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Generation of Synthetic Design Storms for the Upper Thames River Basin CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Condition

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CFCAS project:
Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions

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I. INTRODUCTION

The purpose of this report is to summarize methods available in the literature that synthetically generate rainfall hyetographs (plots of rainfall intensity vs. time). The outputs of selected methods are to be used as inputs to a hydrological model of the Upper Thames River basin, to be used for determination of hydrologic risks and extremes.

The hydrological model used in this study has been constructed via Hydrological Engineering Center's Hydrological Modelling System (HEC-HMS), and is described in detail by Cunderlik and Simonovic (2004). It should be noted that two HEC-HMS models have been constructed for the Upper Thames River basin - event based and a continuous model. The former variant involves simulating rainfall-runoff processes for single storm events; the latter on the other hand, involves simulation of processes with longer time scales, which entail analysis of precipitation runoff sequences over several years. An event model is therefore more simple than a continuous model, as detailed processes such as soil moisture accounting, subsurface flow and evapotranspiration need not be included. The continuous model, because of its longer time scale, needs to take into consideration all of the above mentioned processes. It is noted that the present work deals only with specification of rainfall events not exceeding duration of 24 hrs, and thus uses the event based variant of the HEC-HMS model of the basin.

I.1 Design Storm Hyetographs

Oftentimes problems in hydrological modelling require specification of design storms or rainfall hyetographs. Design storms act as inputs to hydrological models,

while the resulting flows and flow rates of the system are calculated using rainfall-runoff and flow routing procedures (Chow et al. 1988). There exist a variety of ways to define design storms. Some of them are based on a depth of precipitation at a point, on specification of time distribution of rainfall, or on isohyetal maps indicating regional spatial distribution of precipitation. Hyetographs can be constructed from local historical patterns of precipitation, or via synthetic methods able to capture rainfall features of a particular locality. An excellent background on this topic is given by Chow et al. (1988), Chapter 14.

A variety of methods able to generate design storm hyetographs exist in the literature. Veneziano and Villani (1999) suggest that most methods can be classified into one of the following categories:

1. Specification of simple geometrical shapes anchored to a single point of the intensity duration frequency (IDF) curve;
2. Use of the entire IDF curve;
3. Use of standardized profiles obtained directly from rainfall records, and
4. Simulation from stochastic models.

In what follows, a detailed account is given concerning first three categories of design storm hyetographs. Details of two methods in each of the three categories are presented, as well as their outputs. (Methods of category four, for use in the Upper Thames River basin, are described by Burn and Sharif (2004) and are thus not dealt with here.) Comparison of the above noted methods are presented, together with their advantages and disadvantages. A final recommendation is made regarding which of the

above method(s) should be used in conjunction with the event based model for assessment of hydrologic risk and extremes in the basin.

I.1.1 Hyetographs based on a single point on the IDF curve

Methods in this category generate rainfall based on a single point of the IDF curve, such as one shown in Table I-1 describing intensity duration frequency values for MTO (1997) District 2, used for basins East of London. In the most traditional sense return period, T, and storm duration, t_d, are specified, and an average value of rainfall intensity is obtained from the IDF curve. Oftentimes rectangular hyetographs are used, where the average intensity is used throughout the storm duration. This procedure is frequently used in combination of the rational method for design of flood protection measures. However, this method has been found to underestimate the total precipitation volume of rainfall events Veneziano and Villani (1999), and as a result alternate geometric forms are often used. Two such forms are considered in this project---triangular hyetographs of Yen and Chow (1980) and linear/exponential hyetographs of Watt et al. (1986). According to Veneziano and Villani (1999), methods of this type are simple, intuitive and easy to construct, but on the other hand, “do not have a strong conceptual basis and may produce biased flow estimates” (p.2726).

