Chapter 12

Design Storm Events for Urban Drainage Based on Historical Rainfall Data: A Conceptual Framework for a Logical Approach

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Almost twenty-five years after the first generation computer models were made available in the 1970s, we have to recognize that the question of the appropriate rainfall data to use for standard urban drainage design is still unresolved in a completely satisfactory manner. The first attempts to derive a design storm and specific synthetic time distributions were inevitably based on the intensity-duration-frequency (IDF) curves, which are used with the rational method, e.g. the Chicago design storm (Keifer and Chu, 1957). Recognizing the limitations of this approach, many researchers at the end of the 1970s and beginning of the 1980s proposed different alternatives based on a more realistic analysis of the rainfall data (Pilgrim and Cordery, 1975; Walesh et al., 1979; Hogg, 1981; Hogg, 1982); these approaches were not however used widely as they implied tedious calculations and expensive computer time. Practitioners therefore continued using synthetic design storms, as they provided a simple and apparently appropriate tool for routine designs.

The basic argument developed here is that with the powerful micro-computers available today, the costs and complexity of a more thorough analysis are no longer an argument for simplistic design storms applied uniformly for any type of design problems. A methodology is therefore proposed to define a series of design storm events using actual rainfall data and computer simulations. The analysis has a definite practical orientation in order to obtain a set of design storms

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that can be used in different design situations, specifically for new urban developments and considering only the quantitative aspects. The important parameters taken into account are the duration of the rainfall event, the land use and whether there is retention or not.

After a brief examination of the design storm concept with an historical perspective, the proposed conceptual framework is given and discussed. A case study for the Montréal metropolitan area is presented, based on actual rainfall data for the Dorval International Airport in Montréal. Comparison with synthetic design storms commonly used in the area is provided.

12.1 Design Storm Concept: Historical Perspective

Several summaries of synthetic design storm characteristics are available in the literature (Cao, 1993; Marsalek and Watt, 1984; Wenzel, 1982). Basically, the design storms that are still commonly used in practical applications are based on two distinct approaches. In the first case, which is also chronologically the older approach, the total rainfall volume for the event is simply taken from IDF curves and a somewhat arbitrary temporal distribution is thereafter used to obtain the design storm. Probably the most common example for this type of approach is the Chicago design storm (Keifer and Chu, 1957). This design storm and others in that category have been popular mainly because they are very easily constructed, appear to give conservative results and can be standardized for regulatory purposes. The important drawbacks of this approach have been highlighted for many years (McPherson, 1978). The most significant ones are that usually the total rainfall depth is chosen for an arbitrary duration (usually specified by the regulatory agency), that the IDF curves are used to derive the depth of rainfall and, more importantly, that the true return period of predicted peak flows and volumes is unknown.

The other approach which has been proposed is to derive the temporal distribution from an analysis of actual rainfall data for specific storm events. One of the first researchers to use this approach specifically was Huff (1967), who presented such an analysis for 261 storms in Illinois. Huff considered duration as a percentage of total storm duration and classified the storms into four groups depending on whether the heaviest rainfall occurred in the first, second, third or fourth quarter of the storm period. Pilgrim and Cordery (1975) have also attempted to develop average or *typical* temporal distributions of severe rainstorms; they also give a good summary of previous approaches. Finally, for Canadian conditions, Hogg (1980, 1982) has studied the variability of the time distribution of rainfall in various parts of the country for 1 and 12 hour durations. These durations were selected to provide samples of both convective shower events and synoptic scale cyclonic circulation events. The distributions were

plotted for 35 stations across Canada in cumulative form for various probability percentiles.

Each of these two approaches to derive design storm events has significant drawbacks that can affect to some extent the credibility of the associated computer modeling. The major shortcomings of these approaches have been summarized in many publications (Walesh, 1979; James and Robinson, 1982; McPherson, 1978):

1. It is usually assumed that the recurrence interval of the design storm is the same as the calculated discharge or volume produced with the storm. This is not true because the initial conditions, essentially the soil moisture and the potential surface loss rates, are not known or taken into account. Intuitively, however, it can be argued that the impact of not considering the antecedent conditions will not be very important for surfaces with high percentages of imperviousness.
2. Synthetic storms based on IDF curves are derived with data from many different storms of all types, from thunderstorms to cyclonic rains.
3. As usually a fixed duration is specified, synthetic design storms are simply not appropriate for determination of volumes of specified recurrence interval.
4. The characteristics of the design storms are often not varied for different types of analysis: the same design storm is for example used to determine the peak discharges for the pre-development conditions, the peak discharges for the post-development conditions and the volume of the retention basin needed to meet the regulatory constraints. As noted by Adams et al. (1986), different elements of the drainage system are sensitive to different characteristics of a rainfall event. This suggests that a better approach would be to have a set of design storms which could be applied specifically for different design situations.

