

Reliability Studies of Multi-Reservoir System Using Stochastic Approach

by

Jamaldeen M. Esuf Lebbe

A Thesis Presented to the

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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King Fahd University of Petroleum and Minerals (Saudi Arabia), 1991

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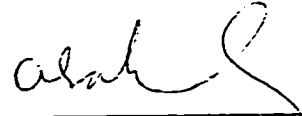
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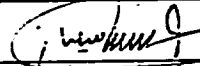
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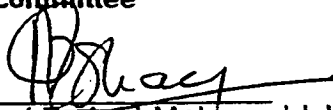


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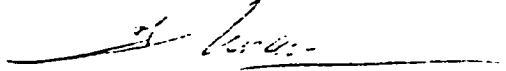


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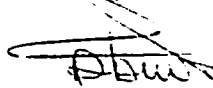
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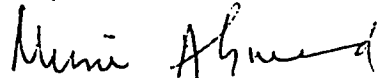
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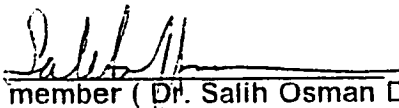
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*This thesis is
dedicated to
my son Anan*

Table of Contents

List of Tables.	i
List of Figures.	iii
Abstract (English)	v
Abstract (Arabic)	vi
CHAPTER 1	1
Introduction and Scope of Research.	1
1.1 Introduction.	1
1.2 Scope of Research.	6
CHAPTER 2	7
Literature Survey.	7
2.1 Introduction.	7
2.2 Stochastic Streamflow Models.	9
CHAPTER 3	13
Theoretical Consideration.	13
3.1 Introduction.	13
3.2 Steps to Choose a Model.	15
3.2.1 Evaluation of Statistics.	15
3.2.2 Time Series and Randomn Numbers.	17
3.2.3 Choosing a Model.	18
3.3 Operation Study.	20
3.3.1 Sequent Peak Algorithm.	20
3.3.2 Ripple Mass Curve Analysis.	22
3.3.3 Flow Generation.	25

3.4 Reliability Studies.	27
3.5 Gumbel Extreme Value Distribution.	30
CHAPTER 4	34
Data Analysis and Methodology.	34
4.1 Data Acquisition.	34
4.1.1 Historical Monthly Flow Data.	34
4.1.2 Key Maps of River Basins.	35
4.1.3 Reservoir Configuration and Power Flow Data.	35
4.2 Model Development.	35
4.3 Data Analysis.	40
CHAPTER 5	58
Analysis of Results	58
5.1 Results of Operation Studies.	59
5.2 Results of Reliability Studies.	60
CHAPTER 6	69
Conclusions and Recommendations	69
References.	71
Appendix 1	74
Appendix 2.	81

List of Tables

Table	page
4.1 Required data for power calculation.	38
4.2 Chi square test for the historical data of Kotmale reservoir.	41
4.3 Chi square test for the historical data of Victoria reservoir.	42
4.4 Chi square test for the historical data of Randenigale reservoir.	43
4.5 Chi square test for the historical data of Rantembe reservoir.	44
4.6 Chi square test for the historical data of Bowatenne reservoir.	45
4.7 Statistics of historical and synthetic flow data of Kotmale reservoir.	52
4.8 Statistics of historical and synthetic flow data of Victoria reservoir.	53
4.9 Statistics of historical and synthetic flow data of Randenigale reservoir.	54
4.10 Statistics of historical and synthetic flow data of Rantembe reservoir.	55
4.11 Statistics of historical and synthetic flow data of Bowatenne reservoir.	56
5.1 Final releases, at the probability level of 42.92 percent (mean), from all reservoirs after simulation. (Values are given in MCM)	63
5.2 Final releases, at the probability level of 99.00 percent from all reservoirs after simulation. (Values are given in MCM)	64
5.3 Total power that can be generated from all hydropower stations in Mahawli scheme at the probability level of 42.92 percent	65

Table

page

5.4	Total power that can be generated from all hydropower stations in Mahawli scheme at the probability level of 99.00 percent.	66
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List of Figures

