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RUNOFF PREDICTIONS AT UNGAUGED SITES FROM RAINFALL STATISTICS USING A GEOGRAPHIC INFORMATION SYSTEM

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Runoff Predictions at Ungauged Sites from Rainfall Statistics using a Geographic Information System" submitted by Stuart John Pomeroy in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

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ABSTRACT

A procedure has been developed that enables hydrologists to estimate flood flows for design purposes at ungauged sites within the study region in the Rocky Mountain foothills in south west Alberta.

The procedure is based on the US SCS unit hydrograph method. A regional unit hydrograph, regional lag curves and runoff curve number relationships are derived from analysis of storms on each of 8 studied watersheds. A Geographic Information System (GIS) is established for the study region to store spatial data that are required for the prediction of runoff. Direct runoff at an ungauged site is estimated through use of the regional curves, together with the GIS data and storm data. The procedure is verified by using published rainfall extreme statistics as the storm input for a number of gauged watersheds. The resulting runoff flows are plotted and compared with the corresponding station flow-frequency analysis. The limitations of the procedure and possible future developments are discussed.

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CHAPTER 1

INTRODUCTION

1.1 General

Hydrology can be defined as the study of the properties of the waters of the earth's surface and their environmental relationships. With regard to surface flow, as opposed to underground flow, hydrology often involves detailed analysis of storm events and streamflow, their interrelation and the frequency of occurrence of either or both.

Hydrologists are frequently asked to estimate the maximum instantaneous flow, corresponding to a specific return period, at a site where limited streamflow data exist in order that bridges, culverts, spillways and flood mitigation works can be correctly designed and constructed. Methods used to determine the estimate vary from country to country according to the availability of regional characteristics. If such characteristics are not available, the hydrologist must either perform a regional analysis using nearby gauging station records or, more simply, find a hydrologically similar watershed for which streamflow records exist.

These approaches both result in the extrapolation of streamflow data whenever the length of flow records is less than the required return period for the design estimate. This is a common occurrence because of the recent installation of many river gauging stations.

Meteorological records, on the other hand, are both easier and cheaper to collect. As a result, the meteorological data records for an area are usually longer than those of the local flow data. Furthermore, spatial rainfall interpolation is feasible for a trained meteorologist.

It is therefore an attractive proposition to utilize the longer period of records of rainfall data to predict the longer return period flows often required for design purposes.

1.2 Objectives of the study

The overall objective of the study was to establish a microcomputer based method to estimate flood flows at ungauged sites within the study region. The selected method was based on the following steps :

1) creation of a Geographic Information System (GIS) to contain the spatially varying hydrological data;
2) prediction of flows using the GIS data

together with the US Soil Conservation Service (SCS) unit hydrograph method.

The entire system was to be implemented on an IBM PC microcomputer linked to a digitizer, printer and plotter.

The objective would be attained by developing and testing computer software to organize the GIS and to model the SCS techniques for the study location in the foothills region of Alberta. The major steps would be as follows :

1) collect and digitize data for GIS;
2) apply SCS techniques to obtain the regional dimensionless unit hydrograph, lag curves and runoff curve number relationships;
3) verify the regional data by comparison of results with frequency curves from gauging stations.

A successful outcome would result in a straightforward method to estimate flood flows at ungauged sites in the study region.

1.3 Scope of the Study

The study was carried out in the forested foothills area of Alberta, Canada. Analysis was carried out on 8 watersheds in the Red Deer River and Bow River basins. The study was limited to these watersheds by requirements for detailed land cover and soil drainage information, in order to compute runoff curve number, CN, and the need for hourly rainfall data to develop the unit hydrographs.

1.4 Thesis Organization

Following this introduction, Chapter 2 is a literature review of those areas pertinent to the present study.

Chapter 3 details the methods used in the analysis from a generalized viewpoint without involving watershed or regional specific issues.

Chapter 4 describes the GIS database that was established for the study and includes the sources of information, uses of the database and a discussion.

Chapter 5 describes fully the hydrological analysis This covers the derivation of regional unit hydrographs and lag curves as well as the results from the verification runs. A discussion is included where appropriate.

Chapter 6 is the conclusion of the study and includes a number of recommendations that may improve the results or expedite expansion of the study region.

The main body of the thesis is followed by 6 Appendices that include sample calculations, background to the software and additional information.

CHAPTER 2

LITERATURE REVIEW

2.1 Rainfall - Runoff Processes

The relationship between rainfall and the resulting direct runoff is very complex. It is affected by climatic factors such as intensity and duration of rainfall, movement of the storm centre, temperature and the antecedent moisture conditions. Physiographic parameters including watershed area, slope of watercourse, length of watercourse, land use and the infiltration capacity of the soil are also involved (Wilson, 1974). Clearly there are a large number of parameters which make analysis difficult particularly when the aim is to apply the method to an ungauged watershed.

One approach that has evolved over the past 50 years has been to separate the factors listed in the previous paragraph into the following categories :

1) those that affect the lag time of the direct runoff from the watershed;
2) those that affect the proportion of rainfall that translates into direct runoff;
3) those that affect the shape of the

direct runoff hydrograph.

These factors and their relationship with the unit hydrograph method are discussed in the next sections.

2.2 The Unit Hydrograph

The unit hydrograph (also known as the unit graph) method of estimating direct runoff was originally proposed by Sherman (1932) who defined the unit-graph as follows :

> "If a given one-day rainfall produces a 1 inch depth of rainfall over a given drainage area, the hydrograph showing the rates at which the runoff occurred can be considered a unit-graph for that watershed".

The depth of rainfall is usually called the rainfall excess and is the part of the total rainfall that forms the direct runoff response. Sherman's definition is often modified by adopting a shorter time step, measured in hours, and employing a depth of rainfall excess measured in millimetres. The unit hydrograph can then be refered to as the P mm T hour unit hydrograph (Flood Studies Report, 1975). A value for P of 10mm is frequently used.

The unit hydrograph concept is frequently criticized for its assumption of linearity whereby twice the rainfall excess results in exactly twice the direct runoff. It is noted in the Flood Studies Report (1975) that, using hydraulic theory, greater depths of water move more quickly than lesser depths. This leads to a revised temporal distribution for the resulting runoff and, therefore, a loss of linearity.

Furthermore, in order to use a unit hydrograph to predict runoff, the assumption is made that the rainfall is distributed in the same temporal and spatial pattern for all storms (Viessman et al, 1977). This is usually interpreted as assuming that the rainfall intensity is constant throughout each period T of the unit hydrograph and that the intensity is uniform across the whole watershed.

Gray (1970) notes that the nonuniformity of areal distribution will impose an upper limit on the size of watershed suitable for unit hydrograph analysis of about 5000 sq. kms. Gray also notes that if only mean daily flow and daily rainfall data are available a lower limit of about 2500 sq. kms. will also apply.

Notwithstanding these assumptions, the unit hydrograph method has been used extensively throughout the world.

2.2.1 The SCS Unit Hydrograph

The US Soil Conservation Service (SCS) derived a method in the 1950's to estimate flows based upon a dimensionless form of the unit hydrograph (National Engineering Handbook Vol 4, 1972).

The dimensionless unit hydrograph (DUH) was based upon the results from a set of storms and the related direct runoff for a number of watersheds. The DUH has no specific duration but is plotted such that the P mm T hr unit hydrograph can be computed for a given watershed. Further details of this method can be found in Chapter 3.

2.3 Watershed Lag Time Estimation

The lag of a watershed can be defined in a number of ways. The two most commonly used are

1) time from the centre of mass of the rainfall excess to the centre of mass of the resulting direct runoff (LG);
2) time from the centre of mass of the rainfall excess to the peak flow rate (LG2).

Snyder (1938) derived the following relationship between LG2 and watershed parameters for the Appalachian mountains :

$$LG2 = C \; (\; L \; L_{ca})^{0.3} \qquad (2.1)$$

where L was the length of the longest watercourse from the point of interest to the watershed boundary and L_{ca} was the length of the longest watercourse downstream of the point closest to the centroid of the watershed.

For L and L_{ca} measured in miles, Snyder found C to be approximately 2.

Linsley (1942) modified Snyders relationship to take account of the stream slope (S) as follows :

$$LG2 = C\ (\ L\ L_{ca})^{a}\ /\ S^{0.5} \qquad (2.2)$$

where a and C were constants derived for a region.

The SCS method further modified equation 2.2 (and used LG in place of LG2) to the form

$$LG = C\ (\ L\ L_{ca}\ /\ S^{0.5}\ )^{X} \qquad (2.3)$$

where X was a regional constant.

Thus, knowing the average lag time for a number of watersheds together with the geophysical parameters, C and X can be determined using linear regression analysis on log(LG) and the corresponding $LL_{ca}/S^{0.5}$ values.

2.4 The Runoff Curve Number

As a part of the SCS method, a technique was derived to estimate the rainfall excess in terms of runoff curve numbers (CN) and the initial abstraction, Ia. A curve number was assigned to each combination of land cover type and hydrologic soil type. CN values ranged from 0 to 100, with zero direct runoff if CN = 0 and direct runoff of all rainfall if CN = 100. The initial abstraction represented the amount of rainfall that must fall before any resulting direct runoff occurred. It was estimated by the following equation :

$$Ia = k\ S\ \text{mm} \qquad (2.4)$$

In equation 2.4, S was estimated from

$$S = 25.4\ ((1000\ /\ CN) - 10) \qquad (2.5)$$

and the recommended value for k was 0.2.

Whenever estimating flows for design purposes, SCS recommended using antecedent moisture condition type II (AMC II) which was defined as the average condition for annual floods. However, if the prevailing condition at the start of a specific storm was not equivalent to AMC II, a calculation based upon k = 0.2 and unchanged CN values would result in an incorrect estimate of the rainfall excess.

Hawkins (1973) performed an analysis of storms on 4 small watersheds in the USA. The results consistently showed that, if a value for k = 0.2 was assumed throughout, then, as the storm depth increased, the effective curve number of the watershed decreased.

A further study by Hawkins (1975) highlighted the relative importance of the curve number. This pointed out that a 10% error in CN values, which can result from the use of a different AMC, can lead to a 50% error in rainfall excess.

Golding (1979) suggested that simply changing the curve numbers to accommodate changes in AMC was invalid and that the initial abstraction should be altered instead. Further, Golding considered that the recommended k value of 0.2 was too high for most purposes and suggested further study of this matter.

2.5 Advances in Data Collection

The traditional method of collecting geographic data, such as the type of land cover, has been to planimeter partial areas from maps or plans. This is a time-consuming and costly procedure. More recently, this process has been superceded by the digital input of map data using large digitizing tablets.

One major field of research related to the current study has been the use of data from earth resources satellites such as LANDSAT. The LANDSAT satellites scan the entire earth's surface between 80° N and 80° S. Images can be obtained in either digital form or as a photographic representation. The pixel size is 80m by 80m which is more than sufficient for most hydrological purposes.

In order to avoid the development of a multitude of classification systems relating remotely sensed land cover data to a numerical code, Anderson et al (1976) devised a 2 Level classification system. Level 1 categories, for example, include forest land, range land and barren land. Each Level 1 category is sub-divided into Level 2 categories. The Level 2 categories for forest land include deciduous, evergreen and mixed forests. This classification system was used in the current study.

The SCS tables for curve numbers contain, for example, for forested land five different CN values for each soil drainage classification. These values are based upon the different hydrologic condition of the ground surface. Ragan and Jackson (1980) showed that it may be possible to broaden these bands such that curve numbers are only required at Level 1. This approach, if successful, would make classification from LANDSAT data more feasible.

Still and Shih (1985) applied these techniques to compare CN values obtained from from LANDSAT imagery with those from conventional maps. At Level 1, good agreement was generally achieved although there was some discrepancies between rangeland and wetland.

Paine (1984) describes a classification carried out using LANDSAT data in one part of the current study area. Paine classified Level 1 and some Level 2 categories and compared the results with a land cover plan of the area. Agreement existed across 94% of the study area. With this accuracy, and if sufficient land cover categories can be identified from the imagery, expansion of a land cover database using LANDSAT data should prove realistic.

2.6 Geographical Data Management

Computerized storage of geographical data for a large area must be carefully planned to ensure efficient use of resources. Where full spatial correspondence exists between data elements, a relational database can be employed. Carstensen (1986) noted that

> "the key advantage of a Geographic Information System (GIS) over a relational system is the ability to compare data elements that have no spatial correspondence".

Carstensen noted soil types and vegetation as two elements without spatial correspondence.

Spatial data can be stored in a GIS in one of two ways. The vector method stores the boundaries between different data categories either as sets of coordinates or as polygons. The raster or grid cell method is similar to a television picture where each component of the picture has a fixed finite size. The value associated with each data element is then assumed constant within the grid square. The vector method is able to give higher resolution whilst the raster method is often faster computationally.

Monmonier (1982) considers raster storage more appropriate for land use data that accounts for all land whereas vector storage is more suitable for items such as transmission lines. Of more importance to the current study, Monmonier notes that abstracting small blocks of data from a database is much simpler and quicker using the raster method. Clarke (1986) notes that, while neither storage structure is appropriate for all applications, raster information is generally easier to overlay and to update.

It is important to consider the management of the GIS whenever implementing such a system. This is particularly important for a production, as opposed to a research or one-off, system and becomes crucial if amendments to one data element alter other elements in the GIS. Dangermond (1986) recommends a transactional approach that automatically checks each amendment for any relational effects. The system makes the necessary changes to ensure the data is fully updated at all times.

Examples of hydrologically-oriented Geographic Information Systems have usually employed the raster approach. Ragan and White (1985) describe a GIS established to aid flood flow estimation in Maryland, USA and Miller (1985) describes the application of a GIS as a tool to input data to a hydrological simulation model. Both these studies successfully used raster techniques to handle the spatial data elements.

CHAPTER 3

METHOD OF ANALYSIS

3.1 General

This chapter describes the techniques used in the study in a generalized format. Details of the application of the methods to the study region can be found in Chapters 4 and 5.

The study was broadly divided into two separate though interrelated parts. The first involved the design and implementation of a Geographic Information System (GIS) to handle the spatial data elements. The second used the GIS data, together with results from numerous storm analyses, to apply the SCS method to the study region and to provide the capability for flow estimation at ungauged sites.

3.2 Organization of the Geographic Information System

3.2.1 General

The first decision made, prior to the establishment of the GIS, was to select the format best suited to handle the various data elements for the purposes of the study. The data for the current study were all represented on maps and plans in vector form as contours or as boundaries between different data categories. Representation of these data in vector form would achieve the greatest accuracy between plans and the digital data. If the prime objective had been of a cartographic nature, rather than a data collection for hydrological analysis, the vector method would probably have been selected. However the complexity of the computer software and their running times would have been greater (Monmonier, 1982). Adequate resolution for the hydrological analysis could be achieved using raster techniques which were, therefore, adopted throughout. A 1km square grid was employed wherever sufficient data existed. The GIS grid corresponded with the Canadian Universal Transverse Mercator (UTM) grid to facilitate cross-reference.

3.2.2 Data Stored in the GIS

The following types of data were collected and input into the GIS for the study area :

1) land cover classification;
2) soil drainage classification;
3) representative elevation;
4) SCS runoff curve number (CN);
5) rainfall extreme values.

The available data for the rainfall extreme values were less precise and a 10km by 10km grid used in this case. Further details on the data can be found in Chapter 4.

3.3 Derivation of Regional Unit Hydrograph and Regional Lag Curve

3.3.1 Choice of Watersheds

The application of the SCS method necessitated that a number of conditions be satisfied before a watershed could be selected for detailed analysis. These constraints can be summarised as follows:

1) the flow must be natural (that is not regulated by man);
2) there must be a current gauging station with an automatic recording device;
3) there must be at least one recording rain gauge either within or very close to the watershed with records for at least 3 or 4 years;
4) there must be data from which the soil drainage and land cover classifications could be assessed for the whole watershed.

The watershed area was limited to a maximum of 1000 sq kms. Elevation and rainfall extreme values were available for the whole of Canada and did not affect the selection of the study region.

3.3.2 Selection of Storms for Analysis

The following guidelines were employed to select those storms suitable for further analysis from the daily rainfall and mean daily discharge data for each watershed :

1) direct runoff hydrograph with a substantial single peak;
2) snowmelt not considered to be a significant factor;
3) snowfall near to zero, even at the highest elevations;
4) rainfall/runoff showing a recognizable response pattern.

The most recent 6 - 10 events for each watershed were selected.

Hourly flow and rainfall values were obtained for each selected event.

In a number of cases instrument malfunction precluded the further use of that storm. Malfunction usually took the form of either complete loss of rainfall record for the event or an unresolvable discrepancy in the timing between rainfall and runoff.

If the hourly flow data showed a distinct double peak, the storm was also discarded as unsuitable for further analysis.

3.3.3 Derivation of Dimensionless Unit Hydrograph

The technique derived by the US Soil Conservation Service (National Engineering Handbook Section 4, 1972) was used to determine the dimensionless unit hydrograph (DUH) for each selected storm. The method can be summarised as follows (refer to Appendix C for a worked example) :

1) determine base flow for each event taking account of the preceding hydrograph recession, if applicable, and assuming that the recession of the direct runoff hydrograph followed a logarithmic relationship. It was further assumed that the direct runoff should be close to zero by the time recommended by Linsley et al (1982) in the equation

$$T = 19.2 \text{ Area}^{0.2} \text{ hours} \qquad (3.1)$$

where Area is the watershed area in sq. kms.;

2) compute the total volume of direct runoff (TOTVOL cumec-days);

3) determine the volume of direct runoff

as a proportion of the total rainfall;

4) determine rainfall losses using the constant Φ-index method;

5) determine the rainfall excess and its duration (D hrs);

6) determine Lag (LG) as time from centre of rainfall excess to time of 50% of direct runoff volume;

7) define TLGD2 as LG + D/2;

8) plot DUH using the following ordinates :

   X-axis Time as % of TLGD2

   Y-axis Flow x TLGD2 / TOTVOL

   and plot on a logarithmic scale.

3.3.4 Derivation of the Regional Unit Hydrograph

The average DUH for each watershed was derived by averaging the time ordinates corresponding to a specific dimensionless discharge. This technique does not give realistic average peak values. These values were obtained by independently averaging peak values of flow and the corresponding times of peak flow.

A similar averaging process was performed to determine the regional unit hydrograph (RUH) except that the values were weighted according to the number of hydrographs studied for each watershed.

3.3.5 Estimation of Lag from Watershed Parameters

The regional lag curves were computed using the following equation :

$$LG = C \ (\ L \ L_{ca} \ / \ S^{0.5} \ )^{X}. \qquad (3.2)$$

Parameters L, L_{ca} and S were determined for each watershed using the digitizer and the regional relationship derived using linear regression analysis on the average watershed lag times.

3.4 Determination of Runoff Curve Numbers

The SCS method assigned a curve number (CN) to each combination of land cover type and soil drainage classification within the watershed. The average curve number for the watershed was derived by weighting according to the area represented by each CN value. The rainfall excess was computed by the following equations :

$$Q = \frac{(P - Ia)^2}{P - Ia + S} \qquad (3.3)$$

$$S = 25.4\ ((1000 / CN) - 10) \qquad (3.4)$$

where P is total rainfall (mm) to present time,

CN is the weighted watershed curve number,

Ia is initial abstraction (often set to 0.2 S) (mm),

Q is the total rainfall excess (mm) to the present time.

Incremental values of Q were determined by subtracting Q for the previous time step.

Tables of curve numbers for different areas, combinations of land cover and soil drainage classifications and methods of data acquisition can be found in Design of Gravity Dams,(1978), Rawls et al,(1980), and Ragan and Jackson,(1980).

Equations 3.3 and 3.4 can be inverted to produce an estimate of the effective CN for each particular storm. Effective CN values were compared with the original estimates of watershed CN values obtained from the GIS data and the assumed CN relationships. Revised CN reference tables were produced and re-tested.

3.5 Flow Estimation

3.5.1 Unit Hydrograph from Regional Unit Hydrograph

The Pmm Thr unit hydrograph was computed as follows :

1) determine watershed area, length of main watercourse, length of main watercourse to centroid of area, mean slope of main watercourse using input from the digitizer;
2) determine lag, LG, using data from 1) and the regional lag curve;
3) select duration of unit hydrograph, T hours (equivalent to D in DUH), approximately equal to 0.2 LG (rounded to a convenient figure);
4) compute TLGD2 (= LG + 0.5 T) and the total volume of 1 unit (10mm) of rainfall excess falling over the whole watershed (= TOTVOL) (cumec-days)
5) derive T-hr unit hydrograph by interpolation from the Regional Unit Hydrograph as follows :
    a) express integer multiples of T as % of TLGD2
    b) q = corresponding flow ordinate x TOTVOL / TLGD2

3.5.2 Runoff from Rainfall

The total rainfall was derived either from storm analysis or from the rainfall extreme values stored in the GIS. The rainfall excess was calculated by application of eqs 3.3 and 3.4 using the computed watershed curve number and assuming a value for the initial abstraction, Ia, as a proportion of S.

The additive properties of the unit hydrograph technique were used to derive the direct runoff hydrograph corresponding to the rainfall excess distribution using the equation

$$Q_i = \sum_{j=1}^{i} RX_j \; U_{i-j+1} \qquad (3.5)$$

where i and j are integer multiples of the duration of the unit hydrograph,

RX is the rainfall excess,

U is the unit hydrograph ordinate,

Q_i is the direct runoff at time iT hrs.

3.6 Verification of the Results

3.6.1 General

The overall objective of the study was to apply the SCS method to the study area in order to facilitate the prediction of flood flows of 5 to 100 year return period at ungauged sites. Modelling of individual events, for which accurate antecedent moisture condition information must be available, was not the objective. Consequently, verification of the derived regional curves was carried out by creating synthetic flow frequency curves. Two methods were used and are discussed in the next sections.

