PROBABILISTIC DROUGHT ANALYSIS

by

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WILLIAM J. DEWIT

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

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ABSTRACT

Drought conditions can have severe consequences for those enterprises that depend upon the availability of water. The operation of a water dependent system must, therefore, take into consideration the fact that these adverse conditions will certainly occur in the future. One method of drought design is to use the drought of record as a design criterion, as is done at Manitoba Hydro. A more theoretical approach would be to investigate the drought characteristics of the region in question. This, however, poses some difficulty since historic records are typically too short to adequately characterize droughts.

This study uses synthetically generated data to investigate droughts in the Manitoba portion of the Nelson River basin. Droughts are censored from the historic and synthetic records using a theory of runs analysis which classifies droughts by their length, severity and magnitude. Exceedence probabilities and return periods are assigned to the events by applying the Weibull plotting position formula to the severity data. Power generation during drought periods is also studied.

The results of the analysis show that the historic record does not provide a good representation of drought events in the study area. The historic data produces a return period of 79 years for the drought of record while the synthetic data gives a return period of 381 years. Using historic data alone produces return period estimates that are very conservative. Relationships between drought parameters and power generation levels showed a high degree of variability.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The need to plan and design for extreme events is a problem that arises in every field of engineering. In the water resources field the high and low flow extremes are of particular interest. The high flow events, or floods, have been studied quite extensively through the years. These events have been investigated in more detail and are thus better understood than low flow conditions, or droughts. This is likely a result of the fact that floods have a much greater potential for causing severe personal damage to the general public, as evidenced by the floods of 1993 in the United States. Droughts on the other hand do not have a great effect on the general public until the lack of water becomes fairly severe. Less severe events impact on areas such as agriculture, water supply and hydro-power generation and this only indirectly affects much of the population. For the water users, however, these events can be critical since they may lead to the failure of the system to meet the demands placed upon it. In the case of a hydro-power utility a severe drought may lead to a significant decrease in the amount of power that can be generated and the reduced capacity may be less than the level of public demand.

The difficulty that a hydro-power utility faces when designing for drought conditions is in selecting the level of drought severity to design for. Obviously it is not possible to design for all conditions which means the utility must choose a specific design level and accept a certain amount of risk that the system will fail at some time.

Designing for an unreasonably severe event would mean the system has a low risk of failure but also leads to excessive construction costs. Designing for a very mild event would reduce the construction costs but would lead to frequent system failure which might incur certain costs in the form of penalties. The design drought lies somewhere between these extremes. One common method of design uses the drought of record as the critical event, where this drought is simply the worst event recorded in the available historic data. While this event is not likely to lead to a severely under-designed system, it does not make any guarantees as to what level of reliability the system is at. It may be above or below the desired reliability of the system. This selection method is not truly based on the statistical properties of the drought events. Compare this to the design for flood events where a dam or levee is constructed to handle floods of specified return periods. This difference occurs because the statistics of flood events are better understood than those of drought events.

Although droughts may appear to be mirror images of floods on an annual flow hydrograph, they are not investigated in the same fashion. The primary reason for this is that the minimum annual flow is typically not a very useful number, unlike the maximum annual flow which can be used to estimate such things as flood stage and potential flood damages. In the case of a drought the duration of the event and the total water shortage during that period are of far greater importance than the lowest flow recorded. The minimum flow recorded during a drought does not necessarily provide any indication as to the length or water deficit of the event. The duration and water shortfall have significant implications on the management of reservoirs in order to compensate for the lack of inflow.

Since the duration and water deficit are important, it is then necessary to determine when a drought period begins and ends. The typical method for defining drought periods is through the application of the theory of runs in the manner first proposed by Yevjevich in 1967 (*Dracup et al.,1980; Yevjevich,1967*). This method says that a drought starts when the flow drops below a specified level, or truncation value, and does not end until the flow rises above a certain truncation value. A continuous series, or run, of flows that fall below specified truncation limits constitutes a single drought event. This definition leads to the development of three drought parameters which are drought length, severity and magnitude. Drought length is the number of consecutive time periods in which flows are below the truncation value. Severity is the cumulative water deficit through the entire event and magnitude is the mean severity of the drought. These three parameters may be easily obtained from the historic record once truncation values are chosen but the statistical information obtained is often not sufficient for a good understanding of drought events.

The lack of long historic records is the main reason that a good understanding of drought events is hard to obtain. Historic flow records in many areas are frequently 30 years in length or even shorter. In a 30 year record it is easy to obtain 30 independent annual maximum flows which may be assumed to be point events. This is not the case with drought occurrences. Droughts cannot be considered as point events since they can last for significant time periods, up to 5 or even 10 years in duration. Also, the impacts of drought events are not necessarily independent. Two mild droughts occurring in close succession can have a greater impact than a single event which is more severe than the two mild droughts individually. Short historic records also tend to weight the statistical distribution of drought events towards less severe droughts because there is simply not enough time available in the record for many severe droughts to be represented. For example, in a single year there could be 6 one month droughts occurring whereas a 30 year record could at most record 5 different 5 year droughts. It is more likely that only one or two very severe droughts will be recorded.

The problems associated with investigating short records for drought conditions can be overcome through the use of synthetically generated flow data. Synthetically generated flows are based on the statistics of the entire historic flow record at a site. The statistics of the historic flow data appear to be more dependable than drought statistics simply because the number of available data points is so much larger. Sets of generated flow data are considered to be flow realizations that have an equal probability of occurrence as the actual historic record. These synthetic records are then investigated for drought conditions so that a better understanding of drought statistics may be obtained. One advantage of modelling the entire flow regime is that no a-priori assumptions are made with regard to the nature of drought events. This thesis proposes to investigate drought conditions in the Nelson River basin through the use of synthetically generated data, focusing specifically on the Manitoba portion of the basin.

1.2 SCOPE OF STUDY

The progression of tasks involved in the analysis of droughts for the Nelson River basin is reflected in the organization of the chapters in this thesis. Chapter 2 provides a review of some of the literature available regarding the study of droughts. It considers the definition of droughts, different areas of drought study and the analysis of streamflow drought. Chapter 3 looks at the selection of a flow modelling tool and describes the SPIGOT program which was ultimately selected for the task of modelling the Nelson River basin. This basin is then described in detail in Chapter 4. These three chapters provide information that is important for the complete understanding of the analysis that is presented in Chapters 5 through 7.

Chapter 5 presents in detail the procedure of choosing a model framework that will be used to generate synthetic flows for the multi-basin, multi-site system under investigation. Choosing the right framework is quite involved and is a crucial part of the entire analysis. The model framework chosen is then used to generate 1000 sets of 80 year records for each flow location in the basin. Chapter 6 describes how the theory of runs is applied to these sets of data. This study also considers power generation levels during drought events and the procedures for estimating generation levels are described in Chapter 6. The results of applying the procedures given in Chapter 6 are detailed in Chapter 7. Finally, Chapter 8 draws conclusions based on the analysis and results that have been presented.

CHAPTER 2

LITERATURE REVIEW

2.1 DEFINING THE CONCEPT OF DROUGHT

While everyone understands that a drought is a period of water shortage, individual perceptions and interpretations of drought vary depending on how each person is affected. One dictionary defines a drought as 'an extended period of dry weather. esp one injurious to crops.' (*Steinmetz and Braham*, 1993). This definition shows how a large percentage of people perceive droughts, that is, they see it as a period which adversely affects the agricultural sector. In countries like Canada and the U.S., where a large part of the economy is based on agriculture, this interpretation is understandable. Water shortages, however, can also impede such activities as supplying potable water, generating hydro-power and maintaining navigable waters to name but a few. These varied effects result in many different definitions of drought, definitions which do not accurately define the specific meaning of drought for each water user. In one study it is suggested that 'The confusion is due to the intrinsic nature of droughts, which exist only because the effects they produce exist...' (*Bravar and Kavvas*, 1991a).

The dictionary definition of drought provided above gives a reasonable, generalized explanation of drought. A more complete general description is provided by Dr. E.F. Roots who defines a drought as 'unusual', 'transient' and 'undesirable' (*Bauer*, 1988). Droughts are unusual because they are periods of deviation away from what might be expected to occur on average. Note that this does not imply that such deviations are unexpected. Assuming a drought to be transient means that one expects the drought to be terminated at some time after it's inception. Not assuming transience of such an event implies the assumption that a significant climatic shift has occurred. Droughts are undesirable because they adversely affect those enterprises which depend on the availability of water. For example, low water availability can result in significant monetary losses for the agricultural sector.

Dracup et al. (1980) provide a general description which is more meaningful to the scientist than the dictionary definition and which is shorter than Dr. Root's definition. The authors suggest that a drought is '...a water shortage with reference to a specified need for water in a conceptual supply and demand relationship.'. The general description provided by *Dracup et al.* is an excellent one because it easily leads to the development of specific definitions required by individual analysts. All one needs to do is specify the particular water source of interest and then relate how the supply of this water affects the specific demand for it. It should be intuitively obvious that low precipitation, or "dry weather," is the driving force behind such drought effects as low streamflow and soil moisture. Despite this, it is generally agreed that '... the impacts of drought can be effectively assessed by also considering other indicators of water availability...' (*Chang and Kleopa*, 1991). This means one can easily assess a drought in terms of a particular water source as is suggested by *Dracup et al.* (1980).

This study, for example, focuses specifically on streamflows since these values are directly connected to hydro-power production. The supply and demand relationship for this study is quite simple. When streamflows decrease, the potential for power generation decreases. For the purpose of this analysis a drought is specifically defined as a period of low streamflow conditions which may compromise the ability to meet the public's demand for power.

2.2 AREAS OF DROUGHT STUDY

Although every analyst may specifically define drought in a different manner, the studies themselves are typically defined as belonging to one of three major classifications. The three classifications of drought studies are atmospheric, agricultural and hydrologic. The common bond between each of these classifications is that in each study an attempt is made to provide a better understanding of drought conditions. These groups differ in the type of data considered, the particular impact that is of interest and in spatial considerations. Analysis conducted under different classifications may consider the same type of data or spatial impact which makes the drought effect considered the prime differentiating factor. In the following pages the three classifications are briefly discussed, giving an indication of what some of the major considerations are for each.

It should be immediately apparent that adverse atmospheric conditions are the root cause of all the undesirable drought impacts that are realized in various sectors. A 1988 report by J. L. Knox and G. Lawford investigates the relationship between atmospheric 'circulation anomalies' and the occurrence of dry and wet periods in the Canadian prairie provinces (*Bauer*, 1988). These anomalies are determined from atmospheric conditions in the Northern Hemisphere from the 15° N latitude up to the pole. The results of their analysis '... clearly distinguish the circulations associated with the DRY and WET regimes...' (*Bauer*, 1988). This suggests that dry or wet periods may be predicted in advance based on atmospheric conditions which would allow for mitigation procedures to be initiated prior to the occurrence of these events. A similar study was conducted by *Pandzic* and *Trninic* (1992) for the Kupa River basin in Yugoslavia. Using the method of principal component analysis, these authors show that there is a strong relationship between anomalous atmospheric conditions and anomalous discharges. Here again the method developed might be used for advance warning of undesirable conditions. While these two studies relate atmospheric conditions to agricultural and hydrologic impacts, typical atmospheric studies focus on the mechanisms of drought formation without considering the impacts on specific water users. An excellent example of such a study is the analysis by *Bravar* and *Kavvas* (1991 a, b) which considers '... the chain of factors that induces and maintains dry conditions at mid-latitudes.' (*Bravar* and *Kavvas*, 1991 a). These authors simulate 300 years of weather patterns for the global region between the 30° N latitude and 50° N. The simulation shows the development of dry and wet periods in the zone, but focuses on the mechanisms producing droughts. Results from the study by *Bravar* and *Kavvas* are of a general interest for the present study and therefore merit further consideration.

The present study investigates drought in the Nelson River basin, Figure 2.1, which lies approximately between the 45° N and 60° N latitudes, placing it in and near the mid-latitude zone studied by *Bravar* and *Kavvas*. Their simulation showed that surface moisture is reduced by high pressure weather systems and is subsequently replenished by low pressure systems. Sometimes, however, extended periods of high

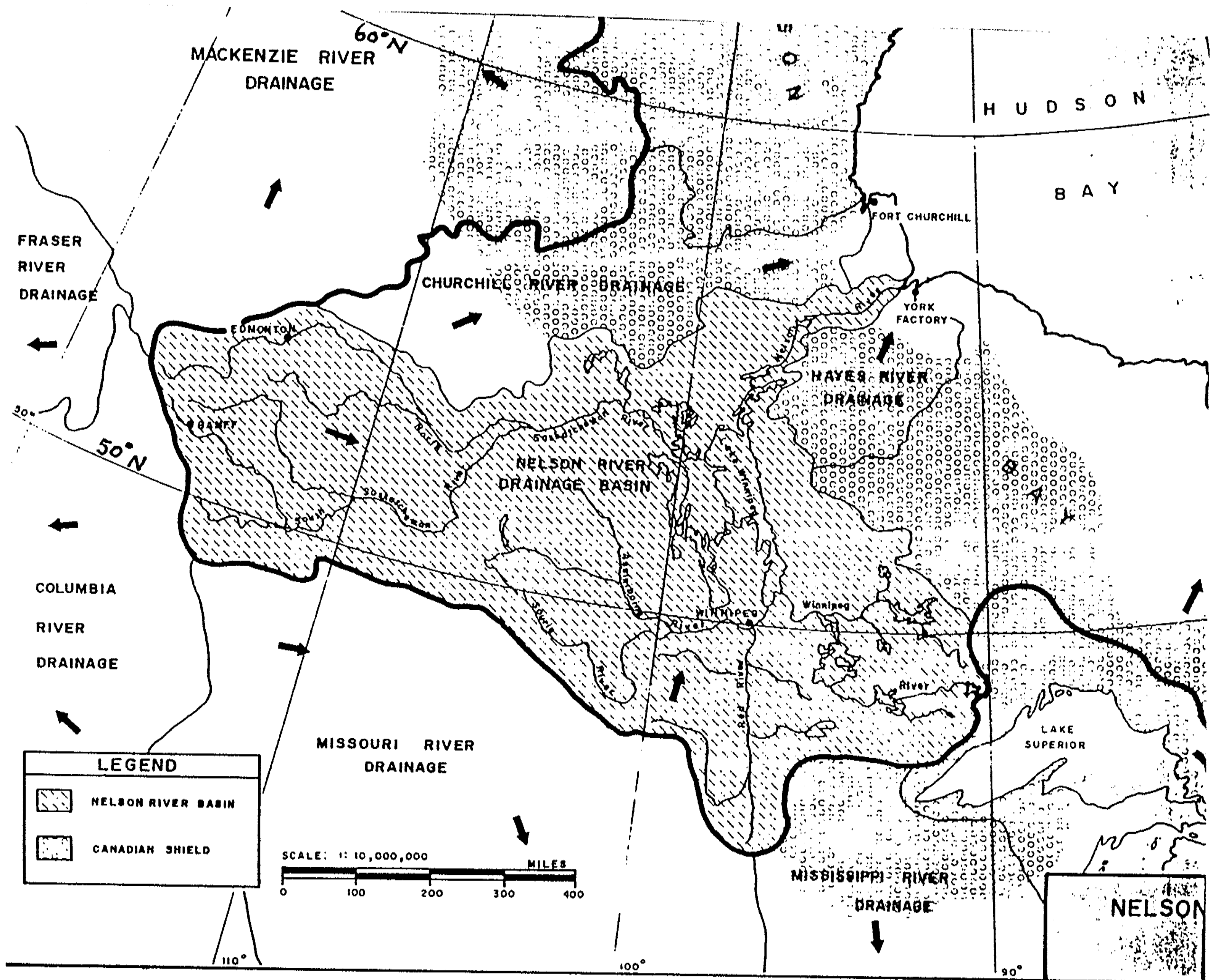

Figure 2.1 : The Nelson River Drainage Basin (*Newbury*, 1968)

pressure occur which leads to severe surface moisture depletion and represents the start of a drought. When a low pressure system moves in there may not be enough surface moisture available to raise the atmospheric moisture levels to a point where precipitation can occur. In this case, the low pressure system exacerbates the drought rather than alleviating it and causes the drought to persist. Termination of the drought can only occur when a low pressure system moves into the area which has sufficient self contained moisture for precipitation to occur. The study describes this effect as a 'positive feedback mechanism' whereby a drought feeds off of itself (*Bravar* and *Kavvas*, 1991 b). The three periods of drought occur over significantly different time periods. Drought inception is limited to 1 month in the study. The period of drought preservation is many months longer while the time it takes to recover is longer still. The preservation and recovery period can be in excess of 50 times longer than the inception period. It is important for water resource managers to realize that when drought termination begins it does not necessarily mean that the drought is over from a management stand point.

As indicated earlier, droughts are most commonly perceived in terms of their impact on agriculture. Numerous studies have been conducted which investigate drought with respect to their influence on agriculture. These studies utilize various types of data in their investigations such as rainfall, soil moisture, atmospheric anomalies, etc. One common goal in many of these studies is to find useful and reliable methods of forecasting when droughts are about to occur. This common concern may be seen in the '*Proceedings of the Prairie Drought Workshop*' (*Bauer*, 1988) which shows that a major focus of the conference is on drought prediction. *Cleaveland* and *Duvick* (1992) indicate that corn and soybean losses in Iowa during the 1988 drought amounted to $1.35 billion, a massive loss that might be minimized in the future with adequate drought forecasting and contingency planning. Prediction methods must be reliable to be useful since a forecasted drought may lead to actions such as not planting certain crops. If the drought does not occur, then millions of dollars may be lost because of forfeited crop production. Note that drought prediction is important for all water users but seems to be studied more often in connection with the agricultural sector.

Diaz (1983) used Palmer drought severity indices (PDSI) for the period 1895 - 1981 to determine if there are definite patterns in the beginning and ending of dry and wet periods in the continental United States. If these dry and wet periods preferentially begin and end in certain months, then that 'would imply a certain degree of conditional predictability' which could be used in drought forecasting. While the results showed only marginal preferences they also suggested that the interior and western U.S. are 'more likely to experience protracted periods of dry weather.' The results also indicate a possible connection between the occurrence of dry/wet periods and the occurence of El Nino/Southern Oscillation (ENSO) climate phenomena. *Cleaveland* and *Duvick* (1992) note that a study by Mitchell et al. (1979) found an approximate 22 year periodicity for the occurence of droughts in the Great Plains region, based on tree ring data. This corresponds to the double Hale sunspot cycle which has also been shown to influence ENSO phenomena (*Cleaveland* and *Duvick*, 1992). A later study by *Stockton* and *Meko* (1983) used tree ring data to confirm the 22 year periodicity and found that Great Plains drought appears to 'recur at ill-defined intervals from 15 - 25 years'. This indicates that assuming a specific periodicity may not be appropriate. *Cleaveland* and *Duvick* (1992) use tree-ring data to reconstruct July Palmer hydrologic drought indices (PHDI) in Iowa for the years 1640-1982. July PHDI values provide a good indication of crop growth potential. The authors find a 'statistically significant negative correlation' between the occurrence of dry/wet periods in Iowa and ENSO phenomena. Confirming the possible connections between solar activity, ENSO phenomena and drought occurrence may provide a valuable tool for long range forecasting of adverse agricultural conditions. *Kumar* and *Panu* (1994) show how drought warning procedures may be used in a real world application. They develop an expert system which will analyze various inputs to determine if a drought is likely and then advise what type of remedial actions may be taken to minimize its impact. Although the model is applied to a specific region in India, the methods developed could be applied in other agricultural regions.

The final type of studies to consider are those which may be classified as hydrologic drought studies. These studies primarily focus on drought from the viewpoint of water users such as hydro-power producers, water suppliers and other reservoir managers. That is, those water user's who's systems and operating policies are entirely dependent on streamflow levels. When streamflow drops during a drought, these users may not be able to meet the demands placed on their systems. While drought prediction is certainly important for optimum system design and management, forecasting is generally not the focus of hydrologic studies. Instead, these analyses tend to focus on the frequency of drought occurrence and the operational reliability of systems during low flow periods. Frequency and reliability are of concern because streamflow dependent systems must be designed for certain critical conditions which may be exceeded at some point during the design life of the system. For example, hydro utilities typically use the worst drought on record as the critical design event but realize that a worse event may occur at some future time.

Joseph (1970) presents the theoretical development of a method for estimating the frequency of a design drought. This study shows that as the useful design life increases so does the likelihood of a specific drought occurring during that design period. Therefore, streamflow dependent systems must be designed for more severe events as their design life increases in order to get the same level of assurance that the design event will not occur. An analysis of water supply dependability for a theoretical reservoir was performed by *Beard* and *Kubik* (1972). These authors determine the storage required to produce uniform yields of 30%, 50%, 70% and 85% of long-term average flow using both historic records and 500 years of synthetically generated data divided into 10 sets of 50 year records. Results of this study show that storage requirements from the different sets of data vary by as much as a factor of 2.0 in order to get the same yield. *Wurbs* and *Bergman* (1990) investigate factors which affect yield and reliability estimates for a system of twelve reservoirs in the Brazos River basin using only historic flow data. The authors show that factors which influence yield and reliability include 'the stochastic nature of streamflow and evaporation, changes in a river basin over time, loss of reservoir storage capacity due to sedimentation, reservoir system operating policies and interactions between multiple water users ...' (*Wurbs* and *Bergman*, 1990). Although this study is based on historic data, the authors suggest that 'using synthetically generated streamflows would be a logical extension of the case study' in order to better understand the influence of different factors. A more recent study by *Johnson* and *Kohne* (1993) uses historic PHDI values to determine the drought susceptibility of 516 American reservoirs. Their analysis shows that the 'mid-continent has the greatest potential for droughts of long duration.'. The method used by these authors is useful for investigating hydrologic drought characteristics over large regions but may not be appropriate for smaller areas. For smaller regions it may be more appropriate to use computer simulations in addition to the historic records.

The hydrologic studies described above indicate that frequency and reliability analyses are possible and necessary. Frequency analysis requires a method for clearly quantifying streamflow droughts and reliability analysis requires investigation of system operation under varied hydrologic conditions. Both of these analyses may be conducted using historic data, but it is generally agreed that the available historic records are not long enough to give a clear representation of either frequency or reliability. The statistical properties of drought parameters typically have a large standard error when based on historic data (*Wijayaratne* and *Golub*, 1991). Previously, it was seen that tree ring data bases have been used to get an extended historic record. This type of data, however, cannot be directly converted to exact streamflow values which means it has limited application for quantitative streamflow analysis. The only way to get more data is to perform synthetic streamflow generation as in the study by *Beard* and *Kubik* (1972). The following section describes methods used to quantify drought based on streamflow values. These methods are similar to those which will be used in the present analysis.

2.3 DROUGHT ANALYSIS BASED ON STREAMFLOW

The hydrologic studies mentioned above deal with aspects of streamflow drought, but they do not specifically focus on the streamflow data itself. The most common method of quantifying a streamflow drought is through the use of the theory of runs. In 1967, Yevjevich used this theory to investigate hydrologic drought and the methods he developed have been used by a number of authors since then (*Wijayaratne* and *Golub*, 1991). The theory of runs states that a drought starts when the flow drops below a given truncation level and ends when the flows rise above the truncation value. A consecutive sequence, or run, of flows below the truncation level is its severity (S_D), its length (L_D) and its magnitude (M_D) (*Wijayaratne* and *Golub*, 1991). Severity is the cumulative volume of water deficit during the drought, length is the number of consecutive low flow time periods and magnitude is the average deficit per time period. Figure 2.1 provides a graphical representation of how these values are obtained using flow data and a constant truncation level, X_c. The severity and magnitude parameters may be defined in equation

$$S_D = \sum_{i=1}^{L_D} (X_c - X_i) \qquad [2.1]$$

form as follows:

and;

$$M_D = \frac{S_D}{L_D} \qquad [2.2]$$

where X_i represents the values from the flow series. Note that flow deficits are calculated as positive values, not negative values.

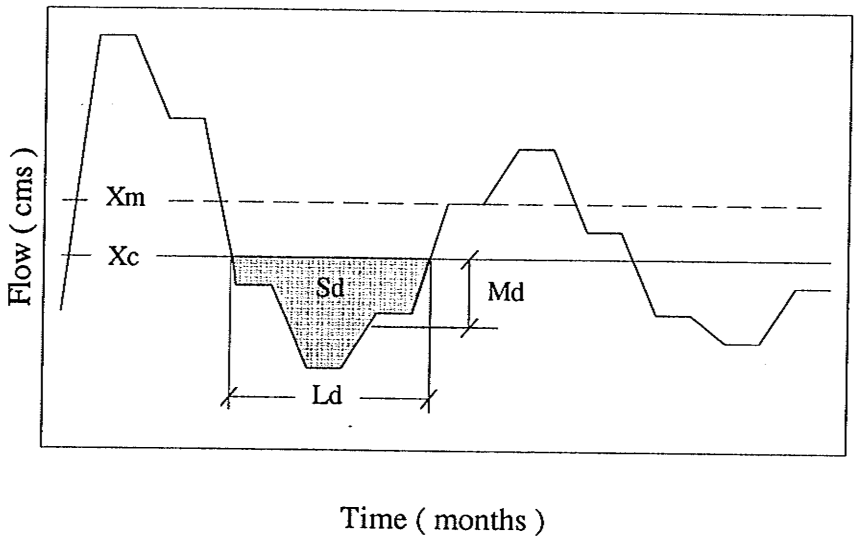

Figure 2.2 : Obtaining Drought Parameters From a Hydrologic Time Series (after *Wijayaratne* and *Golub*, 1991)

The truncation level is the most important variable in the application of the theory of runs. If a higher threshold is chosen then larger severities, run lengths and magnitudes may be realized. Whether or not the number of droughts recorded increases will depend on the particular characteristics of the flow data. Selection of the truncation value is therefore very important. Although the above figure showes a constant value, the threshold may also be a stochastic variable or a deterministic function (*Dracup et al.*, 1980). *Dracup et al.* (1980) indicated that it may be chosen by a function such as;

$$X_c = X_m - e \cdot SD \qquad [2.3]$$

where X_m = mean of the flow data; SD = standard deviation of the data and e = scaling factor. The scaling factor chosen will depend on the system being considered. *Sen* (1990) shows that the truncation value may vary over time based on shifting levels in demand. Essentially, as demand increases, the effects of drought will be felt sooner so that a higher threshold may be more appropriate. Two statistical measures of central tendency, the median and the mean, can also be used as meaningful thresholds (*Dracup et al.*, 1980). Using the median flow produces an equivalent number of high and low flow periods while using the mean results in equivalent values for total water surplus and deficit over an entire period of record. *Dracup et al.* (1980) indicate that the mean may be preferable since it gives more weight to extreme events than the median and it is these extreme events that one is typically interested in. Ultimately, selecting the truncation value will depend upon the system being considered, the level of demand and other factors. After choosing the desired truncation method, analysis of the drought parameters may be performed.

Sen (1980 and 1990) has twice investigated streamflows to determine the exact probability distribution function (PDF) of critical drought durations for finite sample sizes of data. He defines the critical drought duration as the longest drought one might expect to observe during the design life of a project. The 1980 study uses dependent Bernoulli trials which results in a 'non-homogeneous Markov chain with two states' if the process is periodic, which it is. The two states are either drought or non-drought periods. Using enumeration techniques, *Sen* (1980) determines the probability that the final time period in a trial is a surplus or deficit given that a drought of certain length has already occurred.

This method uses four transitional probabilities which describe the likelihood that the current period will be surplus or deficit if the previous period is in surplus or deficit. The probability for a specific period is dependent upon the transitional probabilities and the likelihood of certain occurrences in all previous time periods. The 1990 study is quite similar, except that a second-order Markov chain process is assumed. In this case, the transitional probabilities consider possible states of the previous two time periods, leading to eight transitional probabilities as opposed to four. In both studies *Sen* shows that as the sample size increases so does the critical drought duration, but at a decreasing rate. A curve of critical duration may be developed for any river and thus could be used in designing water resource systems.

Another concern for drought analysts is the investigation of droughts over large regions. *Paulson et al.* (1985) studied 18 streams in California's Central Valley. The authors calculate the severity, duration and magnitude of drought in each basin and then determine exceedence probabilities for severity and magnitude as well as termination probabilities associated with different durations. Severity, magnitude and duration for certain probability levels are then related to 11 different geomorphic and climatic indices using multiple-linear regression. The results of this analysis can be used to estimate the frequency characteristics of droughts for streams within the region, even those streams with no recorded data. This could be a very useful drought analysis method when developing an ungauged stream in any area.

Sadeghipour and *Dracup* (1985) also perform a regional frequency analysis of multi-year droughts in California's Central valley using data from 7 streams. They use the index drought method and the regional extreme drought method to develop a curve of severity versus frequency in non-dimensional form. Non-dimensional droughts are obtained by adjusting for drought length so that droughts of different durations are more easily compared. Severity-frequency curves for specified durations can be developed for any stream by back calculation of the standardization procedure.

Chang and *Kleopa* (1991) apply the theory of runs to streamflow, precipitation, groundwater, temperature and lake elevation data in performing a regional drought analysis of the Scioto River in Ohio. All of the data are used in determining drought severity for the region but the most weight is given to streamflow since it is 'the most representative indication of hydrologic drought' (*Chang* and *Kleopa*, 1991). Truncation levels of 70, 80, 90 and 95% are determined for each variable. The truncation values for streamflow, precipitation and lake level are given by the i^{th} value from the corresponding data set, which was sorted in ascending order, such that $i=(1-X)*N$, where $X=0.7, 0.8, 0.9$ or 0.95 and N is the number of data points. In the case of groundwater and temperature data the same process is used, except that now $i=X*N$ since these data values are higher during droughts rather than lower. For example, if 100 streamflows are recorded then the 70% truncation level equals the flow value of data point number 30 from the sorted data set. The basin is said to be at 70, 80, 90 or 95% severity based on a set of rules that consider the severity level of each variable individually and then weights the importance of each variable relative to each other. The authors then determine the mean drought durations associated with each overall severity level. They also determine the transitional probabilities associated with moving from one severity level to a more severe state. The results show that the probability of moving from a 70% to an 80% severity is much greater than moving from a 90% to a 95% severity. This indicated that a less severe drought is more likely to persist. Results of this analysis are useful for drought monitoring and the development of operating policies.

Finally, an analysis of multi-year drought was conducted by *Wijayaratne* and *Golub* (1991) in order to determine the appropriate theoretical distribution to fit to frequency curves for both drought duration and severity. The authors do this through the use of simulated flows and then compare results obtained for the synthetic data with those for the historic record. Investigating annual flows for the Pequest River in New Jersey, the authors find that the duration approximately follows a 3-parameter Gamma distribution while the severity follows a 3-parameter Log-normal distribution. More importantly, however, the results clearly show that short historic records will underestimate the return period for specific durations and severities. Furthermore, the distributions obtained from the synthetic data cover a much wider range of events than the historic record does. This means that synthetic data may be used to estimate return periods for events more severe than those recorded without having to use extrapolation techniques which introduce another degree of uncertainty.

CHAPTER 3

MODELLING A MULTI-SITE SYSTEM

3.1 SELECTION OF A MODELLING TOOL

The generation of synthetic flows for a large, multi-site system obviously requires a rigorous modelling tool. Any modelling procedure used must be able to reproduce site specific flow statistics such as the mean, variance and correlations. Numerous stochastic modelling procedures which will reproduce these values have been developed. The available literature contains much information on these models so they will not be discussed here. This study, however, deals with a multi-basin, multi-site system in which the site-to-site correlations are important and must be reproduced in the synthetic data along with the site specific statistics. Stochastic modelling techniques for multi-site systems have been developed and are typically variations of single site models. The difference is that the multi-site models are far more complex. There are several computer packages available which will perform stochastic simulation of multi-site systems. This study will use one of these programs rather than attempt to develop a new modelling tool based on information available in the literature.