Table 1 Intensity-Duration-Frequency values for London

	Return period, T					
Duration	$T = 2$ yr	5 yr	10 yr	25 yr	50 yr	100 yr
t_d (min)	i (mm/hr)	i (mm/hr)	i (mm/hr)	i (mm/hr)	i (mm/hr)	i (mm/hr)
5	100	135	155	185	205	230
10	73	100	120	140	160	175
15	60	76	88	100	110	120
30	39	51	59	69	77	84
50	24	32	37	44	48	53
120	12	17	20	24	27	29
360	6.2	8.4	9.9	12	13	14
720	3.7	4.9	5.7	6.6	7.4	8.1
1440	2.1	2.7	3.1	3.7	4.0	4.4

I.1.2 Hyetographs based on an entire IDF curve

As an alternative of using a single point on an IDF curve, methods have been proposed that use the entire set of duration-intensity values for a particular frequency. Methods of this kind investigated in this project are those of Keifer and Chu (1957), known as the Chicago method, and USACE (2000), referred to as the Frequency Based Hypothetical Storm. It is noted that the Ministry of Transportation of Ontario suggests that method of Keifer and Chu (1957) be used as one of the methods for urban storm design (MTO, 1997).

As these methods are based entirely on the IDF curve values for a particular locality, they suffer the same drawback as the IDF curves themselves. As Bedient and Huber (2002) point out:

"A critical characteristics of IDF curves is that the intensities are indeed averages over the specified duration and *do not represent actual time histories of rainfall*. The contour for a given return period could represent the smoothed results of several different storms. Moreover, the duration is not the actual length of a storm; rather, it is

merely a 20-min period, say, within a longer storm of any duration, during which the average intensity happened to be the specified value (p.386, emphasis in original)".

I.1.3 Use of standardized profiles obtained directly from rainfall records

Standardized profiles, also known as mass curves, transform a precipitation event to a dimensionless curve with cumulative fraction of storm time on the horizontal, and cumulative fraction of total precipitation on the vertical axis. Veneziano and Villani (1999) remind us that rainfall records are highly variable because of the uncertainty of what actually constitutes a rainfall event, as well as because of the randomness of the rainfall phenomena itself. Because of this, standardized profiles must use some sort of temporal smoothing, or ensemble averaging (after Veneziano and Villani, 1999, p.2726).

Use of standardized rainfall profiles are quite common in the hydrology literature. Some of the most popular methods are those of Huff (1967) and SCS (1986), both of which are employed in this study. Figure I-1 shows Huff (1967) distribution, including all four of its quartiles. Specifying a particular quartile implies choosing the quartile the storm produces a peak. In other words, choosing quartile I implies the peak will occur in the first quarter of the storm, choosing quartile II means the peak will occur in the second, and so on. Mass distributions for the method of SCS (1986) are shown in Figure I-2 for rainfall durations of 6, 12 and 24 hr.

The main appeal of this category of methods of design storm hyetographs is that the resulting output is based on the actual data of intense regional precipitation. Furthermore, as the methods do not rely on IDF data, precipitation exceeding return period of 100 yrs can easily be used. This is a chief advantage, especially when evaluating hydrologic extremes and risks of the basin. The main weakness of the

methods is that large sample sets of data are required for construction of regional profiles. As was mentioned earlier, due to a large number of uncertainties (i.e., what defines a storm, physical variability of rainfall), temporal smoothing (or other averaging) needs to be performed. This might miss some of the important features of rainfall at the locality of interest.