3.6.2 Gauging Station Data

Annual maximum instantaneous flows were collected for a number of the gauging stations included in the study. Flow frequency curves were drawn for each station. Stations whose records included a significant proportion of snow-influenced maxima were excluded from this analysis.

3.6.3 Flow Estimation using Derived Regional Curves

Two methods were used to verify the derived regional curves and data. The methods are discussed briefly in this section and in more specific detail in Chapter 5.

Both methods used the predictive capability of the GIS-SCS system by abstracting the relevant watershed data from the GIS for a watershed boundary described on the digitizer. Both methods also used the available rainfall extreme values which assumed a Gumbel Extreme Value Type 1 (EV1) distribution for the data. It was therefore possible to estimate the rainfall depth corresponding to any return period or excedence probability.

Method 1 used a set of 100 randomly selected excedence probabilities. The rainfall extreme depth corresponding to each probability was estimated and the resulting maximum flow rate computed. A synthetic flow frequency curve was drawn assuming a Gumbel EV1 distribution for the flow data set. A comparison was made between the gauging station and the synthetic frequency curves.

Method 2 assumed a one-to-one relationship between the rainfall and the resulting runoff return period. The rainfall extreme depths for a number of discrete return periods between 2 and 200 years were estimated. The resulting set of maximum flow rates was compared with the corresponding set obtained from the gauging station records for the same return periods.

Further details of the methods including a discussion of the assumptions can be found in Chapter 5.

3.7 Equipment Used

The entire analysis was carried out on a microcomputer based system comprised of the following elements :

1) IBM PC XT computer with 640kb memory, 10Mb hard disk and 370kb floppy disk drive
2) KURTA Series 3 Model 100 digitizer including a cursor with a 16 key pad and an 8 digit LED display
3) HP 7475A plotter
4) Gemini-15 printer

All programs were written specifically for this study using IBM BASICA and run either in interpretive or in compiled form.

CHAPTER 4

THE GEOGRAPHIC INFORMATION SYSTEM

4.1 General

Chapter 3 described the aim for the Geographic Information System (GIS) in general terms. This chapter describes details specific to this study in the foothills region of Alberta and discusses the methods used together with possible longer term improvements.

4.2 Study Location

The application of the guidelines listed in section 3.3.1 limited to 8 the number of watersheds suitable for detailed analysis. These watersheds were all located in the foothills region on the eastern slopes of the Rocky Mountains. The watersheds each formed a part of either the Bow River or Red Deer River river basins to the west of Calgary. The eastern, and downstream, limit was close to the boundary between the foothills and the prairies whilst the western limit generally followed the eastern most mountain range. The location of the study region is shown on Figure 4.1. The eastern and western limits were dictated by the availability of compatible land cover and soil drainage data. Within these limits, restrictions on

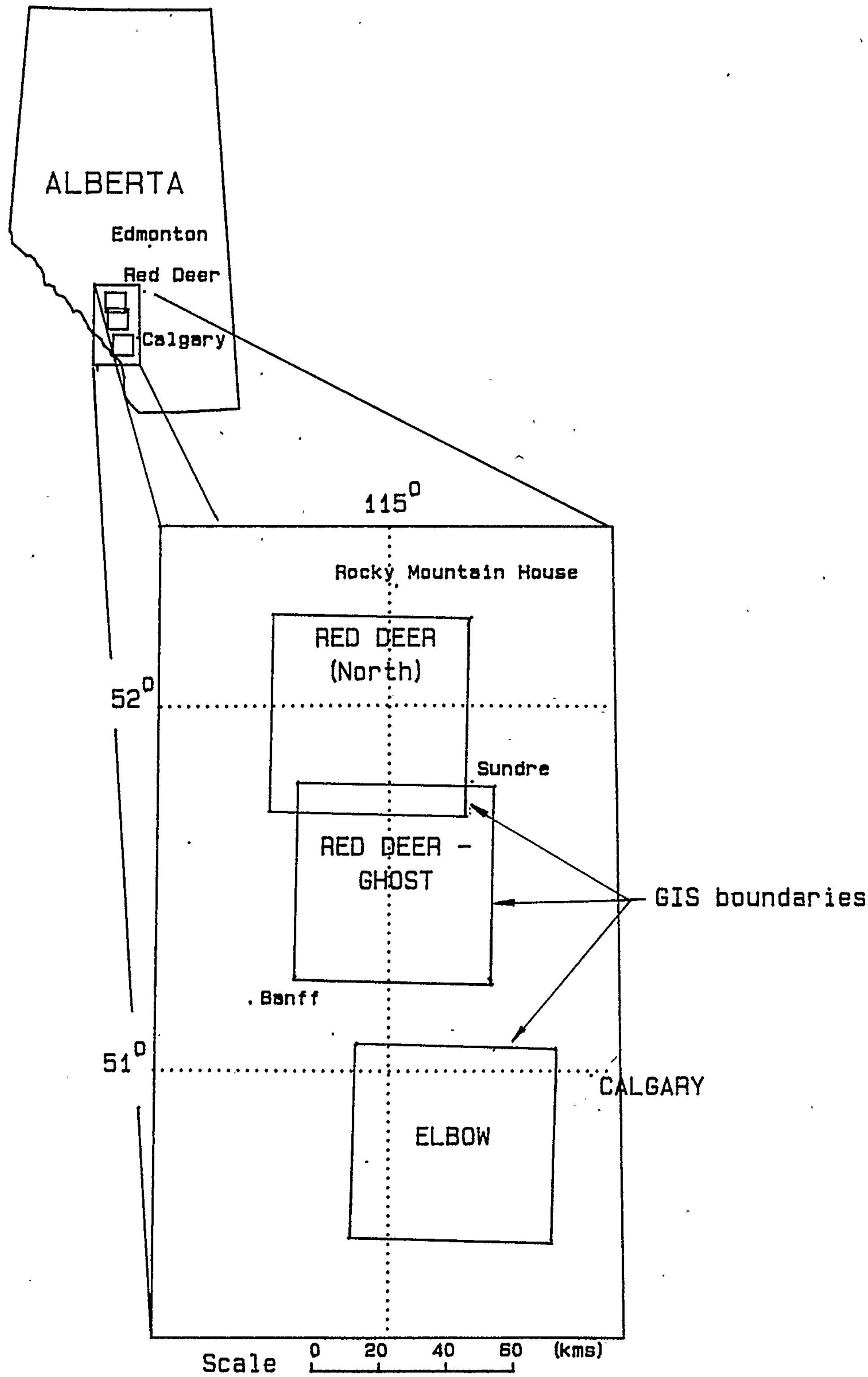


FIGURE 4.1 LOCATION OF STUDY AREA

the selection of natural flow watersheds were generally caused by insufficient rainfall data.

The topography of the area ranged from rugged, barren mountain ridges to the west to rolling forested foothills in the east. The elevation of the study area varied from 3000 m asl in the mountains to 1100 m asl in the east. Land cover was predominantly coniferous or mixed forest. Exceptions to these were areas of exposed bedrock along the higher mountain ridges and deciduous treed grassland areas at the lowest elevations.

The climate contained both cordillera (mountain) and continental (prairie) elements. The continental climate affected the eastern half of the study area and featured long cold winters and short warm summers with 60% of the precipitation occurring between May and September. The cordillera climate featured cool summers and milder winters with the majority of precipitation in the winter. Typical annual precipitation for the summer period was 400mm. The mean monthly temperature at valley level in the study region varied from +13^{o}C in July to -11^{o}C in January.

Surface geology was comprised mainly of glacial moraine and colluvium. Bedrock geology included shales, sandstones and limestone.

Further details on the natural features of the study region can be found in the respective "Ecological Land Classification and Evaluation" report.

The main details of the gauging stations used to mark the downstream limit of each watershed are shown in Table 4.1. The abbreviated station names were chosen for this study and have been used throughout as the reference name for the related watershed. The total area of the watersheds in the study region was 3118 sq.kms.

4.3 Data Storage

4.3.1 General

The GIS was organized to take account of the limited memory of the IBM PC microcomputer. In order to keep the size of the database manageable, the study region was subdivided into three areas as follows :

1) Red Deer (North),
2) Red Deer - Ghost,
3) Elbow.

Each part was formed into a 60 km by 60 km area. There were therefore 3600 values for each variable when stored on a 1km by 1km grid. The UTM grid references defining the limits of each part exactly are given in Table 4.2. The limits are shown on Figure 4.1.

TABLE 4.1

DETAILS OF THE GAUGING STATIONS USED IN THE STUDY

River	Gauging Station	Stn No	Study Code	Drainage Area (sq kms)
James River	near Sundre	05CA002	JAME	820
Bearberry Creek	near Sundre	05CA011	BEAR	233
Fallentimber Creek	near Sundre	05CA012	FALL	484
Little Red Deer River	near Water Valley	05CB002	LRDR	457
Waiparous Creek	below Meadow Creek	05BG009	WCMC	228
Waiparous Creek	near the Mouth	05BG006	WCTM	332
Elbow River	above Elbow Falls	05BJ006	ELBF	435
Elbow River	at Bragg Creek	05BJ004	ELBC	792

Notes 1) Drainage areas quoted and used throughout this study were derived from direct input from the digitizer and vary slightly from those quoted by the Water Survey of Canada.

2) Stations BEAR and FALL are operated by Alberta Environment, the remainder by Water Survey of Canada.

3) WCMC and ELBF are upstream of WCTM and ELBC respectively.

TABLE 4.2

DETAILS OF STUDY AREA BOUNDARIES

No	Study Area	Position of SW corner		
		Latitude	Longitude	UTM Grid Ref
1	Red Deer (North)	51.71°N	115.55°W	PW 000 300
2	Red Deer - Ghost	51.26°N	115.42°W	PG 100 800
3	Elbow	50.54°N	115.17°W	PG 300 000

Notes 1) The grid for each study area follows the UTM grid orientation.

2) East - west length 60km for each area.

3) North - south length 60km for each area.

Data for each variable were extracted manually from maps and plans. This process was expedited considerably through using the 16 key cursor of the digitizer as a numeric keypad. The data were all stored in random access files which enabled instant access to any part of the database. This reduced significantly the time taken to collect data for a watershed from the GIS. The areal extent, for which data were stored, was generally restricted to that within, and immediately outside, the boundaries of the studied watersheds. Further details of the GIS are given in Appendix D.

4.3.2 <u>Land Cover Classification</u>

The land cover classification was abstracted from 1:31680 scale forest cover overlays published by Alberta Energy and Natural Resources. The average land cover type was estimated for each kilometre square. Each different land cover type was assigned a 3 - Level code that followed the recommendations of Anderson et al (1976) for Levels 1 and 2. Level 3 was used to subdivide further the classification, where appropriate, and was set to 1 where not required. The relationship between land cover classification and the digital code is given in Appendix B.

4.3.3 Soil Drainage Classification

The soil drainage data was obtained from a series of "Ecological Land Classification and Evaluation" reports published by Alberta Energy and Natural Resources. Three reports covered the study region ; "Red Deer - James", "Ghost River" and "Kananaskis Country". A 1:100000 scale map accompanied each report . Details shown included the soil drainage classification according to the Canadian National Soil Survey Committee (1974). The classes can be summarized as follows :

Class	Description
1	Rapidly drained
2	Well drained
3	Moderately well drained
4	Imperfectly drained
5	Poorly drained
6	Very poorly drained

The hydrologic soil groups used for the SCS method differ from the above and are described as follows :

Class	Description
A	High infiltration rate - Well to excessively well drained
B	Moderate infiltration rate - Moderately well to well drained
C	Slow infiltration rate - Moderately fine to fine soil texture
D	Very slow infiltration rate - Clays or permanent high water table.

An empirical relationship between the Canadian and SCS classifications was assumed in the application of the SCS techniques. The relationship was modified subsequently to improve runoff curve number prediction. The final relationship is given in Table 4.3.

4.3.4 Elevation Data

The representative elevation for each grid square was determined by visual examination of the contours shown on the National Topographic Survey (NTS) 1:50000 scale map. The raw data was input in hundreds of feet above sea level (asl). The data was converted into metres (asl) and stored on the GIS.

TABLE 4.3

ASSUMED RELATIONSHIP BETWEEN CANADIAN (CANSIS)

AND

US (SCS) SOIL DRAINAGE CLASSIFICATIONS

CANSIS	SCS
1	A
2	B
3	C
4	C
5	C
6	D

4.3.5 Rainfall Extreme Statistics

Values of the mean and the standard deviation of the annual rainfall extremes for storm durations of 2, 6, 12 and 24 hours were interpolated from the plans contained in the "Rainfall Frequency Atlas of Canada" (1985). These were stored in the GIS on a 10 km by 10 km grid as the data did not warrant a finer mesh.

4.4 Uses of the Data

4.4.1 SCS Runoff Curve Number

After completion of the curve number (CN) reference file (see section 5.2.6. for details) program HYDCN was used to obtain the land cover and soil drainage classification for each grid square in sequence, assign the appropriate CN value for that square and store that value on a curve number file. The prior computation of the CN values reduced the time taken to compute a weighted watershed curve number.

4.4.2 Data Abstraction for a Watershed

The chief objective in establishing the GIS was to create a system that allowed rapid access to data for any part of the study region, such as a watershed boundary described using the digitizer.

Program HYDSCS was written to enable the user to describe any area within the study area on any scale of map. The boundary of the watershed was stored as a continuous stream of X,Y coordinates. Using this information the software computed the partial area of each grid square that lay within the watershed boundary. From this data analysis included computation of the overall watershed area, summation of areas of each land drainage and soil drainage classification and computation of the weighted curve number for the watershed. The weighted curve number was computed as follows :

$$CN = \frac{\sum_{i=IXMN}^{IXMX} \sum_{j=IYMN}^{IYMX} A_{i,j} \, CN_{i,j}}{Area} \qquad (4.1)$$

where $A_{i,j}$ is the partial area in grid square i,j,
$CN_{i,j}$ is the curve no for grid square i,j,
Area is the total watershed drainage area,
IXMN and IXMX are the min and max X ordinates rounded down to the nearest km,
IYMN and IYMX as above but for Y ordinates,
$0 < A < 1$.

A similar weighting method was used to compute the weighted values for the rainfall extreme data. The upper limit of A in this case was 100 sq kms because of the larger grid size.

The area and location of the centroid of the watershed were calculated using pairs of X,Y coordinates in turn. Details of the algorithms may be found in Appendix D.

4.5 Discussion

The methods used to store and retrieve the data worked well and facilitated the rapid computation of the parameters associated with the required watershed. The GIS, as developed, should be capable of expansion both in terms of additional data elements and of areal expansion.

How feasible is such an expansion? Chapter 2 included a section on the use of LANDSAT remote sensing data as a source of land cover information. Such data can usually only provide input for Level 1 categories. The availability of detailed forest cover maps for the study region enabled information for Level 2 categories and, in some cases, Level 3 categories to be stored. It was considered desirable for this initial study to include the greater detail contained on the forest cover maps. However, if a major areal expansion of the GIS was planned, serious consideration should be given to the use of LANDSAT or other remotely sensed data. Two major benefits would be the saving in time and money and the virtual global coverage readily available. The only potential drawback concerns the resolution of the raw data into land cover classifications at the required Level to retain reliable prediction of the watershed curve number.

Expansion of the soil drainage database may prove more problemmatical. The reports used in this study were part of a series which covered most, but not all, of the Rocky Mountain Forest Reserve. A number of watersheds to the south of Calgary were excluded from the study because compatible soil data was not published for the whole area. Less detailed soil maps are more generally available and it may prove possible to derive, for these maps, an adequate correlation between soil type and the SCS soil drainage classification. Alternatively, it may prove possible to devise a method using remotely sensed data based, perhaps, on estimating moisture retention at the surface.

If these methods for determining the land cover and soil drainage type proved successful, there would be very few factors limiting the further areal expansion of the GIS.

CHAPTER 5

DETAILS OF THE HYDROLOGICAL ANALYSIS

5.1 General

This chapter details the hydrological analysis carried out to establish and verify the regional relationships. Specific discussion and details of interaction with the GIS are included concurrently with each section. The use of the derived relationships as a predictive tool is discussed at the end of the chapter.

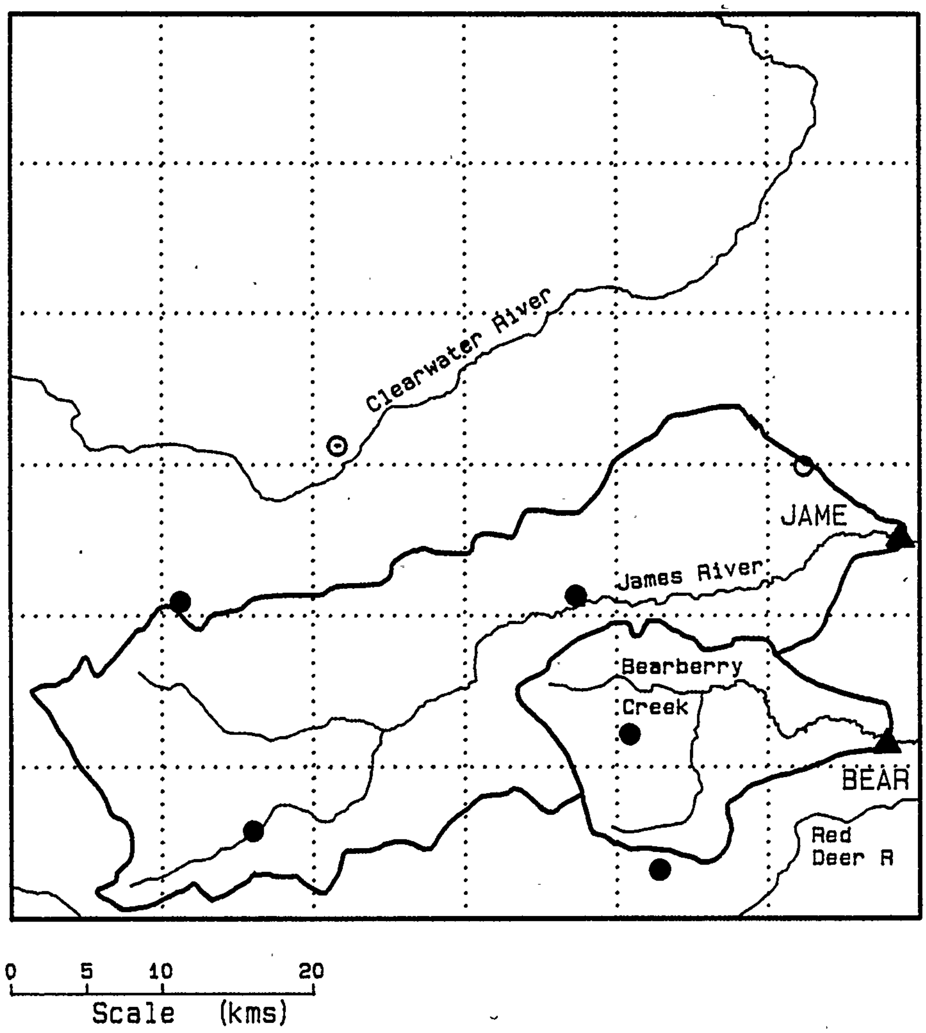
5.2 Application of the SCS Method

5.2.1 Data Collection

The restrictions on the selection of watersheds due to the lack of suitable geophysical data have been noted in Chapter 4. Further restrictions on the selection were caused by the lack of continuous rainfall and runoff data. Details of suitable rainfall stations, including dates of operation, were obtained from the "Alberta Climate Station Catalogue" (1985). Details and dates of operation of the gauging stations were abstracted from "Historical Streamflow Summary - Alberta - to 1984" (1985). The recent installation of the recording raingauges precluded analysis before 1981.

The initial storm selection was carried out by noting daily rainfall values from "Monthly Meteorological Observations in Canada" and mean daily flows from "Surface Water Data - Alberta" for each watershed. The meteorological data indicated the presence of snowfall and, often, included maximum and minimum temperature data. This enabled most snowmelt and snowfall events to be excluded from the data set. The procedure produced a total of 56 station storms suitable for more detailed study.

Hourly flow data were obtained from the respective gauging station operators. Data from the recording rain gauges were abstracted from the computer printouts stored by Alberta Environment, Edmonton. Incomplete records or equipment malfunction, mainly of the rainfall instruments, reduced to 35 the number of suitable station-storms. The locations of the rain gauges and gauging stations in each study area are shown on Figures 5.1, 5.2 and 5.3 respectively. Also shown on these figures are the watershed boundaries and the major watercourses. The widely differing shapes of the watersheds should be noted. For example, on Figure 5.2, watershed FALL has a length to width ratio greater than 5 whereas that for LRDR is approximately 1. Details of the selected storms are given in Appendix A.



