rainfall measurements in a grid of p x q stations. In particular, the following phenomena are considered in the analysis: (1) stationary average spatial distribution of rainfall; (2) probability of occurrence of rainfall of a certain intensity; (3) directional variability in two orthogonal components; and (4) random effects.

The proposed methodology is demonstrated on rainfall data from a network of 16 stations just south of Hamburg, Germany. Using the earlier derived equations and long-term mean daily rainfalls, maximum daily rainfalls on a chosen return period are simulated for all 16 stations.

52. Sifalda, V.

"Entwicklung eines Berechnungregens fur die Bemessung von Kanalnetzen," (Development of Design Storms for Sizing of Sewer Networks), Das Gas - and Wasserfach - Wasser/Abwasser, Vol. 114, No. H9, 1973, pp. 435-440.

(Classification: 1,2)

The paper describes the development of a synthetic design storm on the basis of 91 severe storms which were observed at three locations in Czechoslovakia. The combined length of all the rainfall records is 78 years. The observed storm hyetographs are first classified into seven groups according to their shape. The predominant type is an advanced pattern with the maximum intensity occurring early during the storm.

The observed hyetographs are preprocessed by eliminating sections at the start and end where the intensity or the rainfall depth fall below a certain threshold. After such preprocessing, mean values of storm hyetograph parameters are produced for each location. The most important parameters are the total rainfall depth, the storm duration, the duration of the peak intensity burst, and the chronological location of this burst. Using mean values of such paramters, the design storm hyetographs are constructed for each location. The hyetographs consist of three distinct parts - a trapezoidal part at the start of the storm, a rectangular section representing the peak intensity, and a trapezoidal part after the peak intensity. The hyetograph shape may be described as follows:

| | | | | |
|---|---|---|---|---|
| $t/T$ | 0 | 0.25 | 0.50 | 1.00 |
| $i/\bar{i}$ | 0.00; 0.15 | 1.00; 2.30 | 2.30; 1.00 | 0.20; 0.00 |

where t is the time measured from the storm onset, T is the total storm duration, i is the rainfall intensity, and $\bar{i}$ is the mean storm intensity.

It is recognized that for other locations, different hyetograph patterns and mean paramter values may be obtained.

53. Southeastern Wisconsin Regional Planning Commission

Community Assistance Planning Report No. 4, Floodland Information Report for the Rubicon River, Exh. L, "Selection of Design Rainfall Events," December 1974. (Discusses the following factors that enter into developing or selecting a design storm: geographic location, recurrence interval, duration, volume, area, and depth sequence).

(Classification: 2)

53. (continued)

The mathematical model used to simulate the hydrologic-hydraulic regimen of the Rubicon River system requires, as one item of input, a design rainfall event. The process used to select this design rainfall event and the underlying rationale behind the process are described. Implicit in the use of a design rainfall event is the assumption that the recurrence interval of peak discharge and stage during a flood is approximately equal to the recurrence interval of the causative rainfall event. Six critical parameters are discussed which are needed to completely prescribe such a rainfall event: geographic location, recurrence interval, duration, volume, area, and depth sequence (time distribution of the rainfall throughout the storm).

54. Terstriep, M. L., and Stall, J. B.

"The Illinois Urban Drainage Area Simulator, ILLUDAS," Illinois State Water Survey, Urbana, Bulletin 58, 1974.

(Classification: 1)

The authors present a method for the hydrologic design of storm drainage systems in urban areas and for the evaluation of an existing system. The method, based on a digital model known as the Illinois Urban Drainage Area Simulator (ILLUDAS), uses storm rainfall and physical basin paramters to predict storm runoff from both paved areas and grassed area. ILLUDAS utilizes the directly connected paved area concept of the British Road Research Laboratory (RRL) method but also recognizes and reproduces runoff from grassed and nonconnected paved areas. Included are a description of the theoretical development of the model, verification of the model by its application to 21 existing urban basins in the United States (from 0.39 acres to 8.3 sq miles) and 2 rural basins, and a users manual that describes in detail the actual use of ILLUDAS in design applications. The ILLUDAS is available in the form of a 700-card Fortran IV deck. A description of the input deck in its proper order and the actual content and format for each card are presented. This model provides engineers with a method for urban storm drainage design that requires little more input data than a rational method solution. The model provides several standard design rainstorm distributions and also allows the use of recorded rainfall data as input.

55. Urbonas, B.

"Reliability of Design Storms in Modeling," Proceedings International Symposium on Urban Storm Runoff, University of Kentucky, July 23-26, 1979.

