Chapter 20

Application of a GIS to Assess Changes in Flood Hydrology of Urbanizing Watersheds

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This chapter describes an application of a geographic information system to support hydrologic simulation of runoff on watersheds undergoing urban development. Described are modifications of the Soil Conservation Service runoff curve number method, for prediction of a new flood regime of watersheds undergoing land use and land cover changes such as urban development.

20.1 Introduction

Hydrologists and engineers are concerned with estimating runoff volumes and peaks from rainfall. In areas undergoing rapid development a special concern is how the frequencies of peak flows will change due to urbanization. Predictive techniques have been developed by various authors based on regression of flood frequencies against basin characteristics. For example, Sauer and

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Thomas (1983) of the U.S. Geological survey reported the results of a nationwide study in which a regression-based estimating procedure is used to adjust the equivalent rural peak discharge to the urban condition by means of an index of urbanization called the basin development factor. This factor and basin size, channel slope, basin rainfall, basin storage and impervious surfaces were used in multiple regression analysis to develop prediction equations for urban peak flows of various return periods. A similar study was conducted by Sherwood (1987). Veenhuis and Gannett (1987) made an assessment of the effects of urbanization on floods by analysis of the 25 years of streamflow gauging record in the Austin area. Peak discharges for the 2- and 100-year return periods were found to be 33% and 10% greater in the later period of the record representing higher degree of urbanization. A regression equation they tested generally overpredicted the peak discharges by 20% to 45%.

The major drawback of a regression-based method is the need for discharge data covering both prior and post urbanization periods to develop not only the regression equations but also the flood frequency curves for the two periods. Such data are not readily available in many parts of the world. Furthermore, regression equations have coefficients reflecting local conditions and may not have general validity. An alternative to this empirical approach is to use a physically-based rainfall-runoff model sensitive to changes in watershed parameters caused by urbanization.

The Soil Conservation Service (SCS) runoff curve number method (SCS, 1972) in combination with a dimensionless unit hydrograph is an example of such a model in the domain of lumped systems simulation. The SCS method has gained a wide acceptance among hydrologists because it is relatively simple, requires input data which are usually readily available, and yet retains a significant measure of physical relevance through the use of such parameters as soil type, land use and land cover. In principle, the method can be expanded to distributed or semi-distributed simulation, such as the HEC-1 model.

In recent years, there has been a growing interest in the use

of geographic information systems as the means of integrating hydrologic models with spatial and temporal data, thus producing a time and cost efficient simulation system. Moreover, geographic information systems can readily accept remotely sensed data by satellites. Indications are (Schultz, 1988) that remote sensing is going to play a major role in hydrologic modelling in future.

The following sections describe a geographic information system and hydrologic simulation software originally developed to support flood hydrograph simulation on natural watersheds using the SCS runoff curve number and dimensionless unit hydrograph methods. Because of the sensitivity of the runoff curve number method to land use/cover changes the software has been found well suited to studies involving watershed changes from natural to more developed conditions accompanying the spread of urban settlements. The standard SCS method has been modified to include stochastic components of the rainfall-runoff process. Regional stochastic parameters were derived from analysis of fifty-five watersheds in Alberta. The software was expanded to include a Monte Carlo simulation technique capable of deriving synthetic flood frequency curves corresponding to various stages of development in a watershed. A simplified flowchart indicating the major steps in generation of a synthetic flood frequency curve for a watershed, utilizing a GIS as the source of spatial and temporal data, is shown in Figure 20.1.

20.2 Rainfall Runoff Model

The following discussion focuses on the hydrologic components of the GIS supported simulation of flood hydrographs and synthetic flood frequency curves. This includes the selection of rainfall input, determination of rainfall abstractions, and transformation of excess rainfall into direct runoff by means of a unit hydrograph.

Figure 20.1: Simplified flowchart of simulation procedure.