Figure	page
1.1 River basin map of Sri Lanka.	4
1.2 Reservoir location map and schematic diagram.	5
3.1 Illustration of the sequent-peak algorithm.	21
3.2 Use of mass curve to determine the reservoir capacity to meet a given demand (From Water Resources Engineering Ray K.Linsley and Joseph B. Franzini).	23
3.3: Use of mass curve to determine the possible demand from a reservoir of specified capacity (From Water Resources Engineering Ray K. Linsley and Joseph B. Franzini).	24
3.4a: Influence of the number of traces used to define the distribution of storage (From Use of Stochastic Hydrology to Determine Storage Requirements for Reservoirs Stephen J. Burges.)	26
3.4: Illustration of Reliability curve (From Water Resources Engineering Ray K. Linsley and Joseph B. Franzini).	29
4.1: Flow chart of the program developed for the study.	37
4.2: Lognormally fitted frequency histogram for Kotmale reservoir.	46

Figure	page
4.3: Lognormally fitted frequency histogram for Victoria reservoir.	47
4.4: Lognormally fitted frequency histogram for Randenigale reservoir.	48
4.5: Lognormally fitted frequency histogram for Rantembe reservoir.	49
4.6: Lognormally fitted frequency histogram for Bowatenne reservoir.	50
5.1: Reliability Curve of Kotmale reservoir.	61
5.2: Comparision of total power requirement and the power can be generated from Mahaweli scheme for each month at the probability level of 42.92 percent and 99 percent (Giga Watt Hour).	67

ABSTRACT

This study has been conducted as an initial attempt to find the maximum releases from a multi-reservoir system and to come up with an operating policy. In this case study, streamflow records at a multi-reservoir system (5 reservoirs) in Sri Lanka was considered. Thirty six years of flow data at the reservoir sites were analyzed statistically and 700 traces for each reservoir were generated stochastically, and maximum releases for each month were determined knowing reservoir capacities. Fitting an extreme value distribution to these releases, a reliability curve was obtained. These releases have been used to compute the hydroelectric power that can be generated from the reservoir system. This has been compared with the total power requirement of Sri Lanka considering the benefit of the hydroelectric power generation only. It was found that 52 percent and 55 percent of the total power requirement of Sri Lanka can be met if the releases considered to be at the probability levels of 99 percent and 42.92 percent (mean) respectively.

خلاصة

لقد اجريت هذه الدراسة كمحاولة ابتدائية لايجاد التسرب الأولى الأعظمي من مجموعة خزانات واستخلاص سياسة تشغيلية . في هذا البحث تم دراسة نظام خزانات (خمسة خزانات) في سريلانكا .

لقد تمت دراسة احصائية لمعلومات مدتها ٢٦ سنة وتم عمل ٧٠٠ تتابع ودراستها بالطريقة الستوكاستيكية . وتم حساب التسرب الأعظمي لكل شهر وذلك بعد معرفة سعة الخزانات ، ولقد تم الحصول على منحنيات وثوق وذلك باستعمال القيم العظمي . ثم استعملت هذه القيم لحساب الطاقة الكهرومائية التي يمكن استخراجها من الخزانات وقد تم مقارنة هذا باحتياجات دولة سريلانكا من الطاقة . وبالأخذ بعين الاعتبار فائدة الطاقة فقد وجد أن ٥٢٪ و ٥٥٪ من احتياجات سريلانكا من الطاقة يمكن توفيرها إذا كان التسرب قد حسب على احتمالي ٩٩٪ و ٤٢,٩٢٪ (معدلاً) وذلك على التتابع .

CHAPTER 1

INTRODUCTION AND SCOPE OF RESEARCH

1.1 Introduction

Stochastic science is defined as the art of estimating the probability of things so that in our judgement and actions, we may choose to follow the best, the safest, the surest, or the most soul-searching way. Unfortunately, hydrology is unable to provide either the exact probability distribution of flows or long records of past flows. Existing streamflow records are usually not sufficiently extensive enough to provide estimates of future behavior of streamflows. Strict use of historical record alone in operational study involves several potentially serious problems. One answer to this problem is to generate possible (but not observed) long historical records that may be used to determine several quantities of interest within defined statistical errors. Such streamflows can be generated or synthesized using stochastic streamflow models.