Selecting a package to use requires a comparison of the available programs so that the one best suited to the present analysis may be found. Fortunately, the engineering firm Acres International Limited performed a detailed comparison of four prominent modelling packages by analyzing the Bow River system in southern Alberta (*Acres, 1990*). The four packages analyzed are HEC-4, NATAL, SPIGOT and CARMA. Acres also considered the LAST model but did not investigate it fully since the PC version was still being developed. A final package, CEPEL, is also mentioned but is not used in the study. CEPEL was developed by *Centro des Pesquisas de Energia Electrica* in Brazil and was not available in an English format. With a price tag of $30,000(US), the program is also prohibitively expensive. The conclusions of the Acres report are summarized in the following pages.

HEC-4 has been developed by the Hydrologic Engineering Centre (HEC), which is a part of the United States Army Corps of Engineers (USACE). The package may be obtained from the USACE for a small fee, or from other vendors for approximately $600. While the program does come with userss manuals, they are not very good and the USACE no longer provides support for the program. Synthetic flows generated in the Acres study using HEC-4 reproduce the historic statistics quite well but these flows did not display a desirable level of variability.

The NATAL program was created at the University of Natal in South Africa and can be obtained free of charge from the university. Written support for the package is limited and any further support requires contact with the University of Natal. Despite this the program is quite easy to apply. The Acres study found that the NATAL program reproduced historic statistics quite well and there was a good degree of variability in the synthetic data.

A collaboration of efforts, in various stages, lead to the development of the SPIGOT analysis package. The SPIGOT package can be purchased from the primary developer, Dr. J. Stedinger, at Cornell University for approximately $300. Provided along with the program are a technical description and a users manual. Limited support is also provided by Dr. Stedinger. Like NATAL, SPIGOT was able to reproduce the historic statistics with a reasonable degree of variability in the data. SPIGOT, however, produced a better range of synthetic flow events than NATAL.

The final tool investigated is the contemporaneous auto-regressive moving average, CARMA, model. The CARMA model uses techniques developed by various researchers and was set up using routines obtained from a number of sources. Cost of this program will vary and user's manuals are not available, although the procedures involved are described in the available literature. The CARMA model produced results which were not as good as the previous three packages. CARMA, however, does show good potential. With further research and documentation it could be an excellent modelling tool.

Based on the information presented in the Acres report, the SPIGOT package was selected for the stochastic modelling needs of the present analysis. The program performs well, has a reasonable price, is well documented and comes in a ready to use format. Further, the Fortran source code is also provided along with the installation disks. This allows the user to add to the programs if desired as well as load the program onto a platform other than a PC. This last point is important since the program is to be loaded on a UNIX platform in order take advantage of this system's larger memory capacity and fast running time. A more detailed description of the SPIGOT package is provided in the following section.

3.2 THE SPIGOT STREAMFLOW ANALYSIS PACKAGE

The name SPIGOT is an acronym derived from the names of the principal contributors in the development of this streamflow analysis package. These contributors are Jery Stedinger, Daniel Pei, Jan Grygier and Tim Cohn. The original version of this software package was developed by Stedinger and Grygier at Cornell University while working on a project for the Pacific Gas and Electric Company. Since then, various improvements have been made, leading to the current version, which is version 2.6.

The SPIGOT package is not a single program but is rather a compilation of four separate modules which complement each other. These four modules are referred to as DISPLAY, PAREST, FLOGEN and VALDAT. A fifth module, DEMAND, is also available and may be used to generate synthetic series of flow demands. This module was not necessary within the scope of the current study. A brief description of the flow models available in SPIGOT and the first four modules is provided in the following sections. Note that these descriptions are short summaries of what may be found in the Technical Description and/or the User's Manual. If more information is required it will be necessary to either obtain these documents or contact the program authors.

3.2.1 Flow Models Available in *SPIGOT*

The SPIGOT package offers six different modelling tools which may be used in a variety of combinations, or frameworks. Of these six modelling tools, two use auto-regressive (AR) procedures and the remaining four use disaggregation procedures. The first flow model is the aggregate annual (AA) model which uses an AR(0) or an AR(1) formulation to model the annual flows at a single site. The second is the multi-variate annual (MA) model and it also uses an AR(0) or AR(1) formulation to model annual flows. In this case, however, two or more sites are modelled simultaneously. The first disaggregation procedure is the aggregate annual to monthly (AAM) model and it generates monthly flows at a site based on the annual flow at that site. An aggregate annual to multi-variate monthly (AMM) model is next, and it is used to get monthly flows at multiple sites based on the annual flow at a single site. These multiple sites would be subordinate to the annual flow site, and the summation of their flows would equal the flow at the annual location. The third procedure is the multi-variate annual to monthly (MAM) model which disaggregates annual flows at multiple sites into monthly flows at multiple sites subordinate to the annual flow locations. Finally, a spatial disaggregation (SD) model is used to disaggregate monthly flows at a single site into monthly flows at multiple subordinate sites. SPIGOT attempts to maintain historic site-to-site relationships in each of the models which deal with multiple sites simultaneously. These flow models are conveniently summarized in Table 3.1 for quick reference.

As indicated, these models can be combined in a variety of ways to generate flows at multiple sites. For example, one could model annual flows at a site with an AA model, disaggregate these into monthly flows at that site with an AAM model and then obtain monthly flows at several subordinate sites with an SD model. Alternately, the annual flows for a site could be obtained with an AA model and then monthly flows for all the sites could be obtained with an AMM model. Generally, one would prefer to use as few steps as possible because as more steps are added, the modelling accuracy for sites in the

MODEL NAME		SUMMARY DESCRIPTION
Aggregate Annual	AA	annual flows at one site using an AR(1) or AR(0) model
Multivariate Annual	MA	annual flows at multiple sites with AR(0) or AR(1) and maintains site-to-site correlations
Aggregate Annual to Monthly	AAM	disaggregates annual flows at a site into monthly flows at that site
Aggregate Annual to Multivariate Monthly	AMM	disaggregates annual flows at one site into monthly flows at multiple subordinate sites
Multivariate Annual to Monthly	MAM	disaggregates annual flows at multiple sites into monthly flows at those sites as well as multiple subordinate sites
Spatial Disaggregation	SD	disaggregates monthly flows at one site to monthly flows at multiple subordinate sites

Table 3.1 : Summary of Flow Models Available In SPIGOT

later steps may be reduced. When attempting to model multiple sites in multiple basins the number of possible model frameworks to use can become quite large. For this reason, the authors of SPIGOT suggest 3 basic model frameworks which fit the needs of most analyses, as shown in Figure 3.1. Note that in Figure 3.1 a *basin site* refers to a major site and its flows are the summation of the flows at multiple subordinate *key sites* within the basin. These key sites in turn represent the flow in different subbasins and are the summation of flows at multiple subordinate *control points* within the subbasins. Generally, basin sites are more important than key sites which in turn are more important than control points.

In Framework I, an AA model generates annual flows for an entire basin. These annual flows are then converted into monthly flows for the basin site with an AAM model. The monthly flows are then disaggregated into monthly flows at various key sites using an SD model. A second SD model is used to disaggregate monthly key site flows into monthly flows at subordinate control points.

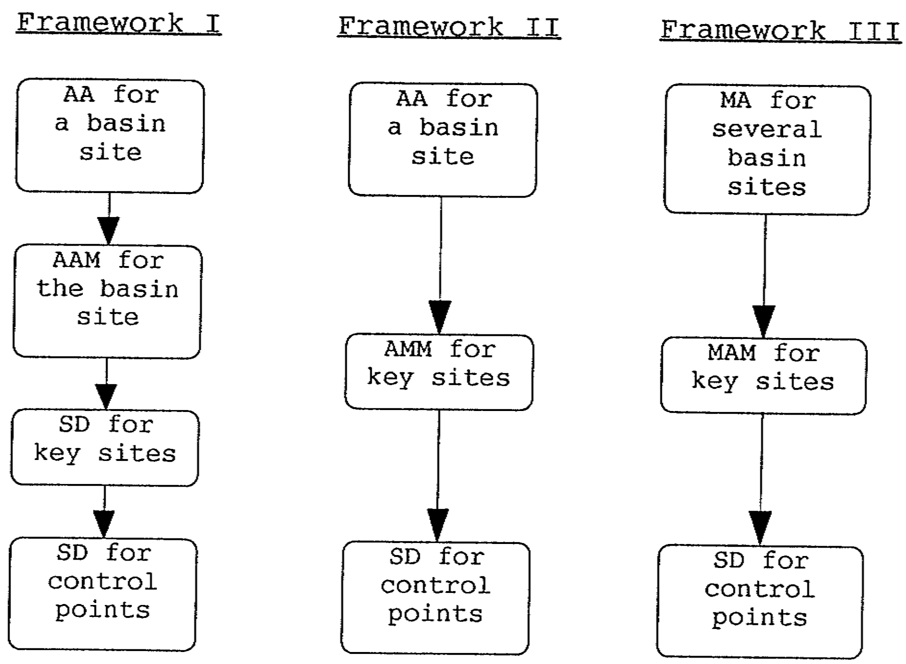

Figure 3.1 : Basic Model Frameworks For SPIGOT Analyses

Framework II, like Framework I, is used to model the flows in a single basin. The annual flow for the basin site is again modelled with an AA model. Monthly flows for basin site and the various key sites are then modelled simultaneously using an AMM model. An SD model then disaggregates the monthly key site flows into monthly flows at the control points. This framework could be used to model the same basin as Framework I, but combines the steps of modelling the monthly basin flows and disaggregation to monthly key site flows into one step with the use of an AMM model.

Finally, Framework III is suggested for multiple basin models. In the first step, annual basin site flows for multiple basins are generated using an MA model. These are then disaggregated into monthly flows at multiple key sites within the various basins with an MAM model. As before the monthly control point flows are determined by disaggregation of the monthly key site flows.

When generating flows the SPIGOT model attempts to maintain the historic statistics as much as possible. These historic statistics include the mean, variance, lag 1 correlations and site-to-site correlations. The site-to-site correlations are maintained both between the sites that are currently being modelled along with the sites that they are dependent upon. For example, site-to-site correlations are maintained for the control points modelled with the SD model in Framework I along with the site-to-site correlations between the key sites and the control points. The site-to-site correlations between the control points and the basin site, on the other hand, are not directly modelled. The basin site and the control points are indirectly connected through the key site flows. This aspect of SPIGOT helps to ensure that all of the generated flows are reasonable with respect to each other, which means two similar sites will not have extremely different flow conditions. One site is unlikely to be in a severe drought while the other experiences a severe flood unless the historic statistics allow for this possibility. Maintaining site-to-site correlations, however, can create some difficulty in the modelling procedure as will be seen later in Chapter 5.

3.2.2 Analysis Modules Available in *SPIGOT*

As mentioned earlier, SPIGOT is comprised of four basic modules named DISPLAY, PAREST, FLOGEN and VALDAT. These modules are used successively to analyze the historic data, develop a model framework for the system, generate synthetic flows and validate the synthetic output. A brief description of these four modules is provided in the following pages.

The DISPLAY module is an analysis tool that is used to obtain a variety of statistics from the historic data. Flow statistics calculated by DISPLAY include the mean, standard deviation, site-to-site correlations, monthly-to-annual correlations and lag 1 to lag 5 correlations. Analysis of the historic data is an essential step when attempting to set up a model framework for a multi-basin, multi-site system like the Nelson River basin. In a large analysis it is necessary to determine which flows represent basin sites, key sites and control points. Making this determination is easy if it is based purely on the physical locations and relationships between all of the sites. The process is more complex if artificial basin or key sites are used in the modelling procedure. Artificial sites would be created by the summation of flows at a number of locations but would not necessarily have to represent an actual physical location within the system. Summing the flows for two control points in different basins would create an artificial site. Since SPIGOT attempts to maintain site-to-site correlations within each modelling step it makes intuitive sense to model highly correlated sites simultaneously and this sometimes requires the creation of artificial sites for modelling purposes. DISPLAY is used to investigate the various relationships and makes the task of choosing an initial model framework much easier.

The second module, PAREST, is likely the most important part of SPIGOT. This module is used to estimate the model parameters required in each step of the model framework when flows are generated. As PAREST calculates the model parameters it also calculates various statistics on the significance of each model parameter as well as statistics that indicate how well each modelling step performs. PAREST first investigates the type of data transformation that should be used to normalize the data for each flow period at each site. Transformations checked are normal, 2 parameter log-normal, 3 parameter log-normal and 3 parameter gamma. The one that has the best Filliben correlation statistic is chosen. The Filliben correlation statistic measures the degree of correlation between the series values and their expected values for a given distribution. A Filliben value of 1 indicates a perfect fit, so the transformation producing the value closest to 1 is used. The selection process gives a slight advantage to the normal and 2 parameter log-normal distributions since they incur a smaller loss in degrees of freedom, which may be important with short data sets. After choosing the transformations, PAREST calculates parameters for each model. In each model there is the option to use a lag 0 or lag 1 formulation and PAREST tests both. The option producing the lower Akaike Information Criterion (AIC) value is chosen. PAREST also determines Filliben correlations, R^2 values, t-ratios and standard errors for each model. These are provided in the output. It is important to check the output and confirm that the selections made by PAREST are the preferred choices since the model with the lowest AIC is not necessarily the best one to use. Choices made by the program may be changed if necessary.

PAREST is also used to test different model frameworks for a system since the initial model framework chosen will probably not be the best one, particularly when modelling many sites. Although PAREST doesn't directly test different frameworks, the PAREST results can be used to indicate what changes might be made to a framework in order to get a better model of the system. This module may be run interactively so that the user can control the selection process in every step of the parameter estimation analysis. For large systems this is not recommended since it would be very time consuming. Furthermore, the selections made automatically by the program are generally the preferred choice when all the available statistics are considered.

When a final model framework is ultimately selected and all the relevant parameters are obtained, the next step is the generation of synthetic flows. This task is accomplished using the FLOGEN module which is run completely in batch mode. The user specifies how many sets of synthetic data are to be generated. Each data set is the same number of years in length and this length is determined by the user. FLOGEN also allows for upper and lower limits to be set on the generated flow values. An upper limit is used to prevent unrealistically high flows to be generated. Similarly, a lower bound of zero is used so that negative values are not generated for actual flow sites. In some analyses, such as groundwater modelling, negative values may be allowed and FLOGEN provides for this option. There are no hard and fast rules regarding how many sets of data to generate, how long they should be and what limits should be used and this is therefore left up to the discretion of the analyst.

The final module provided is the VALDAT program. This module analyzes and compares drought events from the historic and synthetic records using the theory of runs. For each synthetic sequence, VALDAT determines the largest deficit, second largest deficit and the single largest deviation below a threshold and provides a graphical comparison of these values with the corresponding historic values. The VALDAT output allows the user to verify that the synthetic records generated are reasonable.

CHAPTER 4

STUDY AREA

The basin under consideration in this study may be broadly defined as the Nelson River Basin. Although the Churchill River is technically an entirely separate basin from that of the Nelson, this study considers it to be part of the Nelson River system because of the Churchill River diversion at Southern Indian Lake. The Nelson and Churchill River basins are approximately $1.1*10^6$ km^2 and $0.244*10^6$ km^2, respectively, producing a total drainage area in excess of $1.3*10^6$ km^2. The basin stretches from the slopes of the Rocky Mountains in the west, to within 100 km of Lake Superior in the east and to south-eastern Minnesota in the United States. Physiographically, most of the basin's southern portion lies within the Great Plains region while the remaining northern portion is primarily in the Canadian Shield region. Two climatic zones cover a major percentage of the basin. The first is the Humid Continental climate zone which covers much of the southern area and the second is the Sub-Arctic zone covering much of the northern portion. A small percentage of the basin lies in more localized climate zones such as found along the slopes of the Rocky's and along the northern fringes of the basin. Flows reaching the Nelson River originate from regions which represent a number of combinations of climatic and physiographic conditions.

4.1 THE HYDROLOGIC SYSTEM

This study does not consider the entire Nelson River Basin as described above, but focuses on that portion of the basin within the province of Manitoba. That is, the part of the basin which directly influences Manitoba Hydro and comes under Manitoba Hydro's regulation. The remaining portions of the basin are indirectly considered in the study through the analysis of those flows which cross over into Manitoba Hydro's region of purview. In order to be complete, those flows which originate within the region are also considered. Flow data for the analysis was provided by the Power Resources Planning Division of Manitoba Hydro. Figure 4.1 provides a representation of the hydrologic system under consideration and the following pages describe the flow sites which are to be investigated.

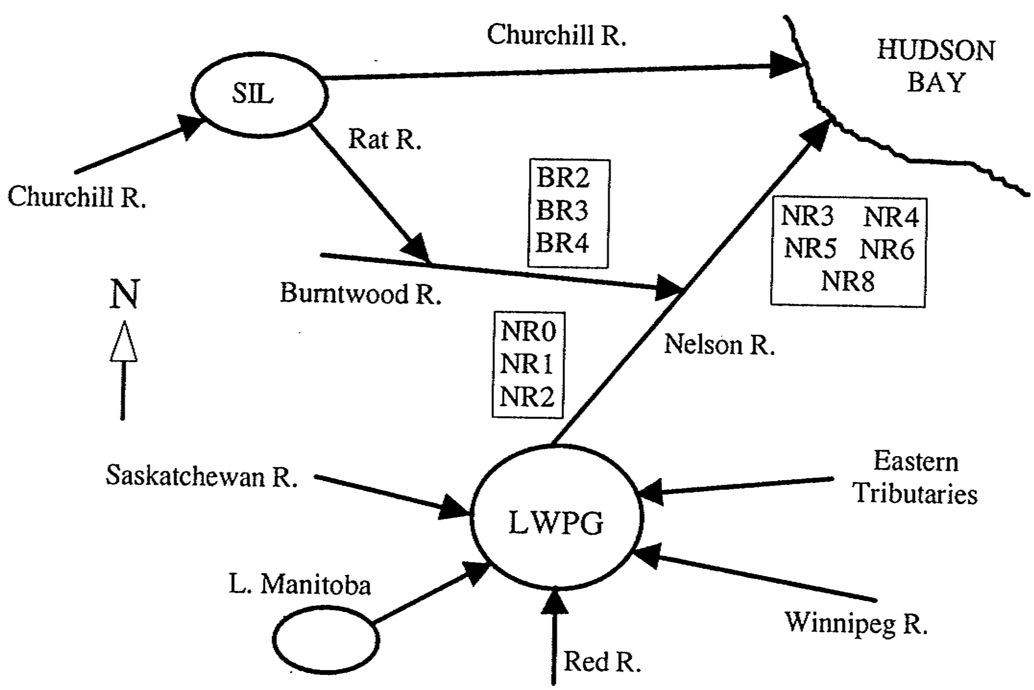

Figure 4.1 : Manitoba Portion of the Nelson River Basin

There are four inflows of major importantance to Manitoba Hydro. These flows are represented by four sites; the Saskatchewan River at Grand Rapids generating station (SASK@GRAND), the Winnipeg River at Slave Falls generating station (WPG@SLAVE), the Churchill River at Southern Indian Lake (CHR@SIL) and lastly, Lake Winnipeg Partial Inflow Available as Outflow (LWPGPIAO). The three rivers originate outside of Manitoba and are regulated to some extent by others outside the province. Each of the four sites have periods of record for the years 1912-1990 inclusive. The sites SASK@GRAND and WPG@SLAVE represent point flows for these two major rivers where they enter the Manitoba Hydro system. The last two sites require some further explanation, starting first with the site CHR@SIL.

Manitoba Hydro diverts a portion of the Churchill River's flow, at Southern Indian Lake, down the Rat and Burntwood River systems and thus into the Nelson River. This increases flows in the lower reach of the Nelson River wherein lies Manitoba Hydro's three largest power generating stations, Figure 3.2. The amount of flow diverted is regulated by the Notigi Control Structure situated on the Rat River and the Missi Falls Control Structure at the northern end of Southern Indian Lake. Historic Notigi release flows are available and were initially considered for modelling purposes rather than the CHR@SIL flows. A problem arises, however, when considering these release flows because Manitoba Hydro must operate Notigi under an interim licnese with the Povince of Manitoba which dictates the maximum release flows allowed through Notigi in particular months. Also, there is a minimum release that must be met at Missi in order to meet riparian water demands on the Churchill River north of Southern Indian Lake.

Churchill River flows are frequently large enough to meet both constraints. This causes much of the Notigi release record to have flow values at a level equal to the maximum allowable which results in a flow distribution that has a large negative skew and essentially bounded on the right. Such characteristics make the Notigi release flows undesirable for modelling purposes. The only alternative is to model the flow entering Southern Indian Lake, that is, the Churchill River flow. Synthetic CHR@SIL flows may then be used to estimate Notigi releases based on Manitoba Hydro's operating policy, as described further in section 6.2.1 of this thesis. Another advantage of modelling these flows is that it provides Manitoba Hydro with greater flexibility in the future. If the maximum or minimum constraints change then all that needs to be done to get new release estimates is to change the constraints in the estimation program. This is far simpler than having to re-run the SPIGOT modelling program, especially since the new flow distribution would be completely unknown.

The LWPGPIAO site, unlike the other three major sites, does not represent the flow conditions at a specific point on a particular river but is instead an amalgamation of a number of factors. Note that Figure 4.1 shows that numerous flows enter Lake Winnipeg via sources other than the Saskatchewan and Winnipeg Rivers. While the contribution of these other flows is important, the individual river flows are not since these rivers do not have any generating stations situated on them. Also, these individual inflows are small enough that they are not likely to be considered for large scale hydro power development. The contribution from these sources is combined into a single value termed LWPGPIAO. This value represents the total inflow to Lake Winnipeg less the regulated flows from SASK@GRAND and WPG@SLAVE (*Manitoba Hydro*, 1990). Adjusting for storage change means that the LWPGPIAO value takes into consideration such losses as evaporation from the lake, which is why it is called partial inflow *available* as outflow. Considering that the lake has a surface area in excess of 15000 km^2 (*Manitoba Hydro*, 1988) the effects of evaporation can be significant during dry weather. In fact, on a few occasions evaporation from Lake Winnipeg has exceeded all the inflows, Saskatchewan River and Winnipeg River inflows included. For a drought study the effects of such a significant factor must be considered, which makes the LWPGPIAO site a particularly important one to be modelled.

Aside from the four major sites discussed above, there are also 11 minor flow sites to be modelled in the analysis. These sites are referred to as minor because their flows combined represent approximately 12% of the flows entering the system. The cumulative effect of 11 such sites, however, can be important. These minor sites represent local inflows to 11 specific portions of the Burntwood and Nelson Rivers. There are 3 local inflow sites on the Burntwood River and 8 on the Nelson River. The sites are named according to the river they are located on, either BR or NR, and also have a site number associated with them, as shown in Table 4.1 and Figure 4.1. This table also shows the major locations on the two rivers which define the local inflow zones. The final data site supplied by Manitoba Hydro is called SUMNR+BR and represents the sum of the 11 local inflows in each month. Historic data for these sites covers the years 1957-1990. Data for the years 1912-1956 was reconstructed (*Manitoba Hydro*, 1988) but the reconstructed flows do not accurately reflect true historical flow variance. It was indicated that the period 1957-1990 is accurate for modelling purposes (*personal communication, B. Girling,* 21/06/93).

SITE	YEARS	LOCATION
BR2	1957-1990	Local Inflow to Burntwood River
BR3	1957-1990	Local Inflow to Burntwood River
BR4	1957-1990	Local Inflow to Burntwood River
NR0	1957-1990	Local Inflow to Nelson River
NR1	1957-1990	Local Inflow to Nelson River
NR2	1957-1990	Local Inflow to Nelson River
NR3	1957-1990	Local Inflow to Nelson River
NR4	1957-1990	Local Inflow to Nelson River
NR5	1957-1990	Local Inflow to Nelson River
NR6	1957-1990	Local Inflow to Nelson River.
NR8	1957-1990	Local Inflow to Nelson River
SUMNR+BR	1957-1990	Sum of all Local Inflows
LWPGPIAO	1912-1990	Lake Winnipeg PIAO
WPG@SLAVE	1912-1990	Winnipeg River at Slave Falls G.S.
SASK@GRAND	1912-1990	Saskatchewan River at Grand Rapids G.S.
CHR@SIL	1912-1990	Churchill River at Southern Indian Lake

Table 4.1 : Flow Records Received from Manitoba Hydro and used in this study.

4.2 THE HYDRO-POWER GENERATION NETWORK

Manitoba Hydro operates 12 hydro-power generating stations within the Nelson River basin in Manitoba. Note that the Slave Falls and Pointe DuBois generating statiions actually belong to Winnipeg Hydro but are considered part of the Manitoba Hydro system in this study. The approximate location and generating capacity of each station is shown in Figure 4.2. Also shown in this figure are the Missi and Notigi Control Structures, which regulate the diversion of Churchill River flows, as well as the East Channel which diverts part of the Lake Winnipeg outflows around the Jenpeg Generating station and into Cross Lake. The East Channel is a natural, unregulated waterway. This figure shows that the generating stations are located in three principle areas, the Winnipeg River, the

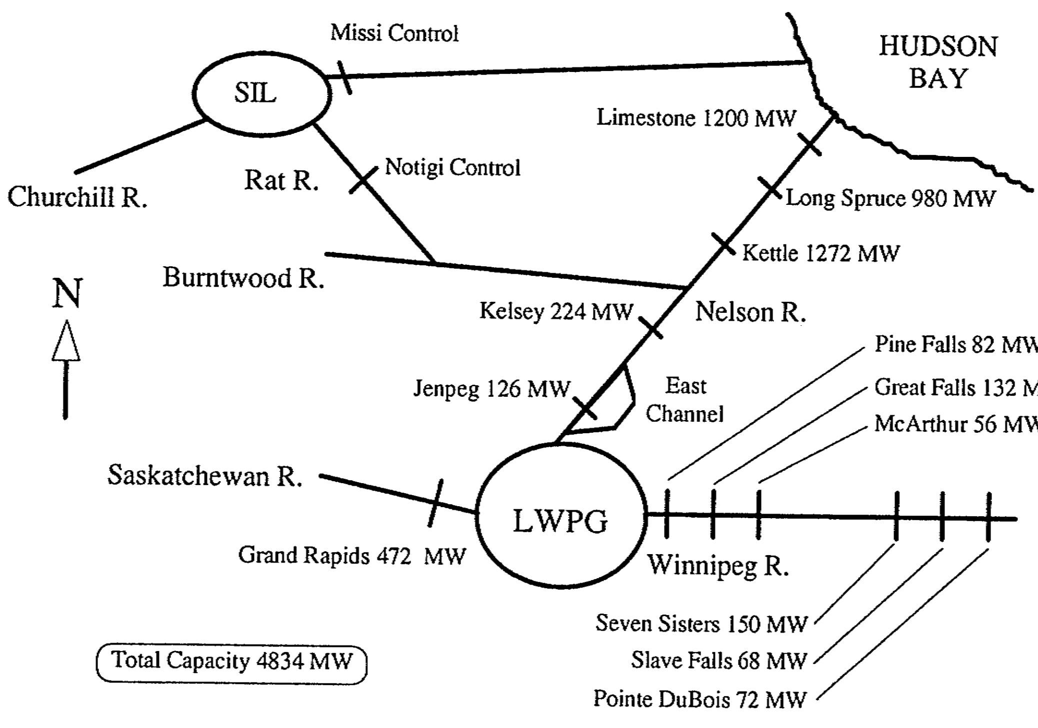

Figure 4.2 : Locations of Manitoba Hydro Generating Stations

Saskatchewan River and the Nelson River. Although the stations are spread out quite well, the plant capacities given in Figure 4.2 indicate that the three stations on the lower Nelson River represent a significant portion of Manitoba Hydro's total installed capacity. The total installed capacity is 4834 MW, of which 3452 MW, or approximately 70%, comes from the three stations on the lower Nelson. The remaining 9 stations contribute 1382 MW or about 30%. The three largest generating stations form the cornerstone of the entire system and droughts which affect these stations can have serious consequences for Manitoba Hydro.

Considering that all of the four major inflows eventually end up in the lower Nelson, it should not be surprising that the bulk of the generating capacity currently lies in this region. This area also presents the greatest potential for the development of future generating stations. In fact, Manitoba Hydro began construction of the new Conawapa Generating Station just down stream of Limestone. This project was subsequently put on hold until further notice. If and when Conawapa is brought on line it will add more than 1000 MW to the total system capacity. Several other locations along the Nelson and Burntwood Rivers have also been identified for potential future development.. While power production at future stations could be considered, this study will only focus on stations which are fully on-line at this time, as shown in Figure 4.2. Note that Manitoba Hydro also operates two thermal generating stations, one in Brandon and the other in Selkirk, and these will not be considered in this study since they are not as severely affected by adverse hydrologic conditions.

CHAPTER 5

MODELLING THE STUDY AREA

5.1 PRELIMINARY SELECTION OF SITE GROUPS

At each step in a model, the SPIGOT program will attempt to preserve the historical statistics of the sites being modelled in that step. These include the distribution parameters, lag-1 correlations, monthly-to-annual correlations and site-to-site correlations. The site-to-site correlations tend to be the most difficult to maintain and this becomes increasingly more difficult as the number of sites modelled in a single step increases. The more stations that are modelled simultaneously, the less accurate the model will tend to be. For this reason it is necessary to subdivide the sites into different groups for modelling purposes. Consideration of geographic position, type of flow and magnitude of cross correlation is required to determine how the available sites should be subdivided into separate groups. The level of cross correlation between sites is an important factor since it is preferable to model sites with a high correlation in a single step in order to assure a more accurate model. The type of flow is also important because some sites, such as major rivers, are obviously more important than minor local inflow sites.

Looking at the data alone, it is readily apparent that the Saskatchewan, Winnipeg and Churchill Rivers, as well as Lake Winnipeg PIAO, are the flows of major importance. Inspection of the cross-correlations between the major sites and the local inflow sites reveals that these correlations are typically quite low (see Appendix A for correlations). For this reason it will not be necessary to model the local inflows in the same step as the major inflows. Since the correlations are low, they may be implicitly maintained by modelling the aggregate site, SUMNR+BR, along with the major inflow sites. It should be noted that the cross-correlations among the four major sites also tend to be rather low, likely due to the geographic diversity affecting the flows at each site. However, strictly maintaining these correlations is considered important since these flows represent the major inputs to the Nelson River system.

The next step is to subdivide the 11 local inflow sites into different groups since it will not be possible to model all of these sites at one time based on the SUMNR+BR flows, as will be seen further on. An obvious method for subdividing the sites is based on the geographic position of the sites. This first leads to grouping the Burntwood River sites together. These three sites are reasonably well correlated over all the flow periods. Next, the local inflow sites on the Nelson River can be divided into groups representing the lower and upper reaches of the river. Which sites to include in each group is determined based on the cross-correlation structure of these 8 sites. Sites NR0, NR1 and NR2 have a good degree of correlation over all the flow periods. Similarly, sites NR3 to NR8 also display a good level of correlation. The cross-correlations between the sites NR0, NR1 and NR2 and the sites NR3 to NR8 tends to be poorer than the correlations within the two groups. Given these results, sites NR0, NR1 and NR2 will represent the upper Nelson River area while sites NR3 to NR8 will represent the lower Nelson River area.