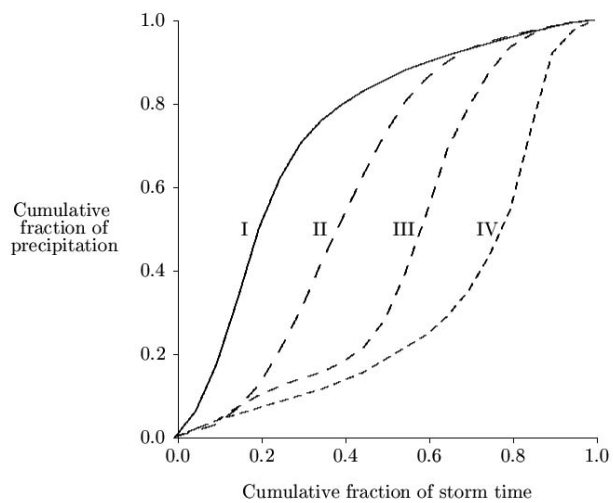

Figure I-1 Huff (1967) Mass distribution curves

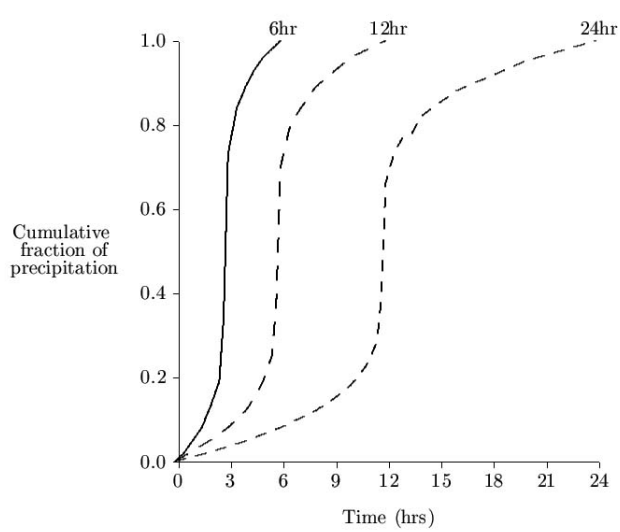

Figure I-2 SCS (1986) Type II mass distribution curves

II. DESIGN STORM HYETOGRAPHS USED IN THIS REPORT

This subsection presents details of six design storm hyetographs used in this work—two methods in each of the first three categories outlined above. For the sake of brevity, equations used to describe each method are not given, but rather a description of input parameters for each method is discussed. By performing such a discussion we can expose limitation and benefits of each method, as well as assess its flexibility and robustness. It is noted that a paper by Marsalek and Watt (1984) present a table of basic characteristics of design storms—which is used heavily in the following sections of this report.

Sample calculations for each method are based on the following design storm characteristics:

- Design return period T yrs;
- Storm duration t_d, hrs;
- Average intensity i, mm/hr;
- Ratio of time of storm peak to storm duration r=0.38, from MTO (1997);

II.1 Method of Yen and Chow (1980)

Originally developed for use in design of small drainage structures, the method because of its simplicity, has seen use in other applications as well. The basic parameters needed for its use are:

- Design return period, T, storm duration, t_d,, and its average intensity, i (all obtained from the IDF curve);

- Parameter r, a ratio of storm peak to storm duration.

It is important to note that there is no restrictions on what the recommended storm duration should be when using this method; as we will see, not all design storm methods share this feature. The authors of the method however, only use storm durations of up to 6 hrs.

The triangular hyetograph is used for the distribution of the rainfall intensities. Total rainfall depth, P, is obtained by multiplying storm duration, t_d, with the average intensity, i. The base of the triangle is chosen as the time of duration, t_d,, while its height, i_p, is adjusted so that the total depth of precipitation is equal to an area under the hyetograph (i.e., $P = 0.5\, t_d,\, i_p$,).

Three points on the triangular hyetograph are therefore constructed, in notation $(t,\ i)$: (0,0), $(t_p,\ i_p)$, $(t_d,,\ 0)$. Using values of above specified design storm parameters, the plot of the hyetograph of this method is shown in Figure II-1.

II.2 Method of Watt et al. (1986)

This method has been developed specifically with Canadian data, for 1-hr urban design design storms, although other storm durations are certainly possible. The hyetograph is described by a linear increase up to the point of t_p, then followed by an exponential decay function from t_p to t_d, for early peaking storms, and an exponential increase up to the point t_p, followed by a linear decrease from t_p to t_d for late peaking storms. The two of its parameters have been evaluated for 45 stations across Canada, and are thus readily available. The parameters needed for its use are:

- Design return period, T, storm duration, t_d,, and its average intensity, i (all obtained from the IDF curve);

- Total depth of rainfall, *D*;
- Parameter *r*, a ratio of time to storm peak to storm duration;
- A decay parameter *k* for use in Ontario (Watt et al., 1986, p.298).

The plot of both early peaking (solid line) and late peaking storms (dashed line) are given in Figure II-1.