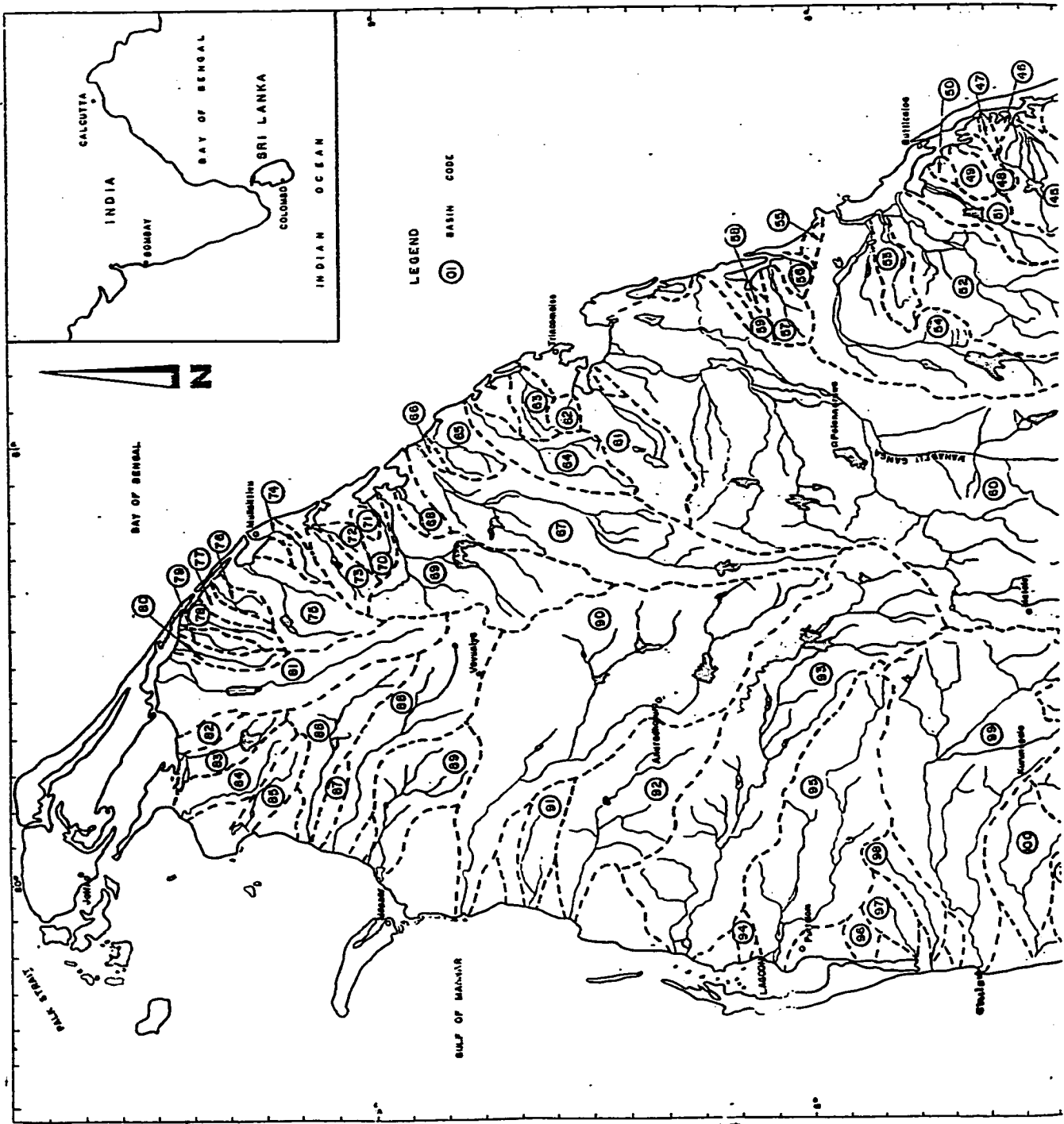
Stochastic hydrology is meaningful only in a design or operational decision making sense. Stochastic methods were first introduced into

hydrology to cope with the problem of reservoir design. But no studies have been conducted to maximize the release from an existing reservoir where operational policy have been changed because of the increase in demands. This is precisely the problem facing the operators of a recently constructed reservoir system (Mahaweli) in Sri Lanka. This reservoir problem in Sri Lanka seems to be an ideal candidate for the analysis mentioned earlier. The historical data required for such an analysis was available in Sri Lanka.

Sri Lanka is a tropical island with a land mass of 25,332 square miles (6 1/2 million hectares), situated in the Indian Ocean, latitude between 6 degree and 10 degree north and longitude between 80 degree and 81 degree east. The island is subjected to two monsoons; the South-West monsoon prevailing from about April to September and the North-East monsoon from October to March. On the basis of distribution of rainfall, the island is divided into two distinct areas; the wet and dry zones. The wet zone comprises of the South-West area, covering about a quarter of the island, extending southwards from Chilaw and terminating with Kandy and Nuwara-Eliya in the east. The area of the wet zone is about 4 million acres. The wet zone, with its two rainy seasons and an annual average rainfall of 95 inches, is well developed with economic crops such as tea, rubber, coconut etc.. The present economy of the country largely depends on the development of the wet zone. The rest of the island consists of its dry zone. Dry zone comprising of over 12 million acres, has only one rainy season, from about October to March, and the average annual precipitation is about 57 inches. The dry zone area is arid and dry, and well suited for irrigated agriculture.