Three artificial sites are created as a result of subdividing the local inflows into different groups. These three sites represent the summation of flows within the three different regions and are given the names SUMBR, SUMNR012 and SUMNR3-8. The site SUMNR+BR can then be obtained through the summation of these three aggregate sites. The SUMNR+BR flows may be used to model the flows at the three new locations, or sub-aggregate sites. These in turn can be disaggregated to generate flows at their respective local inflow sites. This set-up allows the local inflows to be modelled without attempting to maintain cross-correlations for 11 sites at once. In most cases the local inflow sites show a better correlation with their respective sub-aggregate sites as compared to their correlation with SUMNR+BR. Locations NR4 and BR4 are two exceptions, having a lower correlation with their respective sub-aggregate sites than with the site SUMNR+BR. The sub-aggregate sites themselves display a fairly good degree of correlation with SUMNR+BR, with most values being between 0.7 and 0.9. Although sub-dividing the local inflows will lead to an extra modelling step, there should be less loss of accuracy in doing this as opposed to modelling the local inflows all at once.

5.2 TESTING OF DIFFERENT MODEL FRAMEWORKS

Before choosing a model framework it is necessary to select which locations will be considered as basin sites, key sites and control points. As indicated previously, the major flows in the system are given by the sites WPG@SLAVE, SASK@GRAND, CHR@SIL, LWPGPIAO and SUMNR+BR. For this reason these sites will be considered as basin sites in the model. Of these five, only site SUMNR+BR has subservient sites which will be classified as key sites and control points. The sites SUMBR, SUMNR012 and SUMNR3-8 are selected as key site locations while the local inflow locations represent control points. Based upon these classifications various modelling options are to be tested in order to get a model framework which will ensure a high level of accuracy. These choices may be changed if necessary as different models are tested.

The first framework considered, Framework #1, uses exactly the same set-up as Framework III shown in Figure 3.1. In this framework an MA model is used to generate annual flows at the major basin sites. An MAM model then generates monthly flows at the major basin sites and at the key sites. The key site flows are then run through an SD model to generate flows at the control points. A flow chart of Framework #1 is shown in Figure 5.1. The performance of each modelling step is determined by how well

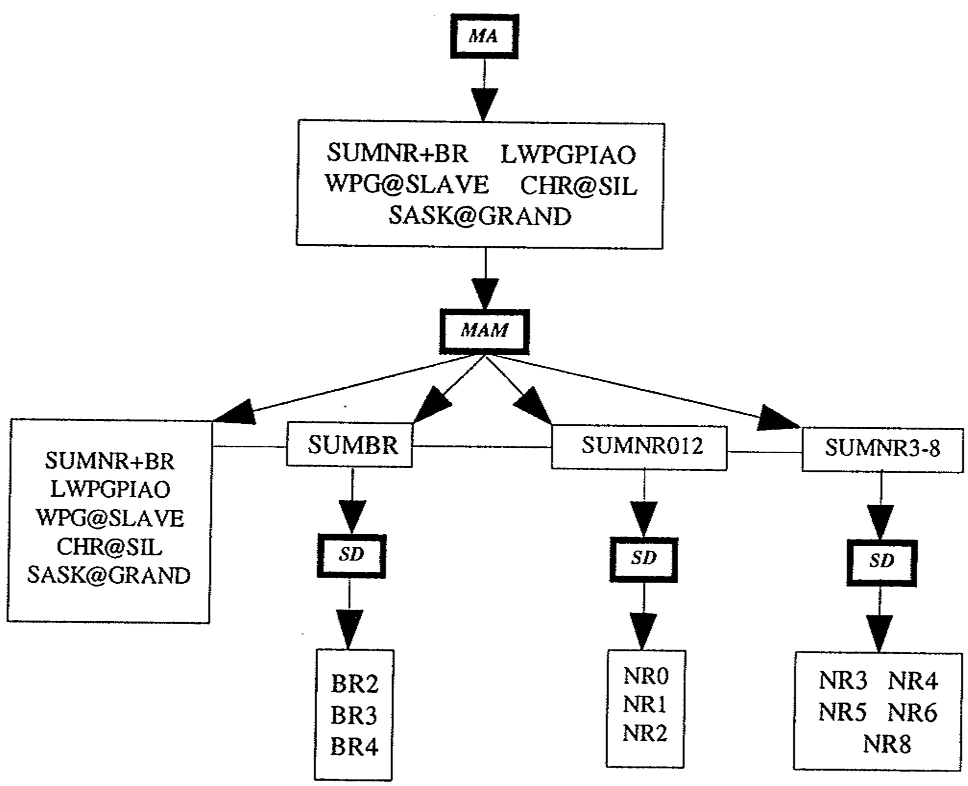

Figure 5.1 : Flow Chart For Framework #1

PAREST is able to maintain the variance-covariance (VCV) matrix for the sites modelled in each step. PAREST uses the VCV matrices in order to model site-to-site statistics. The VCV matrix, however, must be positive definite in order to obtain useful parameters. If the matrix is not positive definite, SPIGOT will adjust the matrix until it is positive definite. The degree of adjustment required is measured as a percentage. Considering too many sites at once tends to reduce the chances of getting a positive definite VCV. In the Framework #1 there are 8 sites modelled in the MAM step and this leads to large reductions of the VCV matrix for this step. Table 5.1 shows the percent of VCV maintained in each month. These low levels of maintenance indicate that a different model is required. There are several options available for improving the model and two of these are investigated in the next framework.

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
MAM - Framework #1 (major basins and key sites)												
% VCV MAINTAINED	100	25	35	35	35	35	30	30	35	30	35	30

Table 5.1 : Partial Summary of Results For Framework #1

The second model framework, Framework #2, first looks at using an MAM model to generate monthly flows at only the major basin sites. If this model were used, it would require an SD model to generate monthly flows at the key sites and then separate SD models to obtain monthly flows at the control points. Using an SD model for the key sites, however, is not investigated in this set-up, but may be investigated later if the results of the MAM model are satisfactory. Instead, an AMM model is used to generate monthly flows at the key sites based on the annual flows from SUMNR+BR. If the results from the AMM model are satisfactory then this option will be looked into further. A flow chart for this framework is represented in Figure 5.2. Note that in this framework the monthly flows for SUMNR+BR obtained in the MAM step would not necessarily equal the sum of the monthly key site flows obtained in the AMM step. This framework is only used to determine which modelling path appears most promising. The percent maintenance of the VCV matrices is again used as the basis for judging how well the models perform. The results for both the MAM and AMM models are summarized in Table 5.2.

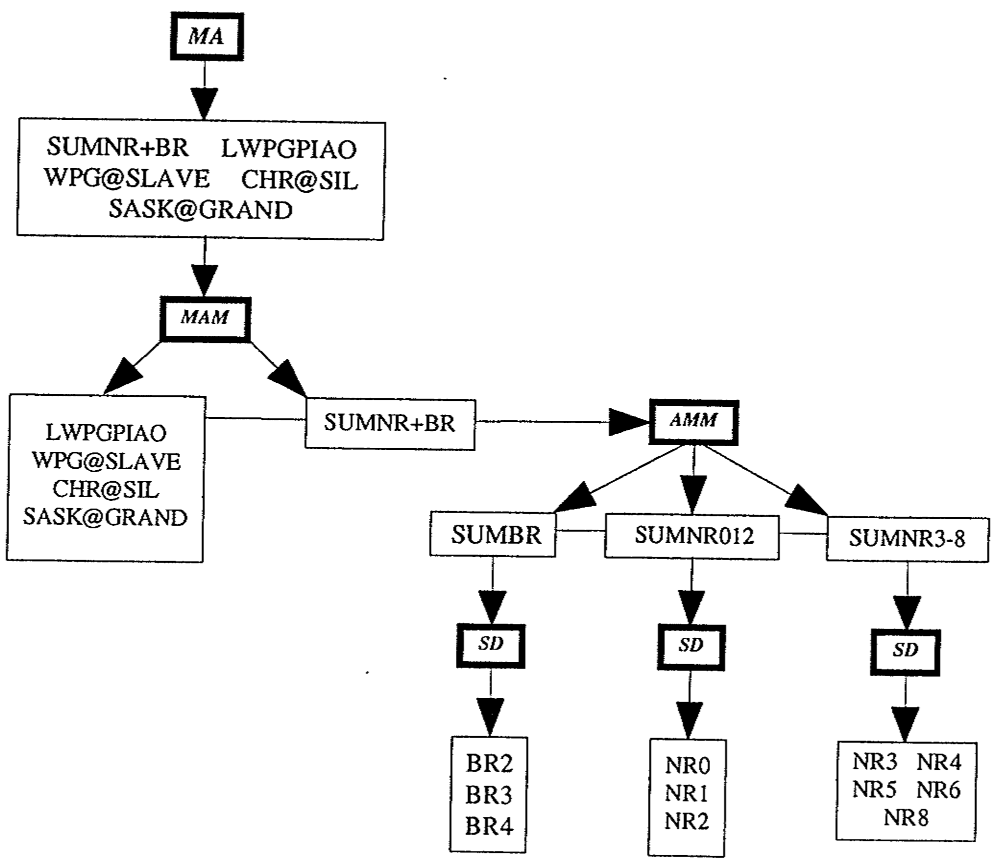

Figure 5.2 : Flow Chart For Framework #2

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
MAM - Framework #2 (major basins)												
% VCV MAINTAINED	100	65	70	45	55	100	45	40	60	40	45	50
AMM - Framework #2 (key sites)												
% VCV MAINTAINED	100	50	100	100	100	100	100	100	100	100	100	95

Table 5.2 : Partial Summary of Results For Framework #2

Looking at the results for the MAM model it is obvious that reducing the number of sites in this step leads to better maintenance of the VCV matrices. The reductions, however, are still too significant to consider using the MAM model to generate monthly flows for the major basin locations. The AMM model, on the other hand, has excellent maintenance of the VCV matrices for generating flows at the key sites. Given these results it is apparent that the AMM modelling option should be investigated further while the MAM model of the five major basins should be reconsidered, which leads to a third model framwork.

Framework #3 starts with an MA model for the major basins as in the two previous frameworks. Two MAM models are then used to generate monthly flows at the major basin sites and the key sites, as seen in Figure 5.3 below. The first MAM model generates monthly flows at the sites LWPGPIAO, WPG@SLAVE, SASK@GRAND and CHR@SIL based on the annual flows for these sites. In the second MAM model the annual flow at SUMNR+BR is used to generate flows at the key sites as well as SUMNR+BR itself. This is similar to the AMM model investigated in Framework #2 except that now the monthly flows at SUMNR+BR are explicitly modelled along with the key site monthly flows. Local inflows are again modelled using SD methods. The VCV maintenance percentages for the two MAM models are summarized in Table 5.3.

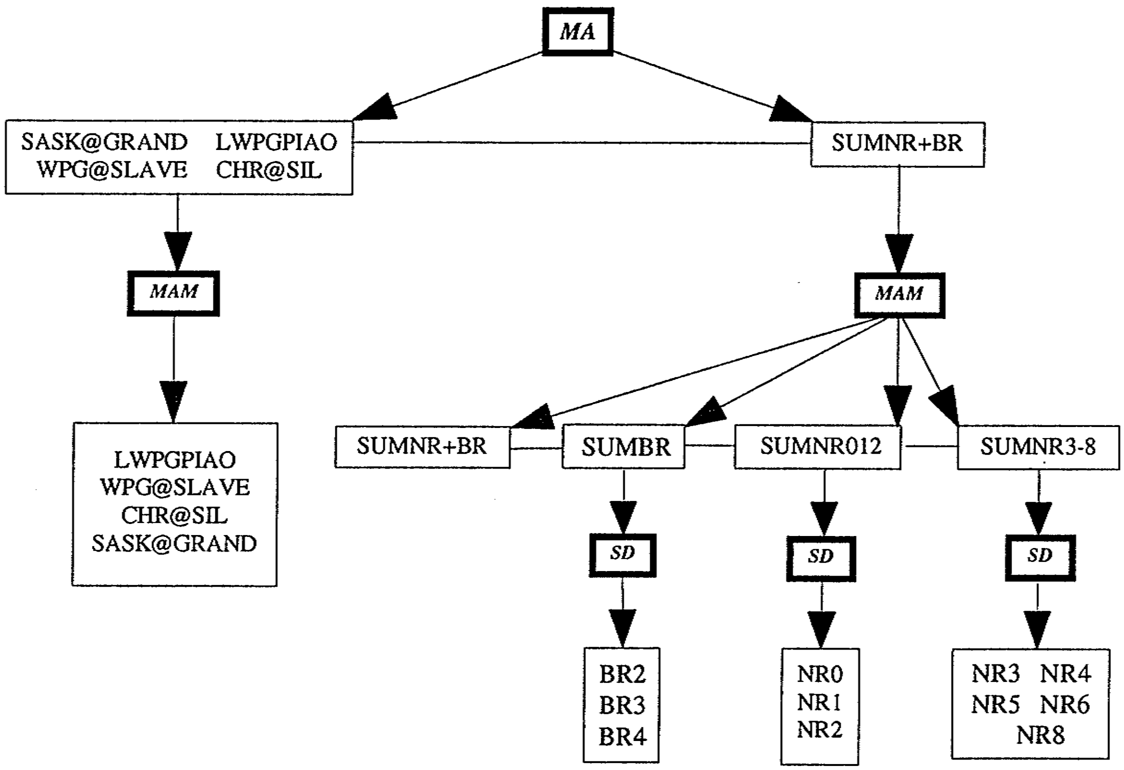

Figure 5.3 : Flow Chart For Framework #3

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
MAM - Framework #3 (4 major basins)												
% VCV MAINTAINED	100	55	50	95	100	100	35	45	100	50	60	45
MAM - Framework #3 (key sites and SUMNR+BR)												
% VCV MAINTAINED	100	50	60	90	100	75	70	40	50	70	75	95

Table 5.3 : Partial Summary of Results For Framework #3

The results for the MAM model of the four major basins are only slightly better than those obtained in model Framework #2 where all five major basins were considered. A better method of modelling these four sites still needs to be determined. Although the MAM model for the key sites and SUMNR+BR is similar to the AMM model in Framework #2, the results for the MAM method are much worse. This MAM model requires the reduction of 8 more VCV matrices than the AMM model, with some of these reductions being very significant. Given this result, the AMM method is the one which will be used to generate flows for the key sites based on the annual flow at SUMNR+BR.

Moving on to Framework #4, an attempt is made to improve the modelling of the four major basins by creating another artificial site. This new site, called BASINSUM, is the sum of flows at LWPGPIAO, WPG@SLAVE, SASK@GRAND and CHR@SIL. An MA model will be used to generate annual flows at BASINSUM and SUMNR+BR, as displayed in Figure 5.4. These two sites have a cross correlation value of 0.566 for annual flows, which is better than the annual correlations of SUMNR+BR with respect to the four component sites of BASINSUM. Key site flows are to be obtained using an AMM model, as recommended from the analysis of Framework #3. Using the AMM model will produce the same VCV adjustments as summarized in Table 5.2. Monthly flows at site SUMNR+BR are then simply the sum of monthly flows at the key sites. The four major basins are modelled using an AMM model and the annual flow at site BASINSUM. The monthly flows at BASINSUM are then found from summation of the monthly flows at the four component sites. Table 5.4 displays how well the VCV matrices are maintained by using the new site BASINSUM.

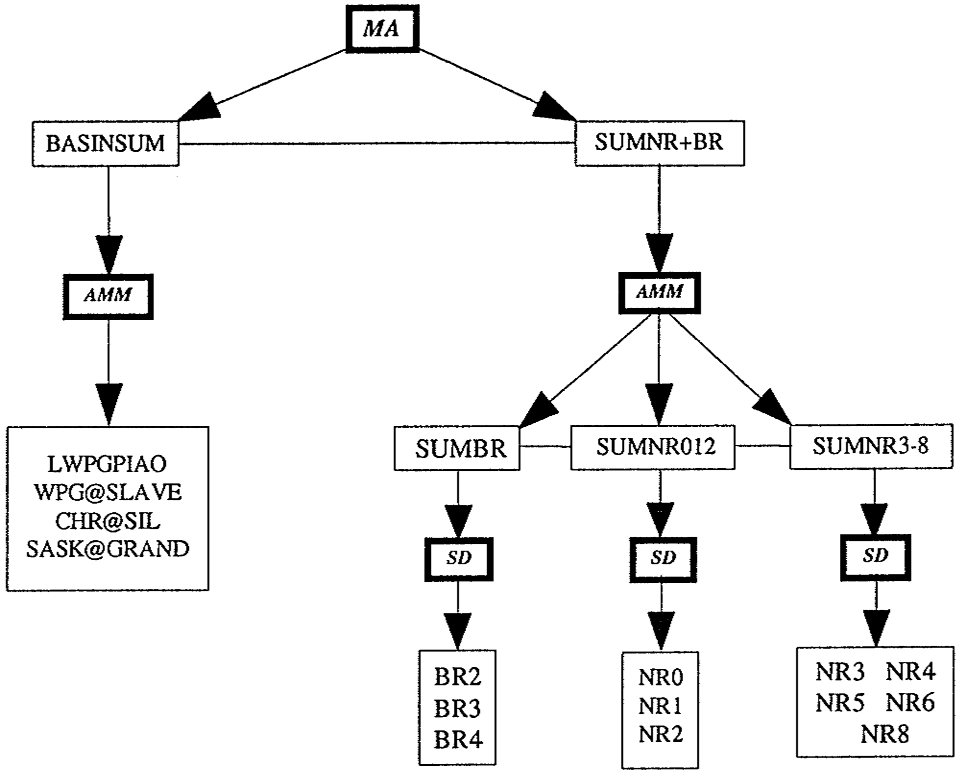

Figure 5.4 : Flow Chart For Framework #4

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
AMM -Framework #4 (4 major basins)												
% VCV MAINTAINED	100	100	100	100	100	100	100	100	100	45	55	100

Table 5.4 : Partial Summary of Results For Framework #4

Only two months show significant VCV adjustments while the remaining months require none. This is far superior to the results obtained from the MAM model of these four major basins in Framework #3, as shown in Table 5.4. The modelling options laid out in Framework #4 produce results which are very acceptable. This framework will be used for the generation of synthetic flows for the sites in the Nelson River Basin.

5.3 DETAILED REFINEMENT OF MODEL PARAMETERS

Having selected the model framework, there yet remains the need to consider more detailed changes to the individual models which may improve the overall modelling accuracy. The first models to be considered are the three SD models used to generate flows at the local inflow sites, which have not been looked at in the preceding discussion. As in the other models, the VCV matrices must be positive definite in order to obtain useful SD model parameters. The SPIGOT User's Manual indicates that non-positive VCV's tend to pose a greater problem in the SD models and thus the program provides two methods for adjusting the matrices. The other models have no such option. The first method reduces the contributions of off-diagonal elements 5% at a time while the second method reduces the contributions of lag-1 correlations 5% at a time. According to the User's Manual the first method generally works better. For this reason, the off-diagonal fix is initially used. The parameter estimation results using this method are investigated to determine which months in each SD model required VCV reductions. Parameters are then re-estimated using a lag-1 method of reduction for those months needing adjustment with the off-diagonal method. The method which causes the least amount of reduction to produce a positive definite VCV is then selected as the one to use for the given month and model. A summary of the results for these two analyses under each SD model is provided in Table 5.5.

These results show that reducing the contribution of off-diagonal elements is indeed the better method of obtaining a positive definite VCV. Of the 25 cases in which the lag-1 method was tried, only two instances required less reduction than the off-

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
SD - Under SUMBR (sites BR2, BR3, BR4)												
OFF-DIAG. % VCV MAINT.	100	100	75	85	95	100	50	60	90	95	95	95
LAG 1 % VCV MAINT.	---	---	60	75	15	---	55	55	40	20	65	30
SD - Under SUMNR012 (sites NR0, NR1, NR2)												
OFF-DIAG. % VCV MAINT.	100	75	75	100	100	50	95	100	65	85	95	60
LAG 1 % VCV MAINT.	---	40	50	---	---	15	30	---	15	70	90	10
SD - Under SUMNR3-8 (sites NR3, NR4, NR5, NR6, NR8)												
OFF-DIAG. % VCV MAINT.	100	65	100	95	100	100	90	90	80	95	85	60
LAG 1 % VCV MAINT.	---	25	---	25	---	---	55	75	50	95	55	80

Table 5.5 : Comparison of VCV Adjustment Methods For SD Models

diagonal option. The first is in July under SUMBR where the percent maintenance went from 50% to 55% and the second is in December under SUMNR3-8 where it improved from 60% to 80%. In these two cases the lag-1 method will be used to adjust the VCV matrices while all other months will use the off-diagonal method. From Table 5.5 it may be seen that in 30 of 36 cases the VCV matrices are maintained at 75% or more. Only two cases require as much as 50% reduction of the VCV. This level of accuracy is deemed adequate for the needs of the present model.

When modelling any of the sites, it is necessary to determine whether or not lag-1 flows should be included in the model for the specific month at the given site. The parameter estimation module tests both options, lag-0 and lag-1, and selects the better of the two. This is done by choosing the option which has the lower AIC value. In a number of cases, however, this results in the selection of a model where the residuals fail the Filliben test for normality at the 90% confidence level. These incidents are investigated to determine if the discarded option might in fact be preferable. This decision is based on the comparison of several descriptive variables from each option. Variables used are the residual Filliben and standard deviation values as well as the R^2(%) and AIC values of each option.

For example, in the AMM model of WPG@SLAVE for February a lag-1 model was selected even though its residuals failed the normality test and the lag-0 residuals passed. The Filliben, R^2(%), AIC and standard deviation values for lag-0 are 0.995, 39%, -112.5 and 0.229, respectively, while the lag-1 option had values of 0.972, 96.3%, -220 and 0.057 respectively. Although the lag-1 residuals show poor normality, they account for only 3.7% (ie. 100-96.3) of the model as compared to the lag-0 case where residuals make up 61% of the model. The lag-1 case also has much better AIC and standard deviation results. Finally, the lag-1 Filliben value, 0.972, is only slightly less than the 90% confidence limit of 0.976. Considering these results it does appear that the lag-1 model is preferable to the lag-0 option, despite the fact that the residuals do not pass the normality test. This example is quite typical of the cases in which a model was selected whose residuals failed the Filliben test for normality. That is, in most cases the selected model had much lower AIC and standard deviation values and significantly larger R^2(%) values. For these situations the model selected by the parameter estimation program, lag-0 or lag-1, will be used. Eight cases, however, are not as clear cut as the above example, so the parameter estimation module was re-run using the alternate option for each of these cases. In 3 of the 8 cases, using the alternate option caused greater reductions of the VCV for the particular month and model as compared to using the option selected by the program. The remaining five cases did not affect the VCV adjustment values, and in each the alternate modelling choice was preferable to the selection made by the program. The five changes to be made are summarized in Table 5.6.

SITE	MONTH	ORIGINAL SELECTION	MODEL TO BE USED
CHR@SIL	April	Lag-1	Lag-0
NR3	June	Lag-1	Lag-0
NR6	April	Lag-0	Lag-1
NR8	April	Lag-0	Lag-1
SUMNR3-8	April	Lag-0	Lag-1

Table 5.6 : Lag-0 and Lag-1 Model Selection Changes

Finally, it is necessary to investigate the methods used to transform the historical flows at each site for the 13 flow periods. The parameter estimation module attempts to fit four different distributions to the data and then selects the best fitting distribution as the method to use to transform the flows. Distributions used are normal, 2 parameter lognormal, 3 parameter lognormal and 3 parameter Gamma. For a given site and flow period, the distribution which has the highest Filliben value is chosen as the one to use for data transformation. In many instances the selected distribution has a Filliben value that is very close, or even equal, to one or more of the other distributions. Obtaining the same Filliben value for two or more distributions does not mean that each one fits the data equally well in all regions of the distribution. One may fit the median flows better than extremes while the next fits the extreme flows better than median flows. The balance of better and worse fits can result in the same, or nearly the same, Filliben values being obtained. Since this study is primarily interested in the low flow regime, it is preferable to use distributions which fit the low flows most closely. This means that in cases where nearly the same or equal Filliben values are obtained the probability plots need to be compared. The distribution which most closely fits the low flows will be selected, whether it be the same as the one selected by the program or not. Note that a comparison is made only if an unchosen distribution has a Filliben value within 0.01 of the Filliben for the selected distribution.

Of the 260 data transformations required, 13 flow periods at 20 sites, there were only 40 cases where the distribution selected by the program was obviously the best choice based on the Filliben values. The appropriate probability plots for the remaining 220 transformations were then investigated, and in only 15 cases was it found that choosing a different distribution might be preferable. The effect of using these alternate distributions is gauged by re-running the parameter estimation module with the 15 changes and comparing these results with those using the original transformation choices. This comparison found three cases where choosing a different transformation caused a significant reduction in the %VCV maintained in the models corresponding to the specific site and month. Five other cases produced significantly worse results for either the Filliben value for residuals, $R^2(\%)$ or AIC in the models of the specific sites. In these 8 cases the original transformations selected by the program are used. The remaining 7 situations produced results which were either better or not significantly worse than the original results. In these 7 cases the alternate distributions are to be used when modelling the flows, as summarized in Table 5.7.

SITE	MONTH	ORIGINAL SELECTION		NEW SELECTION	
		Distribution	Filliben	Distribution	Filliben
SASK@GRAND	July	3 par. lognormal	0.994	3 par. gamma	0.994
CHR@SIL	January	normal	0.982	3 par. gamma	0.984
BR3	July	3 par. lognormal	0.991	2 par. lognormal	0.987
BR4	October	2 par. lognormal	0.984	3 par. lognormal	0.984
NR4	June	3 par. lognormal	0.984	3 par. gamma	0.985
NR8	July	3 par. lognormal	0.991	2 par. lognormal	0.987
SUMNR3-8	August	3 par. lognormal	0.991	3 par. gamma	0.990

Table 5.7 : Distribution Changes for Transformations

5.4 SUMMARY OF THE SELECTED FRAMEWORK

The final framework selected uses the set-up shown in Figure 5.4 and incorporates the recommended changes from the previous section. Tables 5.8 and 5.9, on the following two pages, summarize the option selections made for two major aspects of the flow generation model which has been selected. Table 5.8 shows the distributions which are to be used for transforming the historical data at each station for the 13 flow periods. The lag-0 and lag-1 model selections are summarized in Table 5.9. Note that the two sites under the MA model do not have monthly flows strictly modelled according to the historical values while all other sites do not have the annual flows strictly modelled. These flow periods are obtained from the summation of those periods which are directly modelled, which means the historical statistics may not be maintained as closely for these periods as compared to those that are directly modelled.

	ANN	J	F	M	A	M	J	J	A	S	O	N	D
BR2	4	3	2	2	3	1	3	1	1	3	3	3	2
BR3	2	3	2	3	2	2	2	2	3	3	3	2	3
BR4	1	3	1	1	3	3	3	2	3	3	3	3	2
NR0	1	3	3	1	2	3	3	3	3	2	3	3	4
NR1	3	3	3	2	1	3	2	3	3	2	2	3	3
NR2	3	3	2	2	1	3	2	3	3	2	3	3	4
NR3	1	1	1	4	2	3	1	1	1	1	1	3	1
NR4	3	2	1	1	3	4	4	2	3	3	2	2	2
NR5	3	2	1	1	3	3	3	3	3	3	2	2	3
NR6	3	2	2	2	3	3	2	2	2	3	3	3	2
NR8	3	2	2	2	3	3	2	2	3	3	3	2	1
SUMNR+BR	4	4	3	3	3	3	2	2	4	3	3	3	3
LWPGPIAO	4	3	1	1	3	3	4	3	3	4	4	1	3
WPG@SLAVE	2	2	3	2	3	3	3	3	3	3	3	2	2
SASK@GRAND	2	4	1	1	3	2	3	4	2	3	3	2	1
CHR@SIL	1	4	4	1	1	2	1	2	3	2	3	1	1
SUMBR	4	3	2	2	3	3	3	3	1	3	3	3	2
SUMNR012	1	3	2	3	3	4	3	3	3	2	3	2	3
SUMNR3-8	1	3	1	4	3	3	2	3	4	3	3	3	3
BASINSUM	4	1	1	3	2	2	3	3	1	1	3	1	4

1: Normal   2: 2 Par. Log-Normal   3: 3 Par. Log-Normal   4: 3 Par. Gamma

Table 5.8 : Transformations Used in Final Framework

	ANN	J	F	M	A	M	J	J	A	S	O	N	D
BR2	-1	0	1	1	0	0	0	0	1	1	1	1	1
BR3	-1	0	1	1	1	1	1	1	1	1	1	1	1
BR4	-1	0	1	1	1	1	1	1	1	1	1	1	1
NR0	-1	0	1	1	0	1	1	1	1	1	1	1	1
NR1	-1	0	1	1	1	1	1	1	1	1	1	1	1
NR2	-1	0	1	1	1	1	1	1	1	1	1	1	1
NR3	-1	0	1	1	1	1	0	1	1	1	1	1	1
NR4	-1	0	1	1	1	0	1	1	1	1	1	1	1
NR5	-1	0	1	1	1	0	1	1	1	1	1	1	1
NR6	-1	0	1	1	1	1	0	0	1	1	1	1	1
NR8	-1	0	1	1	1	1	0	1	1	1	1	1	1
SUMNR+BR	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
LWPGPIAO	-1	0	1	0	0	0	1	1	0	1	0	0	1
WPG@SLAVE	-1	0	1	1	1	1	1	1	1	1	1	1	1
SASK@GRAND	-1	0	1	1	1	1	1	1	1	1	1	1	1
CHR@SIL	-1	0	1	1	0	1	1	1	1	1	1	1	1
SUMBR	-1	0	1	1	0	0	1	1	1	1	1	1	1
SUMNR012	-1	0	1	1	0	0	1	1	1	1	1	1	1
SUMNR3-8	-1	0	1	1	1	0	1	1	1	1	1	1	1
BASINSUM	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

-1 : Not Directly Modelled　　0 : Lag-0 Model　　1 : Lag-1 Model

Table 5.9 : Summary of Lag-0 and Lag-1 Model Selections

Finally, Table 5.10 recaps the percent maintenance of the VCV matrices for all of the models used in the final framework. Although the modelling options used are those which were selected in the refined option testing, there are three results in the SD models which are different than recorded in Table 5.5. The first two are in July and

November under SUMBR while the third is in September under SUMNR3-8. These changes result from a combination of effects caused by making the alterations suggested in the refinement of modelling options. The July VCV under SUMBR is now at 90% rather than 55% and represents a significant improvement. In November under SUMBR the VCV maintenance decreases from 95% to 90% while in September under SUMNR3-8 the VCV increases from 80% to 85%. The decrease for November under SUMBR is not considered major and will not be investigated any further.

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
AMM - 4 Major Basins From BASINSUM												
% VCV Maintained	100	100	100	100	100	100	100	100	100	40	55	100
AMM - Key Sites From SUMNR+BR												
% VCV Maintained	100	50	100	100	100	100	100	100	100	100	100	95
SD - Local Inflows Under SUMBR												
% VCV Maintained	100	100	75	85	95	100	90	60	90	95	90	95
SD - Local Inflow Under SUMNR012												
% VCV Maintained	100	75	75	100	100	50	95	100	65	85	95	60
SD - Local Inflow Under SUMNR3-8												
% VCV Maintained	100	65	100	95	100	100	90	90	85	95	85	80

Table 5.10: Summary of VCV Maintenance In Final Model

5.5 GENERATION OF SYNTHETIC FLOWS

Having chosen a model framework and the relevant detailed options, all that remains is to choose what limits to place on the generated flows and how many sets of data to generate. Recall that upper and lower limits may be placed on the values that generated flows may take so that unrealistic flow values will not be generated. The upper limit for each month at each site is set to be five standard deviations from the mean value. This means that if the flow value generated for a given site in a given month exceeds the upper bound, then that value will be set equal to the limiting value. With an upper limit of five standard deviations it is not expected that many of the generated values will need to be reset at the high end of the distribution. At the low end of the distribution the generation limit is set equal to zero for all but two of the 20 sites being modelled. As with the upper bound, this simply means that if negative flows are generated for these 18 sites then these values are set equal to zero. The number of values reset, both high and low, was not significant. The two sites which do not have a lower bound of zero are LWPGPIAO and BASINSUM. As mentioned in Chapter 4, LWPGPIAO takes into consideration such effects as evaporation on Lake Winnipeg which means that when evaporation is very high the LWPGPIAO value can in fact take on a negative value. This possibility must be allowed for in the model. Similarly, since BASINSUM is the summation of all sites including LWPGPIAO, it is possible for the BASINSUM value to be negative.