Many alternatives to synthetic design storms have been proposed (Walesh, 1979). One of the most appealing approaches, apart from a complete continuous simulation, is the use of a series of important historic storms as input to an event model, followed by discharge-probability and/or volume-probability analyses of the model output. This approach eliminates many of the identified shortcomings of synthetic design storms by considering the total storm system, including the antecedent conditions. It therefore provides a meaningful frequency analysis on the runoff parameters of interest - peak flow, runoff volume or retained volume - instead of trying to produce a typical storm time distribution whose recurrence interval is obscurely related to the recurrence intervals of the parameters of interest. Although this concept was proposed more than 15 years ago, its application so far has been difficult and tedious mainly because of the inadequacies of the computational tools. This is no longer the case today with the

widespread availability of powerful micro-computers and adequate programs to extract and analyze rainfall data provided directly at a minimal cost by the governmental agencies.

12.2 Proposed Conceptual Framework

12.2.1 Categorization of Design Problems for Urban Drainage

If we exclude the problems involving pollution control and combined sewer overflows (CSOs), the design problems encountered in standard stormwater management practice can be first classified according to the fundamental parameters involved in the design. Apart from the obvious peak discharges and runoff volumes, an important distinction has to be made for the volume determination with a controlled outflow, i.e. with the very common case where a retention basin has to be designed. Taking into account this controlled outflow will obviously have an impact on the design storm selection, as will be demonstrated with the case study in a subsequent section. Finally, it is worth noting that only the quantitative aspects are considered here and that the categorization can be applied both to new developments or existing ones where the runoff volumes or discharges have to be controlled.

Another aspect to be considered is the duration of the rainfall design event, which should be somewhat related to the time of response of the basin analyzed. This is often realized in standard practice when the Chicago design storm is used for urban areas and the SCS (USDA Soil Conservation Service) design storm, with a duration of 6 or 24 hours, is used to define the pre-development conditions, i.e. for a rural basin. As indicated in Figure 12.1, the different types of basins can be classified as urban or rural and according to the duration of rainfall that will be most critical in each case. We can therefore define a spectrum of durations

Figure 12.1 Classification of basins according to the critical rainfall duration.

which should cover most typical engineering problems for urban drainage: at one end of the spectrum, standard urban basins with a time of response generally less than 1 hour and, at the other end, large rural basins that respond very slowly to the rainfall input and where the rainfall losses due to initial abstractions and infiltration can be very important in evaluating the runoff parameters.

Finally, one last aspect that is important for an appropriate design storm selection is the land use being considered, the essential parameter for the different land use definition being the degree of imperviousness. In the present analysis, four different land uses were identified: the undeveloped conditions (which in the Montréal area usually means a pasture or range land), a residential development with 40% imperviousness (suburban), a multi-residential development with 65% imperviousness and a commercial or industrial development with 85% or more imperviousness.

In summary, the design storm definition from actual historic rainfall data should therefore be based on the *parameters involved* (peak discharges, total runoff volume or volume with controlled outflow), the *rainfall duration* (which should be related to the basin dimensions and its time of response) and the *type of land uses* considered. The following section will describe a methodology to define a series of design storm events by taking into account these three aspects.

12.2.2 Methodology for Design Storm Events Definition

Logically, the selection of appropriate design storm events for typical urban drainage problems should therefore be made by considering the specific runoff parameters governing the design problem. Very simply, depending on the elements of the drainage system being analyzed, three different parameters can be important:

- the peak discharges;
- the total runoff volume;
- the runoff volume to be contained by a retention basin, i.e. with a controlled outlet.

The peak discharges are mostly important to establish the dimensions of the transport elements, i.e. the pipes of the minor system and the elements of the major system (roads and major channels). As far as the runoff volumes are concerned, it is often more appropriate in a stormwater management context to consider the probability of occurrence of the volume detained in a retention basin as opposed to the total runoff volume; the two frequency distributions will obviously be different as the controlled outlet will alter the distribution.