20.2.1 Rainfall Input

The simulation system allows the user to specify rainfall hyetographs of any shape. However, to generate synthetic flood frequency curves, the following procedure is used: 1. The duration of rainfall is randomly determined from its probability distribution. An example of log-Pearson type III distribution fitted to storm durations in southern Alberta is shown in Figure 20.2. 2. The return period of the rainfall T is chosen by drawing a random number from a uniform distribution of numbers between zero and one. 3. The depth of the rainfall P is computed from:

Figure 20.2: Probability distribution of rainfall duration fitted by log Pearson type III distribution.

$$P = \bar{x} + K_T s \quad (20.1)$$

where $\bar{x}$, s and K_T are the mean, standard deviation, and frequency factor, respectively, of the Gumbel distribution of the depth of rainfall, automatically provided by the GIS for the analyzed watershed. 4. The time distribution of the rainfall is determined by a random selection of one of the nine time distribution curves of rainfall in heavy storms described by Huff (1967). The resulting hyetograph is then modified by means of the SCS method for abstractions before it is finally converted into the direct runoff hydrograph. This procedure is repeated several thousand times during the Monte Carlo simulation.

20.2.2 Rainfall Abstractions

Application of the unit hydrograph method for prediction of a flood hydrograph requires the determination of excess rainfall. Excess rainfall is that part of the observed total rainfall which is

neither retained on the land surface nor infiltrated into the soil. Assuming Hortonian overland flow (Chow, 1988), excess rainfall becomes direct runoff at the watershed outlet. The difference between the observed total rainfall and the excess rainfall is called abstractions. Abstractions include interception (i.e. precipitation caught and retained on vegetation above the ground), and infiltration of water into the soil. Interception and depression storage are usually lumped together and termed the initial abstraction.

Various approaches exist for determining the rate of abstractions from rainfall. In this chapter, the Soil Conservation Service (1972) method for abstractions has been adopted. The method, known as the runoff curve number method, has been modified to take into account stochastic properties of abstractions.

Standard SCS Method

The Soil Conservation Service (1972) procedure for computing abstractions from storm rainfall relates the depth of excess rainfall or direct runoff P_e to the total rainfall depth P , initial abstraction I_a , and potential maximum retention S by the following equation:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad (20.2)$$

An empirical relation was developed by the Soil Conservation Service:

$$I_a = 0.2 S \quad (20.3)$$

which after substitution into eq. (20.2) yields:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (20.4)$$

The potential maximum retention S is assumed to depend on soil type, land use and land cover. It is high for deep sandy soils and low for shallow clayish soils. For convenience, the potential maximum retention S is converted into a parameter having the range of values between 0 and 100.

$$CN = \frac{25400}{S + 254} \quad (20.5)$$

The parameter CN , called curve number, is equal to zero when there is no direct runoff generated. The value of 100 on the other hand means no abstractions when the depth of excess rainfall equals the depth of total rainfall.

Curve numbers have been tabulated by the Soil Conservation Service (National Engineering Handbook, Section 4, 1972) on the basis of soil type and land use for three antecedent moisture conditions.

Because the method is relatively simple and requires readily-available information, yet considers physically relevant parameters (soil type, land use, land cover), the SCS method for abstractions gained wide acceptance among hydrologists in North America.

Modified SCS Method

The runoff curve method was developed primarily for design applications in ungauged catchments. The standard tables provide helpful guidelines, but estimation of runoff curve numbers directly from local or regional data is recommended for increased accuracy (Ponce, 1989). Furthermore, the maximum potential retention S and initial abstraction I_a are in fact variables, rather

Figure 20.3: Generation of excess rainfall distribution by modified SCS method.

than constants. The following is an outline of a modified SCS procedure developed by the author for use with local rainfall-runoff data, and which takes into account the stochastic character of parameters S and I_a .

The modified SCS method was tested using data from 55 watersheds located in the Alberta foothills, stretching from Montana border in the south to as far north as the town of Rocky Mountain House. The topography of the area ranges from rugged barren mountain ridges to the west to rolling forested foothills in the east. Land cover is predominantly coniferous or mixed forest. Exceptions to these are areas of exposed bedrock along the higher mountain ridges and deciduous treed grassland areas at the lower elevations. Surface geology is comprised mainly of glacial moraine and colluvium. Bedrock geology includes shales, sandstones and limestone. Soils in the area generally fall into the B or C hydrologic soil group, according to the SCS classification. Runoff curve numbers determined from standard SCS tables and for antecedent moisture condition II, range from 65 to 85.

Modifications to the standard SCS method are schematically shown in Figure 20.3. The essence of the modified method is the recognition of a stochastic behaviour of S and I_a . Analysis of rainfall-runoff data in the study region showed the existence of a general relationship between the maximum potential retention S and the amount of rainfall accumulated within the five days prior to runoff in question. The five day antecedent rainfall, P_5 , has been found to be a random variable having a log-Pearson type III probability distribution. In recognition of this dependency of S on P_5 , the maximum potential retention S is designated to be the dependent stochastic variable.