(Classification: 3)

55. (continued)

This paper summarizes a research effort by the Urban Drainage and Flood Control District in the Denver, Colorado area to develop more reliable runoff simulation techniques. As a part of this effort, the design storm concept is analyzed. This paper discusses only the findings relative to the design storm concept. The findings are based on applying 73 years of rainfall to simulate runoff with computer models. These computer models are calibrated for each basin using rainfall/runoff data collected since 1969. In addition, this paper examines the principles of design storm analysis and offers suggestions on how to develop and test design storms. Emphasis is on utilizing long-term simulations and/or probabilistic analysis of runoff peak and volume distribution to develop reginnal design storms for use in the design and planning of stormwater management systems. The author also cautions against misuse of design storms in certain applications.

56. Vogel, J. L., and Huff, F. A.

"Heavy Rainfall Relations Over Chicago and Northeastern Illinois," Water Resources Bulletin, Vol. 13, No. 5, October 1977, pp. 959-971.

(Classification: 3)

Detailed studies of rainfall frequency and pattern relations are conducted over the Chicago urban region and the surrounding six Illinois counties (Cook, DuPage, Kane, Will, Lake, and McHenry). The studies utilize rain gage records from an urban network of National Weather Service rain gages in the region, primarily for the period 1949 to 1974. Frequency distributions of point rainfall are obtained for periods from 5 minutes to 72 hours and recurrence intervals of 6 months to 50 years. The results indicate a spatial pattern of short-duration, heavy rainfall frequencies related to urban-lake effects, particularly in the huge industrial region over the southern portion of Chicago. The time distribution within heavy rainstorms over the urban region are similar to a 12-yr sample of a dense rain gage network over a rural area in central Illinois. The characteristics of heavy rainfall over northeast Illinois also are studied through the use of heavy, 1-day storms. A total of 87 storms, capable of producing local flooding, are analyzed to determine: (1) the frequency distribution of storm centers, (2) seasonal and diurnal distribution of storms, and (3) orientation and movement of storms.

57. Voorhees, M. L., and Wenzel, H. G., Jr.

"Sensitivity and Reliability of Design Storm Frequency," Proceedings of the Second International Conference on Urban Storm Drainage, Urbana, Illinois, Vol. 1, June 14-19, 1981, pp. 374-393.

(Classification: 3)

57. (continued)

A summary of a sensitivity analysis of the frequency response of urban catchments to design storm paramters is presented along with an illustration of the fitting of design storm model paramters so as to measure the reliability of subsequent frequency response.

The sensitivity study is conducted using a continuous deterministic simulation model based on the Illinois Urban Drainage Area Simulator (ILLUDAS). Continuous rainfall records are utilized to develop design storms based on conventional intensity-duration-frequency analysis and various temporal patterns. The simulation model is used to predict the frequency response of several urban catchments to the historical rainfall records. The response serves as a basis for a graphical comparison with peak runoff from design storms with various temporal patterns and antecedent soil moisture conditions. The results for several catchment-rainfall combinations is presented.

The reliability approach utilizes the triangular and beta distribution design storm models. Expected values of the paramters for these models are obtained using the simulation model and one historical rainfall record. A significant improvement in design storm frequency response agreement with historical response is obtained.

58. Walesh, S. G., Lau, D. H., and Liebman, M. D.

"Statistically-Based Use of Event Models," _Proceedings International Symposium on Urban Storm Runoff_, University of Kentucky, July 23-26, 1979, pp. 75-81.

(Classification: 4)

Continuous hydrologic-hydraulic models have the advantage of producing statistically sound results and a disadvantage of incurring higher computer costs. Event models have the advantage of lowering computer costs and the disadvantage of having to select and use a design storm. A technique is presented for capitalizing on the low cost of the event model while eliminating the need to select a design storm, thus obtaining a statistically more meaningful result. The basis for the technique is assembling and using hyetographs of major rainfall events from a long historic record. Four case studies illustrate the applicability of this technique to a variety of hydrologic-hydraulic analyses.

The historic storm technique (HST) consists of the following three steps: (1) assembling hyetographs and associated antecedent conditions for major rainfall events from a long historic record; (2) inputting the selected hyetographs to the event model and obtaining corresponding direct runoff hydrographs; and (3) selecting annual peak discharges or volumes from the model output and performing statistical analyses resulting in a discharge-probability or volume-probability relationship.