LEGEND

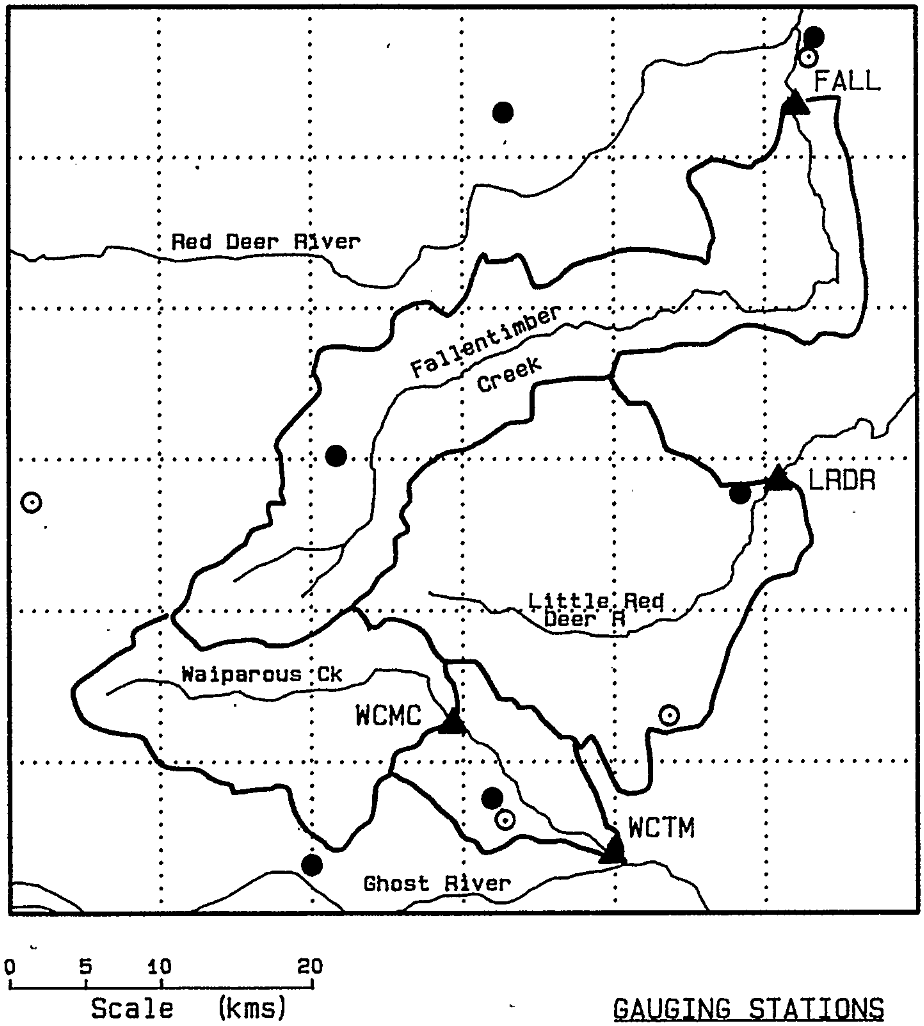
- ▲ Gauging Station
- ● Recording Rain Gauge
- ⊙ Daily Rain Gauge
- ——— Watershed Boundary

GAUGING STATIONS

JAME James River near Sundre

BEAR Bearberry Creek near Sundre

FIGURE 5.1 PLAN OF THE RED DEER (NORTH) STUDY AREA



<u>LEGEND</u>

▲ Gauging Station

● Recording Rain Gauge

⊙ Daily Rain Gauge

—— Watershed Boundary

<u>GAUGING STATIONS</u>

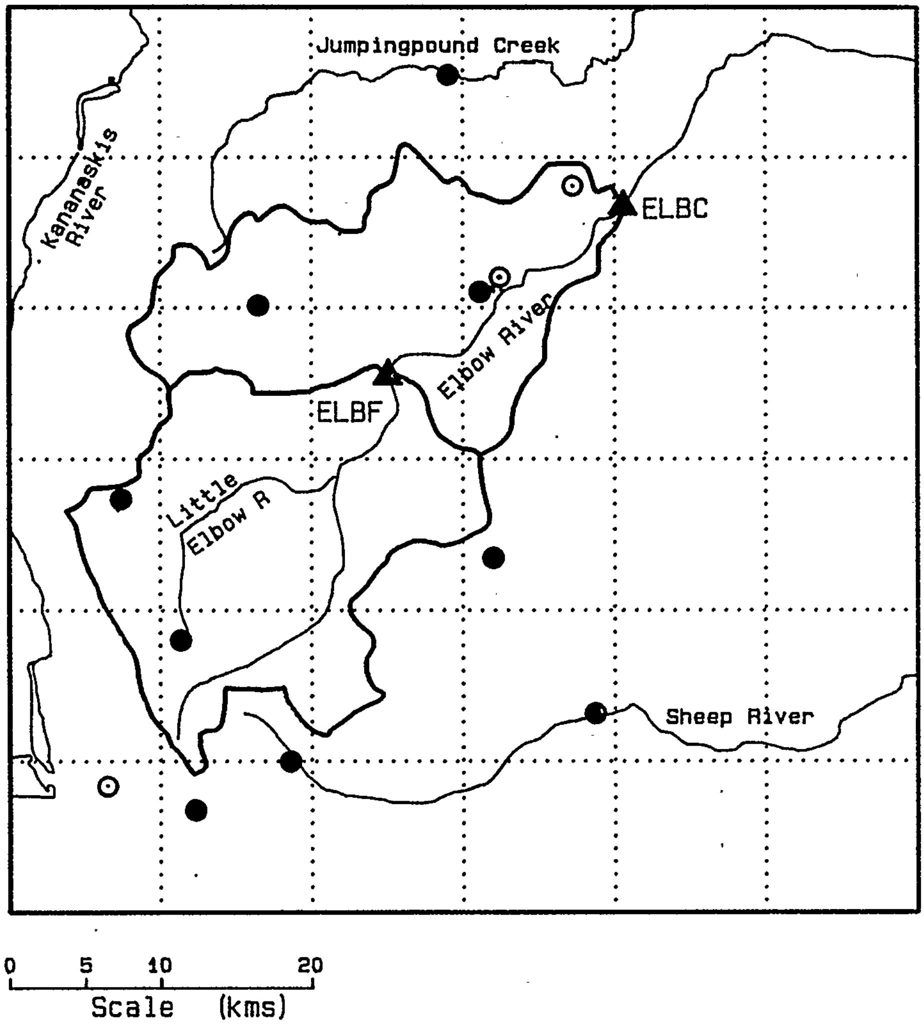
FALL Fallentimber Creek near Sundre

LRDR Little Red Deer River near Water Valley

WCMC Waiparous Creek below Meadow Creek

WCTM Waiparous Creek near the Mouth

FIGURE 5.2 PLAN OF THE RED DEER - GHOST STUDY AREA



LEGEND

- ▲ Gauging Station
- ● Recording Rain Gauge
- ⊙ Daily Rain Gauge
- —— Watershed Boundary

GAUGING STATIONS

ELBF Elbow River above Elbow Falls

ELBC Elbow River at Bragg Creek

FIGURE 5.3 PLAN OF THE ELBOW STUDY AREA

5.2.2 Determination of Average Rainfall Excess

Where two or more continuous rain gauge records existed for a storm, the average rainfall over the watershed was computed using weighting factors assigned by the Thiessen polygon technique. The factors were fixed by the location of the active gauges for each storm. The Thiessen method is purely geometric and cannot account for orographic differences in the pattern of precipitation. This can lead to erroneous results in mountainous regions (Viessman et al, 1977). The alternative was to use the isohyetal method. This approach required a new isohyetal map for each hourly time step and was therefore not considered practical.

The Thiessen polygons for each storm were drawn on a 1:250000 scale map and the partial areas computed using input from the digitizer to program AREA.

In order to compute the rainfall excess for each storm, it was first necessary to calculate the volume of direct runoff. The baseflow was subtracted from the total runoff as described in Section 3.3.3 to leave the direct runoff. The direct runoff volume must be equal to the average rainfall depth applied over the whole watershed area. The distribution of the rainfall excess was calculated by assuming a constant Φ - index loss rate (mm/hour) for each storm. Computer program HYDDUH included a routine to determine the Φ - index. The rainfall excess for each time step was given by the more positive of the following results :

$$RX_t = RF_t - \Phi \cdot \Delta t \quad (5.1)$$

$$\text{or} \quad RX_t = 0 \quad (5.2)$$

where RF_t is the average rainfall depth (mm) in timestep t,

Φ is the Φ - index loss rate (mm/hr),

Δt is the timestep (hrs),

RX_t is the rainfall excess (mm) in timestep t,

Values of the Φ - index varied considerably from storm to storm for the same watershed. The minimum and maximum values were 1.3 mm/hr and 10.8 mm/hr. The latter figure was 50% higher than any other value, and may not be realistic due to inaccurate estimation of the total rainfall depth. The mean Φ - index was 3.7 mm/hr.

It should be noted that the computed Φ - indices cannot be considered totally accurate representations of the rainfall losses as they were obtained from the estimates of total rainfall depth from the Thiessen analysis. Errors in the estimation of total rainfall depth will tend to be absorbed in the calculations. Details of the Φ - indices are included in Appendix A.

5.2.3 Determination of the Dimensionless Unit Hydrograph

The lag, LG, and duration of rainfall excess, D, were determined for each storm. For some storms there were discrepancies between the timing of the rainfall excess and the resulting runoff. Where the direct runoff commenced before the first period of rainfall excess, the following assumptions were made in order to compute the dimensionless unit hydrograph (DUH) ordinates:

D/2 = time from start of direct runoff to the time of centre of rainfall excess;

LG = as elsewhere, time from centre of rainfall excess to centre of direct runoff.

The time TLGD2 (= LG + D/2), used to calculate the dimensionless time ordinate, was then equal to the time from the start of direct runoff or the start of rainfall excess (whichever was the earlier) to the centre of direct runoff. The alteration to D/2 was made chiefly when there was significant low intensity rainfall at the start of the storm.

The SCS DUH was computed for each storm. The peak flow values and the corresponding lag times and storm durations are shown in Table 5.1. The resulting DUH's for each watershed are shown on Figures 5.4 to 5.11 inclusive.

TABLE 5.1

SUMMARY OF DUH ANALYSIS

Event	LG	D/2	TLGD2	Tpk	Qpk
JAME1	19.7	11.5	31.2	83.3	25.6
JAME2	23.3	4.0	25.3	67.2	23.6
JAME3	24.3	11.0	35.3	76.5	27.8
JAME4	44.0	4.3	48.3	76.6	24.2
JAME5	48.9	0.5	49.4	85.0	28.2
JAME6	34.8	4.5	39.3	66.2	24.1
Mean LG	32.5				
BEAR1	31.1	6.0	37.1	72.8	26.5
BEAR2	23.7	4.3	28.0	85.7	27.2
BEAR3	22.8	4.0	26.8	80.2	24.0
BEAR4	44.6	3.1	47.7	90.2	25.3
BEAR5	26.8	4.5	31.3	83.1	28.4
Mean LG	29.8				
FALL1	19.4	3.6	23.0	82.6	20.7
FALL2	33.1	8.2	41.3	87.2	28.2
FALL3	45.5	4.2	49.7	81.5	23.7
FALL4	39.5	3.9	43.4	76.0	23.4
Mean LG	34.4				
LRDR1	14.0	5.0	19.0	73.7	26.9
LRDR2	23.8	14.5	38.3	78.3	29.0
LRDR3	23.3	4.3	27.6	65.2	23.2
LRDR4	19.0	29.2	48.2	80.9	25.1
LRDR5	30.5	3.7	34.2	79.0	21.5
Mean LG	22.1				
WCMC1	27.0	0.5	27.5	50.9	21.9
WCMC2	13.6	9.4	23.0	60.9	19.5
WCMC3	15.3	8.4	23.5	76.6	33.3
Mean LG	18.5				

TABLE 5.1 (cont'd)

Event	LG	D/2	TLGD2	Tpk	Qpk
WCTM1	22.6	0.5	23.1	56.3	22.8
WCTM2	14.1	8.5	22.6	70.8	23.8
WCTM3	13.1	0.5	13.6	73.5	26.9
WCTM4	13.4	3.8	16.9	94.7	27.2
WCTM5	19.5	3.0	22.5	75.6	24.2
Mean LG	16.5				
ELBF1	23.9	9.5	33.4	70.4	24.4
ELBF3	18.4	22.5	40.9	73.4	29.7
ELBF4	21.8	14.2	36.0	75.0	24.5
Mean LG	21.4				
ELBC1	25.6	6.5	32.1	71.7	21.7
ELBC2	21.4	22.5	43.9	76.3	27.3
ELBC4	28.8	9.8	38.6	70.0	24.3
Mean LG	25.3				

NOTES
1) LG, D/2 and TLGD2 are in hours.
2) Tpk is dimensionless
3) Qpk is in hours / day

