RELIABILITY OF DESIGN STORMS IN MODELLING

BY

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Abstract.

Stormwater runoff is generally simulated using a design storm as input. The use of design storms significantly reduces the complexity of stormwater runoff analysis. As a result, the use of design storms is popular among engineers. The basic premise behind their use is that a design storm of a given return frequency will produce a simulated runoff peak and volume having the same return frequency. As an example, using a 5-year design storm will result in a 5-year runoff peak and volume.

Typically, design storms are developed by statistical analysis of rainfall records. The resultant temporal distributions of these design storms may be quite unlike the rainstorms occurring in nature. Worse, the use of design storms may not be resulting in runoff peaks and volumes having the same return frequency. As a result, drainage and flood control facilities designed using design storms may be oversized or undersized. Unfortunately, design storms are, by and large, not tested against long-term rainfall/runoff record simulation to determine if they will reasonably simulate runoff for a given return frequency.

A research effort is underway 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 being analyzed. Although the District's research effort is broad in scope and is exhaustive in nature, this paper discusses only the findings and the work to date 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 were calibrated for each catchment 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.

Introduction

In 1969 the Urban Drainage and Flood Control District (District) serving the metropolitan Denver, Colorado, area, became a cooperative sponsor with the U.S. Geological Survey (USGS) to collect rainfall/runoff data from urban catchments. In 1977 the District started its own data analysis and research effort to develop more reliable urban runoff simulation techniques. As a part of this effort, the design storm concept was analyzed. Although the District's research efforts are broad in scope, this paper presents only the recent findings related to the design storm concept.

Background

The use of design storms is very popular among drainage and flood control engineers and has achieved almost universal acceptance. In practice, it is assumed that a design storm of a given recurrence frequency will simulate a runoff peak and volume having the same frequency. Several techniques to develop the design storm from rainfall records have evolved or have been proposed over the past 20 years, including Chicago[1], ISWS[2], CUHP[3], and Urban Storm Runoff Inlet Hydrograph Study[4]. All of these techniques are based on the statistical analysis of rainfall data with very little, if any, verification of results through the investigation of the resultant runoff. Since only rainfall data are analyzed, independent of the total rainfall/ runoff process, the validity of the design storm concept has been questioned. McPherson[5] has pointed out the fallacy of assigning identical frequencies of occurrence to rainfall and runoff when in reality both processes can exhibit statistical non-homogeneity. The use of the design storm, according to McPherson, may be acceptable when only gross differences in level of protection from flooding are sought, but actual rainfall histories need to be used for the final design of operating facilites.[6]

Recent investigations have reported differences in predicted recurrence probabilities of peak flows using design storms when compared to simulated peaks using actual rainfall histories[7,8,9]. Marsalek observed that for the conditions he investigated in Ontario, Canada, only half of the linear variation in runoff peaks could be explained by the linear variation in rainfall intensity . This led him to conclude that parameters of rainfall distribution are important in the generation of realistic runoff peak flow. Wenzel and Voorhees concluded that the design storm hyetograph and antecedent soil moisture conditions are very important parameters9. Both Marsalek and Wenzel expressed concern about the validity of the computer models used when extrapolating to less frequent large storm events. Both reported their models operated in a surcharge mode during the larger events and, as a result, they felt the accuracy of the predicted runoff peaks during very large rainstorms was suspect.

Rainfall Analysis

Local governments in the Denver area have adopted the use of t e Urban Storm Drainage Criteria Manual (USDCN)3 for planning and design of drainage and flood control facilities. The manual was published in 1969 by the Denver Regional Council of Governments (DRCOG) and contains rainfall isopluvial maps for the Denver metropolitan area for a variety of storm duration and return periods. The USDCM also contains a step by step procedure for reducing the isopluvial information to design storms. Subsequent to the adoption of the USDCM by local governments, another set of isopluvial maps was published by the National Oceanic and Atmospheric Administration (NOAA)10. The two sets of maps did not agree. The local governments continued to use the previously adopted USDCM rainfall information, while Federal agencies used the NOAA Atlas. Occasionally, disagreements occurred between various parties that were based solely on the argument that one set of design storms was better than the other. None of the arguments were backed by runoff data.