58. (continued)

The example applications of the HST presented in this paper all utilize historic rainfall events as continuously recorded by the National Weather Service at General Mitchell Field in Milwaukee, Wisconsin, during the period 1940 through 1976. The HST should be used with caution for several reasons. The method has not been tested with long-term historic gauging data. The HST as described herein is limited to basins on which rainfall - as opposed to snowmelt - cause major floods. The method assumes that the set of historic storms is statistically applicable to the entire study basin even though the meteorologic station may lie outside of the basin.

59. Walesh, S. G.

"Summary - Seminar on the Design Storm Concept," Proceedings Stormwater Management Model (SWMM) Users Group Meeting, May 24-25, 1979, EPA 600/9-79-026, June 1979.

(Classification: 1,2,4)

The purpose of the seminar is to sensitize civil engineers to the positive and negative features of the design storm concept so as to discourage its blind use and to provide a forum for exchange of information and ideas among researchers in the United States, Canada, and elsewhere. This summary is structured so as to collect the ideas and information presented at the seminar into the following six categories: (1) definition of design storm; (2) perceived or demonstrated shortcomings of the design storm concept; (3) perceived or demonstrated positive aspects of the design storm concept; (4) alternatives to the traditional use of design storms; (5) research underway or proposed; and (6) miscellaneous considerations.

The general consensus was that there are two types of design storms: (1) direct use of intensity-duration-frequency (IDF) relationships to obtain a uniform intensity for a given duration and recurrence interval and (2) development of a synthetic hyetograph (or storm profile) from IDF relationships, historic storms, or other means.

One perceived shortcoming is that the recurrence interval of the design storm is the same as the discharge or volume produced by the storm. Observations of rainfall-runoff data reveal instances in which strikingly similar hyetographs produce markedly different hydrographs, suggesting the important role of factors such as antecedent moisture conditions and areal distribution of rainfall over the catchment. Some of the methods used to construct design storms may be incorrect uses of IDF relationships. Design storms do not usually yield all the probability information desired for planning and design studies.

59. (continued)

The design storm enjoys widespread use for three reasons: (1) its use requires minimal resources in terms of time and money; (2) it appears to give conservative results, that is, high discharges and volumes; and (3) application of this approach is generally accepted in practice and one can argue for consistency of methodology in a given jurisdiction or geographic area.

Alternatives to the traditional use of design storms include continuous simulation, continuous simulation with cost-reducing techniques, use of a series of "major" historic storms as input to an event model followed by discharge-probability or volume-probability analyses of the model output, use of improved, rationally developed and statistically meaningful design storms, and use of one or a few readily remembered historic storms for a study area without explicit assignment of a probability or recurrence interval.

Research efforts identified include: use of a series of historic storms with an event model followed by subsequent discharge-probability or volume-probability analyses of the output; reducing the cost of continuous simulation; probabilistic development of a design storm; use of modeling to identify appropriate combinations of hyetographs shape or peakedness, antecedent moisture conditions, duration, and areal availability; and development of computer programs intended to efficiently and effectively screen long-term historic precipitation data to select subsets of storms suitable for simulation, with event models, of discharges, volumes, or water quality.

60. Ward, A., Wilson, B., Bridges, T, and Barfield, B.

"An Evaluation of Hydrologic Modeling Techniques for Determining a Design Storm Hydrograph," Proc. of International Symposium on Urban Storm Runoff, Univ. of Kentucky, 1980, pp. 59-70.

(Classification: 3)

The sensitivity of design hydrographs to temporal rainfall patterns, storm durations, SCS curve numbers and unit hydrograph procedures are evaluated with the WASHMO hydrograph model. The evaluation includes results from 8 synthetic rainfall distributions and 2 hydrograph procedures. The ability of the WASHMO model to predict observed runoff hydrographs is demonstrated in a study with 20 storms on 5 watersheds, ranging from an urban watershed to a steeply sloping forested watershed.

61. Wenzel, H. G., Jr.

"Rainfall for Urban Stormwater Design," Urban Stormwater Hydrology, D. F. Kibler, ed., Water Resources Monograph 7, American Geophysical Union, Chap. 2, 1982, pp. 35-67.

(Classification: 1,2,4)

This chapter discusses conventional procedures for depth-duration-frequency analysis of rainfall data. The various components of design storms are discussed and examples of design storm development using different methods are presented. Current research on the topic is summarized and a discussion of applications for detention storage and water quality studies is presented.