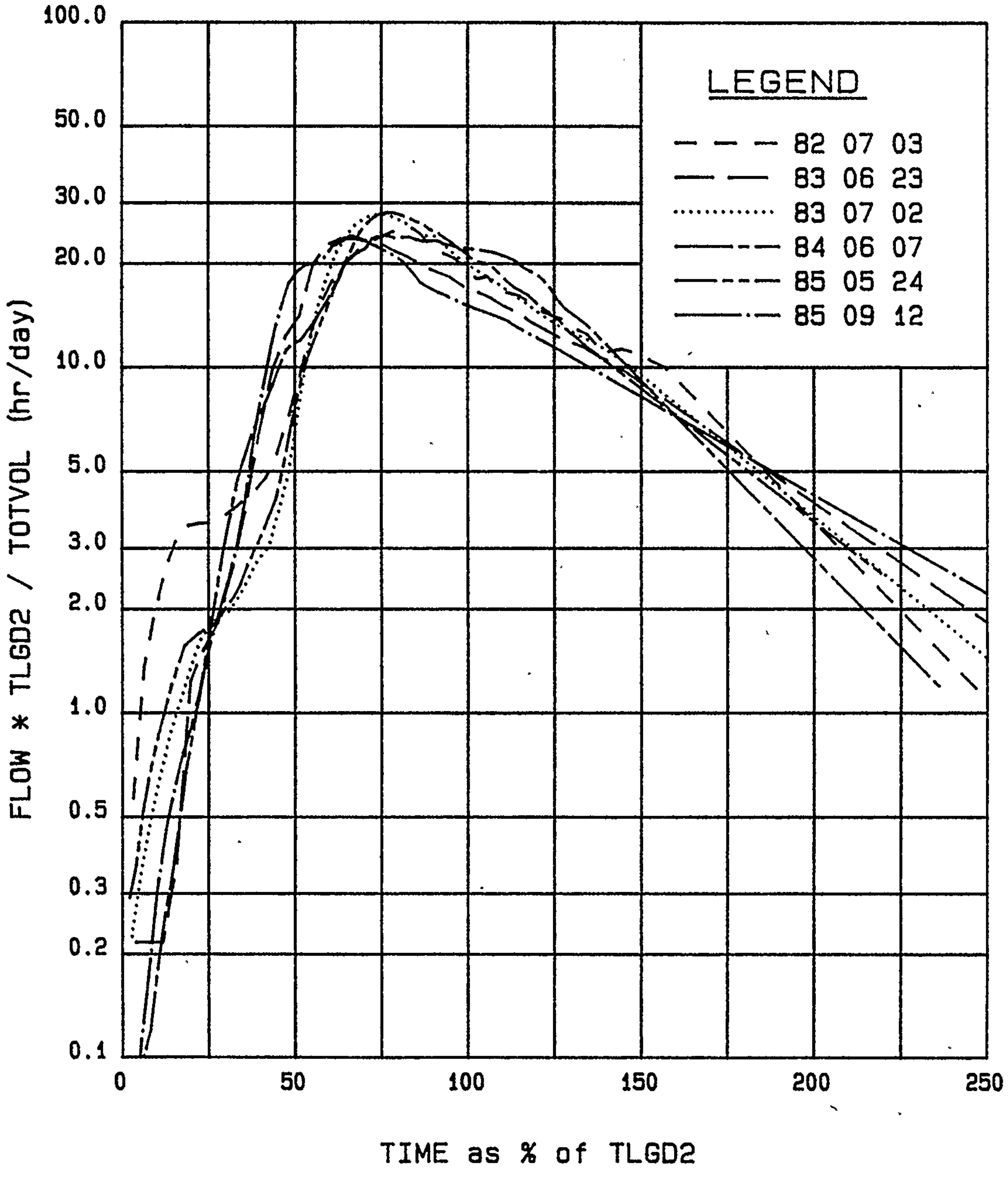


FIGURE 5.4 DIMENSIONLESS UNIT HYDROGRAPHS FOR JAME

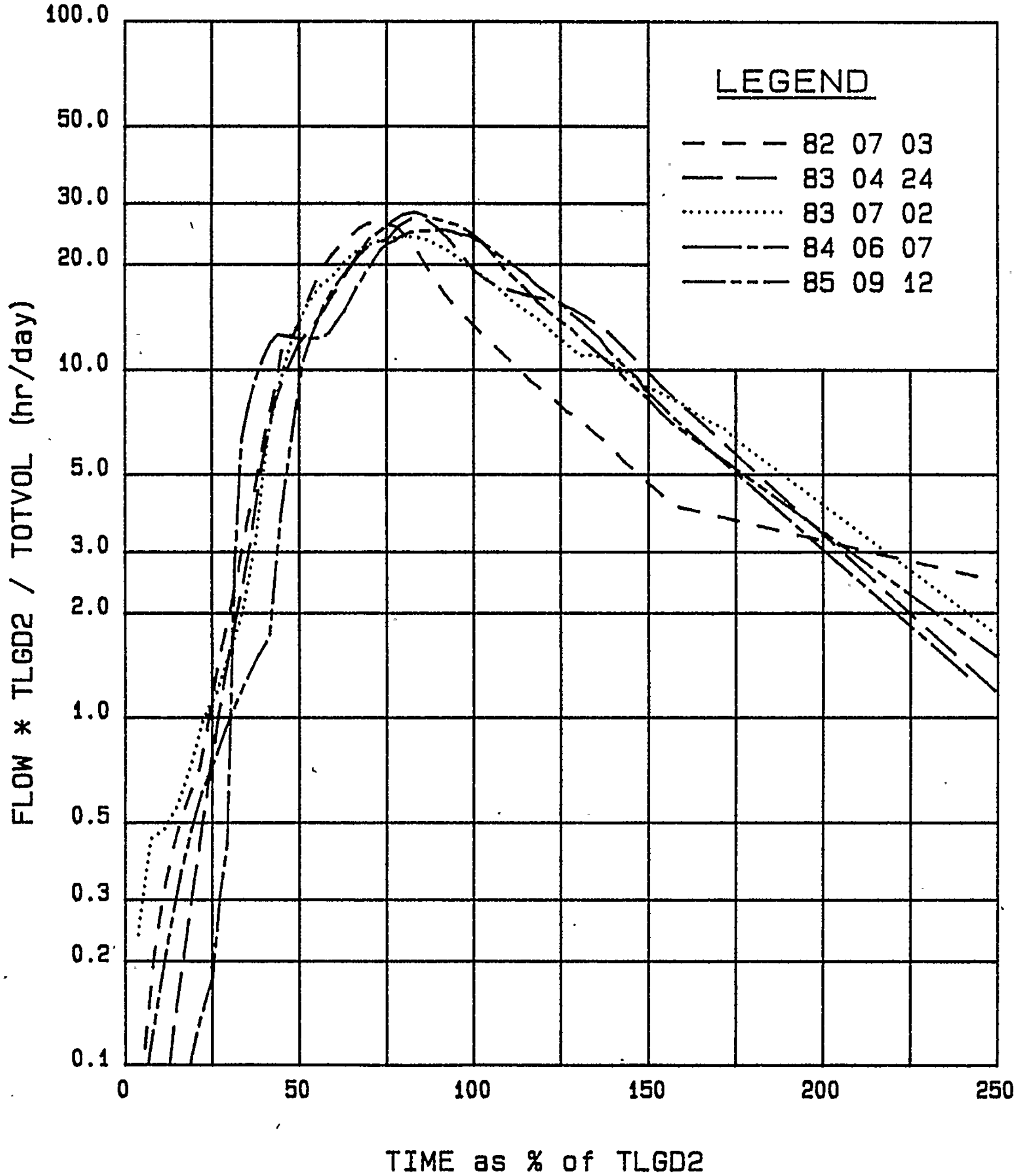


FIGURE 5.5 DIMENSIONLESS UNIT HYDROGRAPHS FOR BEAR

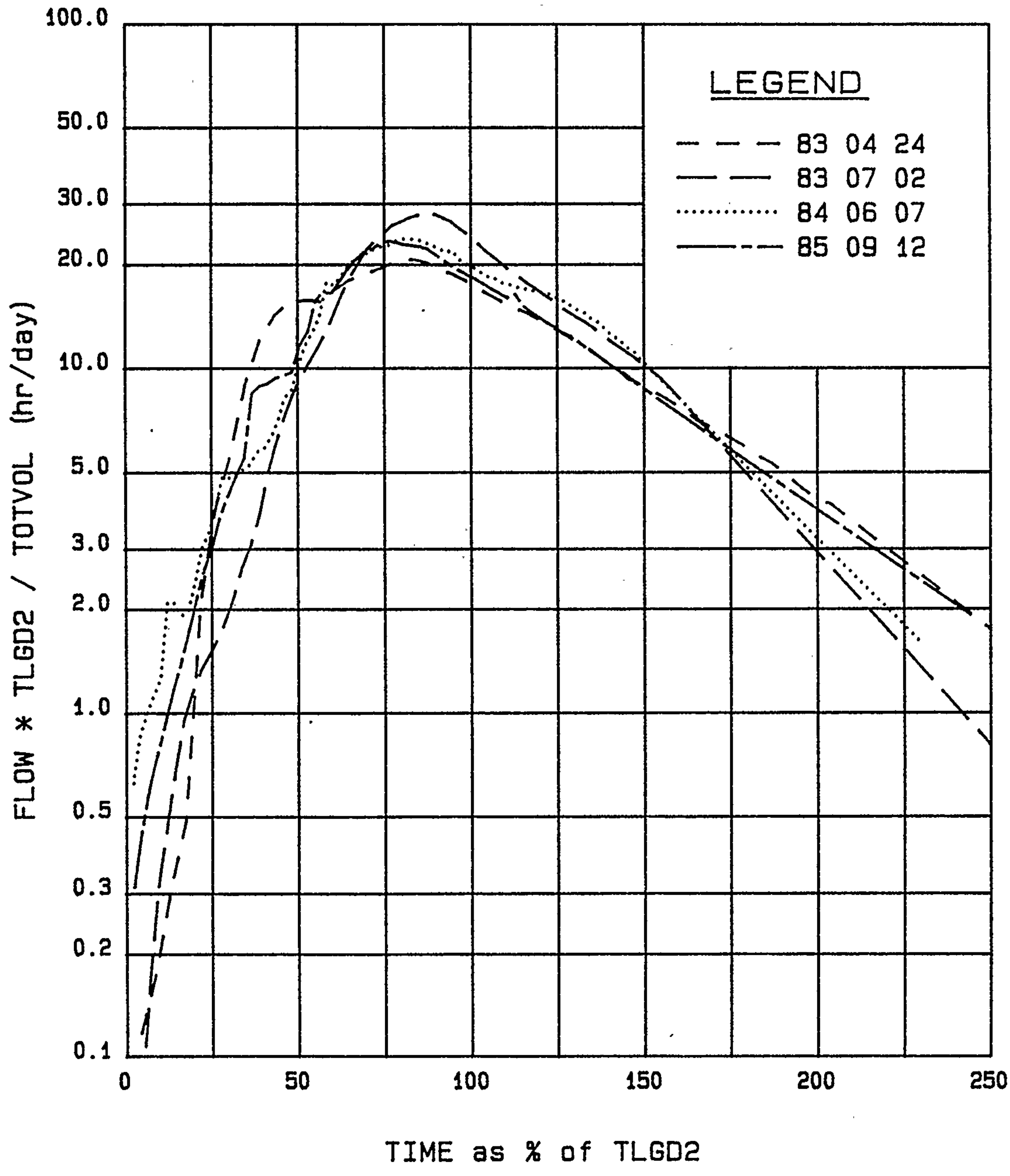


FIGURE 5.6 DIMENSIONLESS UNIT HYDROGRAPHS FOR FALL

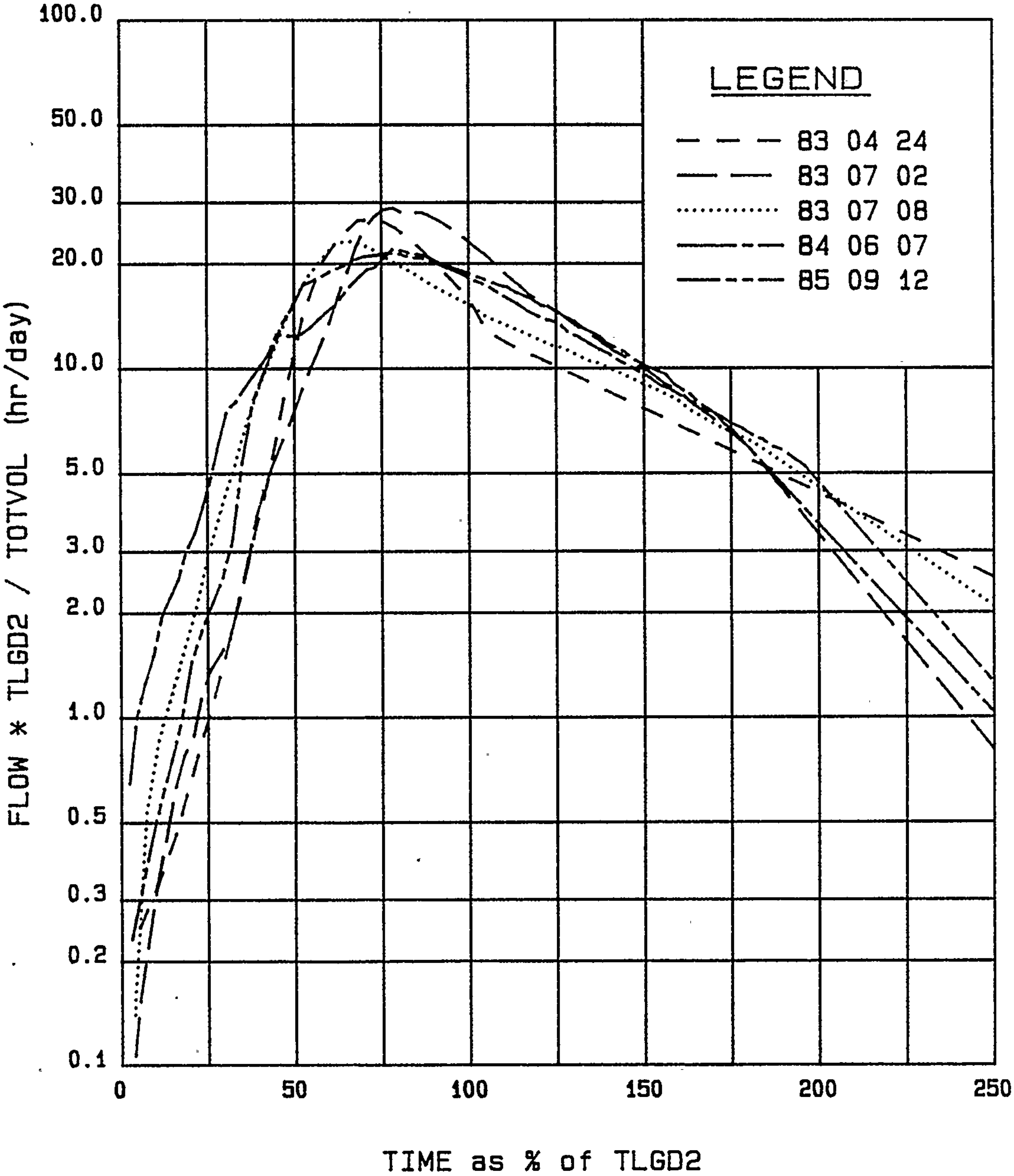


FIGURE 5.7 DIMENSIONLESS UNIT HYDROGRAPHS FOR LADR

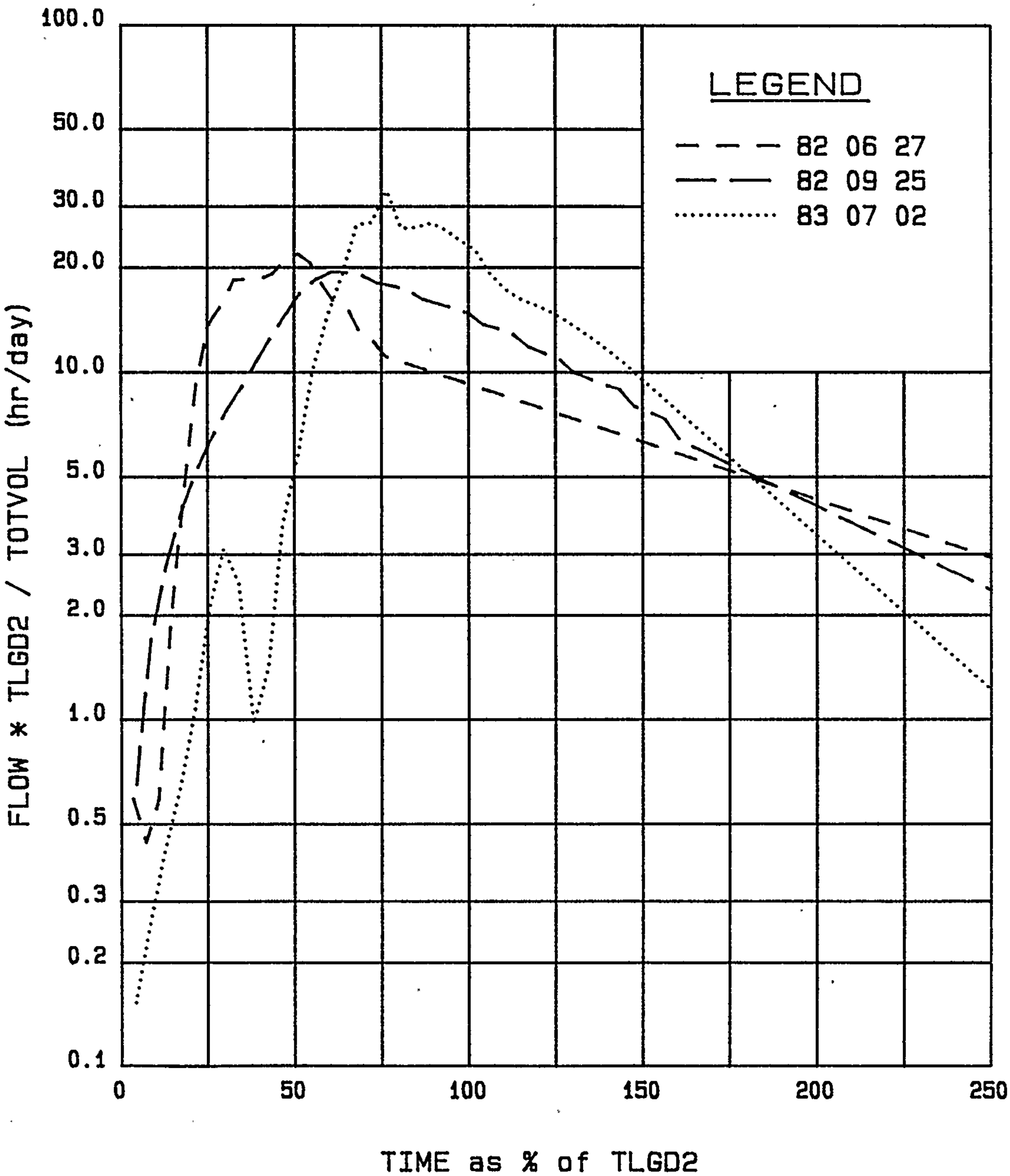


FIGURE 5.8 DIMENSIONLESS UNIT HYDROGRAPHS FOR WCMC

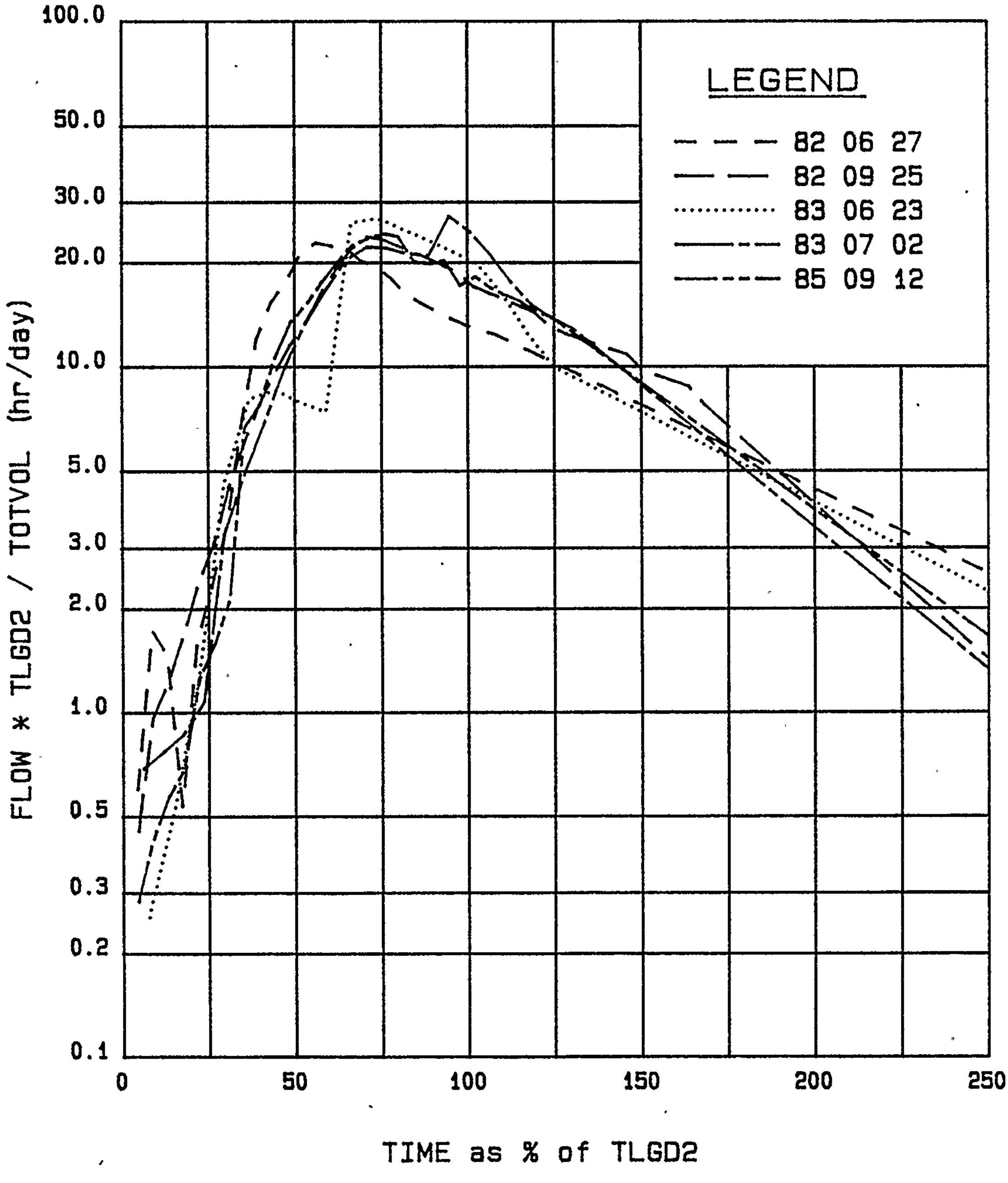


FIGURE 5.9 DIMENSIONLESS UNIT HYDROGRAPHS FOR WCTM

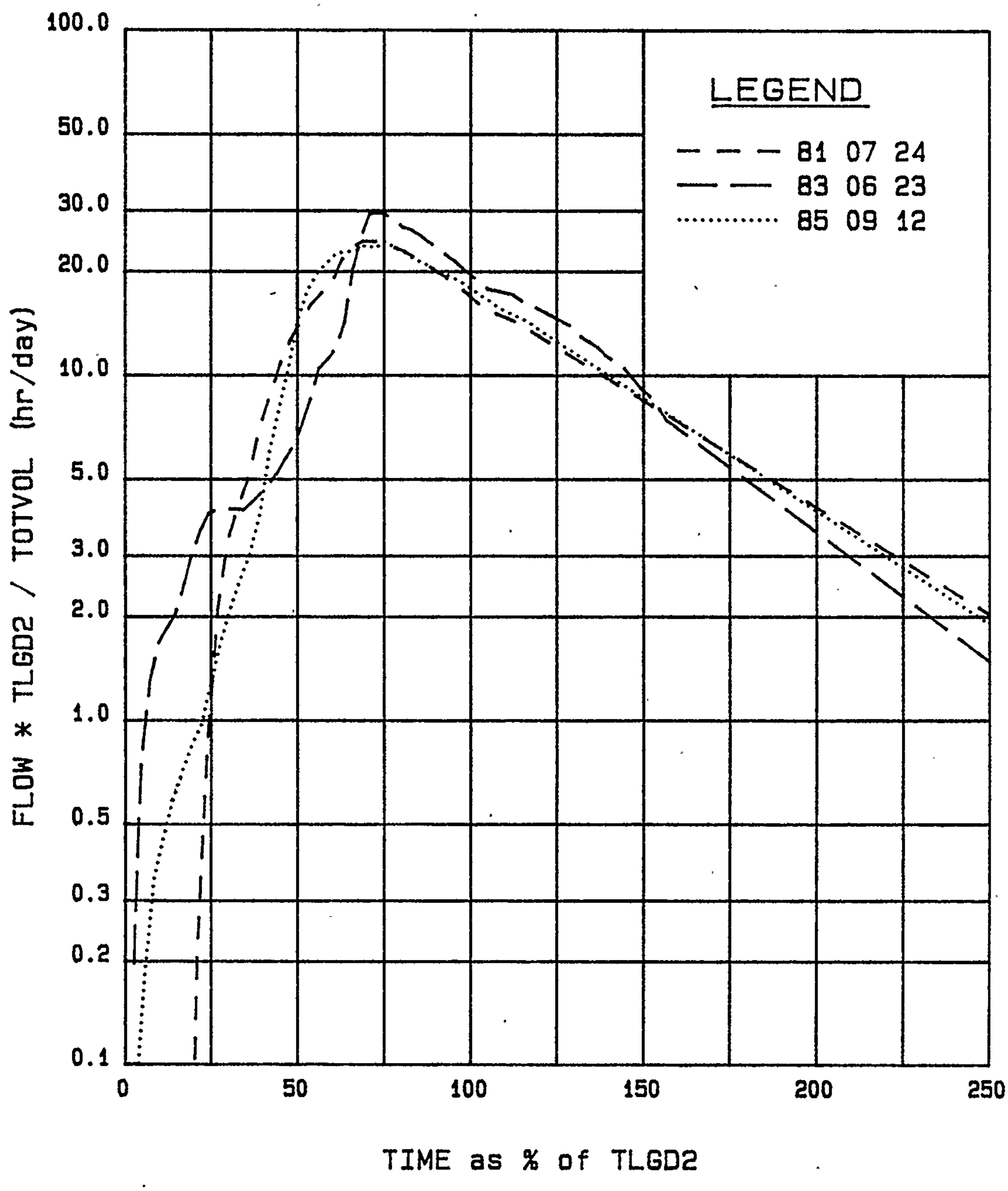


FIGURE 5.10 DIMENSIONLESS UNIT HYDROGRAPHS FOR ELBF

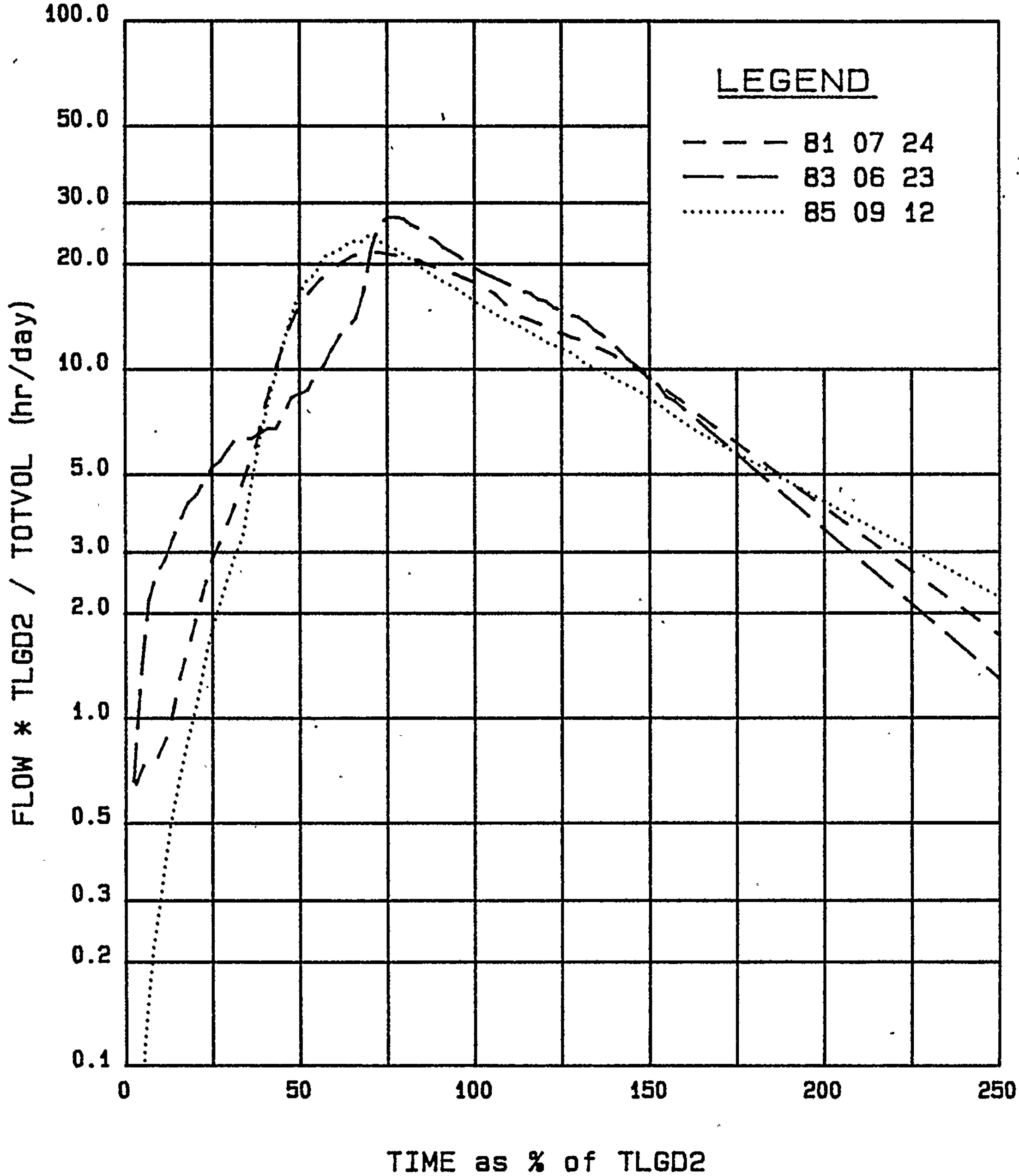


FIGURE 5.11 DIMENSIONLESS UNIT HYDROGRAPHS FOR ELBC

Variability in the shape of each DUH was caused chiefly by the different rainfall intensities and distributions for each storm.

The results for WCMC shown on Figure 5.8 were particularly varied. This gauging station has since been discontinued preventing further analysis to improve the results. Station WCMC was therefore excluded from the regional analysis.

5.2.4 Determination of the Regional Unit Hydrograph

The average DUH for each watershed except WCMC was determined by the method outlined in Section 3.3.4. The regional dimensionless unit hydrograph (RUH) was determined using the same procedure modified to weight according to the number of events analysed for each watershed.

The average DUH's and the resulting RUH are shown in Figure 5.12. The coordinates describing the RUH are shown in Table 5.2. Figure 5.12 shows the close agreement between all 7 average DUH's. The resulting RUH could therefore be applied to any of the selected watersheds. It is further suggested that the RUH could probably be applied to any watershed throughout the study area.