The only source of water in Sri Lanka is direct rainfall. The amount of rainfall varies from place to place. The island is served with a network of rain gauge stations, some of which have been in operation for over a hundred years. The most important stations are equipped with automatic recorders. Today there are over 600 rain gauge stations established all over the island. Runoff from the rivers of Sri Lanka, varies very widely from stream to stream due to variation in rainfall, type of soil, its slope and other factors[1].

For the purpose of assessing the yield from river basins, stream gauging stations have been established to measure the flow of most of the important rivers of Sri Lanka. The territory of Sri Lanka has been divided into 103 natural river basins. The river basin map of Sri Lanka is given in Figure (1.1). Among these river basins, Mahaweli basin is the largest, and covers nearly one sixth of the area of the island. Its length is 207 miles. It has its sources in the central highlands and drops nearly 8000 ft to flow into sea at south of Trincomalee in the eastern province. At present, the Mahaweli scheme contains five major reservoirs and six hydroelectric power stations. Figure (1.2) shows their location map and the schematic diagram in detail. Since this is the largest irrigation scheme in the island and major source of hydroelectric power, reliability studies of these reservoirs be all important in arriving at proper operational rules of these reservoirs.



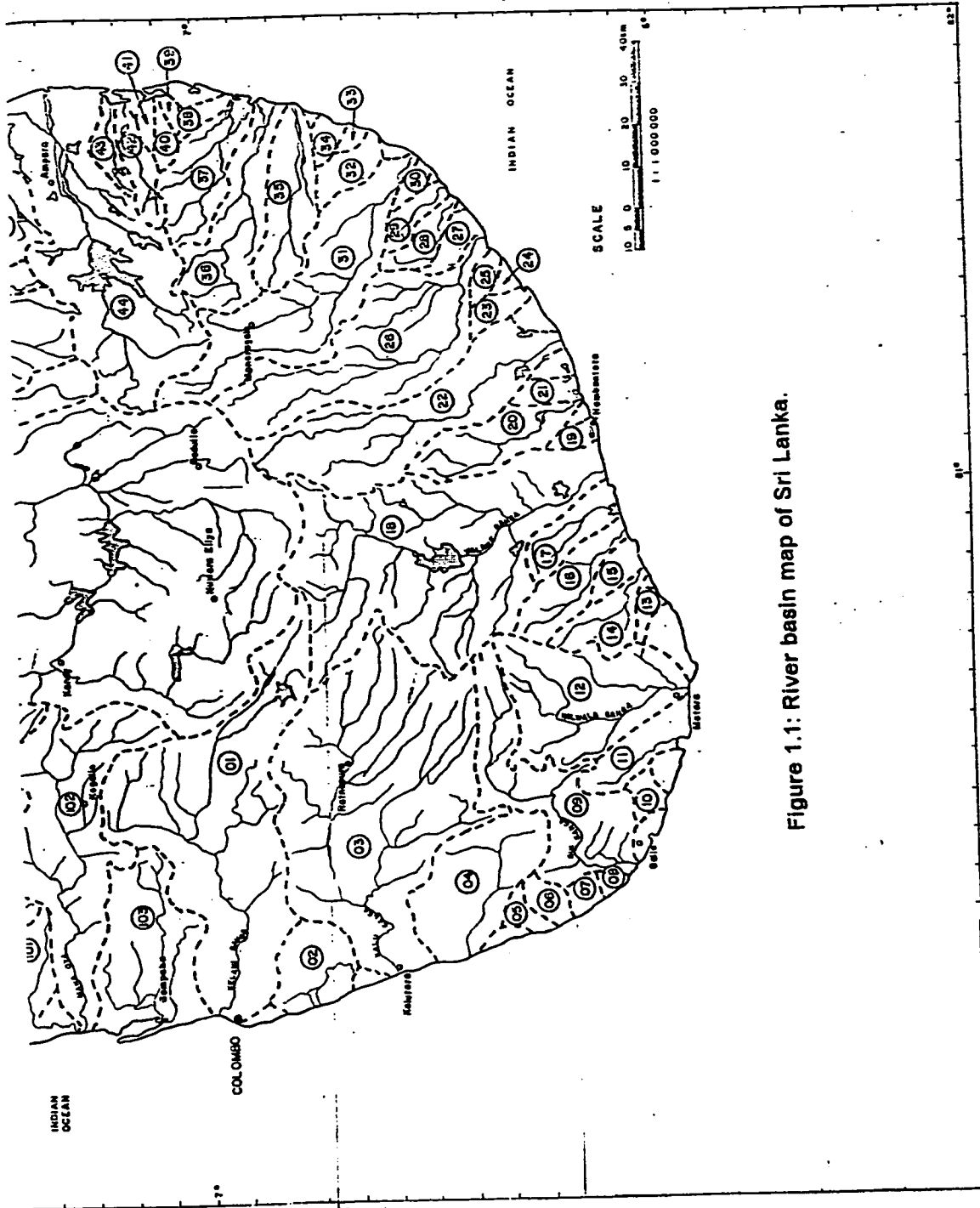


Figure 1.1: River basin map of Sri Lanka.

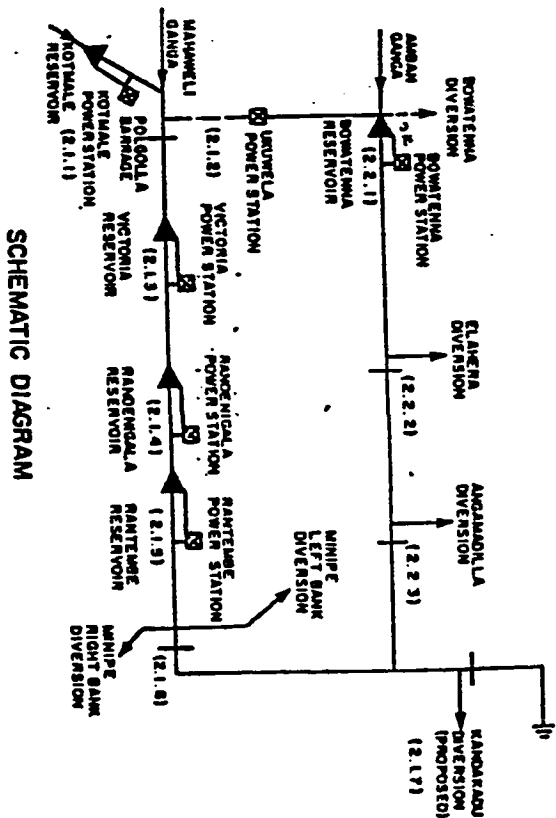
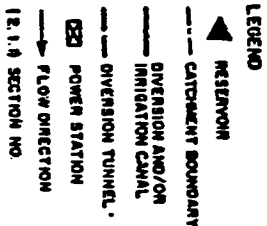
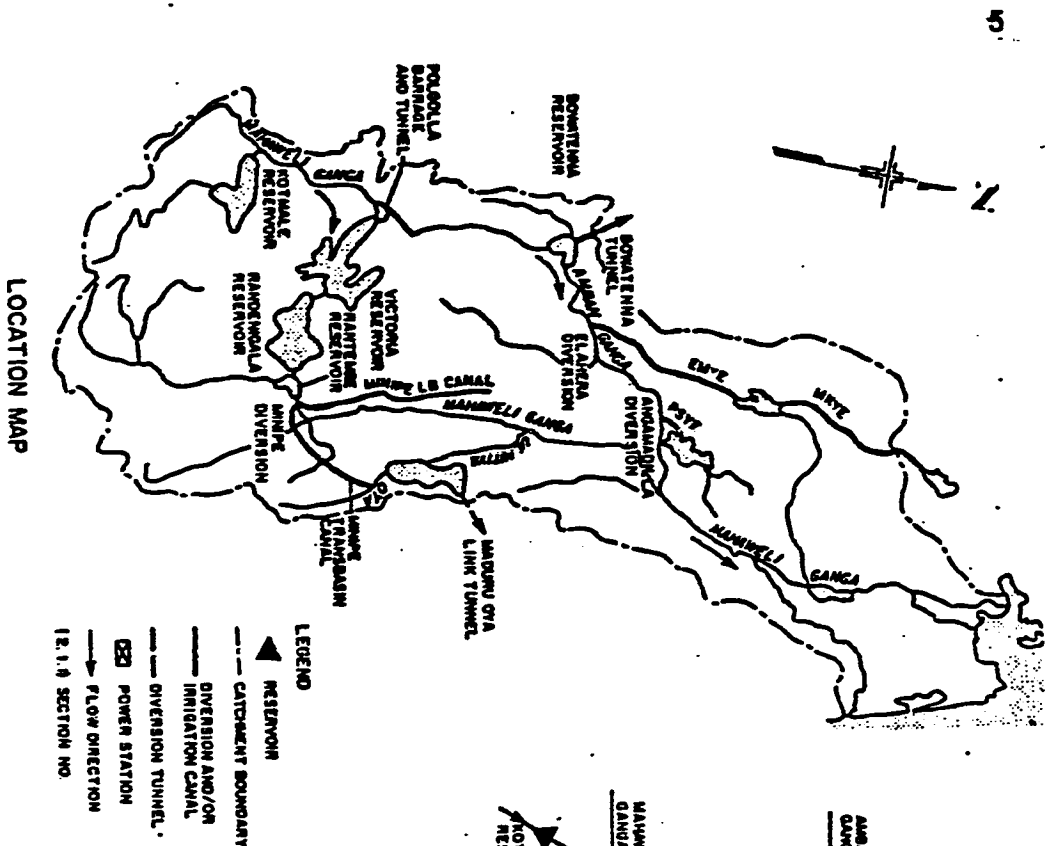