To examine the validity of the published isopluvial maps, the 73 maximum 30-minute rainfall depths recorded at the Denver gage from 1898 through 1971 were reduced to a Weibult probability plotting position. The rainfall data plotted on log normal probability paper are shown on Figure 1. The two lines shown on Figure 1 show the 30-minute rainfall depths obtained from the DRCOG and NOAA isopluvial maps. It is interesting that neither of them fit the rainfall data well, yet the isopluvial maps information was the basis of disagreements between local and Federal officials. If one thoroughly investigated the procedures used to develop the two sets of isopluvial maps, the reasons for these differences can probably be discovered. However, that is not the point. What is important to recognize is that published rainfall depth-frequency-duration maps are often used as the basis for development of design storms. Besides being statistically nonhomogeneous with runoff, the design storms in themselves may originate from information that may not be totally consistent with the rainfall data collected locally.

Also shown on Figure 1 are the 7-day antecedent precipitation data corresponding to each of the rainstorms used. Examining this data reveals that the antecedent precipitation is random in nature and it is not possible to draw any conclusions as to how it may affect the statistical distribution of runoff. To identify the potential effects of antecedent precipitation, it is necessary to examine the runoff peaks simulated while accounting and not accounting for antecedent moisture conditions. Such dual runoff simulation was performed and the results are reported later in this paper.