5.2.5 Determination of the Regional Lag Curve

The watershed parameters required for equation 3.2 were computed using data input from the digitizer and are

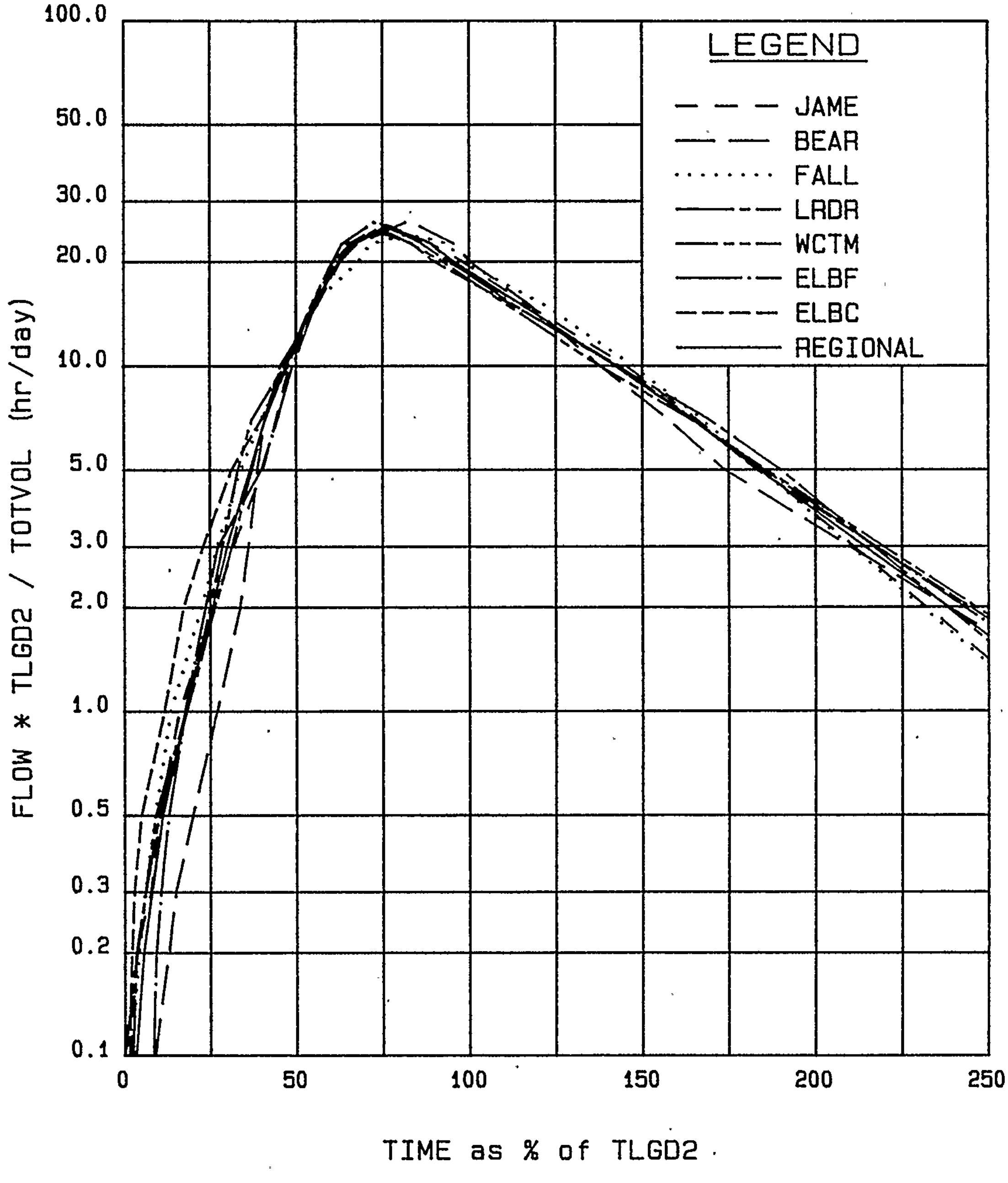


FIGURE 5.12 REGIONAL DIMENSIONLESS UNIT HYDROGRAPH

TABLE 5.2

ORDINATES OF THE REGIONAL DIMENSIONLESS

UNIT HYDROGRAPH

Dimensionless Flow (hrs / day)	Time as % TLGD2
0.1	3.3
0.2	5.7
0.3	8.0
0.5	11.2
1.0	17.9
2.0	25.7
3.0	30.0
5.0	36.8
7.0	41.1
10.0	47.1
15.0	55.2
20.0	62.5
22.5	66.3
25.3	76.7
22.5	89.0
20.0	95.5
15.0	115.0
10.0	142.0
7.0	164.2
5.0	183.4
3.0	213.9
0.5	321.0

tabulated in Table 5.3. The watercourse lengths were estimated for 2 different map scales, 1:50000 and 1:250000. The greater detail of the former produced longer stream lengths. The result was two scale dependent lag curves.

The results of linear regression applied to the data are shown on Figures 5.13 and 5.14 and can also be represented by the following equations :

1) If using 1:50000 maps

$$LG = 8.35\ (L.L_{ca}/S^{0.5})^{0.181} \qquad (5.3)$$

2) If using 1:250000 maps

$$LG = 7.47\ (L.L_{ca}/S^{0.5})^{0.212} \qquad (5.4)$$

where L, L_{ca} are in kms,

S is in m / km,

LG is in hours.

The lag curves were computed for watersheds with drainage areas ranging from 228 to 820 sq kms. and application of the lag curves outside these limits requires careful consideration, particularly for smaller watersheds. As an example a 10 sq km watershed may have values for L = 5km, L_{ca} = 3km and S = 20m/km. Equation 5.3 predicts a lag of 10.4 hours, which is almost certainly an overestimate. An overestimated lag will result in underestimates for the direct runoff.

TABLE 5.3

PHYSIOGRAPHIC DATA FOR EACH WATERSHED

Name	Stream length L (kms)	Length to centroid L_{ca} (kms)	Elevation at divide (m asl)	Elevation at station (m asl)	Slope (m/km)	$\frac{LL_{ca}}{S^{0.5}}$
a) Data measured from 1:50000 scale maps						
JAME	86.7	48.8	2290	1070	14.1	1129
BEAR	44.3	29.9	1470	1120	7.9	472
FALL	95.3	56.8	2170	1110	11.0	1623
LRDR	44.5	27.1	1700	1190	11.5	355
WCMC	30.5	15.7	2680	1430	41.0	75
WCTM	48.2	28.9	2680	1325	28.1	262
ELBF	35.5	12.7	2100	1510	16.6	111
ELBC	59.7	32.6	2100	1300	13.4	532
b) Data measured from 1:250000 scale maps						
JAME	75.7	42.0	2290	1070	16.1	792
BEAR	36.7	23.1	1470	1120	9.5	274
FALL	79.1	44.7	2170	1110	13.4	966
LRDR	38.0	22.0	1700	1190	13.4	228
WCMC	28.4	14.4	2680	1430	44.1	61
WCTM	43.9	25.1	2680	1325	30.9	199
ELBF	33.8	12.6	2100	1510	17.5	102
ELBC	55.5	30.1	2100	1300	14.4	441

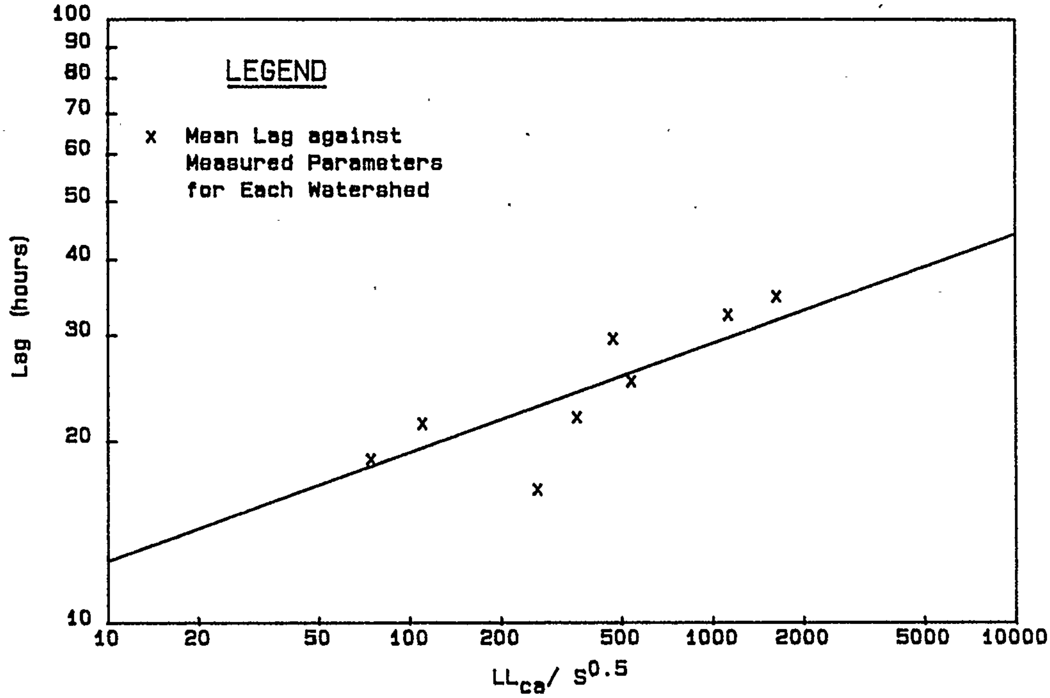


FIGURE 5.13 REGIONAL LAG CURVE FOR 1:50000 SCALE MAPS

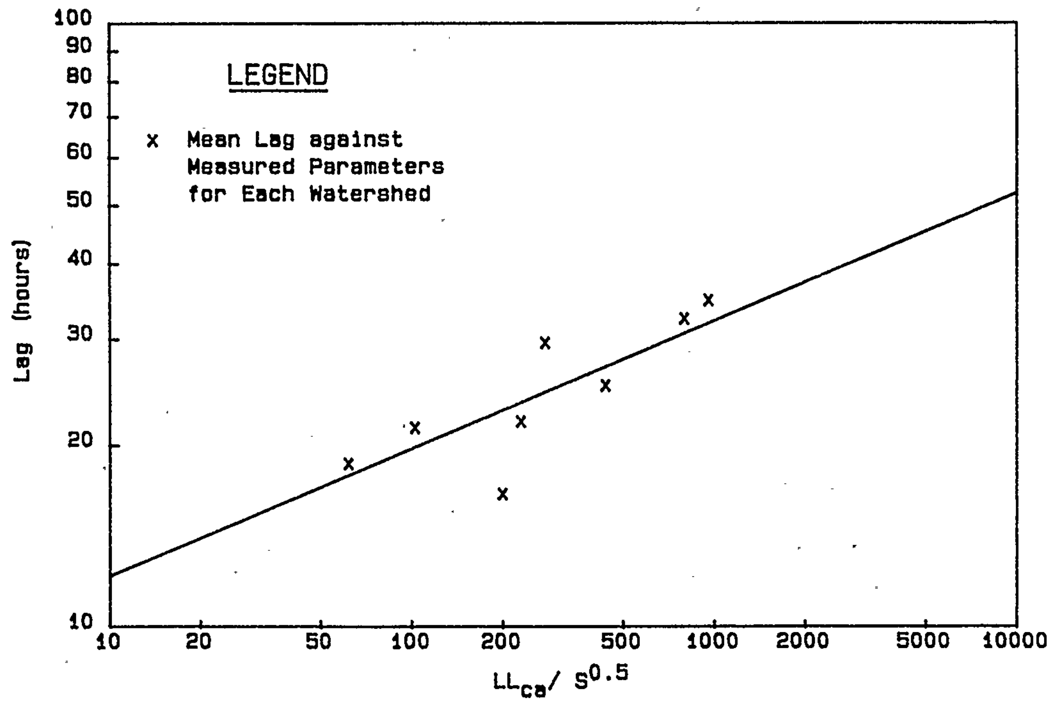


FIGURE 5.14 REGIONAL LAG CURVE FOR 1:250000 SCALE MAPS

It was unfortunate that there was no smaller watershed within the study region suitable for analysis. The 36 sq km gauged watershed at Cox Hill on Jumpingpound Creek in the Elbow area was investigated. Unfortunately, the rainfall and runoff data for the selected storms were incompatible, probably because any timing errors were more significant on the small watershed.

It is recommended that the lag curves be used only for the following condition :

$$60 < LL_{ca}/S^{0.5} < 2000 \qquad (5.5)$$

5.2.6 Curve Number Reference File

A curve reference file was derived to assign a runoff curve number (CN) to each permissible combination of land cover and soil drainage classification encountered in the study region. An estimate of the expected CN for each watershed was made by relating the rainfall excess to the total rainfall for the larger storm events and determining the mean CN. These estimates are shown in Table 5.4.

The initial values assigned to the reference file were taken from CN tables in "Design of Gravity Dams" (1978) and from Rawls et al (1981) where directly applicable and extrapolated elsewhere. Program HYDCN was written to

TABLE 5.4

ESTIMATES OF WATERSHED CURVE NUMBERS

Name	Estimates of Curve Number: Storm Analysis (1)	Original Estimate (2)	Final Estimate (3)
JAME	75	56	71
BEAR	71	66	72
FALL	72	58	71
LRDR	69	59	71
WCMC	74	60	75
WCTM	72	61	73
ELBF	80	55	78
ELBC	79	51	75

create, modify and apply the CN reference file. The weighted CN for each watershed was computed using the same program and a comparison made with the estimate from the storm analyses.

The initial estimates are shown in column 2 of Table 5.4. Discrepancies between CN values in column 1 and column 2 were considered to be a result of the assumptions made relating the map data to a specific CN. The significant land cover and soil drainage combinations were determined for each watershed, enabling revisions to be made to the CN reference file. The number of categories was simplified wherever feasible. The final CN reference file is detailed in Appendix B. The final CN estimate for each watershed is shown in column 3 of Table 5.4.

5.3 Verification of the Procedure

5.3.1 General

The objective of the hydrological analysis was to derive a procedure to predict flood flows of a given return period at a given point. The objective was not the prediction of flows for a specific storm. In order to predict the latter, accurate knowledge of the antecedent moisture conditions (AMC) is necessary to estimate the rainfall excess distribution. The storm specific AMC is not relevant when assessing the longer term record. The hydrologist is more interested in the average AMC prior to the annual maximum storms.

The predictive computer program HYDSCS2 was used to study two methods of deriving synthetic flow-frequency relationships. The two methods are described in full in this section. The synthetic relationships were compared with the annual maximum series analysis for the corresponding gauging station. This approach was only appropriate for those stations whose records did not show a significant proportion of snowmelt influenced maxima. Stations WCTM, ELBF and ELBC were consequently excluded from the verification process. Analysis was carried out on stations JAME, BEAR, FALL and LRDR.

5.3.2 Determination of Annual Maximum Series

Annual maximum instantaneous flow data were abstracted from "Historical Streamflow Summary - Alberta - to 1984" (1985), updated by personal communication with the gauging station operators. The data are included in Appendix A. The data were fitted to the Gumbel EV1 distribution and plotted using the Gringorten plotting position where

$$T = \frac{n + 0.12}{m - 0.44} \tag{5.6}$$

where m is the ranking order of the event,
n is the total number of events,
T is the return period (years).

The gauging station flow frequency curves are shown on Figures 5.15 to 5.18.

The Gumbel EV1 distribution was used because the length of record at each station was too short for a 3 parameter distribution such as the Pearson Type III to predict a reliable skewness. A log-Gumbel distribution was tried but produced a worse fit. The Gumbel EV1 distribution was preferred to alternative 2-parameter distributions as it was also the distribution assumed for the rainfall extreme statistics.

A commonly used plotting position is that proposed by Weibull where

$$T = \frac{n + 1}{m} \quad . \tag{5.7}$$

The top ranked event for a station with 20 years of record will be plotted by equation 5.7 at 21 years and by equation 5.6 at 35.9 years. The average return period for a station with 20 years of data is 29.4 years (Linsley et al, 1982).

The Gringorten position also gives more probable solutions for the next highest events and was therefore adopted throughout this analysis.

5.3.3 Synthetic Flow Prediction

The prediction of flood flows within the study area was divided into 4 key elements :

1) definition of the watershed;
2) estimation of the total rainfall depth;
3) estimation of the rainfall excess;
4) estimation of the resulting runoff.

Each watershed was described on the digitizer. Program HYDSCS computed the necessary parameters including stream length, slope, area and weighted CN. The program also computed and stored the area of each grid square within the watershed boundary. These areas were computed for both the 1km x 1km grid, to estimate CN, and the 10km x 10km grid, to estimate the rainfall depth.

Estimation of the total rainfall depth required two further pieces of data. The rainfall return period was either computed or input manually and the duration of the storm selected from the permissible values of 2,6,12 and 24 hours. The rainfall extreme values for the mean and standard deviation (SD) of the Gumbel EV1 distribution for the selected duration were read from the GIS for each grid square. The total rainfall depth for the given return period and duration in any grid square i,j was derived as follows :

$$RF_{i,j} = Mean_{i,j} + k1 \times SD_{i,j} \qquad (5.8)$$

where $k1 = -6^{0.5} \times (0.5772 + Ln(Ln(T/(T-1))))/PI$,

T is the rainfall return period (yrs),

Ln is the natural logarithm,

RF is the rainfall depth (mm),

PI = 3.14159.

The weighted rainfall depth for the entire watershed was computed as follows :

$$RF = \sum_{\text{All } i,j} (PA_{i,j} \times RF_{i,j}) \; / \; AREA \qquad (5.9)$$

where $PA_{i,j}$ is the area of grid square i,j within the watershed and AREA is the overall watershed area.

Two major assumptions were made in the use of the available data to compute the total rainfall depth.

The rainfall extreme values were only available for 2,6,12 and 24 hour durations. Two options were available for estimating the most critical duration. The direct runoff could be predicted for a storm of each of these durations and the critical duration considered to be that resulting in the maximum instantaneous runoff. Alternatively the values of storm depth could be interpolated or extrapolated for each grid square for other durations. The critical duration for each watershed could then be estimated. The second approach, however, involved further extrapolation of data that has already been extensively worked to create the rainfall extreme statistics. In effect the statistics would have reworked to form intensity-frequency-duration curves for each grid square. It was considered more realistic in the first instance to assume the critical duration produced by the first option. The critical duration for each tested watershed was 24 hours.

The rainfall maximum values computed from the data were point values. It is common to multiply the point values by an areal reduction factor to take into account the size of the watershed. Figures relating area, duration of storm and the corresponding reduction factors for typical areas are noted in Gray (1970) and "Design of Gravity Dams" (1978) amongst others. These show that for a 24 hour storm over a watershed of 500 sq kms the point maxima should be reduced by about 9%. The percentage reduction increases with area and decreases with storm duration for a fixed area. However these curves were not derived for the present study region and cannot be applied with a great deal of confidence. As the reduction was reasonably small, it was considered wise to apply the available data directly and, if necessary, apply a correction at a later part of the prediction procedure.

The distribution of the rainfall was assumed to be uniform throughout the selected storm duration. This at first appears to be a major simplification of the rainfall process as the intensity is rarely constant. Two factors influenced the decision making in the assumption. The procedure involved using a dimensionless unit hydrograph derived from storms for which the rainfall excess distribution was assumed uniform. It can therefore be argued that, to create similar conditions in the predictive mode, a uniform distribution should again be used. The second factor was again the lack of adequate local data. Data has recently been made available by Environment Canada, Ottawa giving probable storm distributions for storms of 1 and 12 hour durations for a number of selected stations. None of these stations lay within the study region and only one, at Calgary, was adjacent. The topographies of the study area and Calgary were significantly different, the study area being more hilly and generally higher. Furthermore, data were not available for 2,6 or 24 hour durations. Until a detailed analysis of storm distribution within the study area is carried out and considering the method of computation of the SCS DUH, it was decided to assume a uniform rainfall distribution and, if necessary, to make a correction elsewhere.

The rainfall excess was computed using equations 3.3 and 3.4. The curve number (CN) used was either the weighted CN value predicted by program HYDSCS or a manually estimated CN. The initial abstraction, Ia, was selected by the user for each run.

Conversion of the rainfall excess into direct runoff was facilitated by computing the T-hour unit hydrograph from the Regional Unit Hydrograph (RUH) having first estimated the watershed lag from the regional lag curve. The lag for each watershed varied from 19 to 35 hours. The SCS method recommended a maximum unit hydrograph duration of approximately 20% of the watershed lag. A duration of 4 hours was adopted throughout. Direct runoff was computed using the convolution integral expressed in equation 3.5 to relate the rainfall excess to the respective unit hydrograph ordinates. The maximum flow rate, Qmax, was stored for use in the flow frequency analysis.

At this point it was common to add a baseflow component to the direct runoff to give the total runoff. This study was aimed primarily at predictions of flood flows with a return period of 5 years or over. As baseflow is usually less than 5% of the total flow of major floods, it was decided to omit the baseflow component. Inclusion at a later date in a refined model may prove possible.

The procedures discussed in the preceding paragraphs were applied to the rainfall return periods determined by both of the methods outlined in Section 3.6.3.

Method 1 involved computation of the maximum runoff, Qmax, resulting from each of 100 rainfall events with randomly selected probabilities of occurrence. A flow-frequency curve was plotted assuming a Gumbel EV1 distribution for Qmax.

Method 2 computed Qmax for 8 discrete rainfall return periods. These were 2,5,10,20,25,50,100 and 200 years. The resulting values for Qmax were plotted assuming a one-to-one relationship between rainfall and runoff return periods.

The assumptions made in the procedure reduced the number of variable parameters by eliminating the selection of storm distribution, storm duration and storm depth for an interpolated duration. The procedure computed lag and the T-hr unit hydrograph from the regional curves. Assuming these curves to be realistic, the only variables were the curve number (CN) and the initial abstraction (Ia). The weighted watershed CN was computed from the GIS data. It was not desirable to alter these values.