Figure 12: Reservoir location map and Schematic diagram.

1.2 Scope of Research

This study is an attempt to find the maximum monthly releases with given reliability from an existing reservoir system where the hydroelectric power generation and irrigation supply are maximized. Finding the monthly constant releases from a reservoir will be of great help for the water management personnel to plan entire activities in advance. Recent studies show that using historical records of flow alone to find releases from a reservoir gives erroneous results. To overcome this problem, stochastic technique is used to generate thousands of synthetic traces. Lognormal Markov's monthly flow model [2] is employed for this purpose. The generated traces, from this model, are used in Sequent Peak Algorithm to find the releases. Reliability studies are conducted for these releases from each trace in order to make sure the certainty of the release.

Chapter 2 reviews the literature in the field of stochastic hydrology and other relative topics which includes stochastic streamflow models, and reliability studies.

Chapter 3 describes the theoretical consideration of this study, while Chapter 4 considers data analysis in which data acquisition and data distribution are considered.

Chapter 5 examines the results of this study and Chapter 6 gives the conclusions and recommendations.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Importance of reservoir reliability studies has been realized long time before. Introduction of probability theory to this field opened the way to determine the reliability of a reservoir to meet a certain demand or to determine the reliability of releases (demands) that can be met from a fixed finite storage capacity. Information on the reliability of the release from a storage reservoir is of crucial importance where operating policy is not known. This chapter summarizes the investigations carried out in the field of reservoir reliability studies.

Prior to the introduction of stochastic streamflow models (SSM) for this analysis mass curve technique (introduced by Ripple 1883) or sequent-peak algorithm (by Thomas and Burden 1963) flow were used. Thus, until the advent of the field of stochastic hydrology, determination of the reservoir design capacity of the release from a storage reservoir seemed simple: one just determined the minimum storage that would have been required over the

N-year historical period to provide the target yield or vice versa with absolutely no water storage. Fiering [6] documents the following three principal shortcomings of the strict use of historical records.

- 1. The analysis is based on solely on the historical records, and it is unlikely that the same flow sequence will recur during the active life of the complete structure.**
- 2. The mass diagram (based solely upon the historical flow sequence) do not help the designer to establish or complete the risk to be taken with regard to water shortage during periods of low flow.**
- 3. The length of the historical record is likely to differ from the economic life of the proposed structure.**

Stochastic streamflow models provide the answers that can be used to circumvent shortcomings of the strict use of the historical record alone. It also can provide estimates of reliability in the face of the rising demands for water [7]. It can be used to provide estimates of expectation and variance of project net benefits, which is an important information for an economic or decision theoretical analysis of storage-water-yield problems. There is almost no case study literature available in the field of demand calculation from a known reservoir capacity using stochastic technique. This proposed study clarifies the possibility of demand calculation from a known reservoir

capacity. This survey will cover stochastic streamflow models, reliability studies of release from a storage reservoir and sequent-peak algorithm.