In order to obtain the frequency distributions for the three parameters, the simple steps involved in the methodology are the following:

1. Screen the hourly rainfall data with a model like the RAIN block of the SWMM model;

2. Based on this preliminary screening, select from the hourly data the rainfall events that appear to be significant, taking into account the different land uses and the durations;
3. Run an appropriate model with the selected rainfall events;
4. Complete a statistical analysis considering the annual maxima for the peak discharges, the total runoff volumes and the runoff volume with controlled outlet.

Usually, in fairly large metropolitan areas, hourly rainfall data will be available for periods generally exceeding 20 years. The methodology presented above should therefore be statistically adequate to define the runoff parameters for the usual return periods associated with design of the minor system, i.e. 1 in 5 or 10 years. For the major system, where the return periods considered are 1 in 50 or 100 years, some sort of typical time distribution combined with the total volume obtained from the statistical analysis will be needed, i.e. a technique similar to the approaches proposed by Huff (1967) or Hogg (1980, 1982).

12.3 A Case Study: Design Storm Events for the Montréal Metropolitan Area

The proposed methodology was applied to the rainfall data available at the Dorval International Airport in Montréal. The hourly rainfall data were first obtained directly from Environment Canada on computer diskettes for the period from 1943 to 1992. The raw data were then analyzed with the block RAIN of the SWMM model, using a minimum inter-event time of three hours. This analysis provided the characteristics of 5936 rainfall events for the 50 year period. These characteristics were then used to select the rainfall events that would be used in the simulations.

12.3.1 Design Storm Events for Pre-development Conditions

As a general rule, runoff processes for the pre-development conditions should be more sensitive to infiltration and initial abstractions than for densely urbanized surfaces. Accordingly, and contrary to the urban basins where short duration and high rainfall intensity are more important, the design rainfall events for this case will most likely be cyclonic circulation events characterized by longer durations and significant average intensity that will help to saturate the soil. The time step used to discretize the rainfall events was one hour (i.e. as obtained directly from AES (Atmospheric Environment Service of Environment Canada)) and a total of 107 events were retained in the first place from the preliminary screening, as some years had multiple rainfall events which appeared at first glance to be important. The characteristics that were used to identify the

events were the total rainfall volume, the maximum rainfall intensity on a one-hour duration and the total duration (which had to be between 6 and 24 hours). Computer simulations with the model OTTHYMO (Wisner et al., 1989) subsequently permitted the selection of one event for each year for each of the runoff parameters (peak discharges and total runoff volumes).

Figure 12.2 presents the results of the frequency analyses with a Weibull plotting position ($m/(n+1)$), both for the peak discharges and the total runoff volumes. The simulations were actually completed for four different rural basins (24 ha, 59 ha, 117 ha and 4298 ha), in order to get a large spectrum of physical characteristics; the results shown on Figure 12.2 are for the basin of 59 ha. Two series of simulations were completed for each basin: one set is for the rainfall events without considering the antecedent conditions and the other is for the rainfall events considering the antecedent precipitation 2 days before the actual events. These antecedent moisture conditions were found to be important for 21 rainfall events. In many cases, taking into consideration the antecedent conditions effectively produced significant increase in both discharge and volume, thereby altering the frequency distributions. The results shown on Figure 12.2 consider the antecedent conditions.

Figure 12.2 Statistical analysis for pre-development conditions (59 ha basin).

Figure 12.3 Mass curves for rainfall events having produced the higher discharge in each year, long durations (for pre-development conditions).

Figure 12.4 Mass curves for the most critical rainfall events, long durations (for pre-development conditions).

A log-Pearson type 3 distribution was also applied to the runoff volumes to obtain a total volume for a return period of 1 in 100 years. As for the typical time distribution, Figure 12.3 shows the 49 major rainfall events in a non-dimensional form. As could be expected, and similarly to the findings of Pilgrim and Corderey (1975), appreciable scatter was found. If we consider however the 12 events having produced the highest discharges, we obtained the results shown on Figure 12.4, where the 5 rainfalls having produced the most important discharges are highlighted (in descending order, the years 1963, 1952, 1975, 1959 and 1987). The results somewhat confirm what could have been deduced intuitively: the time distributions having produced the highest discharges were characterized by a slow beginning permitting the saturation of the soil, followed by a rather steep increase. The extreme time distribution for the rainfall event in 1963, combined with the runoff volume for the 1 in 100 years provided by the frequency analysis, could therefore be used to derive design events for different appropriate durations (6, 12 and 24 hours).