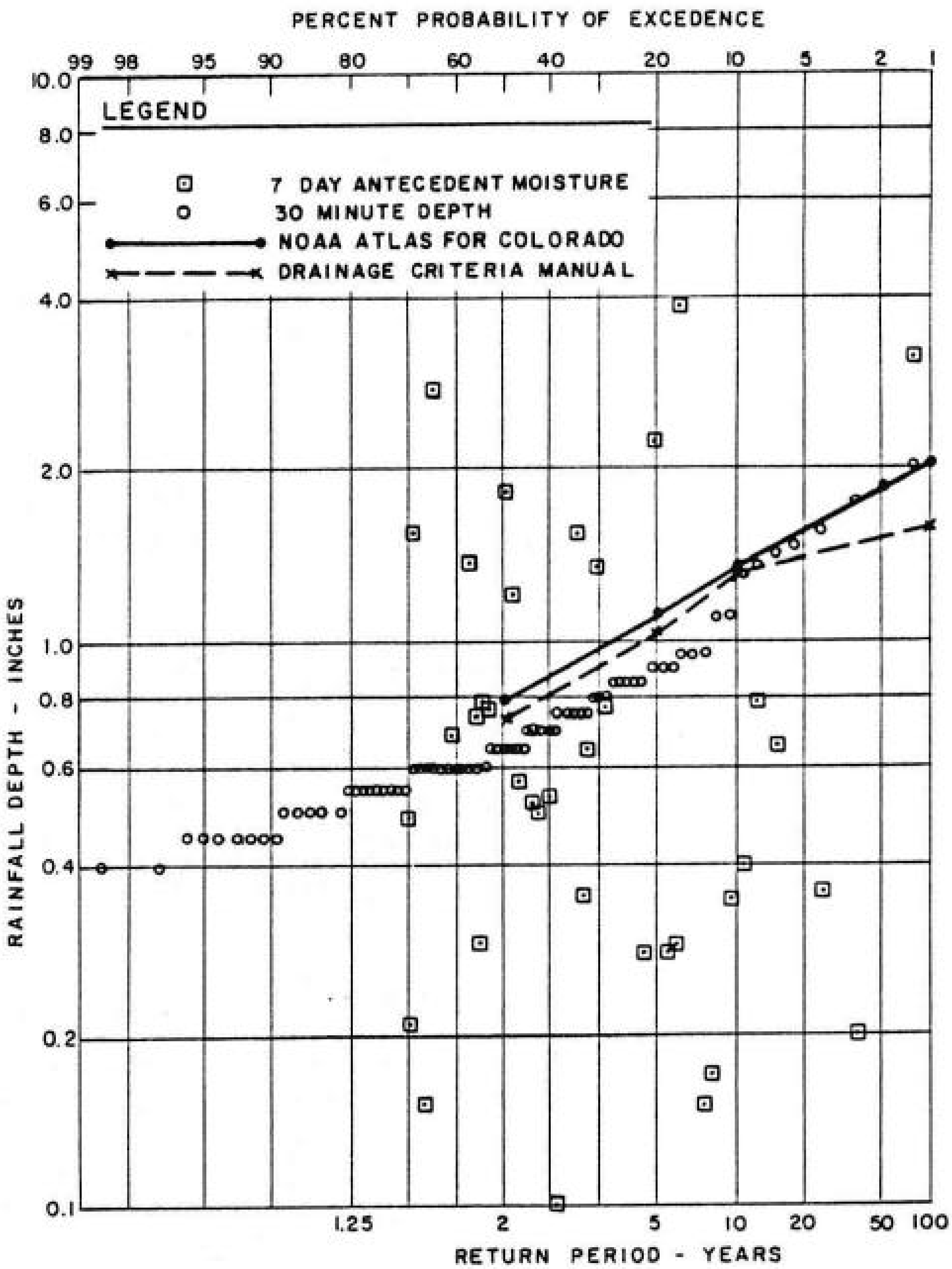

Figure 1. Probability Distribution Of 30-Minute Rainfall Depths at Denver Raingage, 1898 through 1971.

Runoff Analysis

Gauging Program

Shortly after its inception in 1969, the cooperative District and USGS rainfall-runoff data collection program set up approximately 30 gauging stations in the Denver metropolitan area. In 1977 the District started its own data analysis and interpretation effort. After a review of the data collected, approximately one-half of the gauging sites were abandoned and the data collected at these sites were dropped from the records because of problems ranging from variable catchment boundaries to flow gage rating curves that could not be defined. It is difficult to interpret field data obtained even under perfect gauging conditions and the additional difficulties associated with the interpretation of questionable data was sufficient reason to limit data acquisition and analysis to sites where problems could be identified and resolved.

Seven of the stations remaining in the data collection program have been analyzed in detail to date. Of these seven, data from four of the catchments were chosen for use in the investigation of the design storm concept. The four catchments represent a variety of urban land uses, including a mobile home park (Northglenn site), single family residential (Denver and Englewood sites), and an airport terminal. Site maps for each catchment are shown in Figures 2 through 5. Catchment Characteristics for all four are summarized in Table 1.

Table 1. Observed Characteristics of Gauged Catchments

	Area (mi2)	Length (mi.)	Slope (ft/ft)	Impervious (Percent)	Drainage System
1. Northglenn	0.56	1.17	0.034	35	Streets and Grass Channel
2. Denver	0.29	.84	0.005	40	Streets and Concrete Channel
3. Englewood	0.43	1.52	0.010	45	Streets and Pipes
4. Airport	0.15	.97	0.005	97	Large Pipes

The first three catchments were selected for this study because the stormwater runoff is not subject to detention storage routing of any kind within the catchments. There is a possibility of flow surcharge storage at the airport site during rainstorms having a recurrence interval in excess of ten years; however, none of the gauged runoff events indicated a surcharged condition. Although the simulated runoff from the airport site may not accurately reflect the true Probability for recurrence intervals greater than ten years, all four sites can be considered to indicate runoff trends from sites that have no on-site detention storage.