There remains only two modelling options to set before generating synthetic flows. First, the user must choose how many years of data to generate in a single pass through the generation program and second, the user selects how many passes to make through the generation program when it is executed. Thus, when FLOGEN is executed it will generate N sets of data, where each data set represents n years of flows for all 20 sites. The selection of these two values is entirely subjective, so it is up to the user to determine what is sufficient for the analysis being conducted. When choosing what length each data set should be, it was decided that the synthetic records should be approximately as long as the historic record. This allows for the comparison of drought events without having to consider the effects of largely different record lengths. Since the longest historic records are 79 years in length, the length of each generated data set is chosen to be 80 years. The number of 80 year data sets to generate should be large enough that a wide variety of drought events may occur which will allow for a more accurate representation of drought statistics. The amount of data generated, however, should not be so large that it becomes cumbersome to analyze. Generating 1000 sets of 80 year records for the 20 sites should be sufficient for the classification of drought events in the Nelson River Basin.

CHAPTER 6

ANALYSIS OF SYSTEM WIDE DROUGHTS

6.1 APPLYING THE THEORY OF RUNS TO THE BASIN

The present investigation is similar to previous analyses in that it applies the theory of runs for the analysis of streamflow drought. Several past studies have investigated drought from a regional perspective by considering multiple sites in a large homogeneous area (*Paulson et al.*, 1985; *Sadeghipour and Dracup*, 1985; *Chang and Kleopa*, 1991). One common aspect in these studies is that they first determine the drought characteristics at each individual site and then use the results in the regional analysis. While the present study is also a regional analysis, it takes a different approach than the previous studies. The method used considers the basin as a single entity, despite the fact it is comprised of multiple flow sites, and determines drought characteristics for the basin as a whole. This approach is taken because of the way the hydrologic and power generation systems are spatially arranged relative to each other.

Recall from the earlier discussion of the hydrologic system that the four major inflows to the basin enter either the Lake Winnipeg or Southern Indian Lake reservoirs. These major inflows account for approximately 88% of the water entering the lower Nelson River wherein 70% of the power production capacity lies. The remaining 30% of capacity is fairly well dispersed throughout the region. This means that the two reservoirs act as a buffer between the primary inflows and the primary power generating stations. As far as power generation is concerned, the system is relatively indifferent as to where the water comes from. When considering the occurrence of drought, it is not necessarily important to investigate each inflow individually. The effects of one site having below normal flows may be easily compensated for if other sites are above normal. It is also important to keep in mind that one aim of this study is to determine power production levels during severe drought. That is, those periods where it is likely that most of the inflows are below normal. Investigation of these production levels would be complicated by individual site analysis since this implicity requires consideration of the concurrence of drought events at each site. Furthermore, such an analysis makes it difficult to explicitly say when a basin wide drought is occurring. This difficulty may be seen in the study by *Chang and Kleopa* (1991) where a set of rules are required to determine the level of drought severity the basin is currently in. The present study considers instead the total basin inflow, or the sum of all individual inflows to the system. This avoids the complication of site-by-site drought analysis and capitalizes on the system's relative indifference as to where the inflows come from.

Having chosen the method for applying the theory of runs it remains necessary to select the truncation level that will be used to define drought periods. As indicated in Section 2.3, there are a variety of methods by which the truncation value may be selected, but the level chosen will depend on the particular system being studied. For the Manitoba Hydro system there are, as might be expected, several possibilities available. The truncation value could be chosen based on important flow levels for power generation and/or reservoir maintenance. Each inflow would first be considered individually to determine an appropriate truncation level and then these could be aggregated to get a single basin wide truncation value. Using such a method, however, makes it difficult to consider both minor inflows and the generating stations on the Nelson River, whose flows are not modelled. Also, this method would be dependent on the system's present configuration. This means a complete re-analysis of the drought conditions would be necessary if the system changes, which it definitely will.

Instead, a method is needed which can easily consider all inflows and may be appropriate for the current and future system configurations. Manitoba Hydro commonly uses mean flow as a design level for the system, so this would seem to be an appropriate truncation level. As indicated in the study by *Dracup et al.* (1980) using mean flow as a truncation value makes the analysis somewhat more sensitive to extreme events. These extreme events are of interest for the power generation analysis. Using mean flow as a threshold also treats each site equitably, whether it's a major or minor inflow. Most importantly, however, this truncation value is not dependent on the system set-up so the drought characteristics will not change as the system changes. If a generating station is added then its contribution to total power production is easily determined from the synthetic flows.

The basin wide monthly mean flows are calculated as the sum of the mean flows for the sites SUMNR+BR and BASINSUM, as shown in Table 6.1. Note that there are in fact twelve separate truncation values, one for each month. A single value could be applied by using the mean annual flow, converted to volume for each month. The problem with using the mean annual flow is that it can lead to the artificial start or termination of drought periods. This problem arises from the fact that some months will be, on average, below or above the annual mean flow. Therefore, using mean monthly flow as truncation level not only considers individual sites equitably, it also treats individual months in an equitable fashion.

Month	BASINSUM	SUMNR+BR	Truncation Value (X_c)
Jan	6583.9	446.0	7029.9
Feb	5840.8	316.4	6157.2
Mar	6572.0	288.6	6860.6
Apr	8832.8	536.3	9369.1
May	11348.8	2184.2	13533.0
Jun	11242.3	2318.8	13561.1
Jul	10372.3	1793.2	12165.5
Aug	7059.8	1282.4	8342.2
Sep	5784.6	1150.8	6935.4
Oct	6485.4	1121.0	7606.4
Nov	6917.4	843.5	7760.9
Dec	7262.2	614.5	7876.7

Table 6.1 : Calculation of a Basin Wide Truncation Value ($10^6 m^3$/month)

6.2 CALCULATION OF GENERATED POWER

Having now selected the method for considering drought events from the synthetic data, it is necessary to consider how estimates of generated power will be made. Calculating how much power is produced at each generating plant obviously requires that the flows arriving at each plant be known. For the generating stations on the Winnipeg and Saskatchewan Rivers this is simple enough, since these flows have been directly modelled and are available in the synthetic data. The Nelson River stations, on the other hand, pose somewhat of a problem since they depend on release flows from Lake Winnipeg and/or the Notigi Control Structure. As mentioned previously, it was not desirable to model these two flows and they are therefore unavailable from the synthetic data. Before discussing how power generation estimates are made it is necessary to consider how the Notigi and Lake Winnipeg release flows are estimated.

6.2.1 Estimation Of Notigi Release Flows

Manitoba Hydro operates two control structures at Southern Indian Lake which allows for the diversion of some of the Churchill River flows into the lower reach of the Nelson River. This diversion enables Hydro to secure more power generation out of its three largest generating stations. Manitoba Hydro, however, cannot simply divert as much of the Churchill flows as it desires. Operation of the system is governed by the various agreements with local communities and other parties concerned with the regulation of Southern Indian Lake, as discussed earlier. Primary constraints from these agreements are on maximum releases allowed at Notigi and minimum release requirements for Missi. Other constraints include maximum and minimum water surface elevations of Southern Indian Lake and points downstream of Notigi as well as limits on how rapidly these surface elevations may be drawn down or brought up. Various penalties, monetary or otherwise, are incurred for violation of the agreement, except in cases of emergency.

A complete model of the Churchill River Diversion requires consideration of all of these constraints which would lead to a complex hydrologic model. This level of detail is beyond the scope of this study. Instead, only three major constraints are considered in determining how much water to release through Notigi to the Nelson River. The first consideration is that minimum releases at Missi must be maintained if possible. The second consideration is to keep Notigi releases at the licensed maximum or at as high a level as possible. In order to meet these two objectives, the model allows for the use of Southern Indian Lake storage. Use of storage is constrained by maximum and minimum lake surface elevations of 847.5ft (258.3m) and 843.5ft (257.1m), respectively, without consideration of draw-down rates. The available storage volume is 169,000 CFS-WKS, or approximately 2892.67*10^6 m^3. The license release limits are shown in Table 6.2, along with the mean monthly flows for the Churchill River for comparison.

Month	Maximum Notigi Release	Minimum Missi Release	Mean CHR@SIL
Jan	2578.76	303.46	2239.4
Feb	2329.21	205.63	1904.8
Mar	2578.76	151.60	2102.3
Apr	2495.58	146.71	2111.7
May	2654.56	75.80	2609.9
Jun	2568.9	36.81	3161.0
Jul	2654.56	38.03	3477.3
Aug	2654.56	38.03	3217.0
Sep	2568.9	36.81	2789.5
Oct	2654.56	151.60	2769.1
Nov	2495.58	440.38	2593.8
Dec	2578.76	379.26	2538.3

Table 6.2 : Notigi and Missi Control Release Flow Constraints ($10^6 m^3$/month)

Calculation of the Notigi releases based on the constraints used is fairly straightforward, with three basic flow conditions occurring. In the first case, if Churchill inflows exceed the sum of Notigi and Missi limits then the Notigi release is set to the maximum and all or part of the excess is put to storage with the remainder being released from Missi. The second flow case occurs when the inflows can meet Missi requirements but are not enough to bring Notigi up to the license limit. When this occurs, storage is used to bring Notigi up to the limit, or as high as possible. Finally, in the third case, if inflows are less than the Missi minimum then storage is first used to bring Missi releases up to the minimum. Any storage left over is used to maximize Notigi releases. The exact method for calculating the releases may be found in the program code provided in Appendix B. Figure 6.1 shows a comparison of the historic and estimated releases at

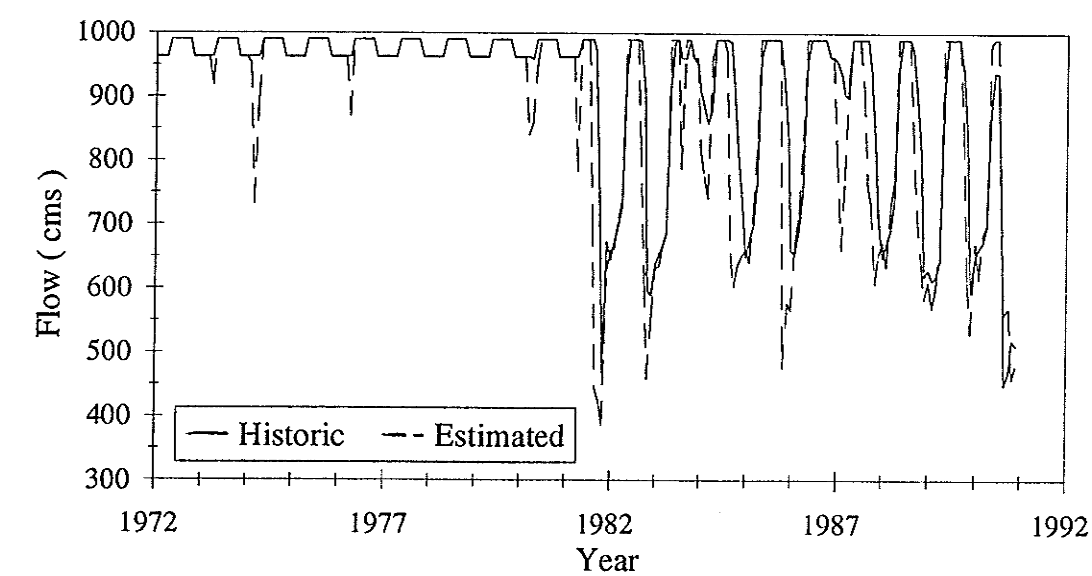

Figure 6.1 : Comparison of Historic and Esitimated Notigi Release Flows

Notigi for the years 1972 to 1991. This graph clearly shows that the described estimation procedure performs very well despite its simplified representation of the system. The estimated flows match the historic for most flow conditions when water is sufficient, and follow the historic very closely during low flow conditions. Comparison of releases for the remainder of the historic period produces similar results but is not shown here in order to maintain clarity.

6.2.2 Estimation Of Lake Winnipeg Release Flows

Lake Winnipeg is Manitoba Hydro's most important reservoir. The size of the lake means it can be used to significantly reduce the impact of extreme flow conditions, either on the high or low ends. As in the case of Southern Indian Lake, however, Manitoba Hydro has various constraints placed upon it which govern the operation of the Lake Winnipeg Reservoir. There are maximum and minimum lake levels Manitoba Hydro attempts to operate within, as well as preferred lake levels which it attempts to maintain. Also, Manitoba Hydro has maximum and minimum release flows that it prefers to operate between. Besides these considerations, the management of the reservoir is affected by other factors such as long range forecasts of precipitation conditions and power demand. For example, if a very dry summer is predicted then Manitoba Hydro may decide to impound a larger than usual portion of the spring run-off, as was the case in the spring of 1993. The ensuing summer of 1993 turned out to be wetter than normal which meant some of the stored water had to be rapidly released to provide room for flood control. The management of Lake Winnipeg is significantly more complex than the management of Southern Indian Lake. Attempting to accurately model Lake Winnipeg's hydrologic and management system is far beyond the scope of this study. Instead, Lake Winnipeg releases are estimated using a simplified representation of the system

The two major constraining factors utilized to estimate releases are limits on lake surface elevation and release flow. Since regulation began in 1976, Manitoba Hydro has attempted to keep the surface elevation between the licence maximum of 715ft (217.9m) and the licence minimum of 711ft (216.7), although it tends to fluctuate mostly between the levels of 713ft (217.3m) and 714ft (217.6m). The second constraint consists of a preferred maximum release which Hydro attempts not to exceed and a preferred minimum which Hydro tries to operate above. Hydro may exceed the maximum or go below the minimum in cases of emergency. Unlike the operation policy at Notigi, Hydro does not attempt to keep Lake Winnipeg releases at or near the maximum level. The preferred minimum flow is 707.9 cms ($1896.04*10^6 m^3$ per month) while the preferred maximum is 4247.5 cms ($11375.16*10^6 m^3$ per month). Total storage capacity between the elevations 711ft and 715ft is approximately $30337.7*10^6$ m^3. At full storage there is enough water to meet the minimum release for 16 months, assuming inflow and evaporation were equal.

Total inflow available for outflow (TIAO) is simply the sum of the PIAO flows and flows from the Winnipeg and Saskatchewan Rivers. Through the PIAO value, the TIAO takes into consideration the effects of losses due to evaporation. Three potential TIAO conditions exist. TIAO may be less than the minimum preferred release, greater than the maximum or somewhere between the two. In the first two cases, operation of the system depends upon the current state of storage. For the third situation, the operation policy is dependent upon the state of storage as well as the month in which the given flow occurs, which makes it somewhat more complex than the other two.

When the inflow is less than the preferred minimum, then storage is used to augment the release flow. If the current surface level is over 713ft the amount taken from storage is equal to the flow deficit (minimum - TIAO) plus a percentage of any excess storage over the target elevation. The percentage of excess released depends on how large the excess is. If storage is between 711ft and 713ft, the amount taken from storage is equivalent to the flow deficit up to the point where storage is brought down to 711ft. In cases where storage is at 711ft, the total outflow is equated to TIAO, unless TIAO is negative, in which case the lake is drawn below 711ft and releases are brought up to one half of the minimum preferred release flow. This last situation is a policy that avoids drawing down below the minimum elevation until absolutely necessary. The next two inflow conditions consider months where TIAO is greater that the minimum release. If the storage is below 711ft in either one of these cases, then all the excess TIAO over the minimum release will automatically be put into storage.

The second inflow conditions is when TIAO is greater than the maximum preferred release. When this occurs, the excess flow will be retained in storage up until the storage level reaches an eleveation of 715ft. After the maximum storage has been reached then Lake Winnipeg outflow will equal TIAO. This model assumes that 715ft is an absolute maximum storage level, since Manitoba Hydro doesn't intend to let the lake exceed this level, and this allows releases to exceed the maximum in some instances.

The third and final inflow condition is when TIAO is between the preferred release limits. In January, February and March the amount of release depends on what the state of storage is relative to the target of 713ft. If storage is above 713ft then Lake Winnipeg release is equal to TIAO, letting storage stay above 713ft. When storage is below 713ft a percentage of TIAO above the minimum release will be retained in storage in order to bring it closer to 713ft. For the months of April to July, the release policy is the same except that a target storage elevation of 714ft is used rather that 713ft In the last 5 months, excess flow is put to storage only if the lake has been drawn down below 711ft. If storage in these months is above 713ft then the releases are equal to TIAO plus a percentage of the excess storage. The exact methods used for this inflow case and the previous two are described in the program code, provided in Appendix B

The release policies outlined above are designed to produce reasonable estimates of Lake Winnipeg Total Outflow (LWTO). Estimates of historic releases using the defined methods are not compared to the actual regulated outflows. Such a comparison would be misleading since a simplified model can not possibly capture the historic regulation of Lake Winnipeg. Similarly, comparison of release statistics such as mean and variance are not justified since the simplified model is not set up to reproduce these values. In any case, attempting to maintain the releases between the two limits suggests that these statistics are nor necessarily meaningful.

6.2.3 Converting Flow To Generated Power

Using the synthetically generated data along with the estimated Lake Winnipeg and Notigi release flows, it is possible to determine the volume of water passing through each generating station in the Manitoba Hydro system. Exact determination of the power generated at each site would require that forebay and tailrace elevations also be known at each station in each month. To get these elevations would require a detailed hydrologic model of the entire system operated by Manitoba Hydro. As indicated in the two proceeding sections, the development of such hydrologic models is beyond the scope of this study. Instead, power generation estimates are made using flow-to-power conversion factors which have been developed by Manitoba Hydro based on historic records. These factors simply assume that a given amount of flow at a particular site will produce a certain amount of power. This is a method used by Manitoba Hydro in its own power generation studies. Table 6.3 shows the flow-to-power conversion factors used for each of the generating stations within the system.

Although Manitoba Hydro may spill some of the flow reaching a generating station, this study assumes that all of the flow is put towards power generation. This is a realistic assumption since it is in Manitoba Hydro's best interest to use all available flows for power production during drought periods. The flow at each generating station is determined by summation of the flows from the appropriate upstream sites and estimated releases as shown in Table 6.3. The selection of these sites is fairly obvious when referring to Figures 4.1 and 4.2. Note that the six Winnipeg River stations, although listed individually, are treated as one station having an inflow equivalent to the Winnipeg River flow at Slave Falls. Another special case occurs when considering the Jenpeg generating station.

Generating Station	Flow-to-Power Factor (MW/1000cfs)	Inflow Site(s)
Point du Bois	3.16	WPG@SLAVE
Slave Falls	2.01	WPG@SLAVE
Seven Sisters	4.24	WPG@SLAVE
McArthur	1.75	WPG@SLAVE
Great Falls	3.93	WPG@SLAVE
Pine Falls	2.87	WPG@SLAVE
Winnipeg R. Total	17.96	WPG@SLAVE
Grand Rapids	9.26	SASK@GRAND
Jenpeg	2.16	LWTO
Kelsey	4.05	LWTO + SUMNR012
Kettle	7.11	Kelsey+Notigi release+ SUMBR + NR(3,4)
Long Spruce	6.09	Kettle + NR5
Limestone	7.89	Long Spruce + NR6

Table 6.3 : Generating Station Inflow Sites and Production Coefficients

Jenpeg gets its flow from Lake Winnipeg releases as well as local inflow represented by site NR0. Portions of these two flows, however, do not reach Jenpeg. The East Channel diverts part of these two flows from Playgreen Lake upstream of Jenpeg to Cross Lake downstream of Jenpeg. The amount of Lake Winnipeg outflow bypassing Jenpeg can range from 10% during high flow conditions to as much as 50% under low flow conditions. To account for this effect, it is assumed that none of the NR0 flow passes through Jenpeg while all of the Lake Winnipeg release flow does. This will lead to a slight overestimation of Jenpeg production under low flow conditions. The amount of overestimation, however, is reasonably small. For example, in the worst historic drought, the system wide power production is estimated to be 1950MW. If only 50% of Lake Winnipeg releases reached Jenpeg, the estimated total production would be close to 1910MW, which means the estimate may be 2% higher than expected. Note that the error is likely somewhat less than 2% since NR0 flows have not been included and that possibly more than 50% of release reached Jenpeg. This level of error is deemed to be well within acceptable limits.

Finally, power production levels for the historic period are obtained by estimating historic Lake Winnipeg and Notigi releases using the methods defined in sections 6.2.1 and 6.2.2 in conjunction with the generation procedure described above. Manitoba Hydro has estimates of historic release flows and power production based on the current system configuration, but those values are not directly used in this study. The historic values are calculated by the methods described so that the historic and synthetic data may be compared on an equal basis. Manitoba Hydro, however, conducted an independent analysis to compare the mean power production levels obtained using their own techniques and those used here. Their analysis confirmed that the drought periods and power generation levels identified in this study are in good agreement with the Manitoba Hydro estimates. Mean power generation levels for extreme drought events were within 100MW of each other. (Personal Communication, Harold Surminski P.Eng, 31/05/94). Based on this comparison, Manitoba Hydro has confirmed that the estimation procedures used in the present study will produce acceptable and meaningful results.

6.3 CHARACTERIZATION OF DROUGHTS

6.3.1 Drought Exceedence Probability

The three drought parameters calculated by applying the theory of runs are severity, duration and magnitude. Any one of these three might be used in order to conduct a drought frequency analysis, although the parameter selected should be meaningful for the system under investigation. The magnitude of an event is a poor parameter for the current system because the difference between events is blurred with the division of severity by length. For example, a one month drought could have the same magnitude as a six month event. It should be apparent, however, that the six month event has more severe implications for reservoir depletion and power generation. Similarly, drought duration is not a good parameter to use. Although one expects longer droughts to have a greater impact on a system, a drought of relatively short duration can be much more critical than a longer lasting event. The final parameter, drought severity, provides the best possibility for comparing different droughts in the Nelson River basin. This parameter is also a practical drought descriptor for Manitoba Hydro since it allows for easy comparison of available storage capacity and the frequency of different drought severity levels. The ability to easily compare these two values is useful since the power generation system relies so heavily on the two main reservoirs.

The exceedence probability for each drought severity is determined through the use of the Weibull plotting position formula which is given as;

$$P_{exc} = \frac{m}{n + 1} \qquad [6.1]$$

where m = order number of drought event and n = total number of events. The order numbers for the events are found by sorting the drought severities in descending order. Although more rigorous theoretical distributions such as the Pearson Type 3 and Exponential are available, it has been decided that the Weibull formula is sufficient for the purpose of this analysis. In their 1985 report, *Paulson et al.* indicate that there is not necessarily any significant advantage to using a theoretical formula as opposed to a graphical method. These authors use the Weibull formula to calculate the exceedence probabilities associated with drought severities as will be done in the present analysis.

A similar study by *Sadeghipour and Dracup* (1985) also uses the Weibull formula to obtain exceedence probabilities for drought events. In their analysis the authors use the exceedence probabilities to calculate return periods for different drought severities. These return period are calculated as the inverse of the exceedence value multiplied by the 'expected time period of a low-flow/high-flow cycle' of the hydrologic time series (*Sadeghipour and Dracup*, 1985). It is not explained exactly why this method is used. The typical method of determining the return period is to simply take the inverse of the exceedence value associated with a particular event. This is the procedure that will be used to determine return periods for the current investigation.

For the historic period the exceedence values are calculated based solely on the events obtained from the available record. Exceedence probabilities for the synthetic droughts on the other hand are calculated based on all of the events obtained from the

1000 sets of 80 year records. This means that while severities were calculated individually for each 80 year record, the severities obtained are then lumped together for the purpose of calculating exceedence values. Doing this is analogous to having approximately 80000 years of flow data where in every 80 years there is a gap in the record. In such a case it could be assumed that the flows are drawn from the same distribution but the calculation of drought characteristics cannot be carried over the gap in the data.

6.3.2 Power Generation Levels During Droughts

The second part of this investigation considers the generation of hydro-electric power in the Nelson River basin during drought periods. There are two values which will be used to investigate Manitoba Hydro's power production levels under these adverse conditions. The first value is the mean power generation level over the course of an entire drought period. Obviously, during a drought the amount of power that can be generated will fluctuate just as flow levels will fluctuate. At some times during a drought it may be possible to meet the demand for power while at others demand cannot be met. Mean power generation levels, however, provide an indication of the overall capacity to meet demand and how much power it may be necessary to import when production is too low. The second value considered is the lowest six month average power generation level during an event. This value is used to provide an indication of generating conditions during the most severe period of a drought. For droughts lasting six months or less the lowest six month average is simply set equal to the mean generation level of the event.

While the lowest single month of power production could be used to quantify the most severe period, it is felt that the six month average will provide a better indication of the worst part of a drought. Also, this average will smooth out the effects of anomalously low months of production as well as any inaccuracies incurred through the use of the simplified flow models discussed earlier. Although the overall mean and the lowest six month mean can be compared with drought severity, no attempt will be made to try and relate the mean generation levels with the exceedence probabilities associated with each severity. Such a comparison cannot be justified and is likely to be more misleading than informative.

CHAPTER 7

DISCUSSION OF DROUGHT ANALYSIS RESULTS

7.1 APPLICATION OF THE THEORY OF RUNS

In Chapter 3 it was mentioned that the SPIGOT program provides the VALDAT module in order to check the performance of the selected model framework. This validation tool is based on the principles of the theory of runs, the same theory used in the present analysis to censor droughts from the various flow records. Although VALDAT utilizes the theory of runs, it is not used to validate the synthetic data generated for this study because of a problem created by different lengths of historic flow records. When applying the theory of runs to the entire basin using VALDAT, the module only uses the concurrent periods of record between the major and minor inflow sites. This means that the data from 1912-1956 at the major sites are not considered in the validation although they are used in developing a model. Excluding more than half the data available for the major sites in this fashion could lead to apparent discrepancies between the synthetic and historic droughts in the analysis. For this reason, the synthetic data are validated using the results obtained from applying the theory of runs as discussed in section 6.1. The method proposed in section 6.1 utilizes different truncation levels for the periods 1912-1956 and 1957-1990, thus using all of the historic data.

The performance of the theory of runs must be verified first before the theory is used to verify the quality of the synthetic data. The theory is verified by checking that it identifies those historic periods which Manitoba Hydro has noted as being critical to the power generation network. In its first study of long-term streamflow data, Manitoba Hydro investigates the period of record from 1912-1967 and identifies three critical low-flow periods. The first extended dry period is 1921-1933, the second is in the late 1930's, particularly the years 1939-1941 and the third dry period is 1960-1962 (Manitoba Hydro, 1988). The second study of long-term streamflow considers the period from 1968-1988 and two critical dry periods are identified. The first is 1981-1982 and the second begins in 1987 and was still in effect up until the report's publication date in May of 1990. Of the dry periods mentioned, the drought of 1939-1941 was the most severe and is thus used by Manitoba Hydro as the criterion on which dependable flow and generation expansion are based (Manitoba Hydro, 1988).

Application of the theory of runs to the historic data identified 114 drought events. Note that the dates of occurence for the historic events may be found in Appendix C along with all the relevant drought parameters, exceedence probabilities and power generation levels which are used throughout this chapter. Four of the five major drought periods mentioned above were also found to be critical single drought events in this analysis. The one exception is for the dry period of 1921-1933. This 13 year period is not identified as a single drought by definition of the theory of runs. These years, however, are marked by frequent periods of below average flow, some of which are quite significant. A comparison of the remaining four periods is shown in Table 7.1. The rank of the drought events is found by sorting the droughts in ascending order by severity, so that the most severe event has a rank of 114. This table shows that three of the four dry periods noted by Manitoba Hydro turn out to be the three most severe events identified in the drought analysis. The basin wide application of the theory of runs has identified exactly those periods deemed critical by Manitoba Hydro. This result indicates that the method of drought analysis chosen will accurately censor those droughts that are critical to Manitoba Hydro from the synthetic data.

Manitoba Hydro Droughts	**Theory of Runs**		**Severity ($10^6 m^3$)**	**Rank**	**Length (months)**
	Start (mon/yr)	**End (mon/yr)**			
1939-41	9/38	9/41	123924	114	37
1960-62	6/60	5/62	46224	112	24
1981-82	3/81	4/82	32189	109	14
1987-90	5/87	4/90	98110	113	36

Table 7.1 : Validation For the Theory of Runs Analysis

The drought analysis results shown in Table 7.1 merit some further consideration. As shown in the table, the 1981-1982 event has a rank of 109 while the 1960-1962 is ranked 112, which means only two of the six most severe events are not shown. The event that ranked 110 was 27 months long, lasting from 5/1936 until 7/1938, and had a severity of $39,895 * 10^6 m^3$. Comparing the dates between this drought and the most severe event shows that there was only one month, August, separating the two droughts. While these events are seen as separate according to the theory, the occurrence of the first event will severely impact Manitoba Hydro's ability to generate power during the second drought. It should be obvious that the first drought will greatly reduce the amount of water available in the Lake Winnipeg and Southern Indian Lake reservoirs. The drought that ranked 111^{th} was 20 months long, lasting from 4/1929 until 11/1930, and had a severity of $45,384*10^6 m^3$. Note that this event occurs at the tail end of the 1921-1933 dry period mentioned in the 1988 report from Manitoba Hydro. Further consideration of the dates for the two droughts above and the most severe event from Table 7.1 reveals that three of the five worst droughts on record occurred between the years 1929 and 1941.

Having verified the performance of the basin wide application of the theory of runs, the theory can now be used to verify that the generated flow data produce drought events that are reasonable. This verification is accomplished by comparing the synthetic drought parameters with those obtained from the historic record.

The 1000 sets of synthetic flow data contained 110665 separate drought events, a number of which were longer and more severe than the 1939-41 drought. While the performance of the theory of runs could be checked by direct comparison of the dates, verification of the generated data cannot use direct numerical comparison due to the large number of synthetic events. For this reason, the historic and synthetic drought parameters are compared graphically, similar to the method used by VALDAT. Figure 7.1, on page 86, provides a comparison of the historic and synthetic drought severities relative to the length of the events. The synthetic drought severities plot well against the historic events, having a similar average increase in drought severity with increasing drought length. The plot does not indicate that there is a significant shift in the relationship of drought severity to drought length when comparing the historic to the synthetic data sets. While there is a third drought parameter, magnitude, it is not used for graphical comparison since it is a function of the other two parameters. If the comparison of severity and length is favourable then the same will be true for the comparison of magnitude relative to its component parameters. Exceedence probabilities for the historic drought severities are calculated based on the historic and synthetic data sets and comparison of these values also confirms the adequacy of the flow generation model. These results are discussed further in the following section.

Figure 7.1 also shows that many of the synthetic droughts were significantly longer than the longest historic event which had a duration of 37 months. This might seem to indicate that the synthetic data are generating too many long duration droughts. However, the 37 month historic drought was preceded by a 27 month drought and these two events were separated by only one month of above average flow. If not for this one month, an historic drought of 65 month duration may well have been realized. So, while a large number of synthetic events are larger that 37 months, only 19 events are 65 months or longer. It does not seem unreasonable to have synthetic droughts with durations that are much longer than 37 months.