II.3 Method of Keifer and Chu (1957)

Developed back in 1957, the method has been extensively applied in the hydrology literature. Its intended application are the sizing of sewers with a storm duration of 3 hrs, although there is nothing in the method to limit it to only these applications. Its parameters are:

- Design return period, *T*, storm duration, t_d, , and intensities, *i*, for all given storm duration of an IDF curve;
- Parameters *A*, *B* and *C*, obtained by fitting an IDF curve for a given frequency;
- Parameter *r*, a ratio of time to storm peak to storm duration;

The method provides equations for calculating peak intensity, and then redistributes the rainfall before and after the peak with appropriate equations. The plot of the hyetograph based on the above parameters for London is shown in Figure II-1.

II.4 Method of USACE (2000)

The frequency based hypothetical storm method of USACE (2000) is embedded into the HEC-HMS modelling platform, and thus has seen much use in recent times. It

has been designed to create a balanced synthetic storm with a known exceedence probability. The required input parameters are:

- Rainfall depth-duration data (can be obtained by manipulating IDF curves);
- Design return period, T, and storm duration, t_d, (anywhere from 1 hr to 10 days);
- Duration of the maximum intensity (anywhere from 15 min to 6 hrs);
- Peak center (25%, 33%, 50%, 67% and 75%)
- Storm area (or the total drainage area, so that an areal reduction factor can be applied to basins greater than 25 km^2).

The method gives the user most flexibility, and especially since it already embedded into the HEC-HMS modelling platform, it is bound to see much use. A sample hyetograph produced with this method for London is given in Figure II-1.

II.5 Method of SCS (1986)

The Soil Conservation Service hypothetical storm method uses standardized rainfall intensities arranged to maximize the peak runoff at a given storm depth. Its primary application has been in the design of small dams, but it has been applied in many rural and urban basins throughout the years. The storm duration parameter is recommended to be in the range between 1-24 hrs; it should be noted that distributions for longer durations are not available. The required input parameters are:

- Distribution type (one of four types, depending on the locality of interest, type II for Ontario);
- Total storm depth; D

The method gives the user flexibility of choosing rainfall depths freely, even rainfall depths exceeding return periods of 100 yrs. However, limited availability of storm durations (1-24 hrs) put constraints on the method that are not present in other methods. Nevertheless, its resulting hyetograph for London is shown in Figure II-1.

II.6 Method of Huff (1967)

The method of Huff (1967) has features similar to the SCS method, except that it gives the user more flexibility—restrictions are not placed on storm durations. The method was developed by considering heavy storms in the mid-western US, ranging up to 400 square miles in size. The total number of storms considered was 291, with durations ranging from 3 to 48 hrs. The derived distributions are grouped according to the quartiles in which the rainfall is heaviest. As described earlier, the quartiles describe when time of peak intensity occurred in a given storm (i.e., in the first, second, third or fourth). The required input parameters are:

- Quantile distribution (I, II, III or IV);
- Storm duration, t_d,
- Total storm depth, D;

It is interesting to note that Hogg (1980) applies this approach to 35 different locations across Canada, and derives standardized rainfall profiles from data of actual 1-hr and 12-hr storms. It is worth noting that most of the derived profiles do not significantly differ from those produced by Huff (1967). Furthermore, Bonta and Rao (1988) in their comparison of design storm hyetographs make the following conclusion:

"Huff curves exhibited a high degree of flexibility, their temporal distributions were developed according to objective criteria, and they better approximated naturally occurring temporal variability of storm rainfall due to their multiple-peaked nature (p.106)."

However, the Huff curves, just as all standardized profile distributions suffer the same drawback—that uncertainties about definitions of rainfall events, as well as physical variability of rainfall phenomena, require use of temporal smoothing, which may sometimes miss relevant peaks or other features. Its hyetographs for London (for all four quantiles) are shown in Figure II-1.