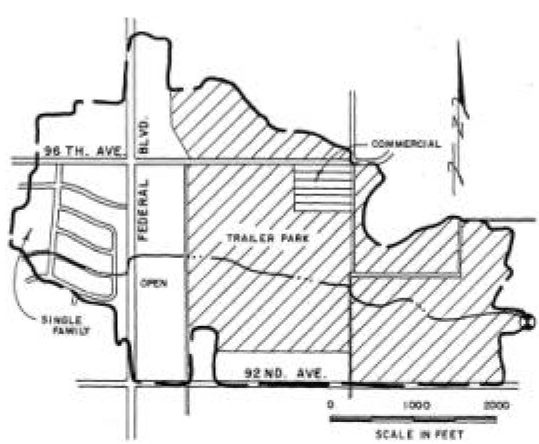

Figure 2. Map of the Northglenn Site

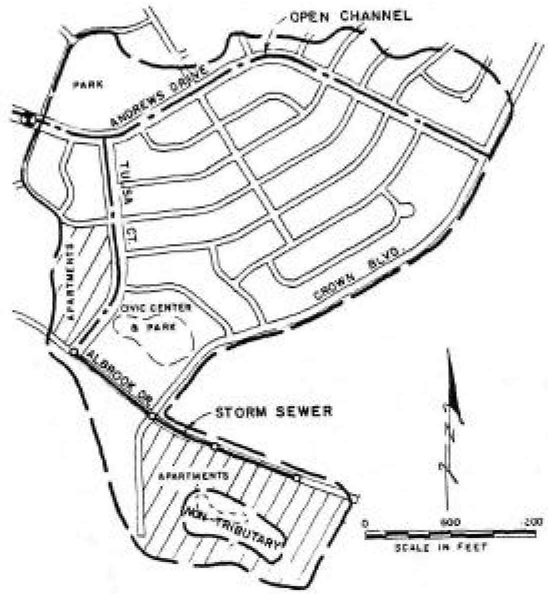

Figure 3. Map of Denver Gauging Site

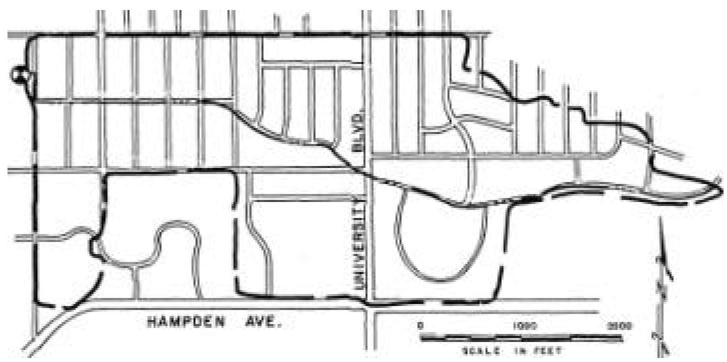

Figure 4. Map of Englewood Gauging Site

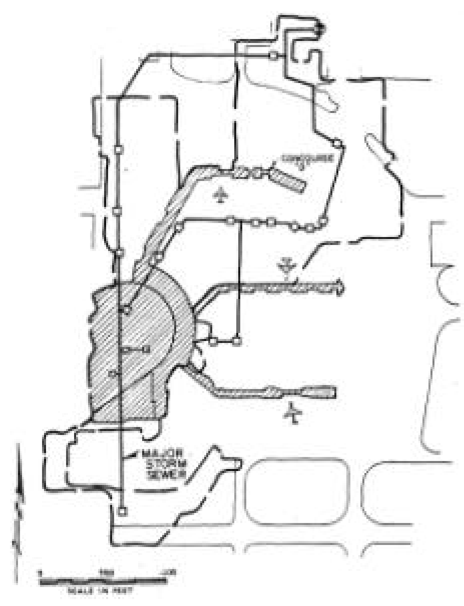

Figure 5. Map of Airport Gauging Site

Model Calibration

Runoff simulation was performed using the District's computer model calibrated for each site. The model uses a linear unit hydrograph in combination with Horton's exponential decay infiltration function.[11] This model was selected for its simplicity and low cost of operation. In addition, after it was calibrated, it reproduce the gauged runoff peaks and volumes consistently. The model was calibrated to match runoff peaks and volumes using the rainfall and runoff data recorded at each of the four gauged catchments. Two kinematic wave models were also calibrated for the Denver site, but they produced less consistent duplication of runoff peaks and were considerably more difficult to use in processing large numbers of storm events. As a result, neither kinematic wave model was used for this investigation.

Table 2 summarizes the calibrated infiltration and other rainfall losses used in the runoff simulations. The data for the four sites were analyzed in detail to gain insight into the effects of antecedent precipitation. Based on what was learned, the initial infiltration and depression storage values were adjusted for each storm to compensate for the effects of the recorded antecedent precipitation data. A comparison of the observed and simulated flow peaks at all four gauging sites is shown in Figure 6, which also demonstrates the validity of the computer model calibration.