While verifying the performance of the flow generation model, the relationship of drought severity to length shown in Figure 7.1 also displays the advantage of using synthetic data in a drought investigation. The plot of the historic values shows that as the length of the event increases the severity also tends to increase. What the historic values do not show very clearly, however, is the wide range of drought severities possible for each drought length, particularly as the length becomes significant. This is due to the fact that there is simply not enough time available in the historic record for such a wide range of possibilities to be realized. The synthetic records, on the other hand, provide a long time period over which widely ranging drought severities can develop. For example, synthetic droughts of 10 months duration had severities that went from approximately $7{,}000*10^6m^3$ to $50{,}000*10^6m^3$, a spread of about $43{,}000*10^6m^3$. As the length increases, the spread between the lowest and highest severity increases. At a length of 50 months, the lowest and highest severities are approximately $100{,}000*10^6m^3$ and $185{,}000*10^6m^3$ respectively, a difference of nearly $85{,}000*10^6m^3$. Conversely, a drought with a given severity might occur over significantly different time periods. For example, a drought of approximately $40{,}000*10^6m^3$ occurred over periods as short as 8 months and as long as 36 months. Although these results might be intuitively expected, the degree of variability displayed cannot possibly be found using the historic data alone. Note that in this synthetic plot, like the historic, the relationship between severity and length becomes more ill-defined at the extreme levels of severity. With the synthetic plot, however, these extreme severity levels will prove to be quite rare occurrences. These results might also suggest that modelling decreases for more extreme events, but this is not investigated.

In the case of drought severity and length it was shown that the synthetic data provides a better picture of the relationship and the same is true when investigating the relationship of magnitude to both length and severity. Figure 7.2, on page 87, shows the synthetic drought magnitudes plotted against the drought lengths. What this plot shows is that while the drought severity increases with drought length, the magnitude does not. Instead, the graph indicates that as drought length increases the minimum magnitude values increase and the maximum values decrease, that is, the spread between minimum and maximum magnitude tends to decrease with longer drought duration. Recall that the spread between maximum and minimum severity tended to increase with the drought

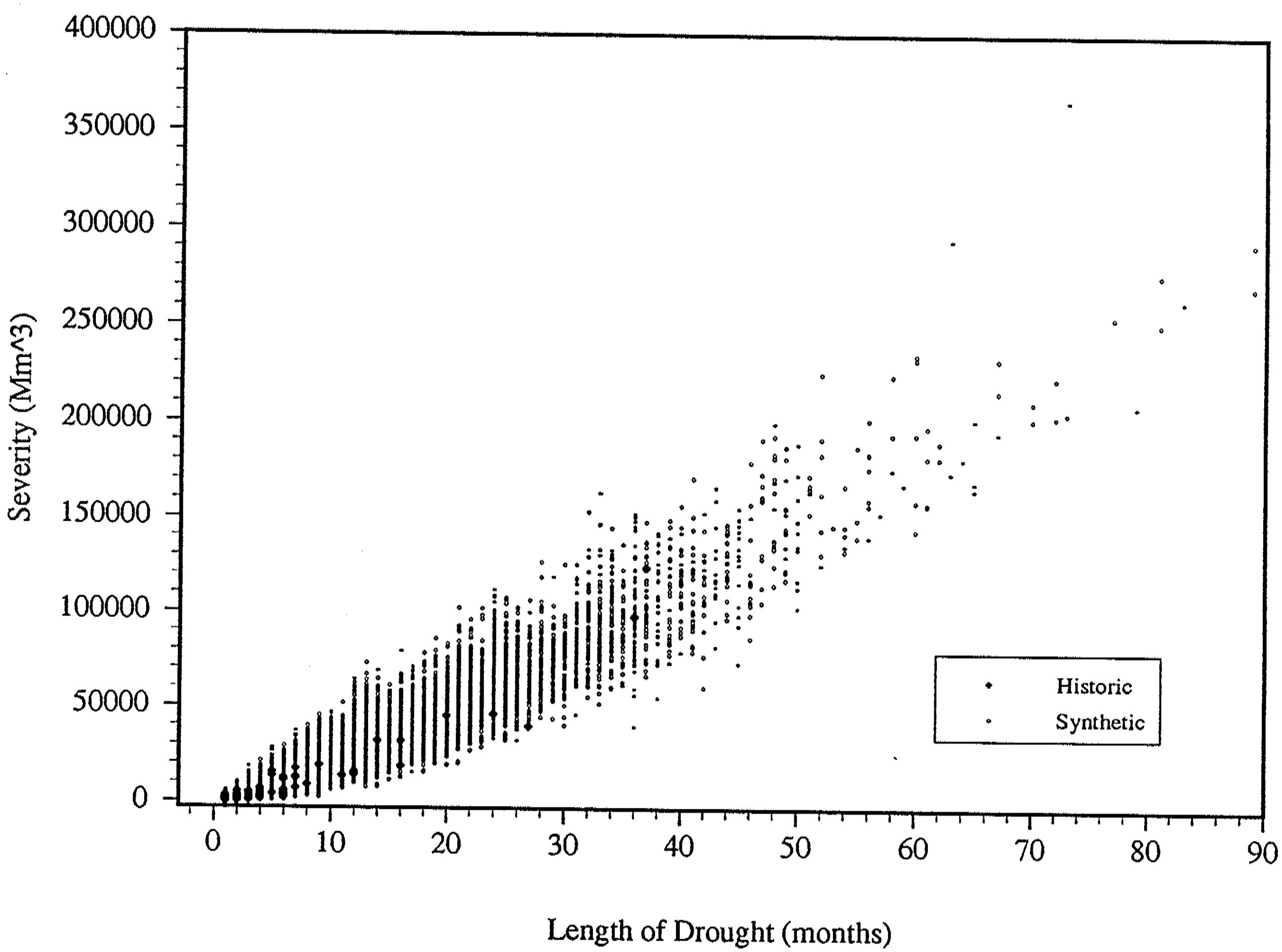

Figure 7.1 : Relationship Between Drought Severity and Length for the Historic and Synthetic Data

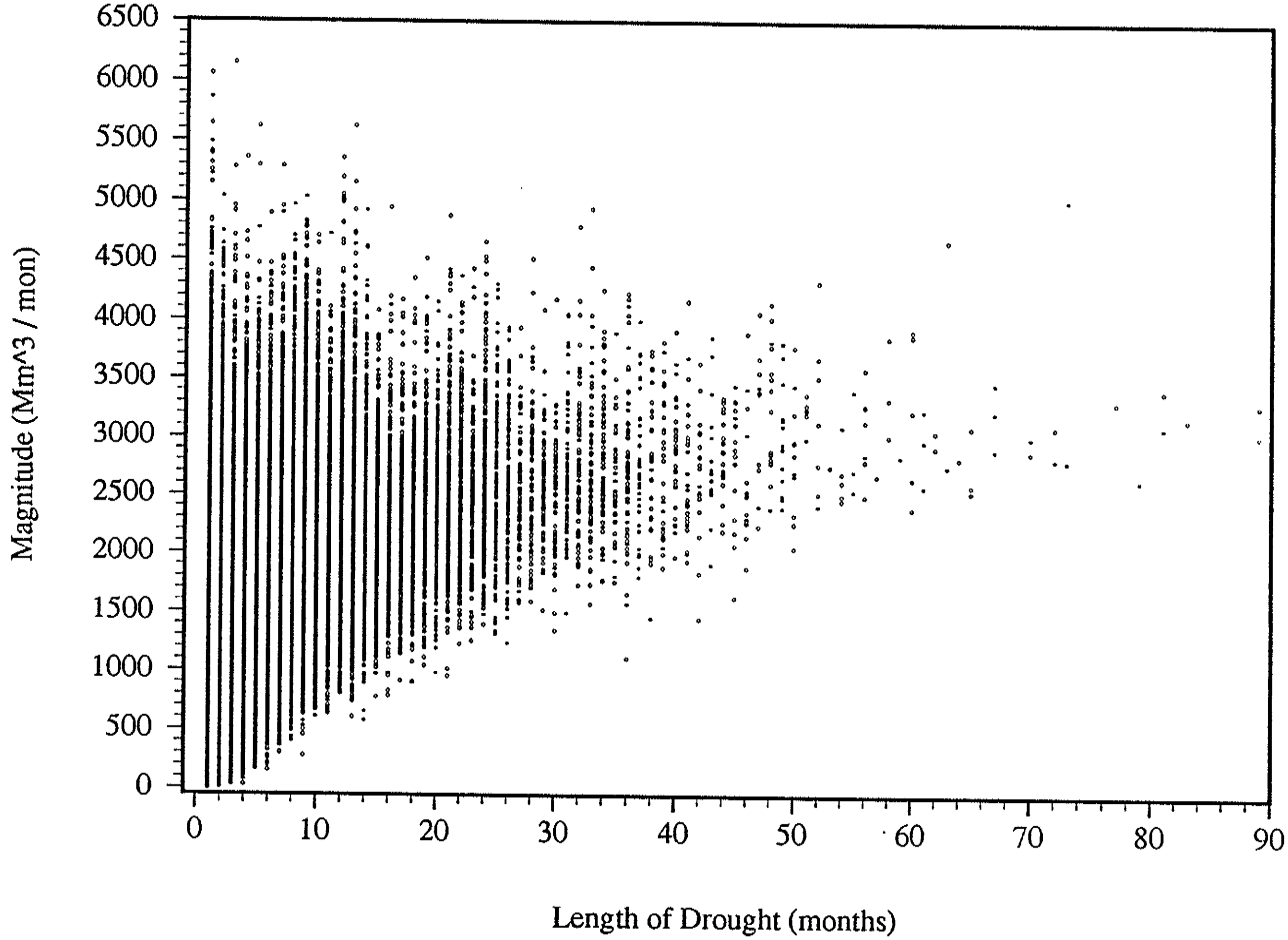

Figure 7.2 : Relationship Between Drought Magnitude and Length for the Synthetic Data

length. Considering these two results together suggests that the range of severity increases at a decreasing rate. The trend of increasing minimum magnitude and decreasing maximum could be expected if one considers drought magnitude in terms of flow. A small magnitude means the flows did not deviate very far from the mean and large magnitudes indicate large deviations from the mean flow. In order to get a long drought with a low magnitude the flows would have to be close to the mean for a prolonged period. Over a long duration, however, it is more probable that the flows would either drop and lead to a drought of greater magnitude, or the flows would rise and terminate the drought. Similarly, a long event with a high magnitude means that very low flows would have to persist for an extended duration. These very low flows have a small probability of occurence on a monthly basis and the probability that they would occur successively over a long time period becomes even smaller. Such low flows might occur over short periods but would eventually give way to larger drought flows which will reduce the drought magnitude. Statistical theory dictates that high and low drought magnitudes become less and less probable as the drought length increases. This, however, does not mean it cannot happen, as evidence by the two high points at drought lengths of 73 and 63 months, where these are the worst and second worst synthetic events, respectively.

The final relationship to be considered is that of magnitude to severity, as shown in Figure 7.3 on page 89. This plot does not reveal anything that has not already been discussed. As with Figure 7.2, this figure shows an increasing minimum magnitude and decreasing maximum magnitude. With increases in severity, the banded effect shown by

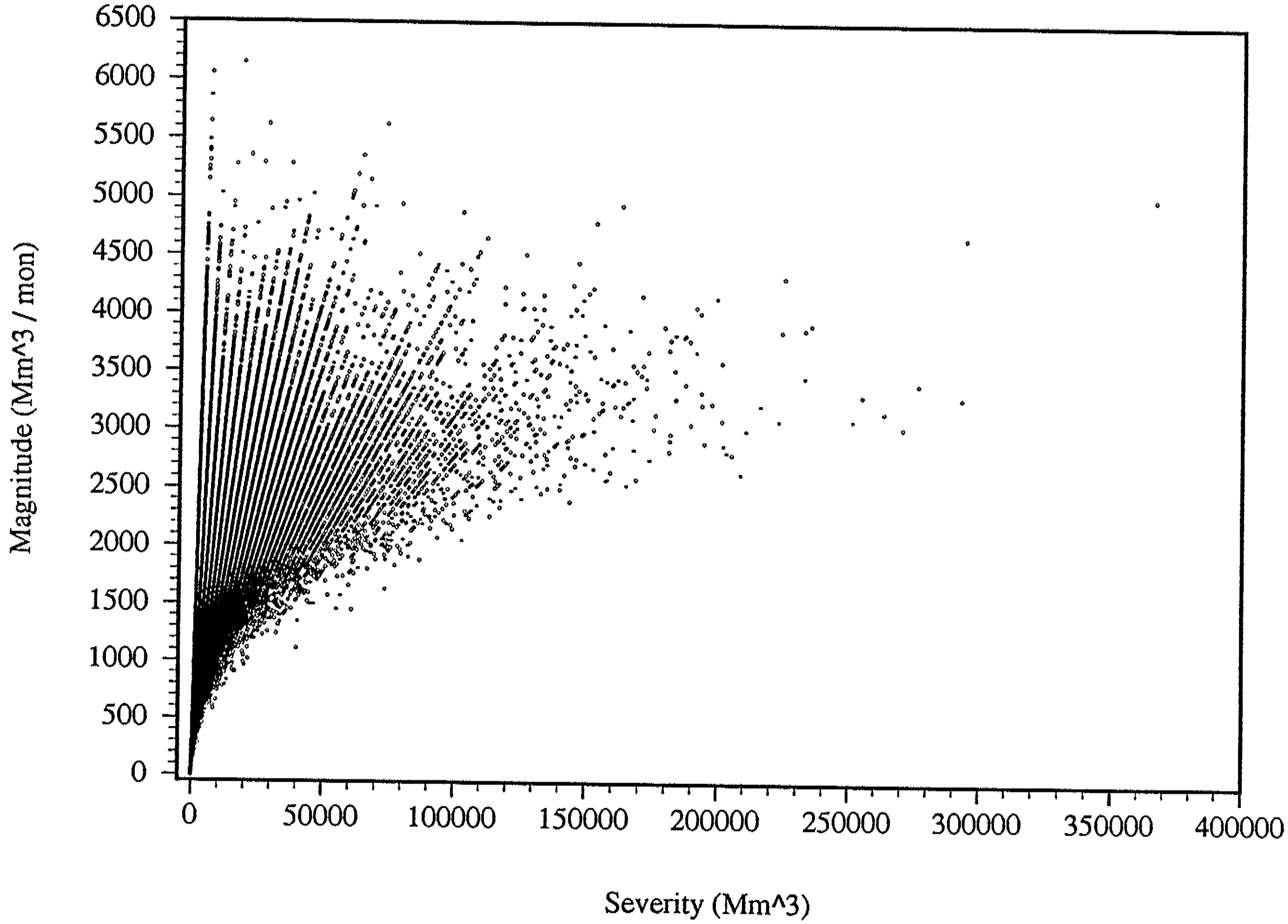

Figure 7.3 : Relationship Between Drought Magnitude and Severity for the Synthetic Data

the data points is merely a result of measuring the drought length in whole number increments. Each band represents a drought of a specific length, with the left most band being one month and then increasing from left to right.

Although the discussion up to this point has focused on graphical representation of the results, some of the actual historic and synthetic drought parameter values should be compared. At the low end of severity scale, for both the historic and synthetic data, there are many droughts that are of little or no consequence to the Manitoba Hydro system. For example, the smallest historic drought had a severity of $2*10^6 m^3$ and occurred in the month of September, a month where the mean basin flow is $6,935.4*10^6 m^3$. This deficit is slightly less than 0.03%. Droughts having this small a severity, and even those that are somewhat larger, can very easily be alleviated by use of water stored in the reservoirs even when they are not at full capacity. If both Lake Winnipeg and Southern Indian Lake are at maximum reservoir elevations then the amount of stored water available is approximately $33,000*10^6 m^3$. Were Lake Winnipeg allowed to drop below the minimum reservoir elevation of 711ft (216.7 m) to as low as 709ft (216.2 m), which it could in the most severe droughts, the maximum available storage could be as much as $48,000*10^6 m^3$.

At the other end of the scale, Figure 7.1 shows that the synthetic data contains a number of droughts that are of longer duration and greater severity than the historic events. The most severe historic event had a severity of $123,924*10^6 m^3$ and the worst synthetic drought is a little less than 3 times larger with a severity of $366,568*10^6 m^3$. While the largest historic events are also the longest, the same is not true for the synthetic data, as can be seen from Table 7.2 which lists the 5 most severe synthetic events. The two longest events lasted 89 months and while they are among the 5 most severe events they are not the two worst events. Instead, the worst event is 16 months shorter and second worst drought is fully 26 months shorter. The 63 month drought and the worst 89 month drought are quite close in severity despite having very different durations. The difference between these two events is reflected by the significantly different drought magnitudes they have.

Severity ($10^6 m^3$)	**Length** (months)	**Magnitude** ($10^6 m^3$/mon)
366568	73	5022
294499	63	4675
293113	89	3293
276557	81	3414
270520	89	3040

Table 7.2 : Drought Parameters for the Five Most Severe Synthetic Droughts

7.2 PROBABILITY ANALYSIS

After calculating the drought parameters for the historic and synthetic data sets the task of obtaining exceedence probabilities is quite simple. The drought severities are sorted in descending order and Equation 6.1 is applied to the two separate data sets. Figures 7.4 and 7.5 show plots of the probability of exceedence (POE) values calculated for the historic and synthetic drought severities respectively. Both figures clearly display the same basic shape. The exceedence values drop very rapidly in the drought severity

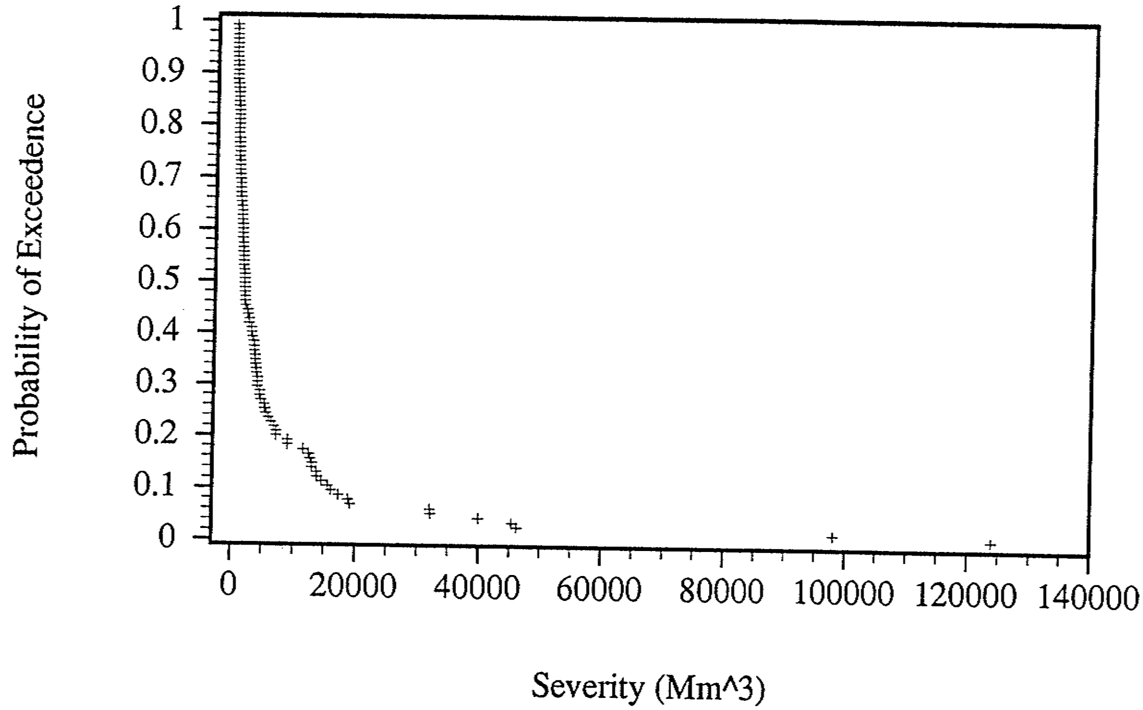

Figure 7.4 : Plot of Exceedence Probabilities for Historic Droughts

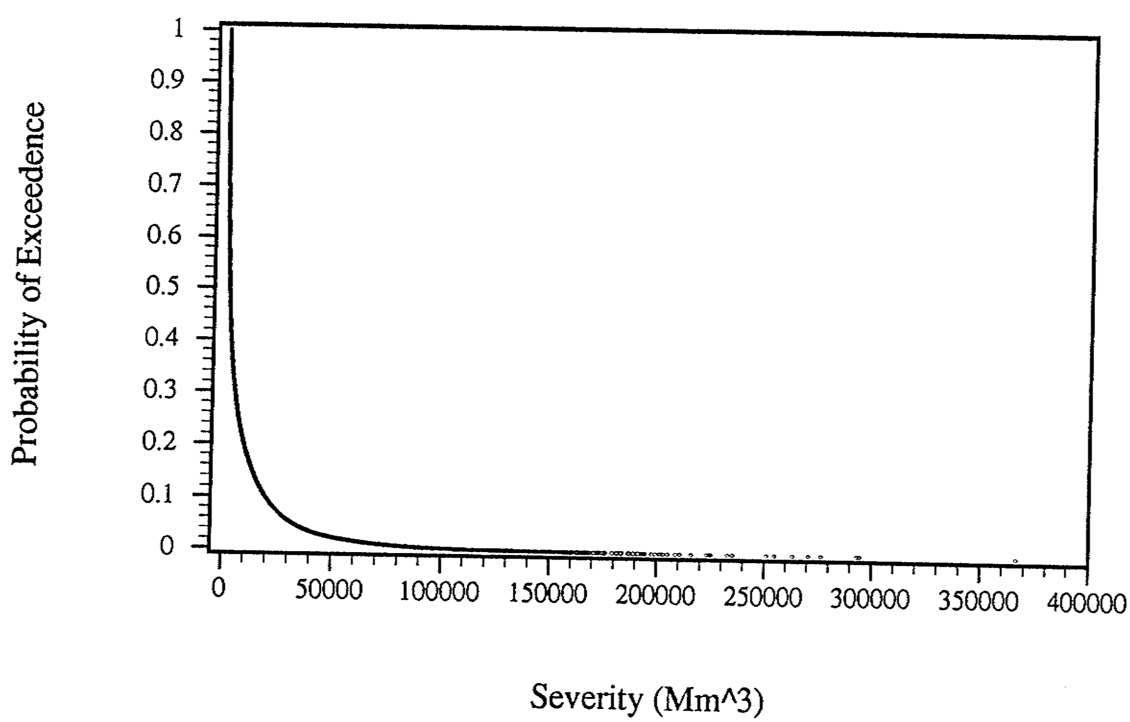

Figure 7.5 : Plot of Exceedence Probabilities for Synthetic Droughts

range 0-10,000*10^6m^3. The POE values then enter a transition phase from approximately 10,000-50,000*10^6m^3 and above this range the POE values are quite small in both cases. These two graphs show that a major portion of the drought occurrences are of small severity relative to the design drought. The drought severity with a 50% POE for the historic and synthetic data sets are approximately 1,730*10^6m^3 and 1,920*10^6m^3 respectively. With a maximum available storage capacity of about 33,000*10^6m^3 it is apparent that the Manitoba Hydro reservoirs should be able to compensate for a large percentage of potential flow deficits, even if the reservoirs are not at maximum storage levels. At a drought severity level of 33,000*10^6m^3 the historic POE is approximately 5.1% while the synthetic POE is about 4.7%. Although the maximum available storage could cover 95% of drought events, the actual number of events fully covered by the reservoirs would be lower. The percentage would be lower because in many cases it will not be possible to fill the reservoirs between drought events. This means that a drought of relatively small severity might not be alleviated and which could then lead to a significant shortfall in power generation.

While the probability plots shown in Figures 7.4 and 7.5 definitely have the same shape they are not identical, which is apparent by the differing severity and POE values given above. Exceedence probabilities for the historic drought severity values can be determined from the synthetic data by using simple linear interpolation. The use of linear interpolation will have a very small error, even for the curved portion of the graph in Figure 7.5, since the synthetic data points are very close together in this area. The exceedence probabilities associated with the historic severities can then be plotted against each other as shown in Figure 7.6. The diagonal line in this figure represents the line of equality between the two axes. Above the line the historic POE is larger than the synthetic value and below the line the historic POE is smaller. Although more of the points plot below the line, the data points do not show any significant shifts away from the line of equality. If the flow model was performing poorly, then one would expect to see a large shift away from the diagonal line either in one direction or the other. For example, if the synthetic records contained a high proportion of low severity droughts, then the synthetic POE values for the historic severities would decrease far more rapidly than the historic POE values. Such a difference would not be readily apparent when looking at a graph like Figure 7.1 where the historic and synthetic drought parameters are

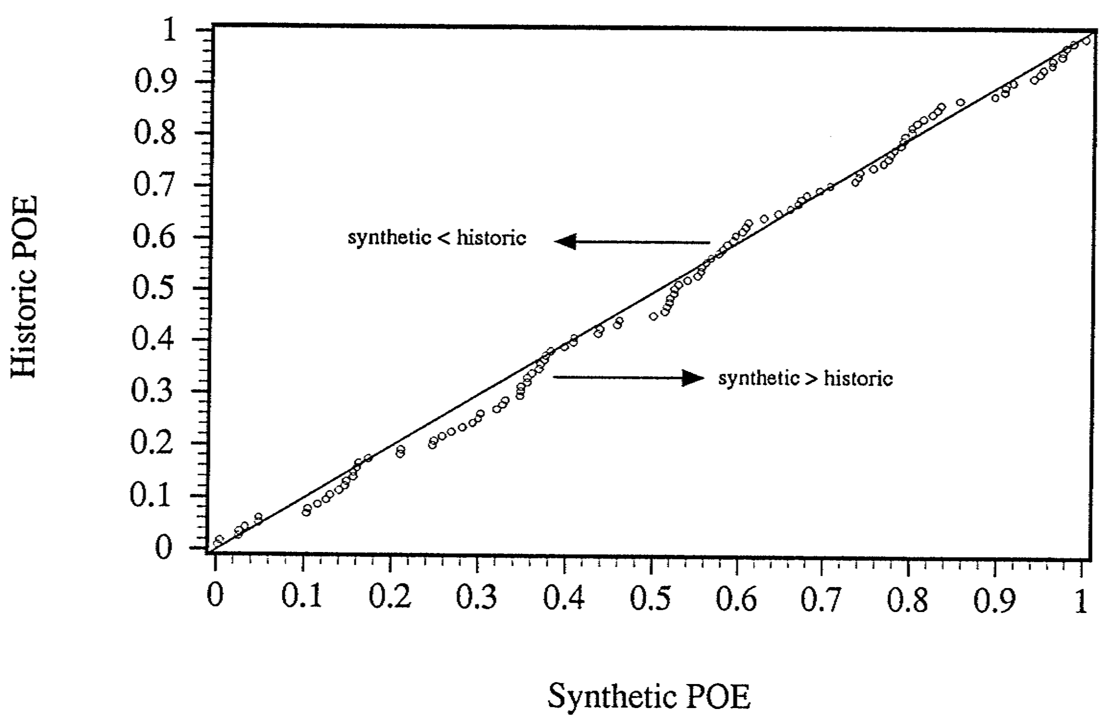

Figure 7.6 : Comparison of Historic and Synthetic Exceedence Probabilities for the Historic Drought Severities

compared. The fact that the data plots close to the line of equality suggests that the modelling procedure adequately represents the basin wide flow regime and, more importantly, the basin wide drought characteristics.

The severity level of interest for this study is that obtained from the 1939-1941 drought period in the historic record since this is the event Manitoba Hydro uses as the basis for dependable flow and generation expansion. As noted previously, this was the most severe drought in the historic record. Since this is the largest historic severity it will obviously have the lowest POE value from the historic record. It has been shown that the flow simulation is providing a good representation of the system. Therefore, if the POE value obtained for the drought of record based on historic events is statistically correct then one would expect to find a similar POE value for this severity level based on the synthetic data. As it turns out, however, the synthetic record predicts a lower POE for this event. That is, according to the synthetic record, this event would be much rarer in its occurrence than might be expected based on 79 years of historic data. Table 7.3 shows the drought parameters and POE values obtained for the drought of record and the two synthetic severities that bracket this event. The historic POE value for the drought of record is approximately 4.6 times greater than the synthetic POE. This means that the historic value will produce a much shorter estimate for the return period of the event. While both POE values show that the drought is quite rare, it may be easier to see the difference by comparing the return periods obtained for the drought.

Event	Severity (10^6m^3)	Length (months)	Magnitude (10^6m^3/mon)	Historic POE	Synthetic POE
Synthetic	123677	41	3017	-----	0.001898
Historic	123924	37	3349	0.00896	0.001894
Synthetic	124283	39	3187	-----	0.001889

Table 7.3 : Comparison of the Drought of Record and the Synthetic Droughts at the Equivalent Severity Level

The return period for the different severities cannot be calculated by simply inverting the POE values. This is because the number of data points exceeds the number of years of record, as opposed to a study of maximum annual flows where a single value is drawn from each year. Inverting the POE values obtained in this analysis gives the recurrence interval of the event in terms of drought periods. For example, a drought severity with a POE of 0.2 has a recurrence interval of 5 drought periods, that is, one in every five drought periods is expected to equal or exceed the given severity level. In order to get the expected recurrence interval in years one must first calculate the average length of wet/dry cycles in the record. The historic record has 114.5 wet/dry cycles in 948 months, giving an average cycle length of 8.28 months. In the synthetic record there are 110,665 droughts, so there must be the same number of wet/dry periods plus or minus 0.5. Over 960,000 months the 0.5 makes little difference so a value of 110,665 is assumed and the average length of a cycle in the synthetic data is 8.67 months, slightly longer than the historic value. The time of recurrence between the end of an event and the beginning of an equal or larger event is found by multiplying the average cycle length by the drought period recurrence interval minus 0.5. Table 7.4 displays the recurrence intervals obtained for the drought of record based on historic and synthetic POE values.

Data Set	POE	Wet/Dry Cycle (months)	Recurrence Intervals	
			No. Cycles	No. of Years
Historic	0.008696	8.28	115	79
Synthetic	0.001894	8.67	528	381

Table 7.4 : Recurrence Intervals for the Drought of Record

Since the 1939-1941 drought was the most severe in the historic record it was obvious that it would have a return period of 79 years without having to perform any calculations. The synthetic value gives a much longer return interval for this event and suggest that the historic estimate for the return period is quite conservative. Although the return period for this basin wide severity is estimated to be approximately 380 years, this does not necessarily mean that each flow site in the basin is experiencing a drought with this long a recurrence interval. The individual sites could in fact be experiencing droughts with a much shorter return period This number indicates that the combination of individual deficits that produced such a large basin wide severity is quite rare. Note that other return periods might be obtained if a different model framework were used or if a different number of data sets were generated. One would, however, expect to see the sysnthetic data produce a longer return period for the drought of record even if another framework or different amount of data were used.

7.3 POWER GENERATION ANALYSIS

Average power generation levels are determined for each drought period overall and for the lowest six months of generation during a drought. These generation values can then be plotted against the different drought parameters for both the historic and synthetic records. In the previous section it was shown that while the historic data provides an indication of the relationships, the synthetic results provide a better picture of variability in these relationships. This is also true for the investigation of power generation levels during drought periods.