The initial abstraction represented the infiltration prior to any direct runoff and was computed as follows :

$$Ia = k\ S. \qquad (5.10)$$

The SCS recommended a value for k = 0.2 be used. The predicted flows from both Method 1 and Method 2 are shown for each tested watershed on Figures 5.15 to 5.18 inclusive. The differences between the results from the station flow frequency analysis and the predicted values are shown on Table 5.5. With just a few exceptions, the predictions underestimated the station analysis results.

In order to achieve closer agreement, a reduced value for k = 0.1 was selected. The predictive analysis was repeated. The results are presented in Table 5.6 and shown on Figures 5.15 to 5.18 inclusive.

The results using k = 0.1 show flows for 3 out of 4 watersheds within 25% for the entire range of the selected return periods. The results for BEAR were approximately 40% low. This station has only been operative for 6 years and this discrepancy may reduce as the station record lengthens. In particular the predictions for the stations with the longest records, JAME and LRDR, showed an average discrepancy of 15%. There were equal numbers of over and underestimates. Use of k = 0.1 together with the GIS data,

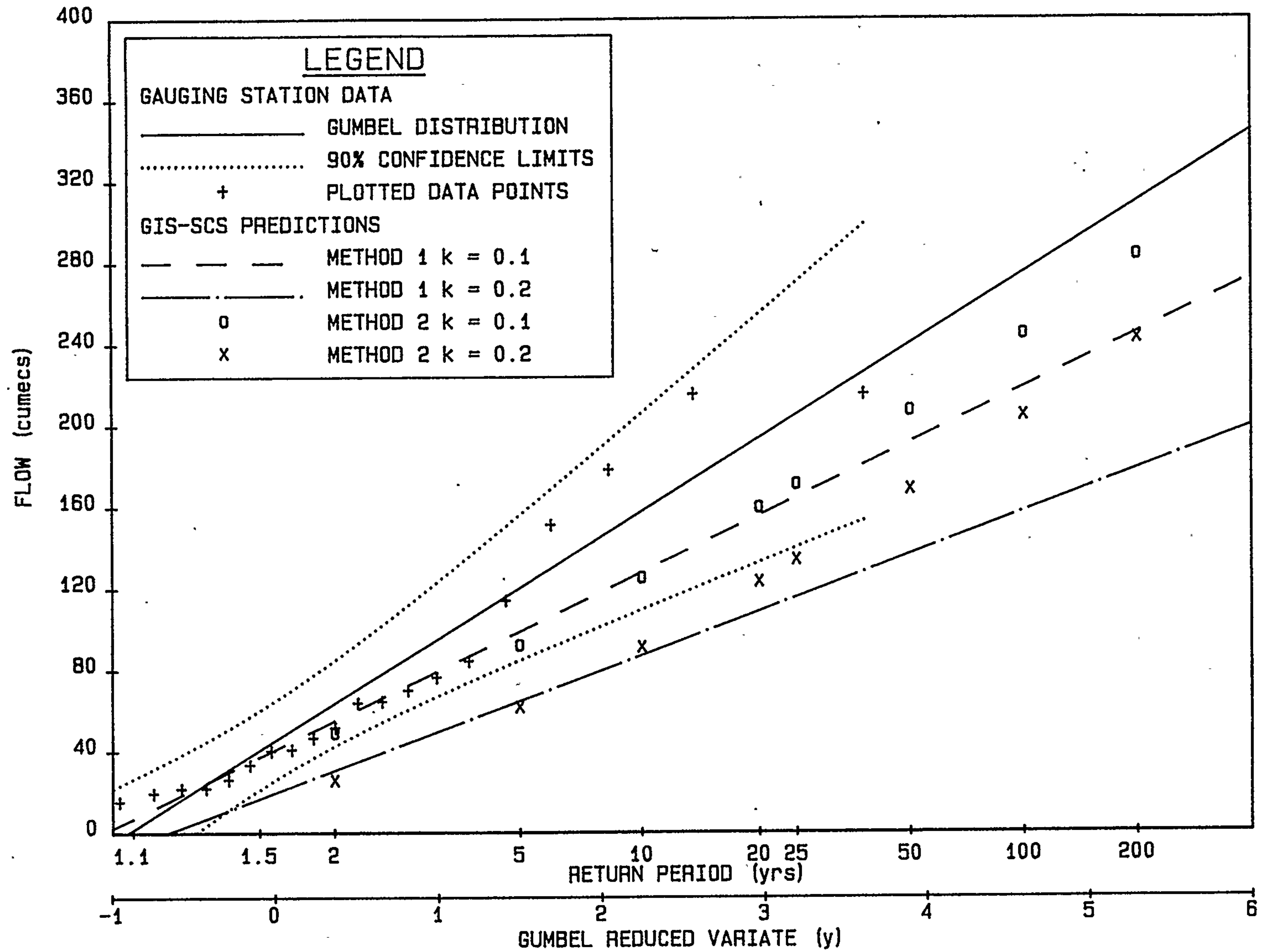


FIGURE 5.15 FREQUENCY ANALYSIS FOR JAME

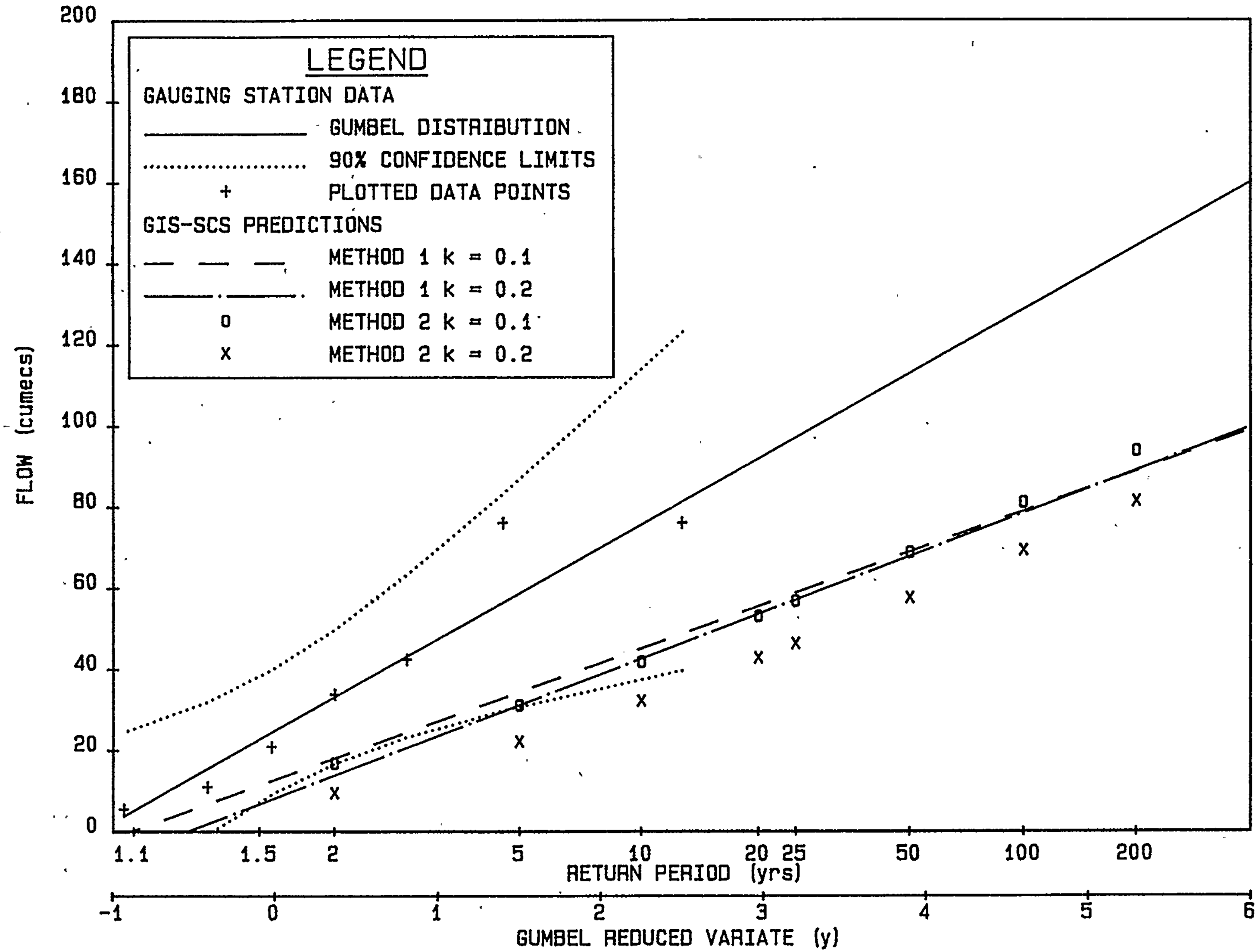


FIGURE 5.16 FREQUENCY ANALYSIS FOR BEAR

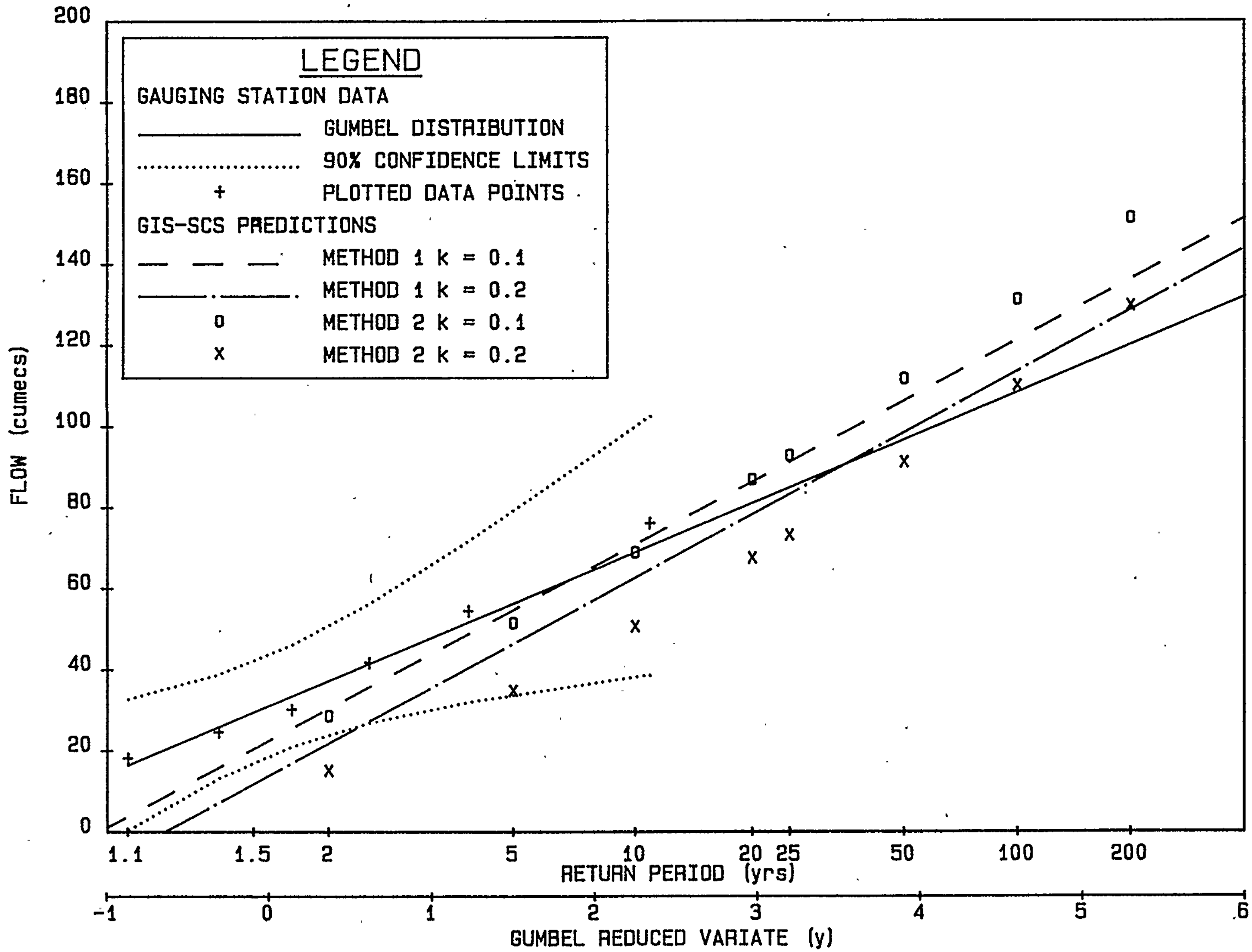


FIGURE 5.17 FREQUENCY ANALYSIS FOR FALL

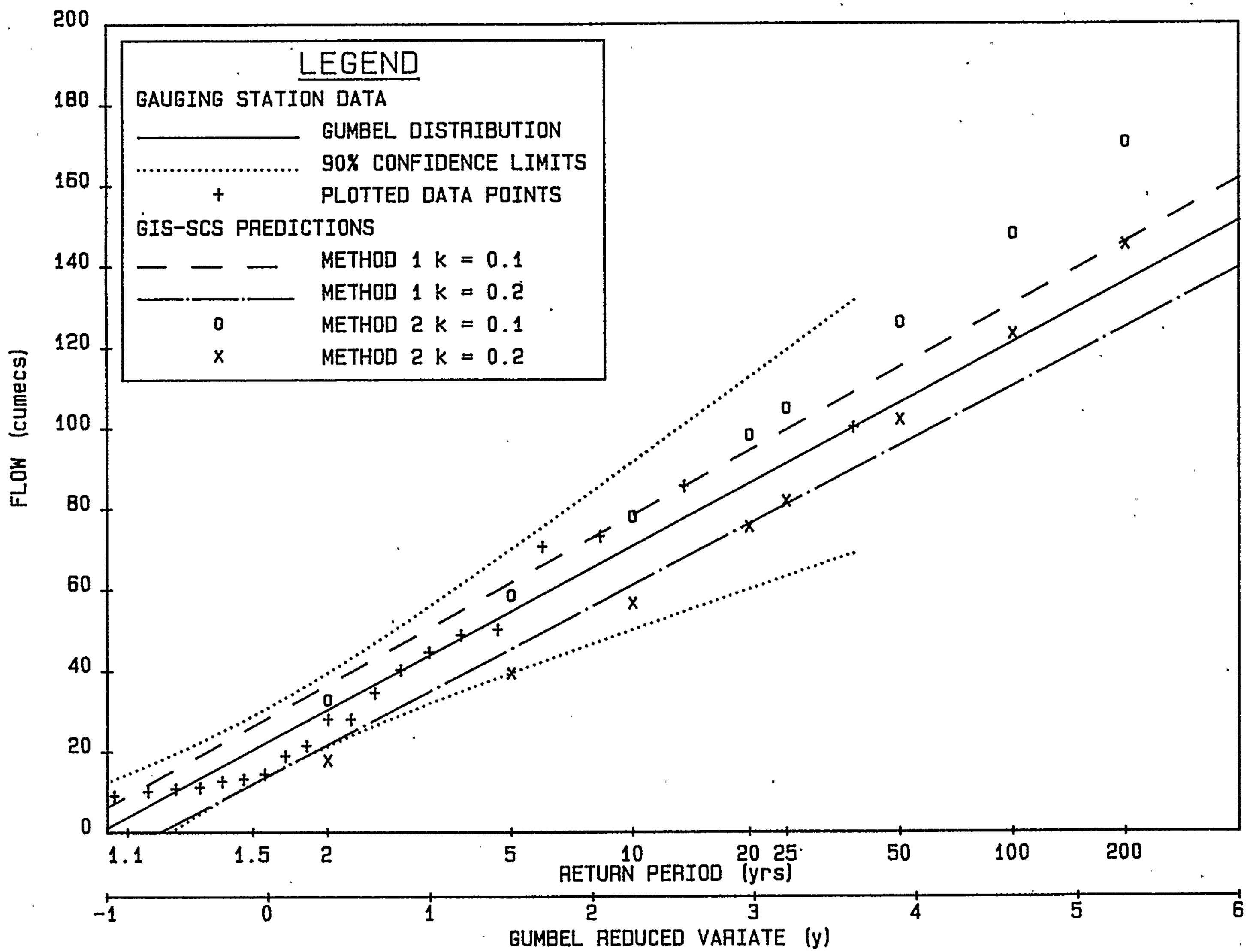


FIGURE 5.18 FREQUENCY ANALYSIS FOR LRDR

TABLE 5.5

COMPARISON BETWEEN FLOWS FROM STATION ANALYSIS (Qsa)

AND GIS-SCS PREDICTIONS (Qmax) FOR k = 0.2

	(Qmax - Qsa) as % of Qsa Return periods (years)				
Station	5	10	20	50	100
METHOD 1					
JAME	-45	-44	-43	-43	-42
BEAR	-46	-43	-41	-40	-39
FALL	-18	-9	-4	+2	+5
LRDR	-18	-14	-12	-10	-10
METHOD 2					
JAME	-47	-42	-37	-30	-25
BEAR	-62	-57	-53	-49	-47
FALL	-39	-26	-17	-5	+2
LRDR	-29	-20	-13	-4	+2

TABLE 5.6

COMPARISON BETWEEN FLOWS FROM STATION ANALYSIS (Qsa)

AND GIS-SCS PREDICTIONS (Qmax) FOR k = 0.1

	(Qmax - Qsa) as % of Qsa Return periods (years)				
Station	5	10	20	50	100
METHOD 1					
JAME	-17	-19	-20	-21	-21
BEAR	-40	-39	-38	-38	-38
FALL	+2	+9	+14	+18	+20
LRDR	+13	+11	+9	+8	+8
METHOD 2					
JAME	-23	-20	-17	-13	-11
BEAR	-47	-44	-42	-39	-37
FALL	-11	0	+7	+17	+21
LRDR	+7	+10	+13	+19	+22

regional curves and watershed parameters gave better correlation with the station analysis.

Methods 1 and 2 both predicted similar flows. Method 1, however, did not produce a fixed relationship. A second set of 100 events with random probabilities predicted a 10% difference in flows. This implied that a set of 100 records was insufficient. A larger number of records would require longer computational time. Method 2 predicted fixed values for each selected return period. As the overall predictive accuracy was similar, Method 2 was adopted as the preferred one for practical reasons.

A sensitivity analysis was carried out to demonstrate the effect of 20 as opposed to 100 years of record. The datafile for Method 1 for JAME was split into 5 sets of 20. This compared well with the station lengths for JAME and LRDR, which were both 21 years. The resulting flow-frequency curves are shown on Figure 5.19. The variation between the curves suggest that there was no reason to expect a closer fit between the station analysis and the predictions.

5.4 Discussion

The previous sections of Chapter 5 have discussed several specific issues encountered during the course of

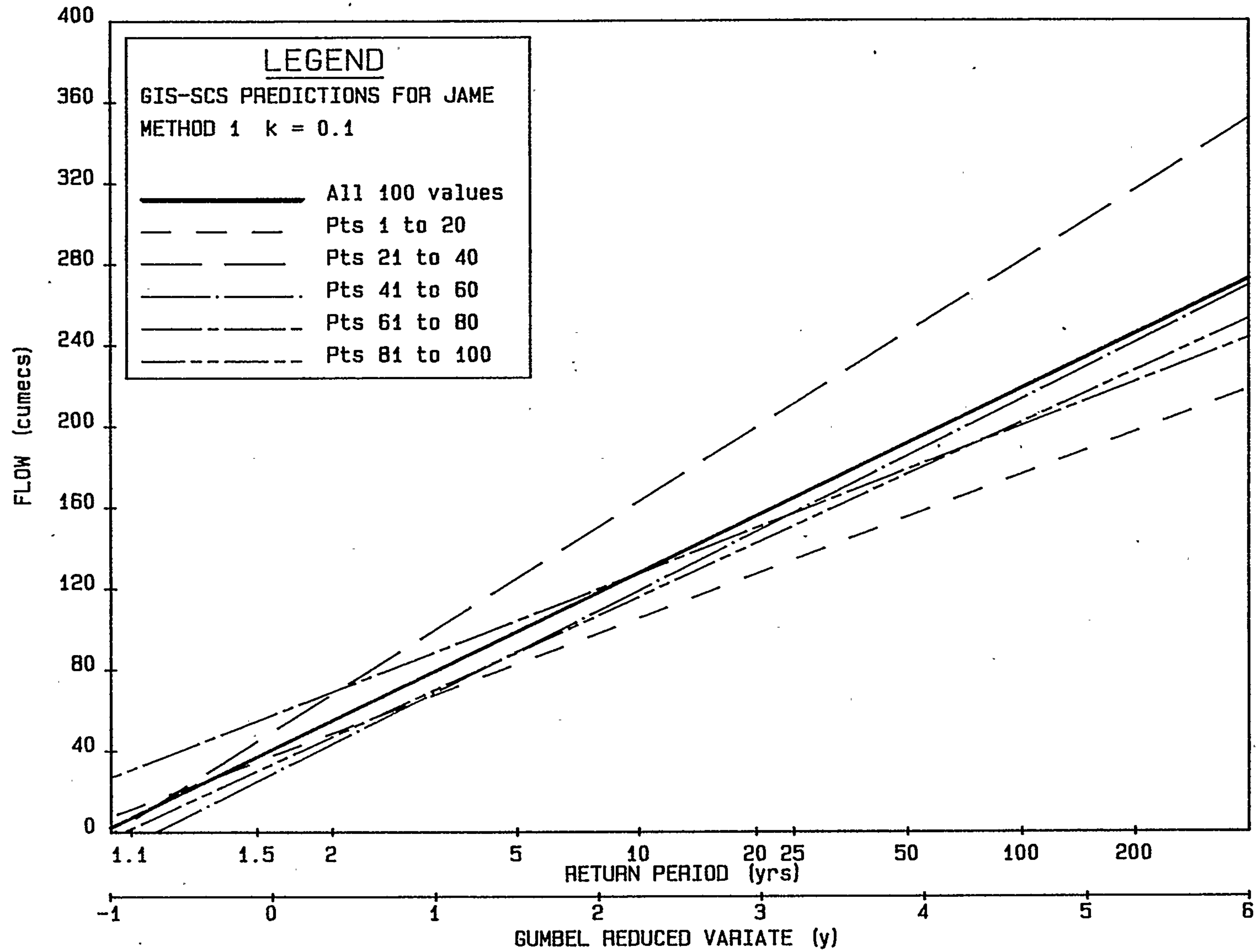


FIGURE 5.19 EFFECT OF RECORD LENGTH ON FLOW FREQUENCY CURVES

the study. This discussion covers the limitations of and possible improvements to the procedure.