The initial abstraction, I_a , on the other hand, is assumed to be a purely random stochastic variable. It has been shown by Chang and Muzik (1991) that the probability distribution of I_a can be well approximated by log-Pearson type III distribution.

In summary, by replacement of deterministic relationships between S , P_5 and I_a by stochastic relationships, the modified SCS method yields a probability distribution of excess rainfall P_e for given total rainfall P , rather than a single value of P_e as

predicted by the standard SCS method. The modified method thus reduces significantly the uncertainty associated with the return period of the peak discharge computed from excess rainfall as the probability of occurrence of excess rainfall and the corresponding peak discharge may be assumed, within certain limits, to be the same.

20.2.3 Dimensionless Unit Hydrograph

Since most small watersheds lack adequate streamflow data for developing a suitable unit hydrograph, a synthetic unit hydrograph approach is used. The method applied here is based on a regional dimensionless unit hydrograph (DUH) developed for a hydrologically homogeneous region (Bureau of Reclamation, 1976). The regional DUH is derived by converting selected direct runoff hydrographs observed within the region into a dimensionless unit hydrograph as illustrated in Figure 20.4.

Figure 20.4: Derivation of a dimensionless unit hydrograph (b) from direct-runoff hydrograph (a).

The key parameter in this conversion is the lag-time, LG, defined as the elapsed time between the centroids of excess rainfall hyetograph and direct runoff hydrograph. Once developed, the regional DUH provides the means of obtaining a synthetic unit hydrograph at an ungauged site. Lag-time is again the key parameter for this reversed conversion. A regional lag-time relationship is therefore required. Lag-time values, previously obtained for the purpose of deriving the DUH, are correlated with certain geomorphological parameters. The correlation equation recommended by the Bureau of Reclamation (1976) is of the form:

$$LG = C (LL_{ca}/S_o)^{1/2x} \quad (20.6)$$

where L is the watershed main stream length, S_o is the average slope of the main stream, L_{ca} is the distance along the main stream from outlet to the point on the stream nearest to the watershed centroid, and c and x are regional constants.

20.3 The Geographic Information Systems

GISs are computer-assisted systems for the capture, storage, retrieval and display of spatial data (Clarke, 1986). The GIS described below has been developed specifically to assist hydrologic analysis and synthesis.

20.3.1 Computer Hardware

The GIS has been designed specially for IBM MS-DOS microcomputers and compatibles. The present GIS has been implemented on a Zenith 80386 microcomputer (with a math coprocessor) linked to a digitizer, a graphic monitor, a printer, a plotter, and a modem (optional). Through a modem the system can obtain archived streamflow and precipitation data files stored on a mainframe computer, such as data provided by the Water

Survey of Canada and the Atmospheric Environment Service. Suggested hardware configuration is shown in Figure 20.5.

20.3.2 Database Structure

The raster data structure is adopted in the present GIS because generally it is easier to perform overlay and update operations than the vector data structure (Clarke, 1986). In the raster method, data structure consists of an array of orthogonal grid cells. Each grid cell is referenced by a row and a column number, and is assigned a number representing the type or value of the attribute of interest. The number assigned is assumed to be constant within the grid square. The cell size of 1 km x 1 km is used to store data except rainfall data for which a 10 km x 10 km cell is applied due to the smaller accuracy of available rainfall frequency maps. These cell sizes are also chosen to facilitate cross-reference to Universal Transverse Mercator (UTM) grid system. To keep the size of the GIS database manageable within microcomputer operating environment, the study region is divided into four 100 km x 100 km areas. For the purpose of manipulating data effectively, each area is subdivided into one hundred 10 km x 10 km blocks. Except for rainfall data, each block is then subdivided into one hundred 1 km x 1 km cells. The coordinates at the southwestern corner of each grid square represent the reference coordinates for the square. To cross-reference all grid squares, the origin of each study area is identified with UTM grid. In order to rapidly retrieve data in any part of area, a record number is assigned to each grid cell and data are stored in random access files.