Table 2. Calibrated Rainfall Loss Parameters

Gauging Site	Initial Infiltration (in/hr)	Final Infiltration (in/hr)	Exponential Coefficient (1/sec.)	Pervious Storage (in.)	Impervious Storage (in.)
1. Northglenn	3.00	0.50	0.0018	0.50	0.10
2. Denver	4.50	1.10	0.0007	0.40	0.10
3. Englewood	4.00	0.50	0.0018	0.40	0.10
4. Airport	3.00	0.50	0.0018	0.40	0.10

Having a calibrated computer model for each of the four gauged catchments, it was possible to simulate the runoff that would result from a series of large rainstorms recorded at the Denver rain gage. Digitized rainfall data for a 73-year period (1898-1971) at the Denver rain gage were obtained by USGS from :he National Weather Service. The 73 rainstorms having the largest recorded one-hour rainfall accumulation were selected to represent a partial duration series for the 73-year period of record. Because the digitized rainfall data was reported in 5-minute time intervals, and because the study catchments were relatively small, a 5-minute unit hydrograph was selected for use in this study.

All 73 storms were used to simulate peak stormwater runoff from the four sites. Before the long-term simulation was started, the antecedent precipitation for each of the 73 storms was quantified and initial rainfall abstractions were adjusted using the trends observed from the rainfall/runoff data at the gauged catchments. A total of 73-runoff peak flows were then simulated and analyzed using the Log Pearson Type III statistical analysis recommended by the U.S. Water Resources Council.[12] An identical statistical analysis was performed using peak flows simulated while ignoring the effects of antecedent precipitation. The resultant Log Pearson Type III distributions of the simulated peak flows vs. their recurrence period are presented in Figures 7 through 10.

Antecedent precipitation appears to have a relatively small effect in the four test catchments. It is possible that the algorithm used in correcting for antecedent precipitation underestimated its effects; however, there are other possible explanations. Denver is located in a semi-arid region of the United States and has an average annual precipitation of only 15 inches, with approximately one-half of that being rainfall. Referring to Figure 1, one can see that only ten of the 73 rainstorms shown had a 7-day antecedent rainfall that exceeded 0.8 inches. The lack of precipitation in this semi-arid region also results in the lack of antecedent precipitation and can explain why it has only a minor effect on the statistical distribution of runoff peaks.

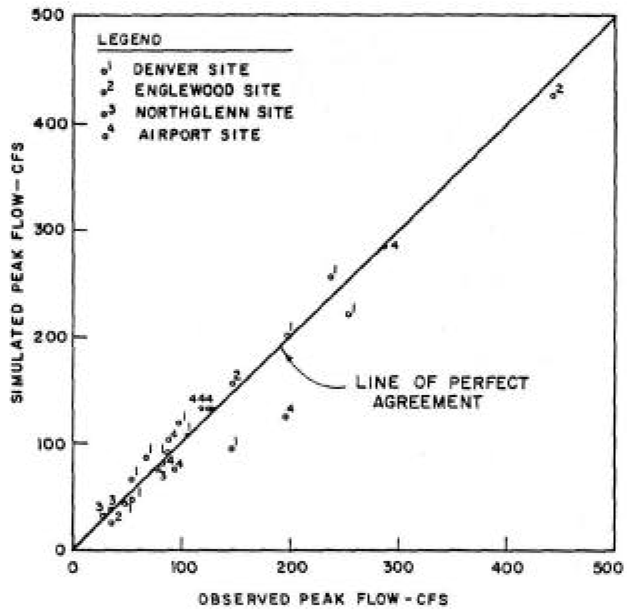

Figure 6. Comparison of Simulated and Observed Peak Flows

The District's studies also indicate that the runoff from impervious surfaces in the Denver area tends to overshadow the runoff from the pervious areas. Runoff from impervious surfaces is very quick to occur and concentrate and is primarily responsible for the peak flow on small urban catchments. At the same time, runoff from pervious areas occurs later in the storm and contributes little to the peak flow during the storms that are common to the semi-arid climate. High antecedent moisture may result in increased volumes, but it appears to have very little impact on peak flows from urbanized catchments in the Denver area and possibly in other communities located in the semi-arid regions of the country.

To illustrate the relative accuracy of the two types of design storms being used in the Denver area, the peak flows estimated using the design storms are also shown in Figures 7 through 10. These design storms were developed in accordance with the USDCM procedures and the DRCOG and NOAA published isopluvials discussed earlier. It appears that using design storms developed solely from rainfall data can result in significant variances in the peak flows when compared to the statistical distribution of simulated peaks.