The scope of the study was restricted by both the length of record and the availability of hydrological data and by the availability of compatible geophysical data. The latter was discussed in Chapter 4.

The hydrological analysis was primarily restricted by the requirement for hourly rainfall data at a station within, or adjacent to, the watershed. The majority of the stations that do exist have less than 5 years of data and a significant number less than 2 years. As a minimum of 3 and, preferably, 6 sizeable flood events were required for detailed analysis for each watershed, it was necessary to reject a number of possible watersheds due to insufficient rainfall data. In the next few years, additional rainfall data will become available and it may prove possible to include additional stations in the regional analysis. Possible additions include gauging stations on the Sheep River, Threepoint Creek, Pekisko Creek and Highwood River.

Additional storms from 1986 onwards should be analysed for the 7 watersheds used in the regional analysis in order to augment the database from which the regional curves and the CN reference file were computed. In particular a major storm occurred in July 1986 over the Red Deer (North) and Red Deer - Ghost study areas. The resulting runoff was the highest or equal highest on record at 4 of the gauging stations. Inclusion of details for this storm should be incorporated in the regional analysis when the full data is available.

The inclusion of additional data whether for new watersheds or extra data for the existing ones could lead to greater confidence in the regional analysis.

Some of the limitations of the procedure have been discussed in previous sections. The drainage area of the watersheds included in the regional analysis ranged from 233 sq kms to 820 sq kms. The aim was to include a smaller watershed. Unfortunately very few small watersheds are gauged and it was not possible to include one. It is therefore recommended that the procedure be used with caution outside the range quoted above.

The previous sections discussed the assumptions made in the hydrological analysis. Were these assumptions valid? In the ideal situation, with limitless high quality data, the answer would probably be no. The limited available data cannot be extrapolated indefinitely and it is suggested that it is better to incorporate a correction factor than to stretch the data too far. A future study could search the local meteorological data sources and estimate areal reduction factors and probable storm distributions for the study region. Another study could attempt to estimate the baseflow for a watershed probably by multiple regression analysis.

The correction used in this study reduced the k factor used in the estimation of the initial abstraction, Ia. It has been suggested by Golding (1979) that the value of k = 0.2 recommended by the SCS is too high for a number of applications. There was no common factor that explained the differences between the station analysis results and the GIS-SCS predictions. For example, inclusion of an areal reduction factor would reduce, and thereby worsen, the predictions for the largest watershed, JAME. Assumption of a non-uniform storm distribution would probably result in higher flow predictions for each station which would improve some predictions and worsen others.

Another important factor is the accuracy of the gauging station data and the reliability of the station flow-frequency curves. Flows were included for each station that involved substantial extrapolation of the rating curves. This data has to be assumed accurate for the frequency analysis. The station frequency curves are also affected by their relatively short record length. One major flood event could alter the station flow frequency curves dramatically.

This is particularly valid for BEAR where the station record is only 7 years. Are the GIS-SCS predictions for

BEAR low because of errors in the procedure or because of the shortness of the record? The record for the adjacent watershed JAME suggests that the latter may be a significant factor. A flow frequency analysis for JAME carried out for the same 7 years predicted flows nearly 15% higher than those predicted from the full 21 years of data. This may account for some of the discrepancy shown on Figure 5.17.

It is suggested that the derived procedure and regional curves are suitable for predictive use within the study region on watersheds over 200 sq kms. With caution the procedure may be used on smaller watersheds particularly if an estimate for the watershed lag is available. Further studies and the inclusion of additional hydrological analysis may result in better predictive capability.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The overall objective of the study was to establish a procedure to enable hydrologists to predict flood flows at ungauged sites within the study area.

Constraints imposed by the availability of meteorological, land cover and soil drainage data restricted the study to 8 watersheds with drainage areas between 233 and 820 sq kms. The total watershed area was 3118 sq kms.

A Geographic Information System was devised to handle 5 different data elements. Data for land cover, soil drainage classification and elevation were abstracted from maps and stored on a 1km x 1km grid basis. Data for the rainfall extreme statistics were subject to less spatial variation and were stored on a 10km x 10km grid. Data for the runoff curve numbers were computed from the land cover and soil drainage classifications and stored on a 1km x 1km grid. The overall study region was subdivided into 3 areas each 60km x 60km. Software was developed to facilitate data input from maps or plans, printout of the gridded data and transfer of data between study areas.

Thirty-five storms were selected for detailed analysis on 8 watersheds. The SCS technique was used to derive a dimensionless unit hydrograph for each storm. The average DUH was determined for each watershed. There was close agreement between all the average DUH's which were combined to form the Regional DUH (RUH). The constituent watersheds had widely differing shapes, slopes and areas which suggested that the RUH can be applied throughout the study region.

Log-normal plots relating the average storm lag to the watershed parameter $LL_{ca}/S^{0.5}$ were produced and a regional curve determined by linear regression analysis. Reasonable agreement was obtained but inclusion of additional data for smaller watersheds or for more large storms should make the curves more reliable for predictive use. This is particularly valid for flow prediction on watersheds smaller than those used in the derivation of the regional curves.

Estimates of the watershed runoff curve number (CN) were made by relating corresponding storm depths and runoff depths. Relationships between land cover and soil drainage classifications and CN were amended to achieve close agreement between the storm estimated CN and the CN predicted from the GIS data. The maximum difference between CN values was 4.

The procedure was verified by use of programs HYDSCS and HYDSCS2 in their predictive mode. Each watershed boundary was described using the digitizer. The weighted watershed CN was computed using the GIS data. Watershed parameter $LL_{ca}/S^{0.5}$ was computed using data input from the digitizer. The previously derived regional curves were accessed to produce the T-hour unit hydrograph for the watershed. The storm depth for each required rainfall return period was abstracted from the the GIS for the given watershed boundary. Rainfall excess was calculated using the SCS technique employing the predicted watershed CN and a selected initial abstraction. The direct runoff for each storm was computed by use of the convolution integral relating the rainfall excess to the T-hour unit hydrograph.

The predicted maximum flows were used to produce synthetic flow-frequency curves for the 4 gauging stations whose records were not affected significantly by snowmelt. Two methods were used. Method 1 produced a Gumbel EV1 distribution for the runoff resulting from 100 randomly selected rainfall probabilities. Method 2 produced the runoff corresponding to a selected rainfall return period. The rainfall return periods and runoff return periods were assumed to be identical.

The results predicted using the SCS recommended value for the initial abstraction were all lower than those predicted by the station analysis. A correction was made by reducing k to 0.1 from 0.2. The differences between the predicted flows and those from the station analysis were less than 25% for 3 out of 4 watersheds for the entire range of interest (return periods greater than 5 years). The results for the fourth station were less good although the apparent discrepancy may be due largely to the short gauging station record. Method 1 and Method 2 gave similar predictions. It is recommended that the simpler Method 2 be adopted for use.

The original objective has been achieved with a reasonable degree of success. The GIS has been successfully created for the study region. The SCS method has been applied to over 30 storms. The agreement between watershed dimensionless unit hydrographs was very good. The regional lag curves and CN relationships were reasonable. Verification of the procedure was of a subjective nature. Comparisons were made between predicted flows and the corresponding gauging station flow-frequency curves. The latter will undoubtedly vary with time. Results with an average difference of 15% for the 2 watersheds with the longest records indicated that the recommended procedure can be used as a tool to predict flood flows at ungauged sites within the study region.

6.2 Recommendations

Three main areas have been identified for future developments. These are

1) expansion of the study region,

2) inclusion of additional storms and

3) improvements to the procedure.

The study region could be expanded dramatically provided good correlation between LANDSAT data, or other remotely sensed data, and land cover classification can be determined and provided soil drainage data can be obtained. It is recommended that the possible use of remote sensing data be pursued.

Further storm analysis, both on the existing and on additional watersheds, would provide a larger database from which to re-estimate the regional curves. In particular inclusion of data from one or more watersheds of less than 200 sq kms would be highly desirable.

The developed procedure involved a number of assumptions concerning storm duration and depth, storm distribution and the relationship between rainfall and runoff probabilities. Additional study on local data, where available, may lead to a refinement of the procedure.

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APPENDIX A

HYDROLOGICAL DATA SUMMARY

This Appendix contains two tables which summarize the meteorological and hydrometric data used in the analysis. Table A.1 gives details of the storms included in the dimensionless unit hydrograph derivation. Table A.2 details the annual maximum flow data used to derive the gauging station flow-frequency curves.

TABLE A.1 STORM DATA

Name and Date	Rain Stn	Rain Depth mm	Thiessen Depth mm	Net Depth mm	Φ index mm/hr	Qmax cumecs	Direct Qmax cumecs	Runoff TOTVOL cumec-days
JAME1 820703	JARS	38.1	38.1	5.8	2.2	64.1	45.3	55.2
JAME2 830623	JARS	15.2	15.2	1.2	4.5	16.7	10.9	11.7
JAME3 830702	JARS LIME	43.2 43.2	43.2	6.6	3.0	57.2	49.7	63.1
JAME4 840607	JARS	43.2	43.2	8.1	2.2	46.5	38.5	76.8
JAME5 850524	COAL	35.6	35.6	2.3	2.8	15.3	12.6	22.0
JAME6 850912	COAL	63.5	63.5	13.5	4.3	83.8	78.3	127.5

TABLE A.1 (cont'd)

Name and Date	Rain Stn	Rain Depth mm	Thiessen Depth mm	Net Depth mM	Φ index mm/hr	Qmax cumecs	Direct Qmax cumecs	Runoff TOTVOL cumec-days
BEAR1 820703	JARS	30.5	30.5	15.9	1.2	33.8	30.8	43.1
BEAR2 830424	JARS	71.1	64.9	15.8	3.1	42.2	41.5	42.7
	COAL	61.0						
	SUND	61.0						
BEAR3 830702	COXH	43.2	42.7	3.8	3.6	10.0	9.1	10.2
	JARS	43.2						
	COAL	43.2						
	SUND	38.1						
BEAR4 840607	JARS	43.2	47.8	6.9	2.3	10.9	9.9	25.3
	COAL	50.8						
BEAR5 850912	COAL	63.5	63.5	8.2	5.0	20.7	20.1	22.2
FALL1 830424	COAL	55.9	53.0	7.0	4.5	37.3	35.3	39.2
	SUND	61.0						
	FALL	48.3						
FALL2 830702	COAL	43.2	51.8	10.0	3.6	41.7	38.3	56.2
	SUND	38.1						
	FALL	61.0						
FALL3 840607	COAL	50.8	46.5	6.0	2.0	18.0	16.0	33.6
	FALL	43.2						
FALL4 850912	COAL	63.5	62.1	9.4	3.9	30.1	28.5	52.8
	FALL	61.0						
LRDR1 830424	FALL	53.3	56.0	6.2	3.6	48.5	46.6	32.9
	GHRS	58.4						
LRDR2 830702	FALL	76.2	56.4	6.8	3.8	29.4	27.1	35.8
	GHRS	38.1						
LRDR3 830708	FALL	12.7	14.1	2.2	3.5	15.6	10.0	11.9
	GHRS	17.8						
LRDR4 840607	FALL	45.7	39.1	4.2	2.5	13.2	11.5	22.1
	GHRS	33.0						
LRDR5 850912	FALL	61.0	61.0	5.4	4.6	18.8	17.8	28.3
WCMC1 820627	GHRS	15.2	15.2	1.4	6.2	6.0	3.0	3.7
WCMC2 820925	GHRS	38.1	33.9	1.5	4.3	4.1	3.3	3.9
	FALL	27.9						
WCMC3 830702	GHRS	38.1	52.7	11.1	2.9	46.5	41.5	29.3
	FALL	73.7						

TABLE A.1 (cont'd)

Name and Date	Rain Stn	Rain Depth mm	Thiessen Depth mm	Net Depth mm	Φ index mm/hr	Qmax cumecs	Direct Qmax cumecs	Runoff TOTVOL cumec-days
WCTM1 820627	GHRS	15.2	15.2	0.9	6.7	7.2	3.4	3.5
WCTM2 820925	GHRS FALL	40.6 27.9	37.0	0.9	5.3	4.9	3.7	3.5
WCTM3 830623	GHRS FALL	33.0 17.8	28.6	1.8	10.8	16.8	13.7	6.9
WCTM4 830702	GHRS FALL	27.9 50.8	34.6	8.7	2.7	60.9	53.9	33.4
WCTM5 850912	FALL	61.0	61.0	9.3	4.0	42.4	38.4	35.7
ELBF1 810724	EBRS	17.8	17.8	3.1	2.1	26.4	11.6	15.9
ELBF3 850912	EBRS COMP EVAN	53.3 50.8 43.2	45.9	11.7	2.6	47.8	40.0	58.8
ELBF4 830623	EBRS FMNT LELB	12.7 15.2 25.4	22.2	3.7	3.6	20.6	13.6	18.7
ELBC1 810724	EBRS	15.2	15.2	2.7	2.1	35.3	16.8	24.9
ELBC2 830623	EBRS FMNT LELB	12.7 15.2 25.4	18.2	2.2	3.1	21.5	12.5	20.1
ELBC4 850912	EBRS COMP EVAN	53.3 50.8 43.2	48.8	11.9	2.6	79.6	68.6	108.8

TABLE A.2

ANNUAL MAXIMUM INSTANTANEOUS FLOWS FOR
STATIONS USED FOR VERIFICATION

Year	Maximum flows (cumecs) for JAME	BEAR	FALL	LRDR
1986	215.0[1]	76.0[1]	76.0[1]	100.0[1]
1985	84.3	20.8	30.1	18.9
1984	46.5	10.9	18.1	13.2
1983	69.9	42.3	41.7	48.8
1982	64.4	33.7	24.5	10.1
1981	178.0	76.0[2]	54.4	40.2
1980	33.3	-		14.4
1979	21.7	5.4		12.6
1978	26.0			28.0
1977	21.8			10.8
1976	19.4			8.8
1975	9.6			11.1
1974	40.2			34.5
1973	63.7			44.5
1972	215.0			50.1
1971	40.8			21.4
1970	151.0			70.5
1969	114.0			85.5
1968	15.3			9.0
1967	76.2			73.1
1966	51.5			28.0

NOTES Data from "Historical Streamflow Summary - Alberta to 1984" (1985) except where marked:

1 Recent data direct from Water Survey of Canada and Alberta Environment

2 Data amended - rating curve revised by Alberta Environment

APPENDIX B

DIGITAL REPRESENTATION OF GEOGRAPHICAL DATA

This Appendix details the digital codes used to represent the 5 data elements stored on the GIS.

Rainfall Extreme Statistics

Values for the mean and standard deviation for 2, 6, 12 and 24 hour durations stored in millimetres.

Elevation Data

Representative elevation for the grid square stored directly in metres above sea level.

Soil Drainage Classification

Data in accordance with the Canadian Soil Classification System (CANSIS) abstracted from maps published with the "Ecological Land Classification and Evaluation" reports. A correlation was derived between the CANSIS and the US SCS classifications. The relationship was given in Table 5.3. Values corresponding to both systems were stored on the GIS.

Land Cover Classification

The land cover data was abstracted from the Alberta Forest Cover overlays at a scale of 1:31680. The legend for these overlays included the following categories :

Forest	Density
	Height
	Composition
	Cut or burnt areas
Non - Forest	Scrub
	Muskeg
	Grassland
	Barren Rock
	Water

The above data was converted into digital form after Anderson et al (1976) as follows :

Description	Classification Level 1	Level 2	Level 3	Comments
Urban or Built Up Land				
Residential	1	1	1	
Agricultural Land				
Cropland and Pasture	2	1	1 - 3	Level 3 set to 2
Rangeland				
Herbaceous	3	1	1 - 3	
Shrub and Brush	3	2	1 - 3	Level 3 set to 2
Mixed	3	3	1 - 3	
Forest Land				
Deciduous	4	1	1 - 5	Level 3 represented
Coniferous	4	2	1 - 5	crown density in
Mixed	4	3	1 - 5	20% increments.
Water				
Lakes	5	2	1	

Description	Classification Level 1	Level 2	Level 3	Comments
Wetlands				
Forested	6	1	1	
Non-forested	6	2	1	
Barren Land				
Bare Exposed Rock	7	4	1	

Runoff Curve Number

The runoff curve number (CN) was derived for each combination of land cover and US SCS soil drainage classification. The relationships used in the verification procedure are given below :

Land Cover	CN for US SCS Soil Groups 1	2	3	4
111	61	70	83	87
212	49	69	79	84
312	48	68	81	88
322	49	69	79	84
332	48	68	80	86
41X	55	63	71	75
42X	46	68	78	84
43X	43	64	75	81
521	100	100	100	100
611	45	66	77	83
621	55	75	84	90
741	100	100	100	100

Note Land cover classification 41X represents classifications 411 to 415 inclusive; similarly for 42X and 43X.

APPENDIX C

EXAMPLES OF HYDROLOGICAL ANALYSIS

1. Input Data Files

The data for each storm was input using program HYDDUH. The input data file for each storm was assigned a name of the form JAMEHYD3 to represent the third storm studied on watershed JAME. The data for storm JAME3 is used in this example. The salient details of the datafile are shown on Table C.1.

The total runoff was obtained from the gauging station records. The baseflow for each storm was assumed to follow a continuing recession curve or, if there was no preceding precipitation, a constant value, until the time of peak runoff. After this time, the baseflow was assumed to rise linearly for the time given by

$$T = 19.2 \quad AREA^{0.2} \text{ hours.}$$

For JAME this equation becomes

$$T_{JAME} = 19.2 \quad 820^{0.2} = 73.5 \text{ hours.}$$

At time T after the peak flow the baseflow was assumed equal to the total runoff.

The Thiessen weighting factors were derived using the areas described on the digitizer. Program HYDDUH checked to ensure that the weighting factors summed to unity. The incremental readings recorded by the raingauges was

0.1 inch or 2.54 mm. The program offered the user a choice of units. A dummy negative value was used to signify the last record for each field.

All data shown on Table C.1 was input with the exception of the column for "Average Rain". This was computed using the Thiessen weighting factors.

TABLE C.1 TYPICAL STORM DATA FROM HYDDUH

DATA FILE NAME A:JAMEHYD3.DAT

Gauging Station James River near Sundre 05CA002

Catchment area 819.7 km2

Date of event 83 07 02
Start time 1400 hrs Delta t 1.00 hrs

No of rainfall stations 3

	Station name	Weighting factor
LIME	Limestone Ridge	0.450
COXH	Cox Hill	0.000
JARS	James River Ranger Station	0.550

TABLE C.1 (cont'd)

TIME (hrs)	TOTAL RUNOFF	BASE FLOW	RAIN STN 1	RAIN STN 2	RAIN STN 3	RAIN STN 4	RAIN STN 5	RAIN STN 6	AVGE RAIN
1.00	7.90	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	8.12	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	8.39	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	8.70	7.50	2.54	0.00	0.00	0.00	0.00	0.00	1.14
5.00	9.07	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.00	9.44	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.00	9.90	7.50	5.08	0.00	0.00	0.00	0.00	0.00	2.29
8.00	10.40	7.50	2.54	2.54	5.08	0.00	0.00	0.00	3.94
9.00	10.70	7.50	2.54	2.54	7.62	0.00	0.00	0.00	5.33
10.00	10.90	7.50	2.54	2.54	2.54	0.00	0.00	0.00	2.54
11.00	11.10	7.57	2.54	2.54	2.54	0.00	0.00	0.00	2.54
12.00	11.40	7.50	2.54	5.08	5.08	0.00	0.00	0.00	3.94
13.00	11.90	7.50	2.54	5.08	5.08	0.00	0.00	0.00	3.94
14.00	12.50	7.50	5.08	2.54	2.54	0.00	0.00	0.00	3.68
15.00	12.90	7.50	2.54	2.54	2.54	0.00	0.00	0.00	2.54
16.00	14.30	7.50	2.54	2.54	2.54	0.00	0.00	0.00	2.54
17.00	16.20	7.50	5.08	5.08	2.54	0.00	0.00	0.00	3.68
18.00	20.70	7.50	2.54	5.08	0.00	0.00	0.00	0.00	1.14
19.00	27.20	7.50	0.00	2.54	2.54	0.00	0.00	0.00	1.40
20.00	34.00	7.50	0.00	0.00	2.54	0.00	0.00	0.00	1.40
21.00	40.50	7.50	0.00	0.00	-25.40	0.00	0.00	0.00	0.00
22.00	46.40	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23.00	50.80	7.50	2.54	2.54	0.00	0.00	0.00	0.00	1.14
24.00	54.30	7.50	-25.40	-25.40	0.00	0.00	0.00	0.00	0.00
25.00	56.20	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26.00	57.10	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27.00	57.20	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28.00	55.90	7.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29.00	54.50	7.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30.00	52.10	7.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31.00	50.90	8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32.00	50.80	8.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33.00	48.40	8.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34.00	46.10	8.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35.00	44.40	8.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36.00	43.00	8.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37.00	41.70	8.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38.00	40.50	8.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39.00	39.20	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40.00	37.90	9.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41.00	36.80	9.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
42.00	35.60	9.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43.00	34.60	9.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44.00	33.60	9.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45.00	32.80	9.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00

2. Derivation of Dimensionless Unit Hydrograph

This section continues the computation for the same storm JAME3 and demonstrates the DUH option of program HYDDUH. Datafile JAMEHYD3 was read into memory.