20.3.3 The GIS Software Modules

Organization of the GIS is shown in Figure 20.6. The system consists of four major menus: (1) handling GIS database; (2) handling parameters of watersheds; (3) hydrologic model; and (4)

Figure 20.5: GIS hardware.

utilities. Each menu contains several submenus. Each menu or submenu has on-line help to assist users in manipulating data and operating the system.

It is not possible to review all software here in detail, however, the features characteristic for this hydrologically oriented GIS are described. Notice that the first four submenus under the "hydrologic model" main menu facilitate the derivation of hydrologic parameters (DUH, regional DUH, lag-time relationship) which are then input into the GIS database. This need for derivation of hydrologic parameters, through relatively complex rainfall-runoff analysis, sets the hydrologically oriented GIS apart from the rest of GISs, assuming that this capability may be considered to be part of the GIS.

A second feature unique to this hydrologically oriented GIS is the ability to calculate runoff curve number (CN) values for each grid cell. This is accomplished by overlaying land use/cover and soil type files. The resulting combination is compared internally with a CN reference file (Handling GIS Database menu) similar to that by SCS (1972), and an appropriate CN value is then assigned to each grid cell automatically. Using the menu "Handling Parameters of Watershed" the software, for example, uses the CN file to compute the average curve number CN for a watershed as shown in Figure 20.7. The software computes the partial area of each grid square that lies within the watershed boundary. From this information the weighted curve number, CN, for the water-shed is computed by:

$$CN = \frac{1}{A} \sum_{i=1}^n A_i CN_i \quad (20.7)$$

Figure 20.6: Organization of the hydrologically oriented GIS.

where n is the number of cells enclosed, A is the watershed area, and A_i is the partial area of cell i enclosed within the watershed boundary.

Similarly, the weighted average depth of precipitation is computed for the watershed, except the grid size used is 10×10 km. The user selects, on an interactive basis with the software, the storm duration from the available 2, 6, 12, and 24-hr. durations, and any return interval. The software then computes the average depth of precipitation for the selected design storm. An option exists in the software, which allows the user to specify any hyetograph for the design storm. Otherwise, the precipitation depth computed for the stored precipitation statistics is used in further computations.

Finally, the GIS software computes the lag-time value, LG , for the watershed from a regional equation of the form given by equation 20.6, and retrieves a regional dimensionless unit hydrograph in digital form. Using the known values of D , LG , and A , the dimensionless unit hydrograph is automatically converted into the watershed's synthetic unit hydrograph, which is then convoluted with excess rainfall.

20.3.4 Data Input and Output

Two categories of data, input required by the system are (1) various spatial data, and (2) hydrologic data. Whenever data input is necessary, users run the software in an interactive way. Data can be entered from either the digitizer or the keyboard. In addition, through a modem the system can obtain archived streamflow and precipitation data files stored on the mainframe computer of the Water Survey of Canada and the Atmospheric Environment Service; or alternatively, the system can read floppy disks storing required archived files. Once the database has been created, the only data input necessary to derive a synthetic flood frequency curve for a watershed of interest, as shown in Figure 20.1, include: (1) watershed boundary and watercourse; (2) elevations of stream's end points; and (3) the number of flood

Figure 20.7: Schematic for the computation of the average CN value for a watershed.

hydrographs to be generated.

Data can be output on the screen, from the printer or the plotter. There are three kinds of data output: 1. graphic output such as including graphic display of various spatial data (each classification is assigned a specific color), watershed boundary, main watercourse, and centroid of watershed; 2. figure output such as including flood hydrographs, rainfall hyetograph, unit hydrographs, a regional dimensionless unit hydrograph, a regional lag-time curve, and flood frequency curves; and 3. text output such as including a variety of tables for tabulating the spatial data and the detailed reports of various hydrologic analyses and simulation results.

Data stored

The GIS database has been implemented for an area covering about 11,000 km² located in the Rocky Mountain foothills of southwestern Alberta, Canada. There are four types of spatial data stored in the GIS database: 1. land cover and land use classification; 2. soil drainage classification; 3. SCS runoff curve number, CN; and 4. extreme rainfall statistics. Except for CN, the data are extracted manually from maps or plans and then input from the digitizer or the keyboard. Land cover and land use data are abstracted from composite forest cover series maps of 1:100,000 scale, and soil drainage data (hydrologic soil groups A, B, C, and D) are acquired from ecological land classification maps of the same scale. The CN value for each cell is then computed automatically by overlaying land cover and land use data with soil drainage data. Furthermore, extreme rainfall statistics stored are the mean and the standard deviation for the Gumbel distribution of the rainfall depth for storm durations of 1, 2, 6, 12, and 24 hours ("Rainfall Frequency Atlas of Canada", 1985). For rainfall durations of 48 and 72 hours, the statistics can be computed by multiplying the values of 24-hour rainfall by a factor of 1.35 and 1.5 respectively ("Hydrological Atlas of Canada", 1978).