62. Wenzel, H. G., Jr., and Voorhees, M. L.

An Evaluation of the Urban Design Storm Concept" Research Report No. 164, Water Resources Center, University of Illinois, Urbana, Illinois, Aug., 1981.

(Classification: 3)

This paper presents a summary of further progress in a study of the design storm concept. The general procedure used is to model an urban catchment, calibrate the model using field data and to use the model to simulate the long-term response of the system to historical rainfall. A frequency analysis is made of this response which can then be compared with the stimulated runoff from various types and frequencies of design storms. Of basic interest is a comparison of the design storm frequency and the frequency of its associated peak runoff, which are usually assumed to be equal.

More recent work has concentrated on the application of the USGS Distributed Routing Rainfall-Runoff Model to several catchments in the Baltimore area. The sensitivity of the design storm runoff frequency curves to antecedent soil moisture and hyetograph is discussed

63. Wisner, P. E., and Gupta, S.

"Preliminary Considerations on the Selection of Design Storms," IMPSWM Progress Report No. 4, University of Ottawa, Ottawa, August, 1979.

(Classification: 2,3)

Several types of design storms used in hydrological practice are briefly introduced. The storms are further evaluated by introducing a "peakiness factor" which is defined as the ratio of the peak intensity, for a selected time interval, to the average storm intensity. Thus,

63. (continued)

the peakiness factor is affected not only by the rainfall temporal pattern, but also by the choice of the time interval used to discretize rainfall data. For drainage design, a modified Chicago-type design storm is recommended. The modification consists in reducing the peakiness of the Chicago-type hyetograph to the values commonly observed for historical storms. Such a reduction can be achieved by selecting a longer discretization interval which would be somewhat related to the time of concentration of the watershed.

64. Yen, B. C., and Chow, V. T.

"Feasibility Study on Research of Local Design Storms," Report No. FHWA-RD-78-65, Federal Highway Administration, November, 1977.

(Classification: 2)

This paper discusses temporal rainfall variability, recognizing that the time pattern of future storms cannot be predicted exactly. The authors believe that the design hyetograph can only be determined probabilistically using statistical values of past events. By using statistical moments, nondimensional hyetographs can be established and then used to produce the design hyetographs. The nondimensional triangular hyetograph method is based on the statistical mean of the first moment of recorded rainstorms and triangular representation of the hyetographs. Simple procedures of how to use the nondimensional triangular hyetograph to produce the design hyetograph are outlined. The possibility of using trapezoidal nondimensional hyetographs is also discussed. However, the authors recommend that more rainstorms from other locations should be analyzed to verify the conclusions of this study. The computer programs together with user's manual for the statistical analysis of rainstorms are also presented.

65. Yen, B. C., and Chow, V. T.

"Design Hyetographs for Small Drainage Structures," Journal of the Hydraulics Division, ASCE, Vol. 106, No. HY6, June, 1980, pp. 1055-1076.

(Classification: 1)

A probabilistic approach is taken to develop a nondimensional triangular hyetograph. An analysis of 7,484 rainfall events at three locations (Illinois, Massachusetts and North Carolina) is made. The statistical mean of the first time moment is computed as a function of duration and location and season. Hyetographs are transformed into dimensionless form using total depth and duration. The mean maximum intensity was found to occur from 32 to 49 percent of the duration, with the nondimensional hyetographs for heavy

65. (continued)

rainfall events being rather independent of duration. An application procedure is presented with examples. Runoff hydrographs resulting from the triangular hyetograph are compared with hyetographs from other shaped hyetographs. The comparison supports the use of the proposed triangular shape.

The results are based on limited data and further work to identify geographic effects is recommended. However, the paper demonstrates the feasibility of the approach.

# REFERENCE LIST BY CLASSIFICATION

## Classification 1

Reference Nos. 1. 6, 8, 9, 11, 13, 16, 19, 21, 29, 38, 44, 45, 46, 48, 52, 54, 59, 61, and 65.

## Classification 2

Reference Nos. 2, 4, 5, 10, 11, 13, 14, 15, 17, 19, 20, 22, 23, 25, 27, 28, 30, 32, 35, 36, 39, 40, 41, 44, 47, 50, 51, 52, 53, 59, 61, 63, and 64.

## Classification 2

Reference Nos. 3, 7, 15, 18, 23, 24, 33, 34, 35, 36, 42, 45, 49, 55, 56, 57, 60, 62, and 63.

## Classification 4

Reference Nos. 26, 31, 36, 37, 38, 43, 44, 58, 59, and 61.