The predominant trend is for the tested design storm to overestimate the peak flow. This is not surprising since the statistical analysis commonly used in the development of design storms tends to maximize rainfall depths for all time increments. However, the author believes that the temporal distribution of the design storm can also affect runoff peak calculations. When a leading or advanced type of design storm distribution is used, the largest rainfall intensities occur at the time when rainfall losses are large and the runoff is reduced. If, however, a lagging storm pattern is used, the reverse is true and runoff is increased.

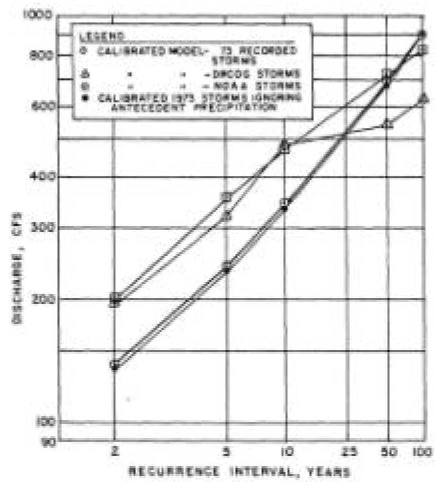

Figure 7. Peak Flow Probability Distribution for Northglenn Site

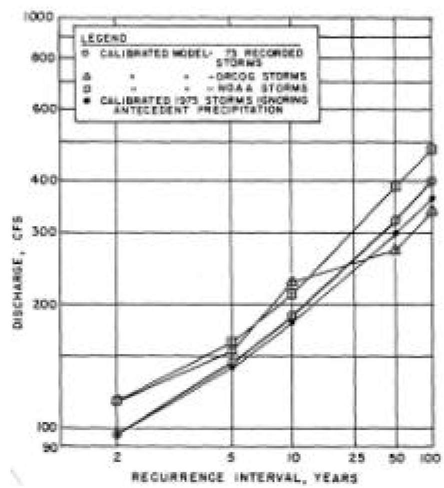

Figure 8. Peak Flow Probability Distribution for Denver Site

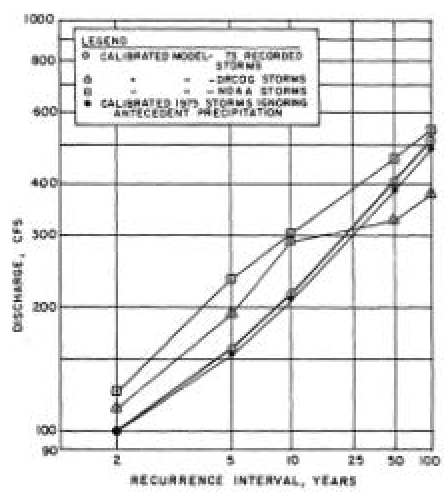

Figure 9. Peak Flow Probability Distribution for Englewood Site

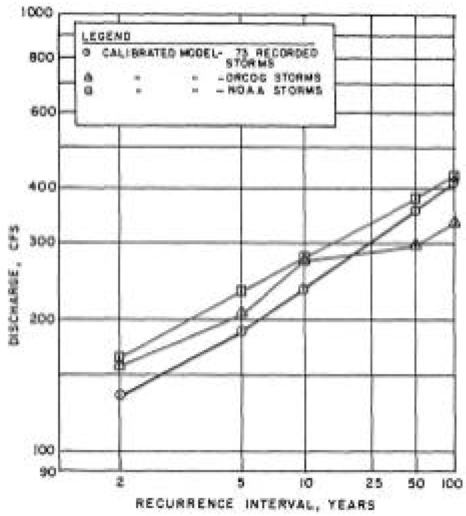

Figure 10. Peak Flow Probability Distribution for Airport Site

Because of the random nature of the temporal distribution of rainfall during rainstorms, it is naive to believe that a design storm can be developed to represent a real storm of a known recurrence interval. Design storms do not represent typical rainstorms and are a conglomeration of many storms that have occurred in the past. However, the concept of a design storm should not be abandoned just because a design storm does not represent a typically occurring rainstorm. A properly conceived design storm can still be a very valuable planning tool for use in estimating rainstorm runoff, provided its shortcomings are understood and it is used only when appropriate.