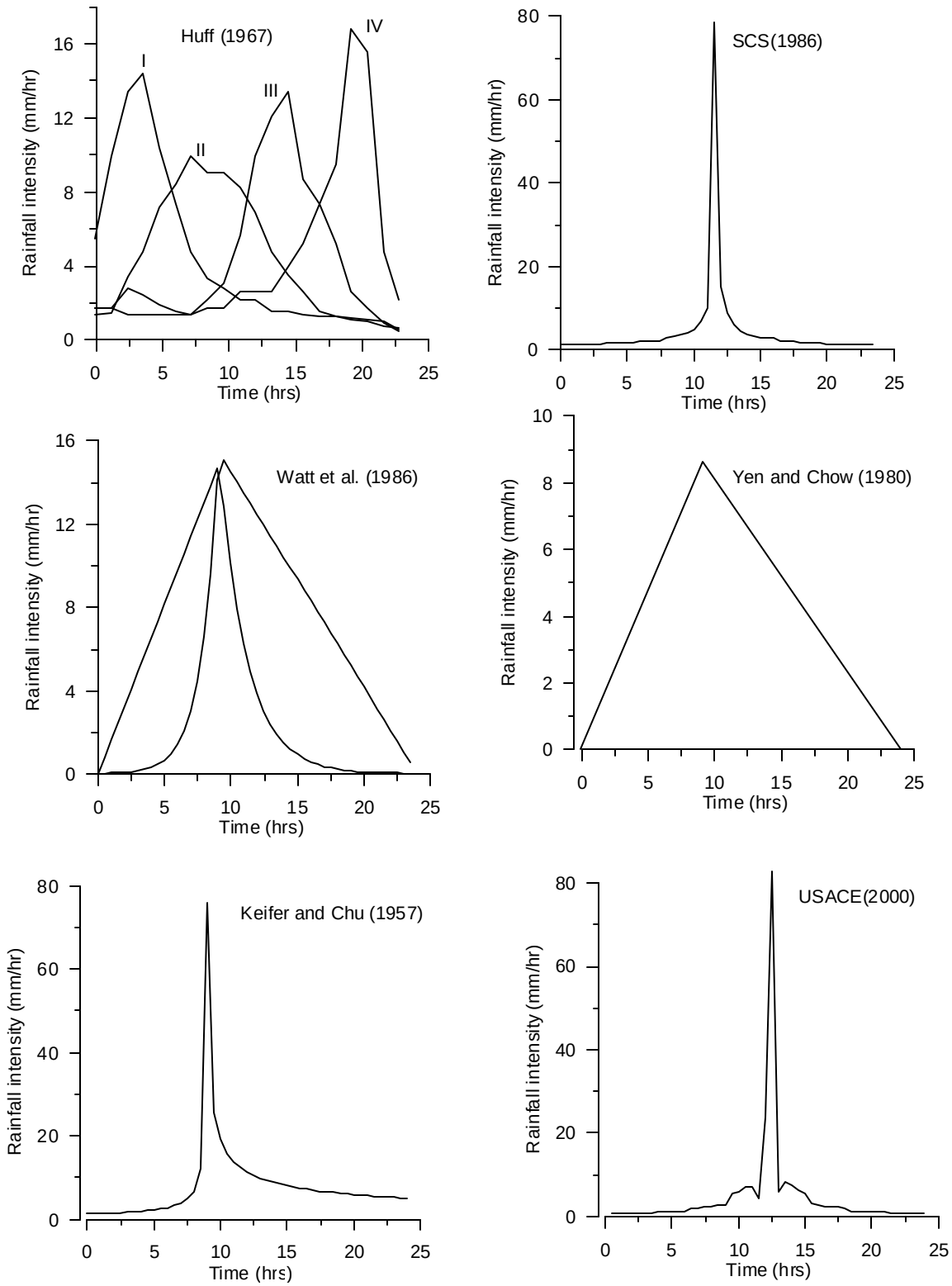

Figure II-1 Hyetographs for use in London

III. RECOMMENDATIONS AND CONCLUSIONS

After a review of three categories of methods of design storm hyetographs, the following recommendation are made:

1. One or more methods from each investigated category should be employed in the study of the Upper Thames River basin. This would allow one to study the response of the basin to varying storm types, from long low intensity storms, to short duration storms with high (intense) bursts. Employing methods of each category would limit biasing of results.

2. Method by Watt et al. (1986) should probably not be used in cases where storm durations of 24 hr and longer are used. This is because its derived parameters pertain only to 1-hr storms. Although the method can be used for durations different than that specified by the authors, it is unknown if the parameters used in 1-hr storms differ from those of other durations. Of course, if the parameters for other storm duration become available, the method could easily be employed. However, the method by Yen and Chow (1980) does not suffer these drawbacks, and should therefore be used, simply because it allows for a wider range of storm durations.