Consider first the relationship of mean generation levels with respect to the length of a drought event. In Figure 7.7 the historic generation levels are plotted together for comparison. Obviously, for droughts of 6 months duration or less the two mean generation values are equal. As drought length increases past six months the difference

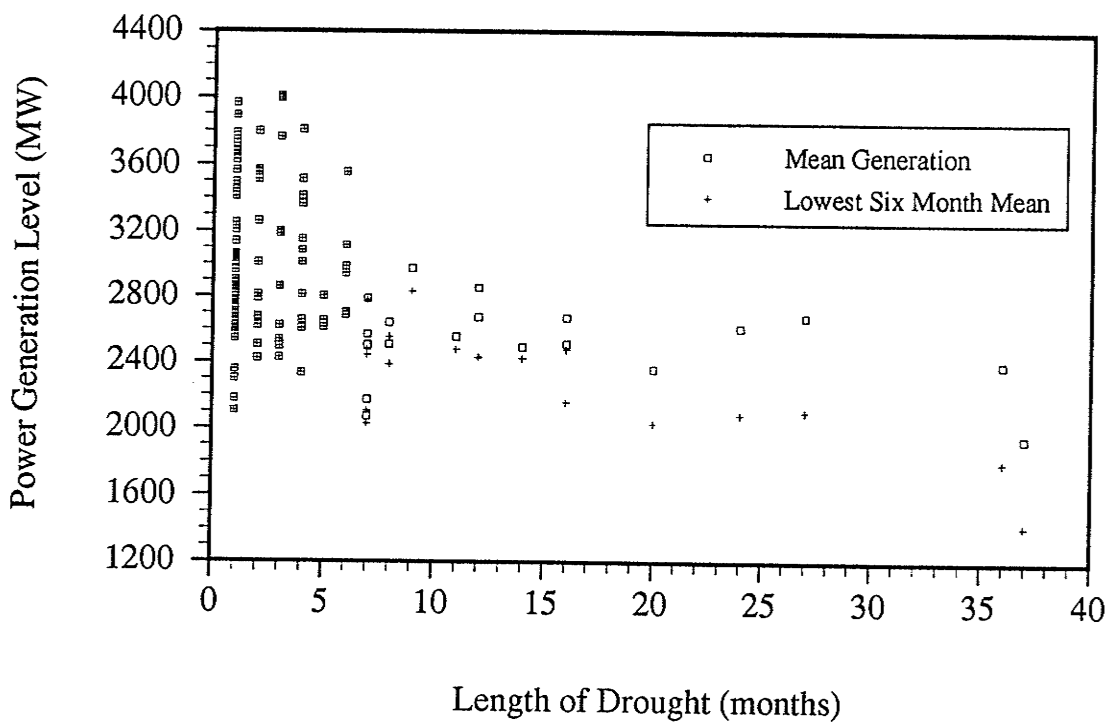

Figure 7.7 : Relationship Between Mean Generation Levels and Drought Length for the Historic Data

between the two averages also appears to increase. For the four events longer than 20 months, the overall mean generation is approximately 600 MW higher than the lowest 6 months. The data in this plot show a large range of variability at short drought lengths and it is expected that the same would be true for longer droughts, although the historic values do not show it. This variability is seen in plots of the synthetic data as shown in Figures 7.8 and 7.9 on pages 100 and 101 respectively. The largest degree of variability is seen at the short drought lengths and the range decreases rapidly up to a drought length of 10 to 12 months for both graphs. This is due to the rapid decrease in the maximum mean generation values up to 10 or 12 months. These values decrease much more slowly thereafter. The minimum average values, on the other hand, do not show any real trends in one direction or another.

The difference between the overall mean generation levels and the corresponding lowest six month averages is not apparent from Figures 7.8 and 7.9. Plotting the lowest six month average against the overall mean, however, shows how large a difference there can be between the two values as seen in Figure 7.10 on page 102. In this figure, the straight line represents droughts of six months duration or less since the average generation values are the same for these events. Points below the line are those cases where the lowest six month average is less than the overall average. The graph clearly shows that there were no droughts longer than six months with a generation level in excess of 3800 MW. Below this level is when differences between the two averages start to appear. As the mean generation level decreases from 3800 MW to approximately 3100 MW the maximum difference between the two averages increases. At mean generation

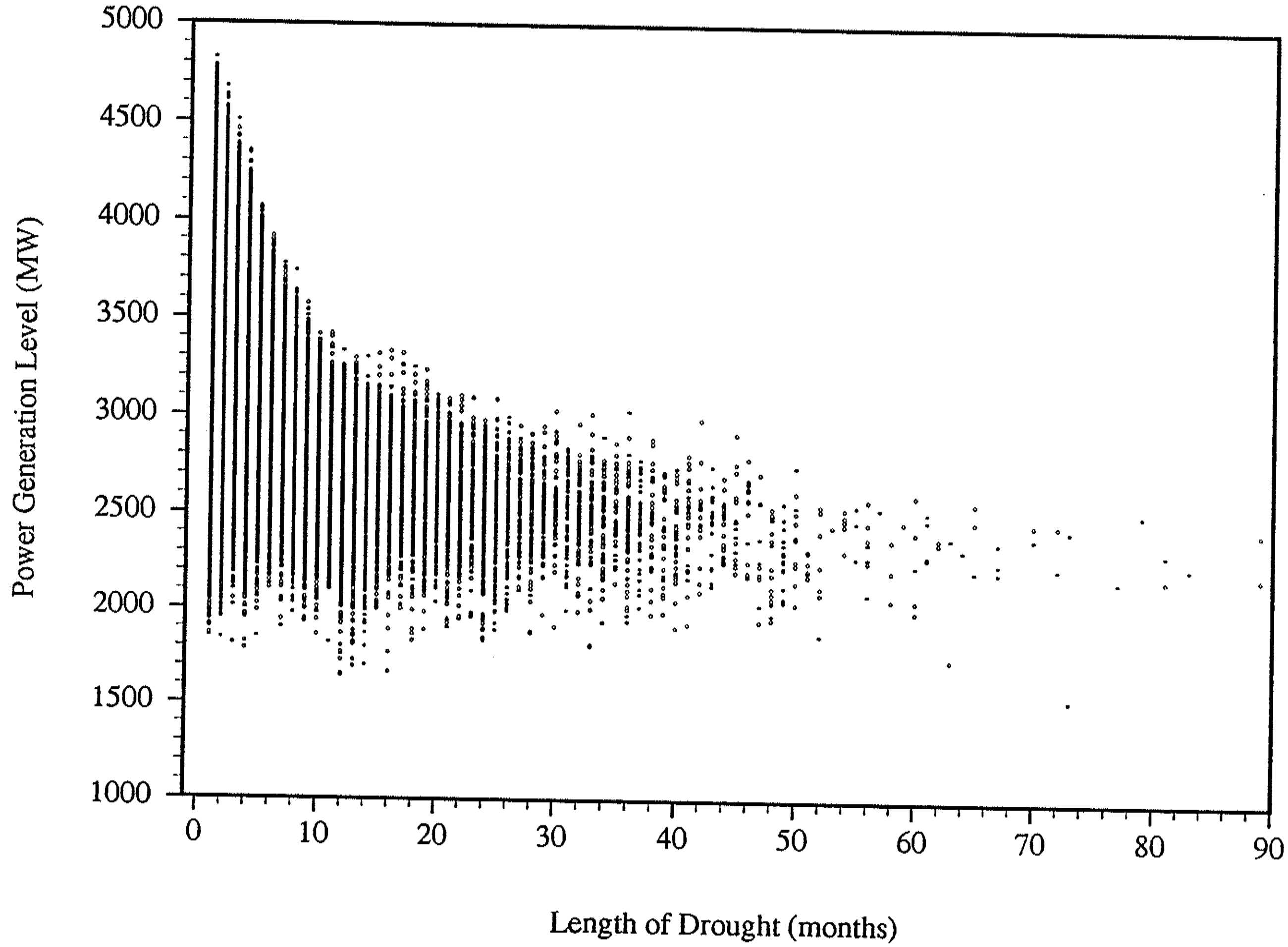

Figure 7.8 : Relationship Between Mean Generation Level and Drought Length for the Synthetic Data

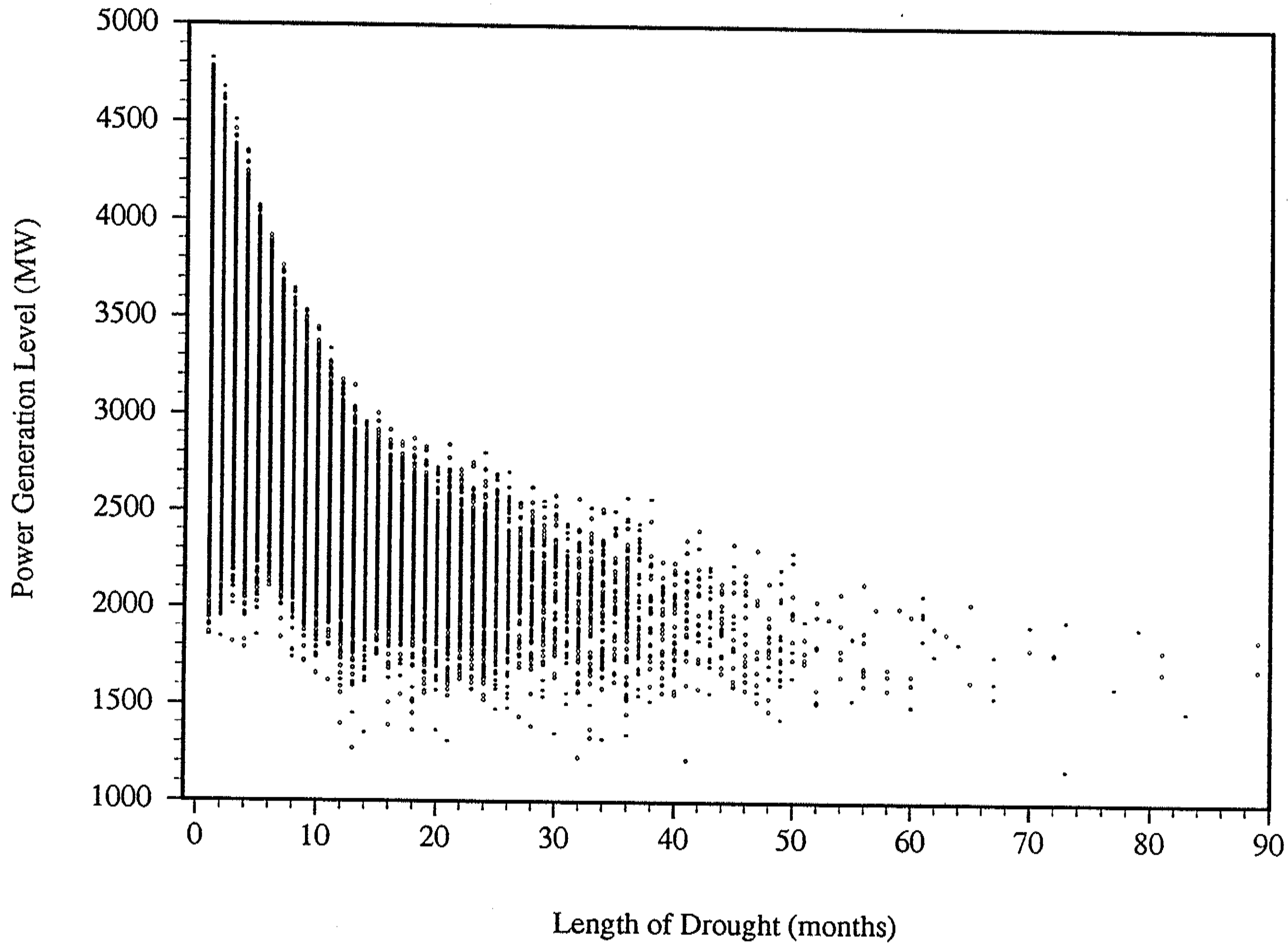

Figure 7.9 : Relationship Between the Lowest Six Months of Generation and Drought Length for the Synthetic Data

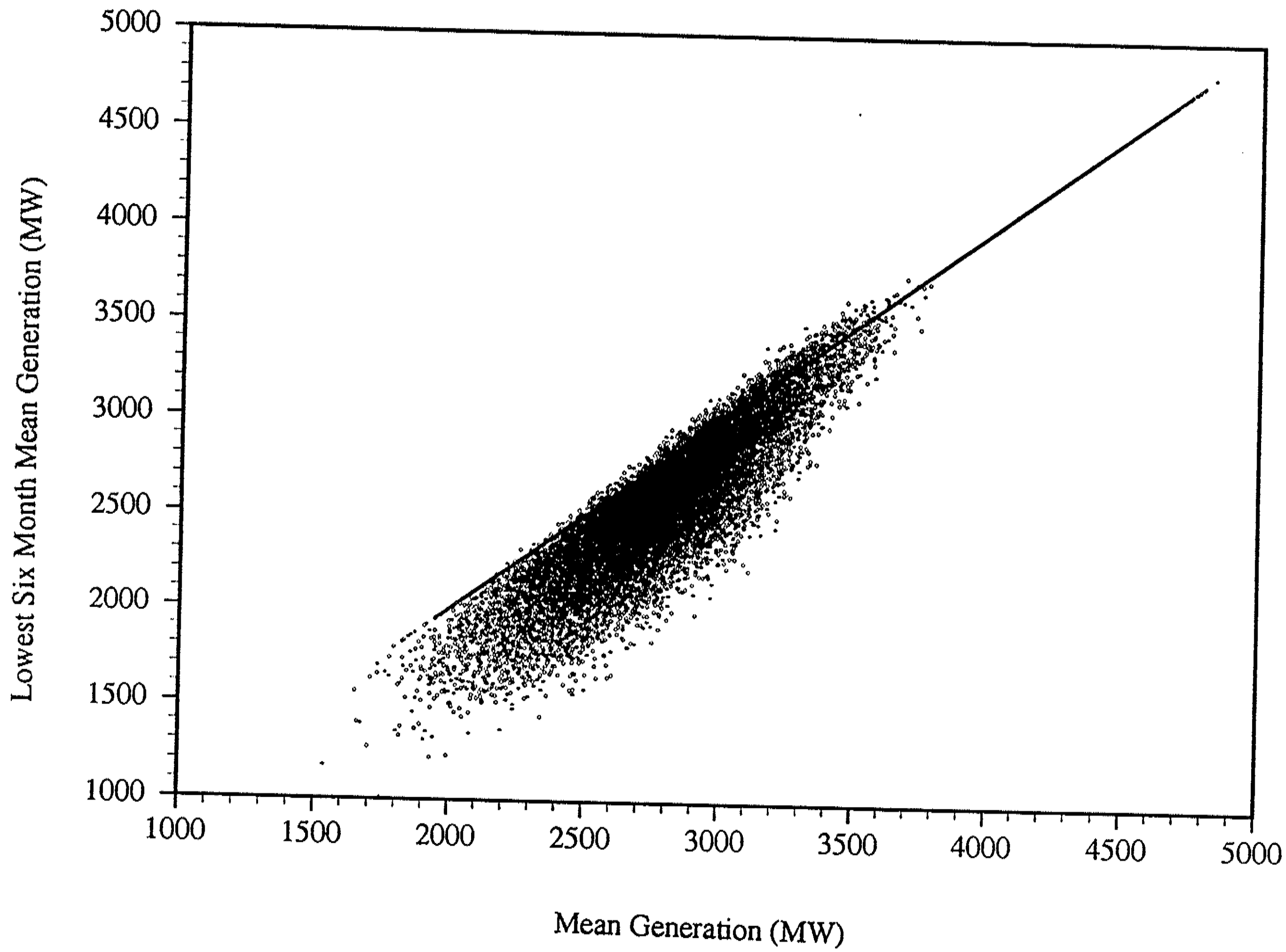

Figure 7.10 : Comparison of Generation Levels for the Synthetic Data

levels below 3100 MW the maximum difference appears to stay relatively constant. The largest difference between the overall mean and the lowest six month average is approximately 900 MW. While this is a significant difference the graph shows that the major portion of the data points lie within 500 MW of the line of equality. This plot also shows a number of events where the lowest six month average is in fact larger than the overall mean which might at first seem to be an impossibility. It can and apparently does occur for droughts of almost any length, although it is likely more common in droughts of 7 or 8 months duration. This can happen for a seven month event if six of the months have low generation values and one month has a high value. The one high month, however, can not be the first or last month of the event.

The next relationship to consider is between the power generation levels and drought severity. Since severity increases with drought length, as discussed earlier, one expects to see a relationship here that is similar to the relationship of generation and drought length. In fact, the plot of historic generation levels relative to severity looks essentially the same as Figure 7.7 and it will not be presented for this reason. The synthetic data, however, reveal more than the historic values and are presented in Figures 7.11 and 7.12. These graphs display the similar basic trends shown in Figures 7.8 and 7.9. Note how rapidly the maximum generation levels decrease in the severity range from 0-30,000*$10^6 m^3$. At severity levels near zero cubic meters the maximum mean generation is 4834MW on each graph and then drops to approximately 3150MW and 2850MW for the overall mean and lowest six month mean respectively. The minimum average values in this severity range are approximately 1800-1900 MW for each plot. Here again the

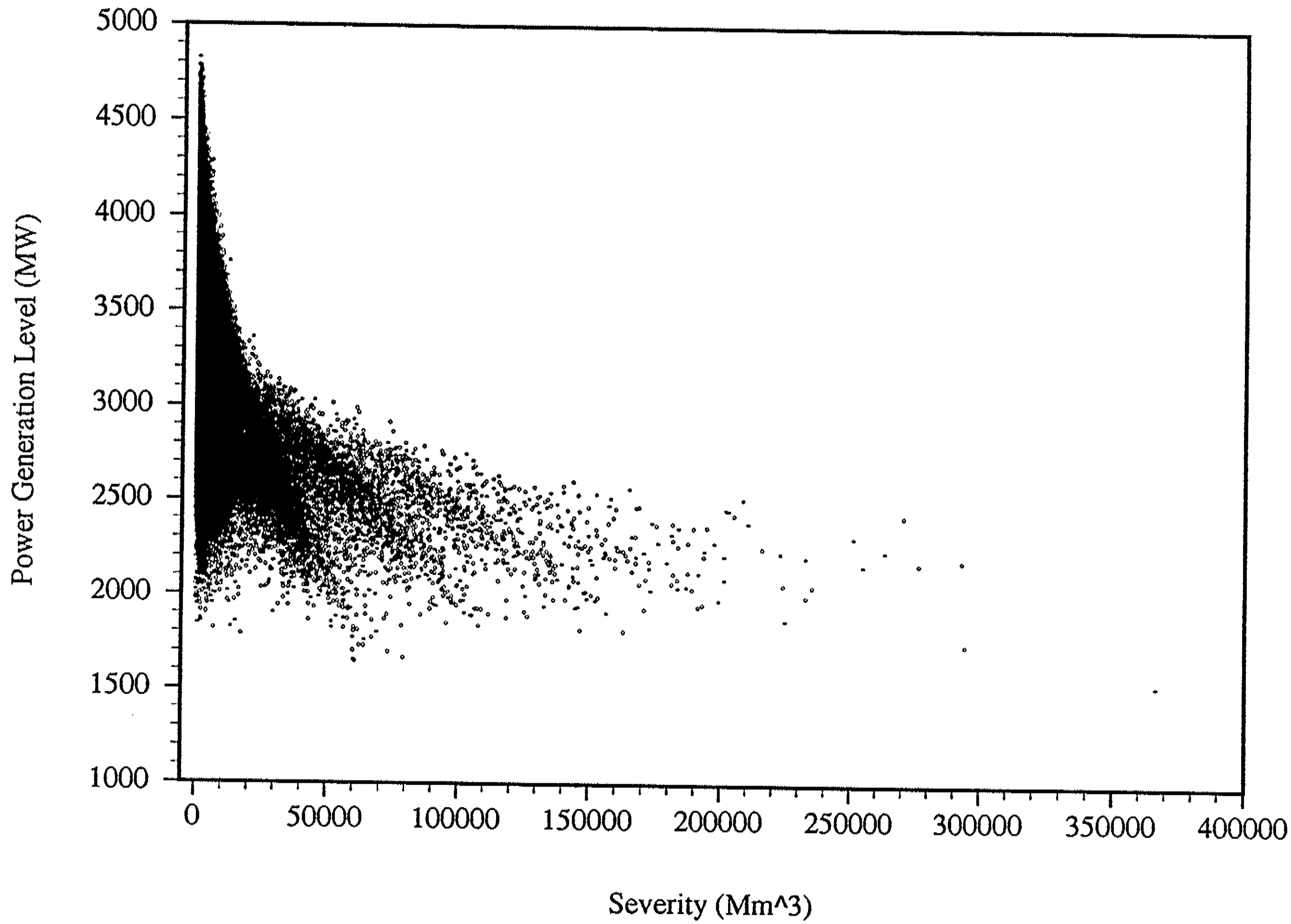

Figure 7.11 : Relationship Between Mean Generation Level and Drought Severity for the Synthetic Data

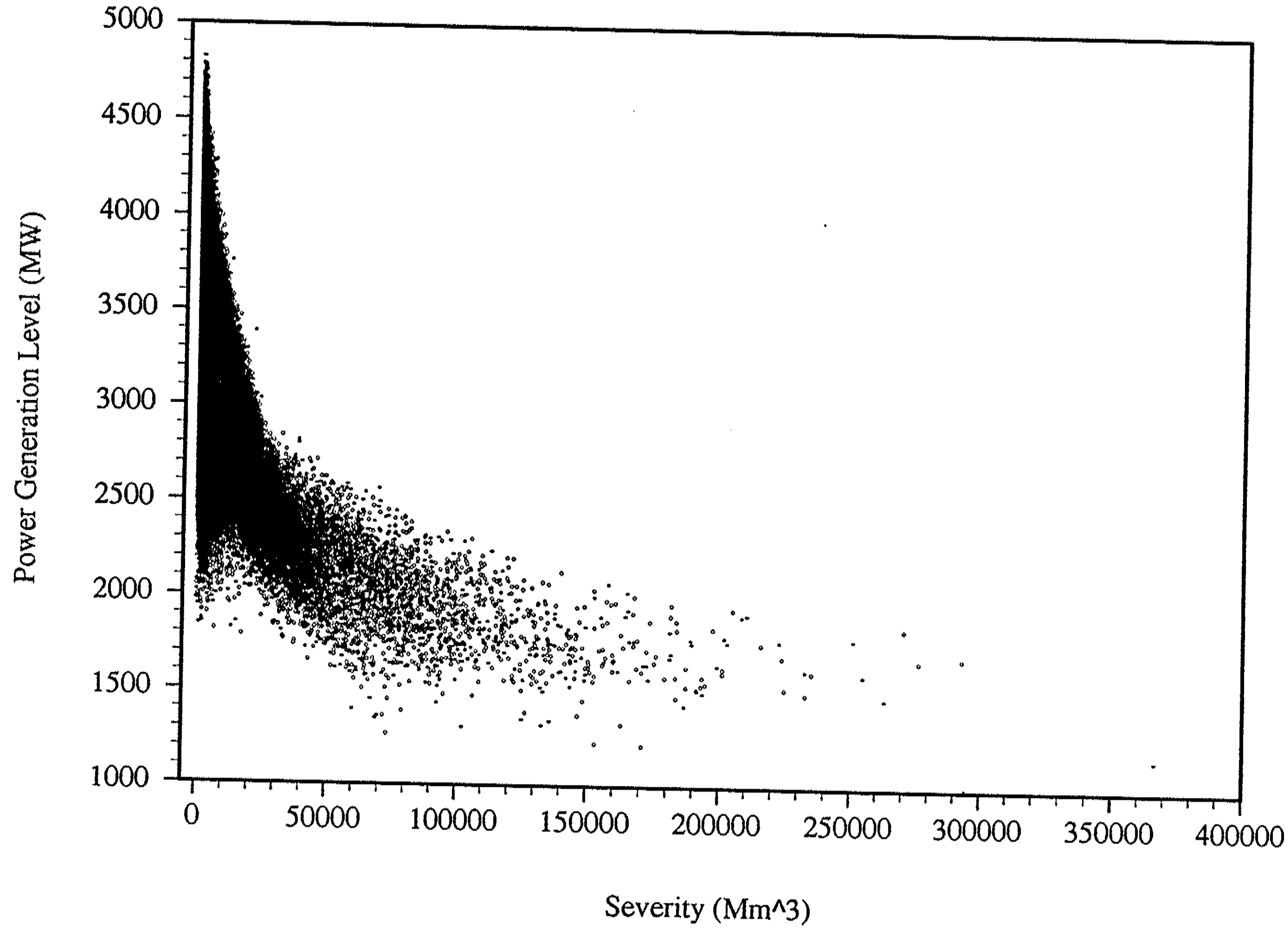

Figure 7.12 : Relationship Between the Lowest Six Months of Generation and Drought Severity for the Synthetic Data

spread between the maximum and minimum values decreases rapidly due to the decreasing maximum average values. The maximum average generation values still decrease as the severity increases beyond $30,000*10^6 m^3$, but at a much slower rate. Similarly, the spread between the values changes very little for the higher severities.

Recall from Figure 7.5 that approximately 95% of the drought events have a severity of less than $33,000*10^6 m^3$ which leads to the rapid decrease in POE values over this range. This means that the area where probabilities change most rapidly coincides with the region where the power generation levels show the greatest variability and have the most rapid drop in maximum value. What this indicates is that even though a drought has a high POE that does not mean the event will be of no significance. For example, the severity with a 50% POE is $1,920*10^6 m^3$ and has an average generation range from approximately 1800 MW up to 4700 MW. This drought event is small considering the volume of deficit is less that 6% of the maximum storage volume in Manitoba Hydro's reservoirs. Yet, despite this fact, this type of drought could easily lead to a power generation level that is likely to be lower than consumer demand. The reason such a small event can have a low generation level is that drought events are not necessarily independent, as was noted previously in Chapter 2. If the low magnitude event occurs just after a large drought, then there may not be enough water available in the reservoirs to alleviate even this small a deficit. Furthermore, the month in which such a deficit occurs can also influence the generation level since the Lake Winnipeg release model tends to conserve water in the spring and release it during the fall and winter. Identical flow and storage conditions can have a very different power generation estimates depending on the season. For droughts of larger severity, and thus greater length, this effect is smoothed out since the drought lasts through many seasonal periods.

At the higher severity levels there is much less spread in power generation levels, although the maximum average values do drop approximately 450 MW in the severity range from 30,000*10^6m^3 to 100,000*10^6m^3. Aside from this drop, the average power generation values for severities larger than 30,000*10^6m^3 lie within a fairly narrow band. For the overall average generation level this band goes from approximately 1900 MW to 2700 MW and for the lowest six month average the band is roughly 1500 MW to 2300 MW. There is not much difference between large severity events as far as average power generation levels are concerned. Droughts of 100,000*10^6m^3 and 200,000*10^6m^3 have similar levels of power generation. So at small severity levels a small change in severity has a large effect on the power generation range while at large severities a large change in severity has a small effect on the power generation range. This reflects the influence that the reservoirs have on the system. During large events the reservoirs will be depleted and begin to operate on an inflow equals outflow basis as long as the drought persists. Once the system gets to this point the power stations rely solely on natural flow patterns. These average flow patterns during prolonged droughts are likely to be similar even if the events themselves have very different severity levels. If a drought with a severity of 100,000*10^6m^3 has the same overall mean generation level as a 200,000*10^6m^3 event, then the larger event will have a similar power supply deficit but lasting over a much longer period. This in turn means that Manitoba Hydro would have to import power from an outside source for a longer duration and this would involve a much larger cost overall.

CHAPTER 8

SUMMARY AND CONCLUSIONS

In this study, a large basin containing multiple sub-basins and multiple gauging stations is investigated in order to characterize the occurrence of hydrologic droughts within the basin. The approach taken is to model the multi-site system and generate a large number of synthetic flow series for each site. Historic and synthetic flow records are then investigated for drought conditions using the theory of runs. This study applies the theory of runs to the basin as a whole rather than investigating each flow site individually. The drought severity parameter is then used to assign exceedence probabilities to the drought events based on the Weibull formula. Probabilities associated with the historic events are calculated using historic and synthetic data and then compared, placing particular emphasis on the drought of record. The analysis also looked at power generation levels during the drought events.

The study area for the analysis is that portion of the Nelson River basin lying within Manitoba. Manitoba Hydro provided flow records from 16 locations and these represent all the relevant inflows to the system. These sites were modelled with the SPIGOT analysis package. SPIGOT uses auto-regressive and disaggregation procedures to model the sites and reproduces site specific statistics such as mean and variance. SPIGOT also maintains site-to-site correlations to the highest possible degree. The program was used to generate 1000 sets of 80 year records for each site. The model's performance is verified through the application of the theory of runs by comparing the synthetic drought parameters to the historic values to be sure they compare favourably. Drought parameters are used to verify model performance since SPIGOT does not directly model these values and they should be independent of the modelling procedure. Comparison of the synthetic and historic parameters, plus a comparison of the exceedence probabilities, confirmed that the model performed adequately.

The drought analysis uses a basin wide application of the theory of runs rather than the typical method of investigating sites individually. This was done first of all because a number of the inflows do not directly impact on hydro-power production and thus the occurrence of droughts at these sites is not necessarily significant on an individual basis. In the second place, the bulk of Manitoba Hydro's generating capacity lies along the Nelson River and these stations may not feel the effects of droughts occurring at separate sites. Given these considerations, the basin is said to be in a drought condition when the sum of monthly flows at all the sites is less than the mean monthly inflow for the entire basin. This results in 12 different truncation levels, although two different sets of levels were used for the historic data since some records were longer than others. Applying the theory to the historic data accurately identified the historic drought periods which Manitoba Hydro had noted as being critical, particularly the most critical period of 1939 to 1941. This verified that the chosen method of analysis performed properly and would be appropriate for the investigation of droughts in the synthetic data.

Results obtained from the drought analysis clearly show the benefits of using synthetic data for the investigation of drought conditions. While the historic data provides some indication of the relationships between drought parameters, it does not show the wide range of variability in these relationships. This is a result of the fact that the historic record is not long enough to develop a wide range of conditions and this problem is most prevalent when considering high severity events. The synthetic data shows that a drought of a given severity can occur over significantly different time periods. Conversely, a drought of given length can have very different severity levels. The historic data displays this variability only for low severity droughts. For droughts of greater severity the historic values plot as individual points that essentially stand alone.

Exceedence probabilities were calculated for both the historic and synthetic records by applying the Weibull plotting position formula to the drought severity values. The severity parameter is deemed to be the best measure of the difference between drought events for the purpose of this study. The probability values for the two data sets showed a rapid decrease at low severity levels so that even droughts which are small relative to the drought of record have a low probability of exceedence. The synthetic results were then used to estimate probabilities associated with historic severity levels, producing two sets of probabilities for the historic events. These two sets of values compared favourably, providing further verification for the flow model used. For the drought of record the historic data produces an exceedence probability of 0.0087 while the synthetic estimate is 0.0019. The historic estimate of the return period is 79 years and the synthetic record produces a return period of 381 years. Analysis of the historic records for drought exceedence probabilities, using the chosen methodology, may not provide the best estimate of the return period for the drought of record since the value obtained is simply the length of the record used. The synthetic estimate suggests that the drought of record occurrs less often than it might otherwise seem, although a sensitivity analysis might be performed to verify the length of the return period.

The power generation analysis shows that production levels are quite low for high severity droughts. Low severity droughts, on the other hand, showed highly variable production levels, with some values that are quite low. This fact indicates that there are situations where the reservoirs are depleted which causes apparently minor events to compromise power production. While one can expect low generation levels during severe events, no definite conclusions can be drawn regarding power production for low severity events. The level of generation obtained during small droughts is entirely dependent upon reservoir usage prior to the event. The results also showed that maximum power generation levels decrease rapidly at low drought severities.