Alternatives to a Design Storm

What alternatives are there to a design storm? One obvious alternative is to perform a long term simulation using a calibrated computer model and recorded rainfall data. This approach would be similar to the one taken during the District's investigation and may be more accurate. Such an approach takes substantial expertise, time and budget. Another alternative is to identify a number of recorded rainstorms , say five to ten, as being representative of a desired recurrence event which can be used to test final design of drainage facilities. The advantages of this approach include the use of recorded rainfall data, which accounts for a number of temporal distributions found in nature, and the user is provided with the argument that an arbitrary design storm is not being used. The use of select recorded storms has disadvantages that are similar to the ones stated for the long term simulation method, without the advantages of using a complete rainfall history. Regardless of how the historic rainfall record is used, it is important to recognize that it is a historic record and is not an absolute predictor of the future.

When the planning effort has substantial potential economic impact, is regional in nature, and a high level of expertise and adequate budget can be committed, then long term simulation is justified and needs to be considered. For instance, regional non-point source water quality planning is an area where the design storm approach has very little merit. The non-homogeneous statistical characteristics of rainfall, antecedent precipitation, pollutant buildup rates, best management practices, and other phenomena, some of which are not well understood at this time, demand that a rainfall record of temporal and spatial distribution be used. Similar arguments can be made for regional flood control planning. However, when the problem shifts to smaller drainage sub-catchments and individual storm sewer or detention pond design, there is a need for simplified approaches to the problem. In such instances the design storm is state-of-the-art to many of the professionals.

Design of a Design Storm

The Urban Drainage and Flood Control District have recognized the need for a simple, straightforward, approach in urban drainage and flood control field. This need prompted the District to pursue the development of design storms that would simulate peak flows to fit the runoff probabilities. The approach required the use of readily available published rainfall information that had a broad base of acceptance. Because the NOAA Rainfall Atlas[10] was used by the State of Colorado outside the District and was exclusively in use by Federal agencies, it was selected as the base source of rainfall information. The one-hour rainfall depths for the various recurrence intervals were taken from the Atlas at the Denver Rain Gage location. A temporal rainfall distribution was then developed for each recurrence interval storm and was converted to a percentage of the NOAA Atlas one-hour rainfall depth. After several runoff simulation trials a series of temporal rainstorm distributions related to the NOAA Atlas information were found to reasonably reconstitute the peak at each recurrence interval for all four test catchments. The results can be seen by comparing the peak flows, obtained using the new design storm, against the distribution curves of the peak flows, obtained using long-term simulation. The comparisons are made in Figures 11 through 14.