12.3.2 Design Storm Events for Urbanized Basins

For urban basins, the rainfall events with the highest hourly rainfall intensity were first selected from the screening analysis as this parameter is arguably the most significant in this case. Once these intense rainfall events were identified, the charts were ordered directly from AES and the events were discretized with a 5-minute time step. This provided a sample of 46 years, as certain charts from specific years were missing.

Figure 12.5 presents the results of the frequency analyses for a parking lot of 1.5 ha, thereby representing a typical project for a commercial or an industrial development (imperviousness of 85% or more). Regarding the volume with outlet controlled, the case given in the figure is that of a retention in a parking lot with a device installed in a catchbasin to limit the discharge at 20 l/s. For that particular application, the outlet discharge can be considered to be approximately constant because it does not vary appreciably with the head created by the detention. A different curve would obviously be obtained for an outlet with the outlet discharge varying with the depth of retention (e.g. a pond with outflow controlled by a culvert or an orifice).

In order to define the events for a return period of 1 in 100 years, a non-dimensional plot was completed for the selected rainfall events. As shown in Figure 12.6, it can be seen that the scatter is still important. A design event with a return period of 1 in 100 years could however be derived with the runoff volume obtained from the frequency analysis and the extreme time distributions having produced the highest discharges, which are shown in Figure 12.7.

Figure 12.5 Statistical analysis for commercial or industrial lot (1.5 ha 100% impervious).

12.4 Comparison with Synthetic Design Storms

In order to compare the runoff parameters obtained with synthetic design storms currently in use in the Montréal metropolitan area, simulations were also completed with the Chicago design storm (3 hours duration and 10 minutes time step), the AES design storm with a duration of 1 hour, as defined by Hogg (1982) for the southern part of the Province of Quebec and the SCS type II design storm (24 hours duration) for the rural basins only. The results for the synthetic design storms were included in Figures 12.2 (rural basins) and Figure 12.5 (industrial or commercial basins). It should be pointed out that the Chicago design storm used has been modified so that the maximum rainfall intensity corresponds to a 15 minute duration. The design storm used in this comparison is therefore not the same as the design storm which would have been derived by the standard methodology given by Keifer and Chu (1957).

Figure 12.6 Mass curves for rainfall events having produced the higher discharge in each year, short durations (for industrial or commercial development).

Figure 12.7 Mass curves for most critical rainfall events, short durations (for commercial or industrial development).

If we first consider the results on Figure 12.2 for the pre-development conditions, it can be concluded that the SCS design storm produces conservative results for the discharges, being 49 % and 11 % higher for the 1/2 year and 1/10 year return periods respectively. On the other hand, if we consider the runoff volumes, the SCS design storm gives volumes that are similar to the volumes obtained with the historical series.

For the commercial or industrial lots, the results on Figure 12.5 indicate that the discharges and the runoff volume, both with the AES and the Chicago design storms, are underestimated as compared with the historical series. The underestimation is more important for the computed runoff volumes. Interestingly, the volumes with a controlled outlet are rather well estimated with the 3 hour Chicago design storm.

It should be pointed out that the results obtained for the Montréal area will not necessarily be the same for a different region. For example in an analysis for a 903 ha basin in Tallahassee, Florida, Huber (1993) found that the greatest predicted peak at high return periods (about 22-25 years) is, for a historic storm event, found from a continuous simulation. The results presented here should not therefore be generalized to any region.

12.5 Conclusions

Synthetic design storms will still be used for some years to come in practice, especially for areas where the detailed rainfall data is lacking or entirely missing. The results presented in this study indicate that, at least for the discharges, the computed values are conservative; for problems involving runoff volumes, however, the approach described here with historical data is believed preferable and more appropriate. It should be pointed out that the analysis has to be completed only once and that the selected design events can be used systematically for all subsequent designs, exactly like synthetic design storms. Use of historical data can certainly add credibility to the whole design process as many drawbacks identified with the synthetic design storms, like the consideration of antecedent moisture conditions, the relation between the return periods of the rainfall events and the runoff parameters and the fixed duration, are no longer a problem with the proposed approach.

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