In addition, some derived regional hydrologic information is also stored in the GIS database. This includes a regional dimensionless unit hydrograph, a regional lag-time relationship, as well as probability distributions for storm duration, 5-day antecedent precipitation, and initial abstraction.

20.4 Application

Performance of the developed hydrologically-oriented GIS has been tested by generating synthetic flood frequency curves for 27 watersheds located in Alberta foothills. These watersheds have records longer than ten years, areas ranging from 64 to 820 km², and average CN varying from 70 to 80. Each synthetic flood

frequency curve was derived by randomly generating 5000 peak discharges. About four-fifths of the synthetic flood frequency curves have the sample mean within the 95% confidence interval of the population mean. Furthermore, 21 out of 27 synthetic frequency curves pass the chi-square goodness of fit test at the level of significance α equal to 0.05. These results compare very favourably with results of the standard flood frequency analyses procedure whereby a probability distribution function, such as log-Pearson type III is fitted to the sample. A distinct advantage of the synthetic flood frequency generation approach over statistically fitted probability distributions is that the former is based on a physical model of runoff (with stochastic parameters S , $P5$ and I_a) and probabilistic rainfall input. This approach makes it possible to combine the knowledge of physical processes governing runoff with the theory of probability, resulting in derived (synthetic) distributions of flood flows (Haan, 1987; Muzik and Beersing, 1989). This is to say that by being able to put reasonable limits on the model's physical parameters we can increase, or at least critically consider, the confidence with respect to the final product of the Monte Carlo simulation - the predicted flood magnitudes and their probabilities. By the same argument, the physically based approach to flood frequency analyses makes it possible to assess the consequences of changes within the watershed such as due to urbanization. This is not possible to accomplish by means of the standard flood frequency analyses.

20.4.1 Operation of the System

The following is a step by step outline of the simulation procedure supported by the GIS for the purpose of deriving a synthetic flood frequency curve. A simplified schematic of the procedure can be found in Figure 20.1.

1. Tape a topographic map on the digitizer table.
2. Specify the scale of the map.

3. Digitize two points on the map to orientate X and Y axes.
4. Digitize the boundary and the main watercourse of the watershed of interest (usually at a rate of 10 pairs of coordinates per second).
5. Input elevations of stream's end points. At this point the software automatically computes the following watershed parameters; drainage area, L, Lca, So, the average CN, and the average extreme rainfall statistics for various storm durations.
6. Input the number of flood hydrographs to be generated, N.
7. Select the representative time distribution pattern of storms. Three types of time distribution are available in the system: (a) uniform distribution; (b) median first quartile curve for point rainfall (Huff, 1967); and (c) time distribution of first quartile storms (Huff, 1967). Option (c) has been used throughout the study since it is the most severe storm distribution pattern. At this point, the Monte Carlo simulation technique generates N independent values of peak discharge by the following steps:
 8. Generate a random value of storm duration, D.
 9. Generate a random value of total rainfall, P.
 10. Given P, compute the time distribution of storm by random selection of one of nine curves in 7(c).
 11. Generate a random value of the 5-day antecedent precipitation, P5.
 12. Given P5, determine S using the P5-S relationships shown in Figure 20.2.

13. Generate a random value of I_a from empirical distribution.
14. Given the storm hyetograph (i.e., time distribution of P), S , and I_a , compute an excess rainfall hyetograph by equation 20.2.
15. Determine the basin lag-time of the generated storm event, LG , using equation 20.6.
16. Derive a synthetic unit hydrograph by coupling the lag-time and the regional DUH.
17. Compute a predicted flood hydrograph by the convolution of the excess rainfall hyetograph with the synthetic unit hydrograph.
18. Find the peak discharge of the predicted flood hydrograph, Q_p .

Steps 8 to 18 are repeated until N peak discharges of flood hydrographs are generated.