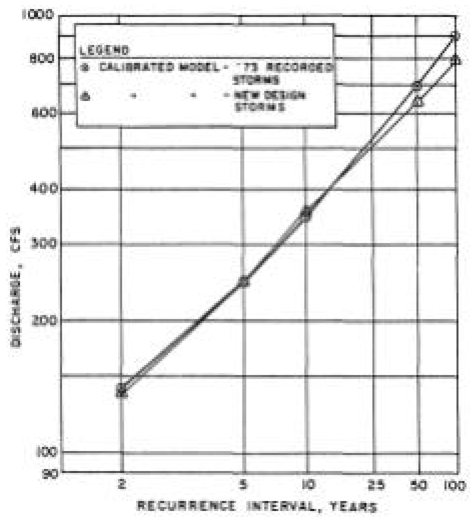

Figure 11. Peak Flow Distribution Using New Design Storms for Northglenn Site

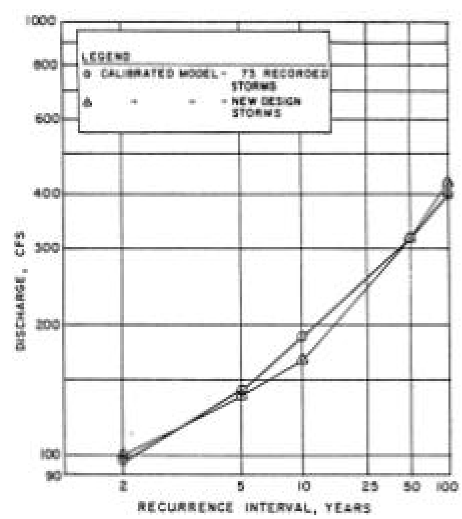

Figure 12. Peak Flow Distribution Using New Design Storms for Denver Site

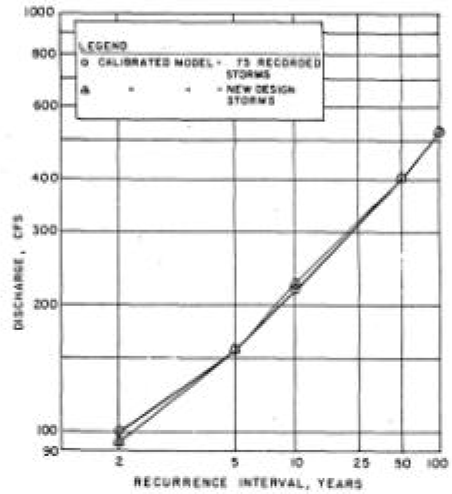

Figure 13. Peak Flow Distribution Using New Design Storms for Englewood Site

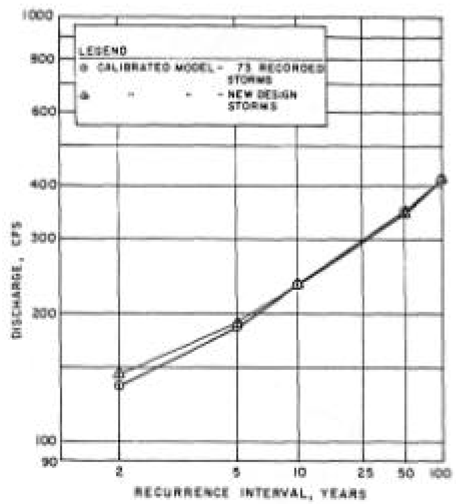

Figure 14. Peak Flow Distribution Using New Design Storms for Airport Site

The results to date look encouraging; however the District is not yet prepared to revise the USDCM. Before permanent policy revisions are made to the design procedures used in the Denver area, the new design storms will undergo further testing using other gauged catchments. The volumetric integrity of the hydrographs simulated using the new design storms also needs to be verified. Flood routing of the hydrographs obtained using the long term rainfall record will be performed using a variety of detention pond designs The routed peaks will then be statistically analyzed and compared against routed peaks obtained using the new design storms. It is hoped that the new design storms will have realistic flood routing characteristics. If they don't, it may even be necessary to develop another series of design storms for use in the design of detention storage facilities. The ultimate goal of the District is to develop design storms that will consistently result in a reasonable prediction of the peak flows and volumes for storm runoff in the Denver area. These design storms will then be available to the engineering profession for use in the design of local drainage and flood control facilities. These new design storms are not intended to be used in regional non-point water quality studies, nor professed to be the only ones to be used in regional flood control projects.

Summary and Conclusion

The Urban Drainage and Flood Control District staff is involved in a research program to develop more reliable urban stormwater runoff simulation tools. As part of this effort, the District is investigating the design storm concepts being used in the Denver area. As a result of this investigation the following observations and conclusions have been made:

1. Design storms are developed using information contained in published isopluvial maps that may not be totally consistent with the long-term rainfall data collected locally.

2. Design storms developed using published isopluvial maps result in runoff peaks that can vary significantly from the peak flows obtained through statistical analysis of long-term simulation of runoff using recorded rainfall.

3. Antecedent precipitation in the semi-arid Denver area appears to have very little effect on the probability distribution of runoff from small urban basins.

4. It is possible to develop. design storms that reasonably duplicate the peak flows from small urban basins at various recurrence intervals. However, this requires substantial rainfall/runoff data to permit calibration of computer models, long term simulation of runoff using recorded rainstorms and statistical analysis of simulated flow peaks and volumes.

5. Design storms developed using long term runoff simulation as a point of reference are useful in the planning of storm sewers, detention ponds and other flood control facilities. Recorded rainfall records that include temporal and spatial rainfall distributions need to be developed and cannot, at this time, be short cut through the use of a design storm whenever water quality studies are performed and/or stormwater management operational systems are designed. The use of design storms for these purposes fails to recognize the non-homogeneous statistical distribution of a large number of variables affecting the results.

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