3. Note that both methods in this category were derived for relatively short storm durations—method of Watt et al. (1986) uses 1-hr storms, while the method of Yen and Chow (1980) has been used for storms up to 6 hrs in duration. Therefore, methods in this category should be applied when considering storms of relatively short durations (between 1-6 hrs).

4. No significant difference is found between methods of Keifer and Chu (1957) and

USACE (2000)—as their hyetographs are nearly identical. The HEC-HMS Frequency Storm Method of USACE (2000) gives more flexibility to the user, which gives it its only edge. Both methods require inputs from IDF curves, which limit its use. For example, if hydrologic extremes are to be investigates (which may exceed 100 yr return period), methods in this category could not be used, unless data for longer return periods are obtained.

5. SCS (1986) method should be used in the study when rainfall of high intensity within a short period of time is needed. The alternate method in this category (Huff, 1967) should be used when rainfall of low intensity, distributed over a longer period of time within the same storm duration, is required. Therefore, application of the particular method varies on questions the modeler is trying to answer; in other words, either one of the methods could be applied, depending on the circumstances. Lastly, because methods of this category do not require data from IDF curves, they would be ideal for use in investigations of hydrologic risks and extremes, some of which could easily exceed the 100 yr return period.

IV. REFERENCES

[1] Bedient, P. B., and W. C. Huber (2002), Hydrology and foodplain analysis, Prentice Hall, Upper Saddle River, New Jersey.

[2] Bonta, J. V., and A. R. Rao (1988), Comparison of four design-storm hyetographs, Transactions of the ASAE, 31 (1), 102-106.

[3] Burn, D. H., and M. Sharif (2004), Assessment of water resources risk and vulnerability to changing climatic conditions, development and application of a k-nn weather generating model, Tech. Rep. III, The University of Western Ontario, London, Ontario, Canada.

[4] Chow, V. T., D. R. Maidment, and L. W. Mays (1988), Applied hydrology, McGraw Hill, New York.

[5] Hogg, W. D. (1980), Time distribution of short duration storm rainfall in Canada, pp. 56{63, Canadian Hydrology Symposium: 80 Toronto, National Research Council of Canada, Ottawa, Ontario.

[6] Huff, F. A. (1967), Time distribution of rainfall in heavy storms, Water Resources Research, 3 (4), 1007-1019.

[7] Keifer, C. J., and H. H. Chu (1957), Synthetic storm pattern for drainage design, ASCE Journal of the Hydraulics Division, 83 (HY4), 1-25.

[8] Marsalek, J., and W. E. Watt (1984), Design storms for urban drainage design, Canadian Journal of Civil Engineering, 11, 574-584.

[9] MTO (1997), Drainage Management Manual, Ronin House Publishing, under contract from Ministry of Transportation of Ontario, Ottawa, Ontario, Canada.

[10] SCS (1986), Urban hydrology for small watersheds, Tech. Rep. 55, Engineering Division, Soil Conservation Service, US Department of Agriculture, Washington, DC.

[11] USACE (2000), Hydrologic Modelling System HEC-HMS, Technical reference manual, United States Army Corps of Engineers, Davis, California.

[12] Cunderlik, J., and S. P. Simonovic (2004), Assessment of water resources risk and vulnerability to changing climatic conditions, calibration, verification and sensitivity analysis of the HEC-HMS hydrologic model, Tech. Rep. IV, The University of Western Ontario, London, Ontario, Canada.

[13] Veneziano, D., and P. Villani (1999), Best linear unbiased design hyetograph, Water Resources Research, 35 (9), 2725-2738.

[14] Watt, W. E., K. C. A. Chow, and K. W. Lathem (1986), A 1-h urban design storm for Canada, Canadian Journal of Civil Engineering, 13, 293-300.

[15] Yen, B. C., and V. T. Chow (1980), Design hyetographs for small drainage structures, ASCE Journal of the hydraulics division, 106 (HY6), 1055-1076.