The results of the drought analysis conducted can be used for future studies of the Manitoba Hydro system. The probability values obtained from the synthetic records make it possible to determine more accurately the severity levels associated with droughts of specified return periods. If a particular severity level is of interest, then its probability of occurrence is better defined by the synthetic data. The synthetic data also provide the opportunity for testing management policies under hydrologic conditions that are significantly different from those seen in the historic record. For example, a management policy based on the drought of record could be tested on synthetic droughts that have a similar severity but are longer or shorter in duration. The synthetic results may allow Manitoba Hydro to evaluate the risks of not protecting against droughts that are more severe than the most worst historic drought from 1939 to 1941. Reservoir operation policies can also be tested to see if the minimum and maximum power generation levels can be increased for low severity droughts. These and other possibilities are worth consideration in order to operate the Manitoba Hydro system as efficiently as possible.

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APPENDIX A

SELECTED SITE-TO-SITE CORRELATIONS

This appendix presents the monthly and annual site-to-site correlations for the 20 sites modelled using framework #4, as shown in Figure 5.4. The values are given in tabular form and each table provides the values for two months since the correlation matrices are symmetric. While the site-to-site correlations for all of the historic sites are given, there are some values that are not provided. For example, the correlation value for the sites BASINSUM and NR2 is not given. Since these sites are not directly connected in the modelling process, their relationship is not considered important.

Selected Site-to-Site Correlations (x 0.01)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		72	67	47	70	61	69	21	36	48	25	99	—	—	86	-8	26	60	25	—
BR3	64		40	63	26	78	42	61	53	33	58	76	—	—	67	3	36	39	35	—
BR4	50	25		45	67	47	61	25	42	54	35	71	—	—	72	-14	35	57	11	—
NR0	35	66	25		51	66	33	45	41	19	45	—	77	—	60	-14	26	43	10	—
NR1	47	-1	62	25		57	62	1	24	49	12	—	84	—	79	-23	22	67	-11	—
NR2	31	49	44	58	62		45	56	55	44	55	—	91	—	76	4	42	57	6	—
NR3	64	36	60	22	46	41		31	41	57	41	—	—	99	89	1	30	58	16	—
NR4	-16	47	-3	33	-33	23	-1		90	44	85	—	—	44	44	11	35	26	20	—
NR5	-13	35	7	19	-8	16	10	90		62	83	—	—	54	55	0	26	35	10	—
NR6	26	17	38	-1	18	22	33	17	27		57	—	—	66	64	-18	38	45	15	—
NR8	10	55	27	42	-25	32	33	79	76	39		—	—	54	52	0	45	22	20	—
SUMBR	99	70	55	—	—	—	—	—	—	—	—		75	70	88	—	—	—	—	—
SUMNR012	—	—	—	59	84	94	—	—	—	—	—	46		61	87	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	99	12	23	43	46	64	57		91	—	—	—	—	—
SUMNR+BR	74	54	69	51	74	74	90	9	16	39	41	77	83	91		-6	38	70	15	45
LWPGPIAO	-9	-2	-24	5	-16	-2	-3	6	-8	-21	2	—	—	—	-8		26	-2	20	76
SASK@GRAND	31	8	25	1	24	12	47	-2	6	36	32	—	—	—	40	21		19	1	55
WPG@SLAVE	49	27	51	34	69	61	55	-10	-5	27	9	—	—	—	70	-4	36		27	54
CHR@SIL	31	59	4	31	-7	28	40	31	24	23	51	—	—	—	38	6	31	3		46
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	53	69	61	61	38	

JANUARY

FEBRUARY

Selected Site-to-Site Correlations (x 0.01)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		55	37	32	36	20	55	-4	6	22	-3	99	—	—	65	15	46	39	23	—
BR3	89		-4	64	-22	32	27	48	22	16	52	62	—	—	38	16	23	15	53	—
BR4	82	70		-4	57	35	38	-1	21	42	-6	40	—	—	52	-1	1	27	-28	—
NR0	59	32	60		7	41	22	33	19	-1	42	—	39	—	41	-4	16	29	30	—
NR1	60	27	65	89		65	46	-33	-8	18	-25	—	86	—	72	-2	23	55	-20	—
NR2	50	42	48	57	72		41	23	16	22	32	—	94	—	76	13	13	53	39	—
NR3	79	66	93	60	65	59		1	23	26	22	—	—	99	86	-15	35	49	16	—
NR4	60	54	85	56	52	45	86		81	21	73	—	—	15	9	-4	-19	-13	-6	—
NR5	61	53	86	57	55	45	88	99		24	63	—	—	35	24	-12	-14	-13	2	—
NR6	78	71	94	58	56	41	85	89	90		28	—	—	37	34	27	17	22	29	—
NR8	67	59	90	61	58	45	88	98	98	96		—	—	35	24	6	5	3	-9	—
SUMBR	99	89	89	—	—	—	—	—	—	—	—		35	56	67	—	—	—	—	—
SUMNR012	—	—	—	91	97	83	—	—	—	—	—	64		49	83	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	95	95	96	96	98	84	64		87	—	—	—	—	—
SUMNR+BR	82	68	95	73	74	62	96	91	92	94	95	88	77	98		1	36	63	26	53
LWPGPIAO	5	-10	-4	30	31	31	11	-7	-4	-12	-5	—	—	—	7		9	20	-9	69
SASK@GRAND	36	30	33	53	42	49	43	24	24	19	23	—	—	—	39	31		33	21	50
WPG@SLAVE	-8	-13	-7	21	23	35	7	-4	-3	-17	-8	—	—	—	2	59	37		4	77
CHR@SIL	55	53	71	46	53	58	71	68	71	74	74	—	—	—	75	26	21	12		24
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	21	91	60	77	38	

MARCH (upper triangle)

APRIL (lower triangle)

Selected Site-to-Site Correlations (x 0.01)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		71	46	63	62	68	19	49	47	16	21	99	—	—	65	8	6	9	5	—
BR3	90		-21	41	8	96	-51	36	14	-39	-35	64	—	—	5	18	-3	9	-49	—
BR4	34	3		32	70	-19	89	33	57	81	81	58	—	—	90	-6	22	8	74	—
NR0	77	75	44		84	51	5	15	12	-7	-4	—	90	—	43	48	44	38	-5	—
NR1	38	17	77	71		21	53	23	35	32	38	—	73	—	74	31	38	34	40	—
NR2	85	92	22	88	48		-49	37	16	-43	-36	—	81	—	8	31	5	23	-46	—
NR3	-24	-57	67	-16	49	-37		29	58	89	89	—	—	96	82	-15	35	49	39	—
NR4	51	41	55	46	56	60	28		94	34	39	—	—	47	60	-4	-19	-13	16	—
NR5	27	10	63	25	58	32	53	94		61	66	—	—	73	79	-12	-14	-13	-6	—
NR6	7	-15	61	7	50	5	67	76	89		98	—	—	96	79	27	17	22	2	—
NR8	2	-15	54	3	46	8	62	81	93	96		—	—	97	83	6	5	3	29	—
SUMBR	99	91	38	—	—	—	—	—	—	—	—		78	36	73	—	—	—	—	—
SUMNR012	—	—	—	96	73	94	—	—	—	—	—	83		-5	43	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	85	69	88	94	93	-1	12		88	—	—	—	—	—
SUMNR+BR	63	43	76	69	83	65	42	89	84	72	70	65	78	70		-8	13	13	63	9
LWPGPIAO	58	44	50	63	53	51	11	-7	-4	-12	-5	—	—	—	57		17	57	9	90
SASK@GRAND	17	13	-16	11	3	10	43	24	24	19	23	—	—	—	-3	8		29	16	51
WPG@SLAVE	51	33	40	45	40	37	7	-4	-3	-17	-8	—	—	—	45	44	31		7	75
CHR@SIL	34	29	9	11	-5	17	71	68	71	74	74	—	—	—	-3	7	20	2		28
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	48	78	56	75	32	

MAY

JUNE

Selected Site-to-Site Correlations (x 0.01)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		80	58	63	53	67	25	64	53	12	4	99	—	—	81	27	25	39	54	—
BR3	68		19	73	31	93	-21	58	31	-14	11	83	—	—	62	-4	23	26	64	—
BR4	58	10		9	37	8	72	59	71	54	31	61	—	—	67	21	-4	15	19	—
NR0	27	58	-7		75	80	-1	43	24	-13	-8	—	94	—	68	10	15	28	33	—
NR1	32	12	32	63		46	46	33	32	7	1	—	71	—	72	28	4	36	-2	—
NR2	39	88	-8	70	29		-22	55	27	-19	-13	—	94	—	62	-10	22	29	42	—
NR3	51	3	67	2	46	-7		26	48	61	39	—	—	88	55	-22	6	-1	83	—
NR4	44	30	69	-6	-1	15	45		94	56	54	—	—	57	80	1	-1	30	17	—
NR5	38	12	75	-17	1	-4	52	98		72	67	—	—	76	76	-10	-1	22	44	—
NR6	21	-13	66	-25	3	-26	55	80	88		88	—	—	89	48	-36	-1	-13	74	—
NR8	27	-10	74	-25	6	23	58	87	94	97		—	—	76	40	-36	-1	-13	75	—
SUMBR	99	73	61	—	—	—	—	—	—	—	—		72	29	83	—	—	—	—	—
SUMNR012	—	—	—	90	62	92	—	—	—	—	—	45		0	73	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	87	78	86	88	91	46	-1		66	—	—	—	—	—
SUMNR+BR	74	49	74	35	52	38	80	73	71	62	66	77	48	83		20	14	36	24	38
LWPGPIAO	2	-5	21	50	52	2	8	39	30	23	17	—	—	—	17		-3	41	2	64
SASK@GRAND	11	16	4	21	18	26	-13	-15	-19	-13	-16	—	—	—	28	-10		29	9	59
WPG@SLAVE	17	20	6	43	43	34	17	28	21	13	10	—	—	—	21	42	25		0	75
CHR@SIL	44	52	17	8	-23	28	-30	-5	-14	-18	-23	—	—	—	32	-5	6	-6		37
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	39	71	44	71	34	

JULY

AUGUST

Selected Site-to-Site Correlations (x 0.01)

SEPTEMBER (upper right triangle)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		78	50	50	47	52	19	56	48	28	32	99	—	—	71	12	-3	11	45	—
BR3	76		14	74	43	90	-25	33	15	-7	-3	80	—	—	47	14	-1	16	31	—
BR4	70	29		9	41	2	61	81	85	83	81	58	—	—	80	10	-7	-7	26	—
NR0	57	72	29		81	77	-19	26	13	-3	2	—	93	—	48	44	-2	35	3	—
NR1	70	45	70	75		49	21	44	39	27	32	—	75	—	67	47	3	40	1	—
NR2	47	87	13	76	47		-34	24	6	-18	-11	—	94	—	38	16	5	30	16	—
NR3	43	-7	76	16	57	5		53	62	67	67	—	—	90	63	1	20	1	19	—
NR4	50	29	76	32	51	56	53		98	79	85	—	—	80	88	13	15	6	45	—
NR5	48	16	81	26	58	42	65	97		86	91	—	—	87	85	10	13	3	43	—
NR6	43	4	78	19	55	24	62	79	87		97	—	—	92	74	8	4	-3	32	—
NR8	42	5	77	29	60	37	67	86	92	92		—	—	92	79	4	8	0	37	—
SUMBR	99	77	75	—	—	—	—	—	—	—	—		60	37	76	—	—	—	—	—
SUMNR012	—	—	—	93	77	90	—	—	—	—	—	65		-7	51	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	94	86	93	91	92	51	16		81	—	—	—	—	—
SUMNR+BR	80	52	87	55	84	43	76	86	85	77	80	84	64	84		21	12	19	39	36
LWPGPIAO	34	-1	42	18	41	-15	45	20	28	37	35	—	—	—	39		5	64	5	74
SASK@GRAND	27	34	20	32	29	40	30	46	36	19	23	—	—	—	43	13		24	16	51
WPG@SLAVE	36	48	9	63	56	59	3	13	6	-10	-5	—	—	—	34	-4	26		-3	66
CHR@SIL	38	49	25	18	15	44	8	37	29	13	15	—	—	—	33	2	8	18		43
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	66	65	56	57	43	

OCTOBER (lower left triangle)

Selected Site-to-Site Correlations (x 0.01)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		74	75	52	58	42	55	44	45	45	47	99	—	—	81	24	27	48	21	—
BR3	73		37	60	28	79	9	42	28	18	27	77	—	—	59	25	37	40	41	—
BR4	74	41		53	75	28	72	52	61	61	68	78	—	—	84	17	18	37	2	—
NR0	53	63	51		78	74	15	32	26	19	29	—	93	—	65	29	27	44	-13	—
NR1	70	30	71	67		48	57	51	58	55	60	—	81	—	83	21	24	52	-25	—
NR2	54	82	39	72	51		5	56	42	24	37	—	89	—	60	20	44	46	22	—
NR3	71	34	70	27	60	30		53	65	62	67	—	—	95	76	7	32	41	2	—
NR4	52	72	36	51	32	72	39		97	79	86	—	—	75	76	18	32	39	23	—
NR5	65	63	52	49	51	63	56	93		87	92	—	—	85	78	14	24	37	16	—
NR6	66	39	72	33	66	47	65	52	67		92	—	—	81	71	3	3	27	16	—
NR8	65	60	61	51	57	63	61	68	78	78		—	—	86	79	13	16	25	17	—
SUMBR	99	76	93	—	—	—	—	—	—	—	—		60	58	83	—	—	—	—	—
SUMNR012	—	—	—	88	82	89	—	—	—	—	—	71		39	78	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	98	52	69	75	73	76	55		85	—	—	—	—	—
SUMNR+BR	90	68	79	66	81	70	84	64	76	77	79	91	84	90		23	39	58	11	54
LWPGPIAO	8	17	4	6	-3	13	28	21	19	-4	-7	—	—	—	17		19	5	11	71
SASK@GRAND	17	31	18	30	23	48	30	33	27	13	27	—	—	—	36	25		24	28	54
WPG@SLAVE	63	44	51	42	58	44	58	47	59	58	43	—	—	—	68	24	21		-9	60
CHR@SIL	30	53	9	20	-4	38	15	41	31	19	32	—	—	—	28	19	45	10		41
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	55	76	59	65	55	

NOVEMBER

DECEMBER

Selected Site-to-Site Correlations (x 0.01)

	BR2	BR3	BR4	NR0	NR1	NR2	NR3	NR4	NR5	NR6	NR8	SUM BR	SUM NR012	SUM NR3-8	SUM NR+BR	LWPG PIAO	SASK@ GRAND	WPG@ SLAVE	CHR@ SIL	BASIN SUM
BR2		61	43	58	50	54	37	57	44	16	15	99	—	—	77	58	35	61	39	—
BR3	—		-35	66	-11	95	-39	40	-3	-50	-46	64	—	—	19	29	22	29	43	—
BR4	—	—		-4	70	-35	90	41	72	82	79	43	—	—	76	34	8	35	1	—
NR0	—	—	—		52	74	-7	20	-6	-37	-35	—	93	—	42	61	36	44	9	—
NR1	—	—	—	—		3	69	25	42	42	41	—	46	—	77	56	31	50	-20	—
NR2	—	—	—	—	—		36	42	0	-50	-44	—	89	—	25	33	27	33	25	—
NR3	—	—	—	—	—	—		44	73	82	79	—	—	97	79	33	20	35	-11	—
NR4	—	—	—	—	—	—	—		89	45	52	—	—	56	74	27	32	39	27	—
NR5	—	—	—	—	—	—	—	—		79	83	—	—	85	80	21	22	33	13	—
NR6	—	—	—	—	—	—	—	—	—		98	—	—	93	60	1	-7	9	-7	—
NR8	—	—	—	—	—	—	—	—	—	—		—	—	92	62	2	-7	8	-10	—
SUMBR	—	—	—	—	—	—	—	—	—	—	—		70	33	78	—	—	—	—	—
SUMNR012	—	—	—	—	—	—	—	—	—	—	—	—		-11	51	—	—	—	—	—
SUMNR3-8	—	—	—	—	—	—	—	—	—	—	—	—	—		79	—	—	—	—	—
SUMNR+BR	—	—	—	—	—	—	—	—	—	—	—	—	—	—		55	34	56	9	57
LWPGPIAO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		31	57	18	82
SASK@GRAND	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		41	-1	66
WPG@SLAVE	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		23	78
CHR@SIL	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		43
BASINSUM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	

ANNUAL

APPENDIX B

RELEASE FLOW ESTIMATION PROGRAMS

B.1 NOTIGI CONTROL

```
C  This program is designed to read in Churchill River flows, created
C  in the SPIGOT 2.6 program, and then generate Notigi release flows
C  based on the criteria provided by Manitoba Hydro.  This program
C  takes into consideration the storage capacity of Southern Indian Lake
C  using a simple storage use relationship.  This setup is termed case 3.
C  The three cases used were ;
C     Case 1 - QN1=QC-QMLIC
C     Case 2 - QN2= (QC-QMLIC) or (QNLIC) whichever is least
C     Case 3 - Same as case 2, but low flows may be augmented using SIL
C              storage, while surplus flow goes into storage up to the
C              maximum allowed as defined below.
C  After testing the three cases, case 3 was found to perform the best
C  and was therefor selected to generate Notigi releases.

      PROGRAM CHRTONOT

C  VARIABLE DECLARATIONS
C  QC      - Churchill inflow in a given month.
C  QN3     - Notigi release flow based on constraints provided.
C  QM      - Missi release, not output but needed in program.
C  MAXSTOR - Total storage volume on SIL between lake elevations
C            843.5' and 847.5' expressed as a flow which would use
C            up the entire storage in a period of 31 days.  Storage
C            is 169000 cfs*WKS (B. Girling, Manitoba Hydro, 02/12/93)
C            which converts to 1080 cms, which underestimates the
C            maximum storage by 0.056%.
C  INSTOR  - Amount actually available in storage for a given month.
C  DEFSTOR - Storage deficit expressed as (MAXSTOR-INSTOR).
C  POSSTOR - Total amount of surplus flow which is available to put into
C            storage. Amount actually put to storage depends on DEFSTOR.
C  OUTSTOR - Amount of flow taken from storage and released to Notigi,
C            dependent on amount of flow required and INSTOR.

      INTEGER     SIM, SEQ, YR, Z, SKIPS, MON
      REAL        QN3(12), QC(12), QM, INSTOR(13)
      REAL        QMLIC(12), QNLIC(12)
      REAL        MAXSTOR, DEFSTOR, POSSTOR, OUTSTOR
      CHARACTER*4 EXT(11)
      CHARACTER*4 HEADER(13)
      CHARACTER*3 FILBAS(9)
```

```
C  BASE NAMES FOR INPUT FILES FROM FLOW GENERATION

      DATA  FILBAS /'s1g','s2g','s3g','s4g','s5g',
     +               's6g','s7g','s8g','s9g' /

C  EXTENSION NUMBERS FOR OUTPUT DATA FILES AND EXTENSION FOR
C  INPUT DATA FILES

      DATA  EXT /'.001','.002','.003','.004','.005',
     +        '.006','.007','.008','.009','.010','.syn'  /

C  THE FOLLOWING DATA ARE THE LICENSE MINIMUM MONTHLY RELEASES THAT
MANITOBA
C  HYDRO MUST PROVIDE TO DOWNSTREAM OF SOUTHERN INDIAN LAKE ON THE
C  CHURCHILL RIVER.  THESE DATA ARE IN 10^6 CM  BASED ON THE FOLLOWING
C  LIMITS IN CFS :
C  4000, 3000, 2000, 2000, 1000, 500, 500, 500, 500, 2000, 6000, 5000

      DATA  QMLIC /303.46,205.63,151.60,146.71,75.80,36.81,
     +         38.03,38.03,36.81,151.60,440.38,379.26 /

C  THE FOLLOWING DATA ARE THE LICENSE MAXIMUM MONTHLY RELEASES THAT
MANITOBA
C  HYDRO CAN ALLOW DOWNSTREAM OF THE NOTIGI CONTROL STRUCTURE.  THESE
DATA
C  ARE IN 10^6 CM BASED ON THE FOLLOWING CONSTRAINTS IN CFS :
C  NOV-APR=34000  MAY-OCT=35000.

      DATA  QNLIC /2578.76,2329.21,2578.76,2495.58,
     +         2654.56,2568.93,2654.56,2654.56,2568.93,2654.56,
     +         2495.58,2578.76 /

C  DATA FOR PRINTING OF HEADER ABOVE EACH NEW SERIES OF FLOWS

      DATA  HEADER /' Jan',' Feb',' Mar',' Apr',' May','June',
     +        'July',' Aug',' Sep',' Oct',' Nov',' Dec','  YR' /

C  START OF MAIN PROGRAM

      DO 5 SIM=1,10                       !# OF SIMULATIONS
       IF (SIM.LT.10) THEN                 !OPEN INPUT SPIGOT FILES
        OPEN(1,FILE='/dsk/u3/wil/spigot/data/'//
     +          FILBAS(SIM)//EXT(11))
       ELSE
        OPEN(1,FILE='/dsk/u3/wil/spigot/data/s10g'
     +          //EXT(11))
       END IF
       OPEN(2,FILE='NOTIGI'//EXT(SIM))          !OPEN NEW NOTIGI FILE
       SKIPS=49
       CALL READLINS(SKIPS)                  !SKIP TO QC IN SEQ=1
```

```
C START OF LOOP FOR THE 100 SEQUENCES IN EACH SIMULATION

      DO 10 SEQ=1,100                    !# OF GENERATED SEQUENCES
       WRITE(2,2000) SEQ                  !NAME+SEQ HEADER
       WRITE(2,2100) (HEADER(Z),Z=1,13)       !MONTH+YR HEADER

       MAXSTOR=2892.67          !ABSOLUTE MAX AVAIL STORAGE IN 1 MONTH
       INSTOR(0)=MAXSTOR         !FULL STORAGE AT TIME ZERO
       IF (SEQ.GT.1) THEN
        SKIPS=40                    !SKIP TO QC IN YR=1 OF NEXT
        CALL READLINS(SKIPS)              !SEQ WHEN SEQ.GT.1
       END IF

       DO 40 YR=1,80                    !# OF GENERATED YEARS
        IF (YR.GT.1) THEN
         SKIPS=39                   !SKIP TO QC NEXT YR WHEN
         CALL READLINS(SKIPS)             !YR.GT.1
        END IF
        CALL READDATA(QC)                 !READ CHURCHILL FLOWS

        DO 50 MON=1,12

C THE FOLLOWING STATEMENTS SET INITIAL VALUES FOR QM, QN AND INSTOR.
C THESE WILL BE ACTUAL VALUES FOR THE RARE CASE WHEN THE INITIAL QN
C VALUE IS EQUAL TO THE QNLIC VALUE.

         QM=QMLIC(MON)                 !MINIMUM MISSI
         QN3(MON)=QC(MON)-QM              !CONDITIONAL NOTIGI C3
         INSTOR(MON)=INSTOR(MON-1)          !CONDITIONAL STORAGE

C THIS IF LOOP IS EXECUTED WHEN THE CALCULATED NOTIGI RELEASE IS GREATER
C THAN THE LICENSE MAXIMUM FLOW.  THE SURPLUS FLOW WILL THEN BE PUT INTO
C SIL STORAGE AND IF ANY REMAINS AFTER THAT IT IS SENT TO MISSI.

         IF (QN3(MON).GT.QNLIC(MON)) THEN
          QN3(MON)=QNLIC(MON)

          IF (INSTOR(MON-1).LT.MAXSTOR) THEN
           DEFSTOR=MAXSTOR-INSTOR(MON-1)
           POSSTOR=QC(MON)-(QNLIC(MON)+QMLIC(MON))

           IF (POSSTOR.LE.DEFSTOR) THEN
            INSTOR(MON)=INSTOR(MON-1)+POSSTOR
           ELSE
            INSTOR(MON)=INSTOR(MON-1)+DEFSTOR
           END IF

          END IF
         END IF

C THIS IF LOOP IS EXECUTED WHEN THE CALCULATED NOTIGI RELEASE IS LESS
```

```
C  THAN THE LICENSE MAXIMUM.  NOTIGI RELEASE WILL BE BROUGHT TO THE MAXIMUM
C  BY TAKING FLOW FROM STORAGE IF THAT MUCH IS AVAILABLE.  IF THERE IS NOT
C  ENOUGH IN STORAGE, THEN STORAGE WILL BE BROUGHT TO ZERO.  IF STORAGE IS
C  ALREADY ZERO THEN RELEASE FROM STORAGE IS NIL. (NO BRAINER !!)

          IF (QN3(MON).LT.QNLIC(MON)) THEN

           IF (QC(MON).LT.QMLIC(MON)) THEN
            OUTSTOR=QMLIC(MON)-QC(MON)          !SET MISSI RELEASE
            IF (OUTSTOR.GE.INSTOR(MON-1)) THEN
             OUTSTOR=INSTOR(MON-1)
            END IF
            QM=QC(MON)+OUTSTOR
            INSTOR(MON)=INSTOR(MON-1)-OUTSTOR

            OUTSTOR=QNLIC(MON)                  !SET NOTIGI RELEASE
            IF (OUTSTOR.GE.INSTOR(MON)) THEN
             OUTSTOR=INSTOR(MON)
            END IF
            QN3(MON)=OUTSTOR
            INSTOR(MON)=INSTOR(MON)-OUTSTOR
           ELSE

            OUTSTOR=QNLIC(MON)-QN3(MON)         !CONDITIONAL STORAGE USE
            IF (OUTSTOR.GE.INSTOR(MON-1)) THEN
             OUTSTOR=INSTOR(MON-1)
            END IF
            QN3(MON)=QN3(MON)+OUTSTOR
            INSTOR(MON)=INSTOR(MON-1)-OUTSTOR
           END IF

          END IF

 50       CONTINUE

        WRITE(2,2200) (QN3(MON),MON=1,12), YR    !OUTPUT RESULTS
        INSTOR(0)=INSTOR(12)                     !STORAGE CARRYOVER B/W YEARS

 40      CONTINUE
 10     CONTINUE
 5    CONTINUE
C  FORMAT STATEMENTS USED IN THIS PROGRAM

 2000 FORMAT ('NOTIGI  SEQUENCE # : ',I4)
 2100 FORMAT (12A9,A4)
 2200 FORMAT (12F9.2,I4)
      END

C *********************************************************************

C  THIS SUBROUTINE IS USED TO SKIP DOWN OVER THOSE LINES OF DATA WHICH
```

```
C  DO NOT NEED TO BE READ IN.  IN EACH CASE IT IS USED TO SKIP DOWN TO
C  THE NEXT QC VALUE .

      SUBROUTINE READLINS(N)

      INTEGER N, X
      DO 100 X=1,N
        READ(1,*)
 100  CONTINUE
      RETURN
      END

C ******************************************************************

C  THIS SUBROUTINE READS IN THE QC FLOWS FROM THE SPIGO DATA FILES.

      SUBROUTINE READDATA(FLOW)

      INTEGER      SITNUM, X
      REAL         ANN, FLOW(12)
      CHARACTER*17 SITNAM
      READ(1,3000) SITNUM, ANN, (FLOW(X),X=1,6)
      READ(1,3100) SITNAM, (FLOW(X),X=7,12)
 3000 FORMAT (I3,3X,F12.2,6F10.2)
 3100 FORMAT (1X,A17,6F10.2)
      RETURN
      END
```