19. Perform flood frequency analysis for Q_p series. Final product is a synthetic flood frequency curve plotted in lognormal probability scale which can be output on the screen for temporary display or output from the printer or the plotter for hard copy.

In general, to derive a synthetic flood frequency curve for watershed area of the order of 1000 km^2 , it takes about five minutes to digitize the watershed boundary and main watercourse and one minute to compute all parameters required for hydrologic simulation. Generating 5000 flood hydrographs by the Monte Carlo simulation technique and performing frequency analysis of peak flows requires further eighteen minutes. In total it takes about 24 minutes to obtain the final result. It is evident that applying the GIS in hydrologic simulation can substantially shorten this type of hydrologic simulation.

20.4.2 Example

The outlined procedure is best illustrated by an example. However, the existing GIS database does not include any Alberta watershed with a recent significant urban development. The following example thus considers a hypothetical scenario whereby a predominantly natural watershed of James River near Sundre (station no. 05CA002) undergoes urban development resulting in a 15 percent increase of the average runoff curve number for the watershed.

Figure 20.8: Flood frequency curves for James River near Sundre, Alberta.

The watershed, having a drainage area of 821 sq. km, is almost completely covered by forest with some rangelands in the lower elevations. The topography is rolling hills, only a small western part of the watershed reaches into the mountains consisting of bare rock and reaching elevations over 2000 m. The average CN value determined from SCS tables for the watershed is 75.

The two synthetic flood frequency curves generated for the natural and 15% urbanization condition, respectively, are shown in Figure 20.8. Also shown in the figure is the empirical frequency curve consisting of 24 observed annual maximum discharges.

The results show that: (a) the synthetic flood frequency curve for natural conditions fits the observed flow very well, (b) a 15% increase in runoff will result in a significant increase of flood flow; for example, the 50-year flood will increase from about 300 m³/s to 400 m³/s, or by 33%, (c) the two synthetic curves gradually converge on both sides of the probability scale; this is expected, unless a different physical process dominates extreme flows. Such conditions could be accounted for in the simulation if deemed necessary.

20.5 Conclusions

Results of the described study show that a microcomputer-based geographic information system supporting a flood prediction model can effectively provide parameters required for generating a physically-based synthetic flood frequency curve for a watershed without or with limited streamflow data. Main conclusions derived from the study are:

Regarding the use of GIS:

1. Once the GIS database is created the time required for hydrologic simulation is up to 100 times shorter than would be needed for simulation not supported by the GIS.

2. Regionalization of hydrologic parameters, which is promoted by the GIS, improves accuracy of simulation results.
3. It is easy to update or modify the GIS database in order to study the impact of watershed changes, such as urbanization, on runoff.
4. Output in form of text, tables, graphs, thematic maps, etc. is easily produced.

Regarding the simulation methodology:

5. The overall approach of derived (synthetic) distributions of flood flows is physically based, thus allowing extrapolation of empirical frequency curves, and computation of frequency curves for changed watershed conditions.
6. The lumped model used in the study is based on a modified SCS method for abstractions and a synthetic unit hydrograph. This model performed well in simulating flood frequency curves for most tested natural watersheds. It is sensitive enough to respond to relatively small variations in runoff conditions, thus it should be very useful in planning studies exploring impacts of various stages of urban development on flood flows.
7. The scope of the present study did not include distributed simulation. It is suggested, however, that the presented methodology of derived (synthetic) flood frequency curves shows a great potential in assessing impact of changed watershed characteristics, and is equally applicable to both lumped and distributed modelling.

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20.7 List of Symbols

A	watershed area (km^2)
A_i	cell area within watershed boundary (km^2)
C	regional constant
CN	runoff curve number
D	excess rainfall duration (h)
I_a	initial abstraction (mm)
K_T	frequency factor for Gumbel distribution
L	longest stream length from watershed divide to outlet (km)
L_{ca}	length of the longest stream from point closest to watershed centroid to outlet (km)
LG	lag time (h)
N	number of generated peak discharges
P	total depth of rainfall (mm)
P_e	total depth of excess rainfall (mm)
P_5	total depth of five day antecedent rainfall (mm)
Q	discharge (m^3/s)
Q_p	peak discharge (m^3/s)
S	maximum potential retention (mm)
S_o	stream slope (m/m)
s	standard deviation of rainfall (mm)
T	return period (years)
V	volume of direct runoff (m^3)
$\bar{x}$	mean of rainfall (mm)