2.2 Stochastic Streamflow Models

Stochastic monthly streamflow models are often used in simulation studies to evaluate the likely future performance of water resource systems. Stochastic hydrology took several steps before reaching presently available sophisticated models.

The work of Fiering [5] was a useful starting point for techniques applying autoregression studies to the problem of storage. This approach was considered to be best for economic studies of reservoirs.

Lloyd [13] gave a relatively complete summary of the state of art of stochastic reservoir theory. It was unfortunately long and often the principles involved were not obvious. All the work described depended on Markovian storage relationship and relatively simple releases. Then the basic Markov model was extended to the case of seasonal inputs after Lloyd [14]. He next summarized correlated inflows and as a logical extension summarized correlated seasons. Time dependent results and the effects of initial storage conditions were examined in Lloyd's summary. White [23] surveyed the stochastic aspects of reservoir storage. He advocated use of Markovian methods and pointed to the erroneous results involved in reservoir capacity

determination. He, however, showed that the method described by Hazen (1914) gave reasonably acceptable results, when compared with Markovian studies, provided the probability of emptying is low. But he did not define reservoir failure and the reservoir problem involved.

Klemes [9] developed a technique for computing certainty distribution for specified reservoir life for random input and uniform or random reservoir draft. Later Klemes [10], he extended his study to examine variability of a storage reservoir having seasonal input.

Burges [2] did a critical analysis on the use of stochastic hydrology to determine storage requirements for reservoirs. In this study, normally distributed Markov model was used to generate monthly and annual flows. It has been shown most storage cases satisfied the basic extreme value (Type I) distribution when mathematically correlated input parameters were used. But for the case when the generator coefficient of variation and the demand are small, eye fitting gave a better fit.

Hoshi and Burges [8] used annual streamflow volumes, modeled by Autoregressive(AR(1)) and Autoregressive Moving Average (ARMA (1,1)) process to study the impact of seasonal flow characteristics and demand patterns for one required reservoir storage. They pointed out that incorporation of the long term persistence into an annually generated flows by using ARMA(1,1) model with Hurst coefficient 0.7 did not significantly

influence storage requirements. They concluded that AR(1) is quite suitable for practical application. Procedures for its use for the multi-site case are given in Hoshi and Burges [8].

Hirsch [7] used six synthetic models in the study of water supply reliability and pointed out that a new type of auto-regressive-moving-average model was operationally superior to an autoregressive model.

Stedinger and Taylor [16,17] studied the performance of a wide range of monthly streamflow models and compared using data for the Upper Delaware River basin in New York state. It was shown that Thomas-Fierring monthly autoregressive Markov model and the AR(1) annual flow model with disaggregation to obtain monthly flow showed better behavior than other models. Furthermore, among these two models Thomas-Fierring Markov monthly models showed better behavior than AR(1) model.

Stedinger, Cohn and Pei [18] developed a condensed version of Valencia-Schaake disaggregation model which describes the distribution of monthly streamflow sequences using a set of coupled univariate regression models rather than a multivariate time series formulation. They concluded that condensed disaggregation model is attractive because it has fewer parameters but can still reproduce the mean, variance and period-to-period correlations of the individual flows while approximately preserving the relationship among the monthly and annual flow values. But they failed to

state that how accurate the reproduction of the mean, variance and correlations.

Vogel and Stadinger [20] have illustrated the study of the value of stochastic streamflow models in overyear reservoir design applications that fitting an AR(1) lognormal model leads to more precise estimate of annual storage requirements than if only the historical flows are employed, even in situation when the flows were not generated with an AR(1) lognormal model.

CHAPTER 3

THEORETICAL CONSIDERATIONS

3.1 Introduction

An important tool in water resource system planning is synthetic streamflows, which allows the planner to evaluate proposed system designs more thoroughly and in a more statistically sophisticated manner than was possible with previously available methods. Synthetic streamflows and operational hydrology together open the way to add to the planning process, the capacity for increased scope and sensitivity of evaluations.

In fact past civil engineers knew that the flow pattern varies considerably from stream to stream and historical record provides a very valuable clue to the future behavior of the stream. They used Ripple mass curve analysis to investigate the storage capacity using historical records. Similarly a historical record for a stream had been used to examine the aspects of following patterns and design appropriateness. Such use of the historical record alone however, involves the following serious problems.