B.2 LAKE WINNIPEG

```
C*************************************************************************
C
C  This program calculates Lake Winnipeg Total Outflows (LWTO) based on
C  Lake Winnipeg Total Inflow Available for Outflow (LWTIAO). Some of the
C  important variables are explained below.
C
C  QBSUM      : sum of flows from Winnipeg R., Saskatchewan R.,
C                Churchill R. and Lake Winnipeg Partial Inflow Available
C                for Outflow (LWPIAO)
C  QC         : Churchill River flow
C  QTIAO      : QBSUM - QC
C  QTO               : LWTO
C  QTOMIN     : minimum preferred LWTO
C  QTOMAX     : maximum preferred LWTO
C  MAXSTORA          : license maximum storage elevation (715')
C  MAXSTORB          : intermediate storage elevation (714')
C  MAXSTORC          : target storage elevation (713')
C              NOTE : storages are given as the volume of water
C                over the license minimum elevation of 711'
```

```
C DEFSTOR  : volume of storage deficit
C POSSTOR  : possible amount of QTIAO which may be put to storage
C TOSTOR   : actual amount of QTIAO put into storage (QTO=QTIAO-TOSTOR)
C OUTSTOR  : amount of water taken from storage (QTO=QTIAO+OUTSTOR)
C W        : weight factor used to determine how much flow to put into
C            storage or to how much should be taken from storage
C
C Three different flow cases occur and these are analyzed for different
C possible states of storage.
C
C CASE 1 : QTIAO < QTOMIN
C      a : if sufficient storage is available it is used to make QTO=QTOMIN
C      b : if INSTOR>0 but insufficient to make QTO=QTOMIN then storage
C          is depleted and QTO<QTOMIN
C      c : if INSTOR=0 and QTIAO>0 then QTO=QTIAO
C      d : if QTO<0 despite use of storage, then storage below 711' is used
C          to make QTO=0.5*QTOMIN which then results in a negative value
C          being obtained for INSTOR
C
C CASE 2 : QTOMIN < QTIAO < QTOMAX
C      a : if INSTOR<0 then all excess QTIAO over QTOMIN put to storage
C      b : if 0<INSTOR<MAXSTORC then a portion of the excess goes to storage,
C          the larger the deficit, the more excess is put to storage (note
C          that this may not apply in some months, see SUBROUTINE CALCFLOW)
C      c : if MAXSTORC<INSTOR<MAXSTORA then a portion of the excess storage
C          is released, the larger the excess the larger the release, in this
C          case QTO can not exceed QTOMAX (again this may not apply in some
C          months, see SUBROUTINE CALCFLOW)
C
C CASE 3 : QTIAO > QTOMAX
C          excess QTIAO is put into storage until INSTOR=MAXSTORA, when
C          storage is at maximum capacity, then excess QTIAO allowed to be
C          released and then QTO>QTOMAX
C
C**************************************************************************
      PROGRAM CALCQTO

      INTEGER     SIM, SEQ, YR, MON, SET
      INTEGER     SKIPS, I, X
      REAL        QBSUM(12), QC(12), QTIAO(12), QTO(12)
      REAL        INSTOR(13), STORLOW(12)
      REAL        QTOHIGH(12), QTOLOW(12), QABSLOW(12), QABSHI(12)
      CHARACTER*4 EXT(11)
      CHARACTER*4 HEADER(13)
      CHARACTER*3 FILBAS(9)

C BASE NAMES FOR INPUT FILES FROM FLOW GENERATION

      DATA  FILBAS /'s1g','s2g','s3g','s4g','s5g',
     +              's6g','s7g','s8g','s9g' /
```

```
C  EXTENSION NUMBERS FOR OUTPUT DATA FILES AND EXTENSION FOR
C  INPUT DATA FILES

      DATA  EXT /'.001','.002','.003','.004','.005',
     +         '.006','.007','.008','.009','.010','.syn'  /


C  DATA FOR PRINTING OF HEADER ABOVE EACH NEW SERIES OF FLOWS

      DATA  HEADER /' Jan',' Feb',' Mar',' Apr',' May','June',
     +         'July',' Aug',' Sep',' Oct',' Nov',' Dec','  YR' /

C  START OF MAIN PROGRAM

      OPEN(3,FILE='LWTOLOW')                !LOW QTO FLOWS IN SEQUENCES
      WRITE(3,2000) (HEADER(I),I=1,12)
      OPEN(4,FILE='LWTOHIGH')               !HIGH QTO FLOWS IN SEQUENCES
      WRITE(4,2000) (HEADER(I),I=1,12)
      OPEN(5,FILE='LOWSTORAGE')              !LOWEST STORAGE VALUES
      WRITE(5,2000) (HEADER(I),I=1,12)

      DO 60 I=1,12
       QABSLOW(I)=1000000.0               !INITIAL ABS MAX AND MIN QTO
       QABSHI(I)=-1000000.0              !VALUES OVER ALL SERIES
       STORLOW(I)=1000000.0               !INITIAL LOW STORAGES
60    CONTINUE

C  START OF MAJOR LOOP FOR THE TEN SIMULATIONS

      DO 10 SIM=1,10                     !# OF SIMULATIONS
       IF (SIM.LT.10) THEN                !OPEN INPUT SPIGOT FILES
        OPEN(1,FILE='/tmp_mnt/home/ce/u3/wil/spigot/data/'//
     +            FILBAS(SIM)//EXT(11))
       ELSE
        OPEN(1,FILE='/tmp_mnt/home/ce/u3/wil/spigot/data/s10g'
     +           //EXT(11))
       END IF
       OPEN(2,FILE='LWTO'//EXT(SIM))         !OPEN NEW QTO FILE
       SKIPS=49
       CALL READLINS(SKIPS)                 !SKIP TO QC IN SEQ=1

C  START OF LOOP FOR THE 100 SEQUENCES IN EACH SIMULATION

       DO 20 SEQ=1,100                      !# OF SEQUENCES
        WRITE(2,2100) SEQ
        WRITE(2,2200) (HEADER(I),I=1,13)
        INSTOR(12)=15168.85                 !INITIAL STORAGE AT OPTIMUM
        DO 70, I=1,12                      !RESET HI-LOW VALUES
         QTOLOW(I)=1000000.0
         QTOHIGH(I)=-1000000.0
70      CONTINUE
```

```
      IF (SEQ.GT.1) THEN
       SKIPS=32                       !SKIP TO QC IN YR=1 OF NEXT
       CALL READLINS(SKIPS)                !SEQ WHEN SEQ.GT.1
      END IF

C  START OF LOOP FOR THE 80 YEARS OF DATA IN EACH SEQUENCE

      DO 30 YR=1,80                    !# OF GENERATED YEARS
       IF (YR.GT.1) THEN
        SKIPS=31                      !SKIP TO QC NEXT YR WHEN
        CALL READLINS(SKIPS)               !YR.GT.1
       END IF
       CALL READDATA(QC)                   !READ CHURCHILL FLOWS
       SKIPS=6
       CALL READLINS(SKIPS)                !SKIP FROM QC TO QBSUM
       CALL READDATA(QBSUM)                  !READ BASIN TOTAL FLOWS
       INSTOR(0)=INSTOR(12)               !STORAGE CARRYOVER

C  START OF LOOP TO CALCULATE FLOWS FOR THE 12 MONTHS JUST READ IN
BASED
C  ON THE EQUATIONS IN THE SUBROUTINE CALCFLOW.  ALSO DETERMINE THE HIGH
C  AND LOW FLOWS FOR EACH SEQUENCE AS WELL AS THE ABSOLUTE MAX AND MIN
FLOWS
C  OVER ALL 10 SIMULATIONS.

       DO 40 MON=1,12
         QTIAO(MON)=QBSUM(MON)-QC(MON)     !TOTAL INFLOW AVAILABLE
                                   !FOR OUTFLOW
         CALL CALCFLOW(QTIAO,INSTOR,QTO,MON)
         CALL STATS(QTO,QTOLOW,QTOHIGH,QABSLOW,QABSHI,
     +                              INSTOR,STORLOW,MON)
40      CONTINUE

       WRITE(2,2300) (QTO(X),X=1,12), YR   !OUTPUT QTO RESULTS
30     CONTINUE

      SET=100*(SIM-1)+SEQ               !SEQ # 1 TO 1000
      WRITE(3,2400) SET, (QTOLOW(X),X=1,12)  !OUTPUT LOW STATS
      WRITE(4,2400) SET, (QTOHIGH(X),X=1,12) !OUTPUT HIGH STATS
20    CONTINUE

10  CONTINUE

     WRITE(3,2500) (QABSLOW(X),X=1,12)       !OUTPUT ABSLOW STATS
     WRITE(4,2500) (QABSHI(X),X=1,12)       !OUTPUT ABSHI STATS
     WRITE(5,2500) (STORLOW(X),X=1,12)       !OUTPUT LOWEST INSTORS

C  FORMAT STATEMENTS USED IN THIS PROGRAM

2000 FORMAT ('  SEQ',12A8)
2100 FORMAT ('LWTO  SEQUENCE # : ',I4)
```

```
 2200 FORMAT (12A9,A4)
 2300 FORMAT (12F9.2,I4)
 2400 FORMAT (I5,12F8.1)
 2500 FORMAT (5X,12F8.1)

      END

C ************************************************************************

C  THIS SUBROUTINE IS USED TO SKIP DOWN OVER THOSE LINES OF DATA WHICH
C  DO NOT NEED TO BE READ IN.  IN EACH CASE IT IS USED TO SKIP DOWN TO
C  THE NEXT QC VALUE EXCEPT WHEN IT IS USED SKIP FROM QC TO QBSUM WHEN
C  READING IN THE DATA FOR A SINGLE YEAR.

      SUBROUTINE READLINS(N)

      INTEGER N, X
      DO 100 X=1,N
       READ(1,*)
 100  CONTINUE
      RETURN
      END

C ************************************************************************

C  THIS SUBROUTINE READS IN THE QC AND QBSUM FLOWS FROM THE SPIGOT
C  DATA FILES.

      SUBROUTINE READDATA(FLOW)

      INTEGER      SITNUM, X
      REAL         ANN, FLOW(12)
      CHARACTER*17 SITNAM
      READ(1,3000) SITNUM, ANN, (FLOW(X),X=1,6)
      READ(1,3100) SITNAM, (FLOW(X),X=7,12)
 3000 FORMAT (I3,3X,F12.2,6F10.2)
 3100 FORMAT (1X,A17,6F10.2)
      RETURN
      END

C ************************************************************************

C  THIS SUBROUTINE COMPARES THE CALCULATED MONTHLY QTO FLOWS WITH THE
C  MAXIMUM AND MINIMUM FLOWS OBTAINED SO FAR FOR EACH SEQ AND EACH SIM.

      SUBROUTINE STATS(FLOW,LOW,HIGH,ABSLOW,ABSHI,STOR,SLOW,M)

      INTEGER  M
      REAL     FLOW(12), LOW(12), HIGH(12), ABSLOW(12), ABSHI(12)
      REAL     STOR(13), SLOW(12)
```

```
      IF    (FLOW(M).LT.LOW(M))      LOW(M)=FLOW(M)
      IF   (FLOW(M).GT.HIGH(M))    HIGH(M)=FLOW(M)
      IF (FLOW(M).LT.ABSLOW(M))  ABSLOW(M)=FLOW(M)
      IF  (FLOW(M).GT.ABSHI(M))   ABSHI(M)=FLOW(M)
      IF  (STOR(M).LT.SLOW(M))   SLOW(M)=STOR(M)
      RETURN
      END

C ********************************************************************

C THIS SUBROUTINE IS USED TO CALCULATE THE LAKE WINNIPEG TOTAL OUTFLOWS
C USING VARIOUS RELATIONSHIPS WHICH WERE DEVELOPED USING THE HISTORIC
C OUTFLOW RECORD.

      SUBROUTINE CALCFLOW(AQTIAO,AINSTOR,AQTO,M)

      INTEGER M
      REAL    AQTIAO(12), AINSTOR(13), AQTO(12)
      REAL    MAXSTORA, MAXSTORB, MAXSTORC
      REAL    DEFSTOR, POSSTOR, TOSTOR, OUTSTOR, W
      REAL    QTOMIN, QTOMAX, MAXREL

C SET CONSTANT VALUES IN MILLION CUBIC METERS BASED ON THE
C CORRESPONDING VALUES IN CMS (VAL*3600*24*31/1*10^6)

      QTOMIN=1896.04         ! 707.9   cms  MIN PREFERRED OUTFLOW
      QTOMAX=11375.16         ! 4247.5  cms  MAX PREFERRED OUTFLOW
      MAXSTORA=30337.70       ! 11326.7 cms      elev 715'
      MAXSTORB=22753.28       ! 8495.0  cms      elev 714'
      MAXSTORC=15168.85       ! 5663.4  cms      elev 713'
                    ! 0 cms represents elev 711'

C TAKE FROM STORAGE WHEN QTIAO IS LESS THAN QTO MINIMUM.  FLOW
C IS BROUGHT UP TO QTOMIN, UNLESS THE STORAGE IS ABOVE ELEV 713',
C IN WHICH CASE SOME EXTRA IS ADDED TO GET RID OF EXCESS STORAGE.
C IF QTO STILL ENDS UP BELOW ZERO, THEN STORAGE IS TAKEN BELOW THE
C 711' ELEVATION WHICH IS NOT A PHYSICAL LOWER BOUND ANYWAY.  NOTE
C THAT IN THIS CASE THE FLOW IS BROUGHT UP TO ONLY 1/2 QTOMIN IN ORDER
C TO REDUCE DEVIATIONS BELOW 711'.

      IF (AQTIAO(M).LE.QTOMIN) THEN
       IF (AINSTOR(M-1).GE.15168.85) THEN
        W=0.6-(0.3/15168.85)*(AINSTOR(M-1)-15168.85)
       ELSE
        W=0.0
       END IF
       OUTSTOR=W*(AINSTOR(M-1)-15168.85)+(QTOMIN-AQTIAO(M))

       IF ((AQTIAO(M)+OUTSTOR).GT.QTOMAX) OUTSTOR=QTOMAX-AQTIAO(M)
       IF (AINSTOR(M-1).LT.OUTSTOR)       OUTSTOR=AINSTOR(M-1)
       IF ((AQTIAO(M)+OUTSTOR).LT.0.0)    OUTSTOR=0.5*QTOMIN-AQTIAO(M)
```

```
   AQTO(M)=AQTIAO(M)+OUTSTOR
   AINSTOR(M)=AINSTOR(M-1)-OUTSTOR
  END IF

C PUT TO STORAGE WHEN QTIAO EXCEEDS MAXIMUM OUTFLOW AMOUNT
C PUT INTO STORAGE UP TO MAXIMUM STORAGE VALUE. WHEN MAXIMUM
C EXCEEDED THE EXCESS FLOW IS DUMPED

  IF (AQTIAO(M).GE.QTOMAX) THEN
   DEFSTOR=MAXSTORA-AINSTOR(M-1)
   POSSTOR=AQTIAO(M)-QTOMAX
   IF (POSSTOR.GT.DEFSTOR) THEN
    TOSTOR=DEFSTOR
   ELSE
    TOSTOR=POSSTOR
   END IF
   AQTO(M)=AQTIAO(M)-TOSTOR
   AINSTOR(M)=AINSTOR(M-1)+TOSTOR
  END IF

C ADD TO STORAGE OR TAKE FROM STORAGE WHEN QTIAO IS BETWEEN
C MAXIMUM AND MINIMUM ALLOWABLE VALUES OF QTO

  IF ((AQTIAO(M).GT.QTOMIN).AND.(AQTIAO(M).LT.QTOMAX)) THEN

C CALCULATE WEIGHTS FOR STORING WATER DURING 3 PERIODS OF THE YEAR,
C WHICH ARE MONTHS 1-3, 4-7 AND 8-12.  FOR MONTHS 1-3 WATER IS PUT TO
C STORAGE ONLY IF THE WATER SURFACE IS BELOW 713'.  FOR MONTHS 4-7
C WATER IS PUT TO STORAGE WHEN WATER SURFACE IS BELOW 714' WHILE
MONTHS
C 8-12 ARE PRECLUDED FROM PUTTING INTO STORAGE.  IF, HOWEVER, STORAGE
HAS
C BEEN BROUGHT BELOW 711' (NEGATIVE STORAGE) THEN ALL FLOW IN EXCESS OF
C QTOMIN IS PUT INTO STORAGE, REGARDLESS OF THE MONTH.

   IF (M.LE.3) THEN                    !MONTHS 1-3
    DEFSTOR=MAXSTORC-AINSTOR(M-1)
    IF (DEFSTOR.GE.(7584.43)) THEN
     W=1.0
    ELSE
     W=0.25+(0.75/7584.43)*DEFSTOR
    END IF
   ELSEIF (M.LE.7) THEN                !MONTHS 4-7
    DEFSTOR=MAXSTORB-AINSTOR(M-1)
    IF (DEFSTOR.GE.(15168.85)) THEN
     W=1.0
    ELSE
     W=0.25+(0.75/15168.85)*DEFSTOR
    END IF
   ELSE                                !MONTHS 8-12
    DEFSTOR=0.0
```

```
      END IF
      IF (AINSTOR(M-1).LT.0.0) THEN          !CHECK FOR NEGATIVE STOR.
       DEFSTOR=MAXSTORC-AINSTOR(M-1)
       W=1.0
      END IF

C  IF DEFICIT STORAGE CONDITIONS EXIST DURING MONTHS 1-8 THEN
C  WATER IS PUT TO STORAGE.  IF SURPLUS CONDITIONS EXIST, THEN
C  WATER IS RELEASED FROM STORAGE, BUT ONLY DURING MONTHS 8-12.
C  THIS SCENARIO TRANSFERS LARGER SPRING AND SUMMER FLOWS TO THE
C  WINTER PERIOD.

      IF (DEFSTOR.GT.0) THEN
       POSSTOR=W*(AQTIAO(M)-QTOMIN)
       IF (POSSTOR.LE.DEFSTOR) THEN
        TOSTOR=POSSTOR
       ELSE
        TOSTOR=DEFSTOR
       END IF
       AINSTOR(M)=AINSTOR(M-1)+TOSTOR
       AQTO(M)=AQTIAO(M)-TOSTOR
      ELSE
       MAXREL=QTOMAX-AQTIAO(M)
       IF (M.GE.8) THEN
        W=0.6-(0.3/15168.85)*(AINSTOR(M-1)-15168.85)
       ELSE
        W=0.0
       END IF
       OUTSTOR=W*(AINSTOR(M-1)-15168.85)
       IF (OUTSTOR.LT.0) THEN
        OUTSTOR=0.0
       ELSEIF (OUTSTOR.GE.MAXREL) THEN
        OUTSTOR=MAXREL
       END IF
       AQTO(M)=AQTIAO(M)+OUTSTOR
       AINSTOR(M)=AINSTOR(M-1)-OUTSTOR
      END IF
    END IF

    RETURN
    END
```

APPENDIX C

HISTORIC DROUGHT ANALYSIS RESULTS

C.1 EVENTS IN CHRONOLOGICAL ORDER

SEVERITY	AVGPWR	6MONAVG	RUN	START		END	
Mm^3	MW	MW	mon	year	mon	year	mon
3478.60	2943.96	2943.96	6	1912	1	1912	6
505.06	3200.53	3200.53	3	1912	9	1912	11
378.07	3407.51	3407.51	1	1913	5	1913	5
1.95	3227.98	3227.98	1	1913	9	1913	9
12402.99	2786.49	2778.18	7	1914	3	1914	9
12908.15	2505.05	2445.79	7	1914	12	1915	6
1223.57	3563.77	3563.77	1	1915	8	1915	8
1727.87	2655.67	2655.67	4	1916	1	1916	4
1428.01	3448.64	3448.64	1	1917	5	1917	5
1022.01	3495.22	3495.22	1	1917	7	1917	7
5174.84	2538.28	2538.28	3	1918	3	1918	5
1734.46	3042.47	3042.47	1	1918	7	1918	7
2550.45	2622.74	2622.74	2	1918	9	1918	10
18899.78	2671.79	2479.66	16	1918	12	1920	3
4643.52	3513.75	3513.75	4	1920	5	1920	8
7147.02	2569.08	2477.36	7	1920	11	1921	5
1281.81	3469.90	3469.90	1	1921	7	1921	7
2294.64	2704.63	2704.63	6	1921	11	1922	4
1772.38	3761.84	3761.84	3	1922	6	1922	8
9006.22	2509.41	2389.10	8	1922	10	1923	5
772.91	3742.31	3742.31	1	1923	7	1923	7
14474.41	2676.93	2430.49	12	1923	10	1924	9
3839.13	2336.23	2336.23	4	1924	12	1925	3
1797.63	2901.92	2901.92	1	1925	5	1925	5
432.76	3672.79	3672.79	1	1925	7	1925	7
199.26	3009.14	3009.14	1	1925	12	1925	12
11515.10	2686.48	2686.48	6	1926	3	1926	8
126.94	3054.66	3054.66	1	1927	12	1927	12
3338.76	3259.11	3259.11	2	1928	5	1928	6
56.38	3206.70	3206.70	1	1928	9	1928	9
1466.57	2810.84	2810.84	4	1928	11	1929	2
45384.05	2361.40	2031.46	20	1929	4	1930	11
17332.38	2070.43	2027.99	7	1931	1	1931	7
12922.18	2171.73	2104.59	7	1931	11	1932	5
319.72	2104.34	2104.34	1	1932	10	1932	10
2926.18	2605.98	2605.98	4	1933	2	1933	5
817.60	2422.93	2422.93	2	1933	9	1933	10
1346.38	2506.75	2506.75	2	1934	3	1934	4
223.42	2617.22	2617.22	1	1935	2	1935	2
1814.07	2813.27	2813.27	2	1935	4	1935	5
39895.14	2680.42	2103.08	27	1936	5	1938	7
123923.95	1943.14	1423.68	37	1938	9	1941	9
3581.16	2428.58	2428.58	3	1941	12	1942	2
916.73	2355.07	2355.07	1	1942	4	1942	4
7092.85	3364.25	3364.25	4	1942	6	1942	9
4016.21	2653.73	2653.73	5	1942	11	1943	3
658.63	3795.26	3795.26	2	1943	5	1943	6
16077.30	2855.85	2432.77	12	1943	9	1944	8
1265.66	2671.86	2671.86	2	1944	12	1945	1
493.25	3247.48	3247.48	1	1945	5	1945	5

545.93	3783.96	3783.96	1	1945	8	1945	8
537.91	2582.07	2582.07	1	1946	2	1946	2
3843.90	3412.12	3412.12	4	1946	5	1946	8
386.75	2961.44	2961.44	1	1946	12	1946	12
80.45	2788.69	2788.69	2	1947	3	1947	4
110.87	3058.53	3058.53	1	1947	12	1947	12
55.45	2771.38	2771.38	1	1948	3	1948	3
13789.87	2556.00	2479.47	11	1948	9	1949	7
47.42	2771.18	2771.18	1	1950	3	1950	3
30.52	3137.77	3137.77	1	1950	12	1950	12
4000.45	3805.41	3805.41	4	1952	5	1952	8
9029.38	2640.96	2555.06	8	1952	10	1953	5
603.24	3008.13	3008.13	2	1953	10	1953	11
1320.10	2859.83	2859.83	3	1954	3	1954	5
563.46	2883.48	2883.48	1	1955	10	1955	10
1191.48	2541.70	2541.70	1	1956	4	1956	4
497.72	3892.59	3892.59	1	1956	8	1956	8
2939.20	2299.49	2299.49	1	1956	10	1956	10
671.38	2659.48	2659.48	1	1957	1	1957	1
905.00	3260.19	3260.19	2	1957	4	1957	5
653.73	3965.67	3965.67	1	1957	7	1957	7
5426.64	2676.28	2676.28	2	1957	10	1957	11
13670.50	2612.15	2612.15	5	1958	2	1958	6
5221.95	2863.36	2863.36	3	1958	8	1958	10
524.49	2856.47	2856.47	1	1958	12	1958	12
3443.08	2496.95	2496.95	3	1959	2	1959	4
46223.88	2614.76	2084.02	24	1960	6	1962	5
2326.09	3010.40	3010.40	4	1962	10	1963	1
1929.96	2644.58	2644.58	1	1963	4	1963	4
1769.75	3567.16	3567.16	2	1963	8	1963	9
1532.32	2686.93	2686.93	1	1963	11	1963	11
3095.67	2622.92	2622.92	3	1964	2	1964	4
3999.34	4009.09	4009.09	3	1964	6	1964	8
1374.72	3554.89	3554.89	2	1966	9	1966	10
6672.13	3084.49	3084.49	4	1967	7	1967	10
4462.08	2986.87	2986.87	6	1968	1	1968	6
1503.11	3625.38	3625.38	1	1969	6	1969	6
197.30	2877.48	2877.48	1	1970	1	1970	1
102.99	3648.11	3648.11	1	1970	9	1970	9
1099.81	3677.61	3677.61	1	1971	8	1971	8
3734.84	3186.46	3186.46	3	1972	8	1972	10
80.17	2883.32	2883.32	1	1973	2	1973	2
12617.69	3115.28	3115.28	6	1973	4	1973	9
32026.16	2513.28	2157.28	16	1976	5	1977	8
4401.09	3997.90	3997.90	3	1978	5	1978	7
5844.31	3553.64	3553.64	6	1979	7	1979	12
178.00	2817.50	2817.50	1	1980	3	1980	3
15536.84	2804.22	2804.22	5	1980	5	1980	9
2579.50	2175.09	2175.09	1	1980	11	1980	11
32188.77	2492.96	2424.68	14	1981	3	1982	4
1205.04	3889.64	3889.64	1	1982	6	1982	6
3554.35	3512.29	3512.29	2	1982	8	1982	9
1693.03	2691.14	2691.14	1	1982	11	1982	11
468.07	2725.51	2725.51	1	1983	4	1983	4
6276.58	3152.89	3152.89	4	1983	7	1983	10
878.04	2853.18	2853.18	1	1983	12	1983	12
402.98	2763.70	2763.70	1	1984	3	1984	3
19132.08	2974.83	2832.89	9	1984	5	1985	1
469.94	2775.30	2775.30	1	1985	3	1985	3
452.85	3697.08	3697.08	1	1986	7	1986	7
1614.13	3047.98	3047.98	1	1986	9	1986	9
1501.22	2813.12	2813.12	1	1986	11	1986	11

955.29	2583.66	2583.66	1	1987	1	1987	1
98110.00	2393.60	1801.11	36	1987	5	1990	4

C.2 EVENTS SORTED BY SEVERITY

SEVERITY	RUN	MAGNITUDE	MEANPOWER	LOWSIX	EXCEED----PROBS	
Mm^3	mo	S/R	MW	MW	HIST	SYNTH
2.0	1	2.0	3228.0	3228.0	0.9913043	0.9990050
30.5	1	30.5	3137.8	3137.8	0.9826087	0.9850720
47.4	1	47.4	2771.2	2771.2	0.9739130	0.9768400
55.5	1	55.5	2771.4	2771.4	0.9652174	0.9729050
56.4	1	56.4	3206.7	3206.7	0.9565217	0.9723480
80.2	1	80.2	2883.3	2883.3	0.9478261	0.9608570
80.4	2	40.2	2788.7	2788.7	0.9391304	0.9607350
103.0	1	103.0	3648.1	3648.1	0.9304348	0.9499390
110.9	1	110.9	3058.5	3058.5	0.9217391	0.9464270
126.9	1	126.9	3054.7	3054.7	0.9130435	0.9387140
178.0	1	178.0	2817.5	2817.5	0.9043478	0.9156000
197.3	1	197.3	2877.5	2877.5	0.8956522	0.9063300
199.3	1	199.3	3009.1	3009.1	0.8869565	0.9054860
223.4	1	223.4	2617.2	2617.2	0.8782609	0.8948920
319.7	1	319.7	2104.3	2104.3	0.8695652	0.8547320
378.1	1	378.1	3407.5	3407.5	0.8608696	0.8319670
386.8	1	386.8	2961.4	2961.4	0.8521739	0.8288000
403.0	1	403.0	2763.7	2763.7	0.8434783	0.8225780
432.8	1	432.8	3672.8	3672.8	0.8347826	0.8120660
452.9	1	452.9	3697.1	3697.1	0.8260869	0.8049625
468.1	1	468.1	2725.5	2725.5	0.8173913	0.7992570
469.9	1	469.9	2775.3	2775.3	0.8086957	0.7986140
493.2	1	493.2	3247.5	3247.5	0.8000000	0.7904750
497.7	1	497.7	3892.6	3892.6	0.7913043	0.7889720
505.1	3	168.4	3200.5	3200.5	0.7826087	0.7863360
524.5	1	524.5	2856.5	2856.5	0.7739130	0.7792390
537.9	1	537.9	2582.1	2582.1	0.7652174	0.7747010
545.9	1	545.9	3784.0	3784.0	0.7565218	0.7721330
563.5	1	563.5	2883.5	2883.5	0.7478261	0.7666160
603.2	2	301.6	3008.1	3008.1	0.7391304	0.7543440
653.7	1	653.7	3965.7	3965.7	0.7304348	0.7391030
658.6	2	329.3	3795.3	3795.3	0.7217391	0.7377230
671.4	1	671.4	2659.5	2659.5	0.7130435	0.7340380
772.9	1	772.9	3742.3	3742.3	0.7043478	0.7052410
817.6	2	408.8	2422.9	2422.9	0.6956522	0.6930700
878.0	1	878.0	2853.2	2853.2	0.6869565	0.6777040
905.0	2	452.5	3260.2	3260.2	0.6782609	0.6709100
916.7	1	916.7	2355.1	2355.1	0.6695652	0.6679630
955.3	1	955.3	2583.7	2583.7	0.6608695	0.6584990
1022.0	1	1022.0	3495.2	3495.2	0.6521739	0.6438010
1099.8	1	1099.8	3677.6	3677.6	0.6434783	0.6269510
1191.5	1	1191.5	2541.7	2541.7	0.6347826	0.6083780
1205.0	1	1205.0	3889.6	3889.6	0.6260870	0.6054340
1223.6	1	1223.6	3563.8	3563.8	0.6173913	0.6017670
1265.7	2	632.8	2671.9	2671.9	0.6086956	0.5940960
1281.8	1	1281.8	3469.9	3469.9	0.6000000	0.5913310
1320.1	3	440.0	2859.8	2859.8	0.5913044	0.5843300
1346.4	2	673.2	2506.8	2506.8	0.5826087	0.5794580
1374.7	2	687.4	3554.9	3554.9	0.5739130	0.5746510
1428.0	1	1428.0	3448.6	3448.6	0.5652174	0.5658510
1466.6	4	366.6	2810.8	2810.8	0.5565217	0.5599570
1501.2	1	1501.2	2813.1	2813.1	0.5478261	0.5543420
1503.1	1	1503.1	3625.4	3625.4	0.5391304	0.5541337

1532.3	1	1532.3	2686.9	2686.9	0.5304348	0.5497519
1614.1	1	1614.1	3048.0	3048.0	0.5217391	0.5383930
1693.0	1	1693.0	2691.1	2691.1	0.5130435	0.5278830
1727.9	4	432.0	2655.7	2655.7	0.5043478	0.5235485
1734.5	1	1734.5	3042.5	3042.5	0.4956522	0.5225960
1769.8	2	884.9	3567.2	3567.2	0.4869565	0.5180175
1772.4	3	590.8	3761.8	3761.8	0.4782609	0.5176680
1797.6	1	1797.6	2901.9	2901.9	0.4695652	0.5146830
1814.1	2	907.0	2813.3	2813.3	0.4608696	0.5124770
1930.0	1	1930.0	2644.6	2644.6	0.4521739	0.4987960
2294.6	6	382.4	2704.6	2704.6	0.4434783	0.4599820
2326.1	4	581.5	3010.4	3010.4	0.4347826	0.4571297
2550.4	2	1275.2	2622.7	2622.7	0.4260870	0.4372700
2579.5	1	2579.5	2175.1	2175.1	0.4173913	0.4349300
2926.2	4	731.5	2606.0	2606.0	0.4086956	0.4080980
2939.2	1	2939.2	2299.5	2299.5	0.4000000	0.4072975
3095.7	3	1031.9	2622.9	2622.9	0.3913043	0.3969018
3338.8	2	1669.4	3259.1	3259.1	0.3826087	0.3812260
3443.1	3	1147.7	2496.9	2496.9	0.3739130	0.3752945
3478.6	6	579.8	2944.0	2944.0	0.3652174	0.3735000
3554.4	2	1777.2	3512.3	3512.3	0.3565217	0.3691764
3581.2	3	1193.7	2428.6	2428.6	0.3478261	0.3676953
3734.8	3	1244.9	3186.5	3186.5	0.3391304	0.3595170
3839.1	4	959.8	2336.2	2336.2	0.3304348	0.3544315
3843.9	4	961.0	3412.1	3412.1	0.3217391	0.3542433
3999.3	3	1333.1	4009.1	4009.1	0.3130435	0.3469910
4000.4	4	1000.1	3805.4	3805.4	0.3043478	0.3469662
4016.2	5	803.2	2653.7	2653.7	0.2956522	0.3463110
4401.1	3	1467.0	3997.9	3997.9	0.2869565	0.3292595
4462.1	6	743.7	2986.9	2986.9	0.2782609	0.3264500
4643.5	4	1160.9	3513.8	3513.8	0.2695652	0.3195238
5174.8	3	1724.9	2538.3	2538.3	0.2608696	0.3010580
5222.0	3	1740.7	2863.4	2863.4	0.2521739	0.2993097
5426.6	2	2713.3	2676.3	2676.3	0.2434783	0.2926615
5844.3	6	974.0	3553.6	3553.6	0.2347826	0.2801010
6276.6	4	1569.1	3152.9	3152.9	0.2260870	0.2679500
6672.1	4	1668.0	3084.5	3084.5	0.2173913	0.2575400
7092.9	4	1773.2	3364.2	3364.2	0.2086957	0.2477683
7147.0	7	1021.0	2569.1	2477.4	0.2000000	0.2465842
9006.2	8	1125.8	2509.4	2389.1	0.1913043	0.2097930
9029.4	8	1128.7	2641.0	2555.1	0.1826087	0.2094258
11515.1	6	1919.2	2686.5	2686.5	0.1739130	0.1728985
12403.0	7	1771.9	2786.5	2778.2	0.1652174	0.1620499
12617.7	6	2102.9	3115.3	3115.3	0.1565217	0.1594916
12908.2	7	1844.0	2505.1	2445.8	0.1478261	0.1562672
12922.2	7	1846.0	2171.7	2104.6	0.1391304	0.1561393
13670.5	5	2734.1	2612.1	2612.1	0.1304348	0.1476713
13789.9	11	1253.6	2556.0	2479.5	0.1217391	0.1461885
14474.4	12	1206.2	2676.9	2430.5	0.1130435	0.1395637
15536.8	5	3107.4	2804.2	2804.2	0.1043478	0.1295293
16077.3	12	1339.8	2855.9	2432.8	0.0956522	0.1247962
17332.4	7	2476.1	2070.4	2028.0	0.0869565	0.1148927
18899.8	16	1181.2	2671.8	2479.7	0.0782609	0.1040667
19132.1	9	2125.8	2974.8	2832.9	0.0695652	0.1023928
32026.2	16	2001.6	2513.3	2157.3	0.0608696	0.0489387
32188.8	14	2299.2	2493.0	2424.7	0.0521739	0.0484726
39895.1	27	1477.6	2680.4	2103.1	0.0434783	0.0333169
45384.1	20	2269.2	2361.4	2031.5	0.0347826	0.0264300
46223.9	24	1926.0	2614.8	2084.0	0.0260870	0.0255630
98110.0	36	2725.3	2393.6	1801.1	0.0173913	0.0041273
123924.0	37	3349.3	1943.1	1423.7	0.0086957	0.0018841