The following options and data selections were made :

1) lag measured from time of 50% rainfall excess to 50% direct runoff;
2) data included from first increment;
3) logarithmic recession to direct runoff hydrograph started at time 53 hours;
4) second point on logarithmic recession selected at time 83 hours;
5) baseflow at time 83 hours selected as 15 m^3/s, (so baseflow close to total runoff by time T_{JAME} after peak runoff);
6) DUH ordinates computed from time of commencement of direct runoff (T = 0) (rather than from the start of estimated rainfall excess at T = 7 hrs).

The printed output is shown on Table C.2. The DUH ordinates were stored on file JAME3SC2 to represent the output from the second run made on storm JAME3. The ordinates were included on Figure 5.4.

TABLE C.2 TYPICAL DUH OUTPUT FROM HYDDUH

================================
SCS UNIT HYDROGRAPH DERIVATION
================================

GAUGING STATION James River near Sundre
Drainage area 819.7sq kms

DATE OF STORM 83 07 02 Start time 1400 hrs

Total rainfall 43.18 mm. Percentage as direct runoff 15.4%
Rainfall losses - Constant PHI 2.98 mm per time interval

Lag measured from time of 50% rainfall excess to 50% direct runoff
Duration of rain (D) 22.0 hrs. Lag 24.3 hrs. Lag + D/2 (TLGD2) 35.3 hrs
Total direct runoff volume 5454000 m3 or 63.1 m3-days

TIME hrs	NET TIME hrs	RAINFALL EXCESS mm	TOTAL RUNOFF m3/s	BASE FLOW m3/s	DIRECT RUNOFF m3/s	TIME AS % TLGD2	DR * TLGD2 /TOT VOL hrs/day
1.0	1.0	0.00	7.90	7.50	0.40	2.83	0.22
2.0	2.0	0.00	8.12	7.50	0.62	5.67	0.35
3.0	3.0	0.00	8.39	7.50	0.89	8.50	0.50
4.0	4.0	0.00	8.70	7.50	1.20	11.33	0.67
5.0	5.0	0.00	9.07	7.50	1.57	14.16	0.88
6.0	6.0	0.00	9.44	7.50	1.94	17.00	1.08
7.0	7.0	0.00	9.90	7.50	2.40	19.83	1.34
8.0	8.0	0.96	10.40	7.50	2.90	22.66	1.62
9.0	9.0	2.36	10.70	7.50	3.20	25.50	1.79
10.0	10.0	0.00	10.90	7.50	3.40	28.33	1.90
11.0	11.0	0.00	11.10	7.57	3.53	31.16	1.97
12.0	12.0	0.96	11.40	7.50	3.90	33.99	2.18
13.0	13.0	0.96	11.90	7.50	4.40	36.83	2.46
14.0	14.0	0.71	12.50	7.50	5.00	39.66	2.80
15.0	15.0	0.00	12.90	7.50	5.40	42.49	3.02
16.0	16.0	0.00	14.30	7.50	6.80	45.33	3.80
17.0	17.0	0.71	16.20	7.50	8.70	48.16	4.87
18.0	18.0	0.00	20.70	7.50	13.20	50.99	7.38
19.0	19.0	0.00	27.20	7.50	19.70	53.82	11.02
20.0	20.0	0.00	34.00	7.50	26.50	56.66	14.82
21.0	21.0	0.00	40.50	7.50	33.00	59.49	18.46
22.0	22.0	0.00	46.40	7.50	38.90	62.32	21.75
23.0	23.0	0.00	50.80	7.50	43.30	65.16	24.22
24.0	24.0	0.00	54.30	7.50	46.80	67.99	26.17
25.0	25.0	0.00	56.20	7.50	48.70	70.82	27.24
26.0	26.0	0.00	57.10	7.50	49.60	73.65	27.74
27.0	27.0	0.00	57.20	7.50	49.70	76.49	27.79
28.0	28.0	0.00	55.90	7.60	48.30	79.32	27.01
29.0	29.0	0.00	54.50	7.70	46.80	82.15	26.17
30.0	30.0	0.00	52.10	7.80	44.30	84.99	24.77

TABLE C.2 (cont'd)

TIME hrs	NET TIME hrs	RAINFALL EXCESS mm	TOTAL RUNOFF m3/s	BASE FLOW m3/s	DIRECT RUNOFF m3/s	TIME AS % TLGD2	DR * TLGD2 /TOT VOL hrs/day
31.0	31.0	0.00	50.90	8.00	42.90	87.82	23.99
32.0	32.0	0.00	50.80	8.10	42.70	90.65	23.88
33.0	33.0	0.00	48.40	8.20	40.20	93.48	22.48
34.0	34.0	0.00	46.10	8.30	37.80	96.32	21.14
35.0	35.0	0.00	44.40	8.50	35.90	99.15	20.08
36.0	36.0	0.00	43.00	8.60	34.40	101.98	19.24
38.0	38.0	0.00	40.50	8.80	31.70	107.65	17.73
40.0	40.0	0.00	37.90	9.10	28.80	113.31	16.11
42.0	42.0	0.00	35.60	9.30	26.30	118.98	14.71
44.0	44.0	0.00	33.60	9.60	24.00	124.65	13.42
46.0	46.0	0.00	32.30	9.80	22.50	130.31	12.58
48.0	48.0	0.00	31.20	10.10	21.10	135.98	11.80
50.0	50.0	0.00	29.80	10.30	19.50	141.64	10.91
52.0	52.0	0.00	28.40	10.60	17.80	147.31	9.95
54.0	54.0	0.00	26.90	10.88	16.02	152.97	8.96
56.0	56.0	0.00	25.70	11.30	14.40	158.64	8.05
58.0	58.0	0.00	24.60	11.66	12.94	164.31	7.23
60.0	60.0	0.00	23.60	11.98	11.62	169.97	6.50
62.0	62.0	0.00	22.50	12.05	10.45	175.64	5.84
64.0	64.0	0.00	21.50	12.11	9.39	181.30	5.25
66.0	66.0	0.00	21.00	12.56	8.44	186.97	4.72
68.0	68.0	0.00	20.50	12.92	7.58	192.63	4.24
70.0	70.0	0.00	20.00	13.19	6.81	198.30	3.81
72.0	72.0	0.00	19.60	13.48	6.12	203.97	3.42
77.0	77.0	0.00	18.90	14.21	4.69	218.13	2.62
82.0	82.0	0.00	18.40	14.81	3.59	232.29	2.01
87.0	87.0	0.00	17.70	14.95	2.75	246.46	1.54
92.0	92.0	0.00	17.10	15.00	2.10	260.62	1.18
97.0	97.0	0.00	16.60	14.99	1.61	274.79	0.90
102.0	102.0	0.00	16.70	15.47	1.23	288.95	0.69

3. GIS - SCS Flow Prediction

The flow prediction program HYDSCS2 is demonstrated for watershed JAME, using the watershed parameters computed by program HYDSCS. A summary of these parameters eas given in Table 5.3. The partial areas of each 10km by 10km grid square within the watershed boundary were also stored by HYDSCS. The input file for this example was JAMEWS.

This example shows a typical example performed as Method 2 of the verification process.

Additional datafiles

IDF	File holding rainfall extreme statistics for the study area
REGDUH	Regional DUH ordinates
REGLAG	Regional lag curve parameters

Options selected for run

Rainfall return period	50 years
Duration of storm	24 hours
Duration of T hr UH	4 hours
Map Scale used in HYDSCS	1 : 50000
Curve number	71 (from input data)
Initial abstraction, Ia	0.1 S (ie k = 0.1)

The results are shown on Table C.3. The "Actual Runoff" column shows the total runoff hydrograph if modelling an actual storm. The peak runoff value was abstracted and plotted on Figure 5.15.

TABLE C.3 TYPICAL FLOW PREDICTION FROM HYDSCS2

========================
GIS - SCS FLOW PREDICTION
========================

Watershed title James River near Sundre

IDF Analysis - Duration of storm 24 hrs
Rainfall return period 50.0 yrs

Duration of Unit Hydrograph (T) 4 hrs
Runoff curve number CN = 71 Ia = 0.10 * S

Time hrs	Total Rain mm	Excess Rain mm	Unit Hydrograph m3/s/10mm	Actual Runoff m3/s	Predicted Runoff m3/s
4	14.5	0.2	1.73	0.0	0.0
8	14.5	2.7	5.71	0.0	0.6
12	14.5	5.2	16.13	0.0	2.7
16	14.5	7.0	35.20	0.0	9.1
20	14.5	8.3	60.62	0.0	24.2
24	14.5	9.3	74.61	0.0	53.3
28	0.0	0.0	67.75	0.0	95.8
32	0.0	0.0	55.29	0.0	144.3
36	0.0	0.0	45.91	0.0	185.8
40	0.0	0.0	38.02	0.0	207.1
44	0.0	0.0	31.47	0.0	198.7
48	0.0	0.0	25.80	0.0	169.5
52	0.0	0.0	21.07	0.0	139.6
56	0.0	0.0	16.91	0.0	115.5
60	0.0	0.0	13.62	0.0	95.1
64	0.0	0.0	11.03	0.0	78.0
68	0.0	0.0	8.93	0.0	63.4
72	0.0	0.0	7.23	0.0	51.3
76	0.0	0.0	5.86	0.0	41.4
80	0.0	0.0	4.75	0.0	33.4
84	0.0	0.0	3.84	0.0	27.1
88	0.0	0.0	3.11	0.0	21.9
92	0.0	0.0	2.52	0.0	17.8
96	0.0	0.0	2.04	0.0	14.4
100	0.0	0.0	1.66	0.0	11.7
104	0.0	0.0	1.34	0.0	9.4
108	0.0	0.0	1.09	0.0	7.6
112	0.0	0.0	0.88	0.0	6.2
116	0.0	0.0	0.71	0.0	5.0
120	0.0	0.0	0.00	0.0	4.1

APPENDIX D

DETAILS OF THE GIS AND THE ASSOCIATED SOFTWARE

This Appendix describes the organization of the GIS together with the details of the software written specifically for this part of the study.

The study region was subdivided into 3 areas each 60km by 60km so that data could be efficiently handled. The data for each area were stored on a separate floppy disk. Alternative dimensions for the areas could be selected if required.

1. Data Organization

Each area was divided into 10km by 10km blocks numbered in the same sequence as the NTS maps. The block numbering system is shown on Figure D.1.

05					55
04					
03					
02					
01					
00	10	20	30	40	50

FIGURE D.1 GIS BLOCK DETAILS

The GIS block numbers differ from the NTS ones as the former were related to a datum at the SW corner of the study area.

The data for each element were stored in a random access file to permit instant access to the data for any part of the area. The method used to store data on a 1km by 1km grid is shown on Figure D.2.

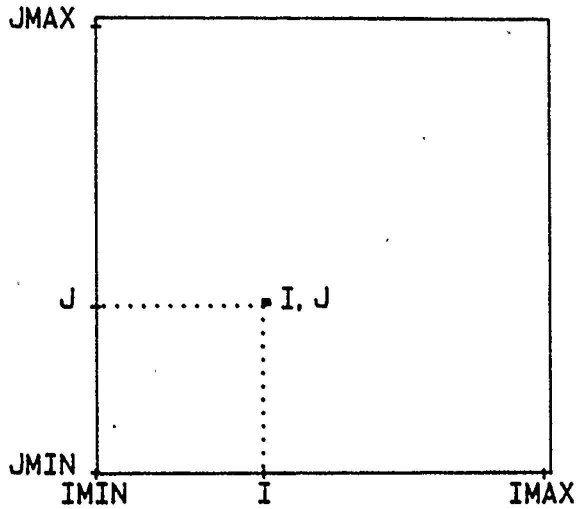

FIGURE D.2 GIS NUMBERING SYSTEM

JREC = JMAX - JMIN + 1 = 60

IREC = IMAX - IMIN + 1 = 60

The X,Y coordinates at the SW corner of each grid square formed the reference ordinates I,J for that square. Further, I,J ordinates at any point X,Y were equal to the rounded-down integer parts of the respective X,Y coordinates. Data were stored in sequence from JMIN to JMAX for each I value in turn.

The record number, K, for any grid square I,J was computed as follows :

K = (I - IMIN) * JREC + (J - JMIN) + NSTART

where NSTART is the record number for the first grid square (= 1 in most cases).

For the present study, IMIN and JMIN were both zero. Therefore

K = I * JREC + J + 1.

Data for the rainfall extreme statistics were stored on a 10km by 10km grid and were handled in a similar manner except that JBMX replaced JREC and that NSTART was dependent upon the storm duration as follows :

NSTART = JBMX * IBMX * (IDN - 1) / 100 + 1

where IDN is the storm duration in hours and

JBMX = IBMX = IREC (= JREC = 60) /10 = 6.

2. Data Input

The 16 key cursor was used as a keypad to input the data from the maps and plans. The software was written to expect data sequentially for each 10km by 10km block. The layout of the cursor is shown on Figure D.3.

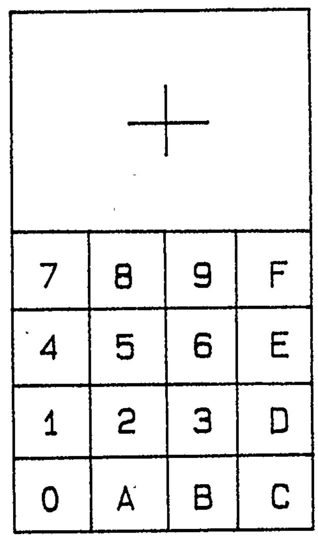

FIGURE D.3 CURSOR DETAIL

The keys marked by letters had the following responses :

A Same value as last entry

B Leave data unchanged

C Quit present input option

D Return to previous entry

E Initiate process to input same value for a number of sequential squares

F Null entry - No data available.

3. <u>Data Storage</u>

Data for each area were stored separately on different floppy disks. This enabled the same file names to be used for the same data element throughout. The filenames adopted were

Filename	Data stored
TITLES.DAT	Title of study area (for checking purposes)
LCOV.DAT	Land Cover Data
DRNCLASS.DAT	Soil Drainage Data
CN.DAT	Curve No Data (computed from LCOV and DRNCLASS)
ELEV.DAT	Elevation Data
IDF.DAT	Rainfall Extreme Statistics

4. <u>Program HYDGIS</u>

Program HYDGIS was written to handle the data for all the parameters noted in 3. above for the whole study region. The program also transferred blocks of data from one area to another and printed out and/or displayed on the screen blocks of data as requested.

5. <u>Program HYDCN</u>

Purpose 1) To input and edit data for the curve number (CN) reference file.

2) To compute the CN datafile for the study area using the CN reference file together with the Land Cover and Soil Drainage data.

1) Input file None or CNREF.DAT

Output file CNREF.DAT

Random access files used. Data elements stored for each record were

Land cover code,

Soil drainage code (US SCS),

CN value corresponding to the above codes.

2) Input files LCOV.DAT

DRNCLASS.DAT

CNREF.DAT

Output files CN.DAT

Program assessed and stored the corresponding CN value for each grid square by relating the land cover code and soil drainage code for that square to the CN reference file.

6. Program HYDSCS

Purpose - The first part of the flow prediction process, the chief purpose being to compute the spatial parameters relating to a watershed.

Input - Watershed boundary and longest watercourse described on the digitizer or watershed parameters input from the screen.
Curve number file CN.DAT

Output - Sequential file containing watershed parameters
Typical filename JAMEWS (JAME WaterShed)

Method - Digitizer input was used throughout

The program permitted input from maps of any scale and made the necessary geometric correction to align the digitizer coordinates with those of the map.

The low resolution mode (8pts/mm) of the KURTA digitizer was used throughout. The continuous stream of data used to describe the watershed boundary was set at 10 pts per second from the digitizer. Further the program ensured a minimum 0.5mm cursor movement between points stored for analysis.

The watershed boundary was described in a clockwise direction and the data stored as a set of X,Y coordinates in kms in terms of the study area grid.

In order to determine the weighted watershed CN it was necessary to compute the partial area of each grid square within the boundary. This is demonstrated in Figure D.4.

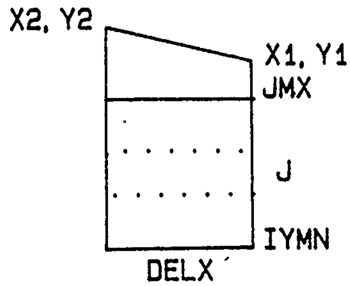

FIGURE D.4 PARTIAL AREA COMPUTATION

IYMN was the computed minimum Y grid square for the whole watershed.

The partial areas corresponding to each successive pair of data points were computed as follows :

RAT(I,J)=RAT(I,J) + DELX , for IYMN < J < JMX

RAT(I,JMX)=RAT(I,JMX) + DELX*(Y2 + Y1 - 2*JMX) /2

where RAT on completion of computation for all data points represented the absolute area of each grid square within the watershed boundary.

The programming was complicated by the necessity to add data points wherever the grid square boundaries were crossed to permit the above algorithm to be used universally.

The watershed area was computed as follows :

$$\text{AREA} = 0.5 \sum_{n=1}^{Num} X_{n+1}\, Y_n - X_n\, Y_{n+1}$$

$$\text{where } X_{Num+1} = X_1 \text{ and } Y_{Num+1} = Y_1.$$

The centroid of the drainage area was computed as follows :

$$\text{XBAR} = 0.25 \sum_{n=1}^{Num} (Y_n\, X_{n+1}^2 - Y_{n+1}\, X_n^2\,) \,/\text{AREA}$$

$$\text{YBAR} = 0.25 \sum_{n=1}^{Num} (X_{n+1}\, Y_n^2 - X_n\, Y_{n+1}^2\,) \,/\, \text{AREA}$$

The watercourse was described on the digitizer and the stream length computed assuming straight lines between each pair of data points.

The distance between each watercourse data point and the centroid was determined and the point closest to the centroid located. This enabled L_{ca} to be calculated.

Elevations at the divide and at the point of interest were input manually using map data and the mean slope computed and stored in metres / kilometre.

The data were stored in the following sequence :

Description of Watershed

Drainage area (sq kms)

Length of Longest Watercourse (kms)

Length of Watercourse
Downstream of Centroid

Slope (m/km)

$LL_{ca} / S^{0.5}$

Weighted Curve Number

XBAR

YBAR

XCA

YCA -- (pt on watercourse nearest centroid)

RT10 -- 36 values giving the Area of the
Watershed within each
10km by 10km grid square.

APPENDIX E

DETAILS OF THE SOFTWARE FOR HYDROLOGICAL ANALYSIS

1. Program HYDDUH

Purpose - To derive the SCS DUH for storms with subroutines to facilitate data input and printout, and to plot the results.

Input data were stored on random access files in the following sequence :

Record No	Data
1	Station Name, Area
2	Date of storm, Start time, Time step
3	No of rain stns, Gauging stn no
4 - 9	Rain station name and codename, and Thiessen weighting factor (max 6 stations)
10 - end	Time, Total runoff, baseflow, rainfall for each station.

Filenames followed the form JAMEHYD2 to represent the second storm studied on watershed JAME.

Output file - Included summary of storm details, and the dimensionless unit hydrograph ordinates. File name followed the form JAME2SC1 to represent the second storm for JAME and the first DUH for that storm.

The DUH was computed for each storm in accordance with the SCS recommendations. The method was amended so that computation could commence at the start of direct runoff rather than the start of rainfall excess if desired.

The plotting option allowed up to 6 output files to be plotted, using the SCS recommended log - normal scales, on the HP plotter. Examples of this output are included as Figures 5.5 to 5.11 inclusive.

2. <u>Program HYDSCS2</u>

Purpose - The second part of the flow prediction software; to use watershed parameters, together with the regional curves to compute the T-hour unit hydrograph and hence the direct runoff hydrograph.

Input file -The output file from HYDSCS eg JAMEWS.

Method - In general the SCS procedure was followed.
Read input file
Either read actual storm rainfall data eg JAMEHYD2 or, as in the verification runs, select rainfall return period and duration, access rainfall extreme statistics in GIS and

compute weighted rainfall depth for the watershed.

Use CN from input file, select initial abstraction Ia

Determine rainfall excess

Read regional lag and regional unit hydrograph data.

Select duration of unit hydrograph (T).

Compute 10mm Thr unit hydrograph ordinates.

Convolute rainfall excess with Thr UH ordinates to produce direct runoff hydrograph.

APPENDIX F

APPLICATIONS OF THE SOFTWARE

This Appendix details the sequences in which the computer programs, developed for this study, are used to perform the some of the available options.

1. <u>To Expand or Amend the GIS Data</u>

   a) Input raw data for required elements using HYDGIS.

   b) Create new or revised CN file using HYDCN.

2. <u>To Derive the Dimensionless Unit Hydrograph for a Storm</u>

   a) Input storm rainfall and runoff data using HYDDUH.

   b) Compute the DUH using HYDDUH.

3. <u>To Make Flow Predictions from GIS Data</u>

   a) Ensure data exist for all elements for the whole watershed.

   b) If any data incomplete, return to 1. above.

   c) Determine watershed parameters using HYDSCS with boundaries and watercourses described on the digitizer.

d) Make flow predictions using the IDF analysis option of HYDSCS2.

4. To Make Flow Predictions using GIS Rainfall Statistics Data but with Manually Estimated Curve Number

a) Ensure rainfall extreme statistics data covers entire watershed.

b) If incomplete, input as necessary using HYDGIS.

c) Determine watershed parameters using HYDSCS with boundaries and watercourses described on the digitizer and the estimated CN input manually when requested.

d) Make flow predictions using the IDF analysis option of HYDSCS2.

5. To Model Real Storms

a) General requirements as for 3. or 4. above as applicable, except that rainfall statistics are not needed.

b) Input storm data (rainfall data essential, runoff data can be included for comparison with prediction) using HYDDUH.

c) Determine watershed parameters as per 3c) or 4c) as appropriate using HYDSCS.

d) Make flow predictions using storm analysis option in HYDSCS2.