- 1. Any historical record of flows for any given stream is quite short because exact pattern of flows during the historical period is extremely**

unlikely to recur during that period in which the proposed system would be operative. Furthermore, characteristics of the recorded flows are not at all likely to be maintained during the economic life of the system. In all cases planners would certainly agree that the worst flood (or drought) on record is not the worst possible flood (or drought). Also, the historical record may not be long enough to provide the planner with as much data as he needs.

2. An important fact is that in eventually proposed designs this use of the historical record alone gives no idea of the risks involved[6].

In order to overcome these problems engineers use operational hydrology to estimate expected frequency and severity of failures. But hydrology is unable to provide either the exact probability distribution of flows or long records of past flows to engineers to conduct operational studies. Therefore, hydrologists had to devise some models that should be sufficiently realistic while at the same time improve the planning significantly. Early attempts were made to come up with manually generated flows in hydrological studies, but the tremendous amount of calculation consumed much of their valuable time. After the invention of the modern electronic computers large scale analysis of data in hydrology became possible and helped to improve new statistical techniques which improved the synthetic streamflow models. Several sophisticated synthetic streamflow models are now in use. Some recommended models for simulation studies are:

- 1) Thomas- Fiering monthly autoregressive Markov model.

- 2) The best autoregressive moving average (ARMA) model of the deseasonalized monthly flows.
- 3) A fractional Gaussian noise (FGN) model of the deseasonalized monthly flows.
- 4) The best ARMA model of annual flows using disaggregation to obtain monthly values, and
- 5) A fractional Gaussian noise (FGN) model of annual flows using disaggregation to obtain monthly flows.

3.2 Steps to choose a model

Choosing a model for the use of operational requires several steps. First step is statistical evaluation of the historical data to select the family of distributions for the use in the flow generation. Second step is analysis of time series and random numbers. Third step is selecting a generating scheme for the synthetic flow.

3.2.1. Evaluation of the Statistics

Evaluation of the statistics of the historical record are usually carried out in the following manner. The historical record is examined to see whether they are regulated (any man made changes in the flow) or unregulated. If unregulated then flows can be synthesized as described here. If the historical flow is regulated in the past, then the unregulated portion of

historical record is taken for synthesis.

The mean of the historical flow is calculated for whatever time intervals are considered to be important (i.e. months and year). In this study monthly mean is used. The mean is defined by

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

The standard deviation of the historical flows is calculated using

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n x_i^2 - \frac{n}{n-1} \bar{x}^2. \quad (2)$$

The serial correlation coefficient is calculated by

$$\rho = \frac{\sum_{i=1}^{n-1} x_{i,j} x_{i,j-1} - n \bar{x}_j \bar{x}_{j-1}}{(n-1) s_{x_j} s_{x_{j-1}}} \quad (3)$$

Where

i = Sequence index

j = Monthly index

Next, logarithms of historical flows are calculated and the mean, standard deviation, and correlation coefficient are calculated for logarithmic values. Then normal probability paper is used to fit the historical flows. If the best fitting curve is straight line then the historical flows are said to be following a normal distribution. If the flows are not following normal distribution, then lognormal probability paper is used to fit the logarithmic values of historical flows. If the best fitting curve is straight line the flow said to be following lognormal distribution. If the flow data are not following normal or lognormal

distribution then other alternatives are possible such as gamma distribution ect. will have to be tested for.

3.2.2 Time series and Random Numbers

Whenever a sequence of values of synthetic flows for a given stream are generated, we should consider the flows to be the results of a random process. The history of the stream provides valuable information about probable future flows. Models for generations should use such information and must include random, competent to reflect our inability to predict future flow sequences exactly. A set of historical or synthetic flows for a stream is a sequence of numbers or values produced by a random process in a succession of time intervals: such a sequence is called time series. In general, the i^{th} number of a time series, which we write as x_i , is the sum of two parts:

$$x_i = d_i + e_i \quad (4)$$

Where

d_i = deterministic part

e_i = random number with certain probability distribution or pattern.

Let us consider random part of our time series. The programmer who is considering a simulation problem must have a source of random numbers.

There are several random number distributions, but in this study normally distributed random numbers with zero mean and unit standard deviation, are used. The reason why normally distributed random numbers were selected, will be explained later in this chapter.

Let us consider the second part of the time series, which is the deterministic part. This deterministic part should be devised so that the generated flows show the same characteristics as the historical flow record does. In other words, the generated flow should have the same statistical characteristics such as mean, standard deviation and serial correlations coefficient.

3.2.3. Choosing a Model

After the sample parameters of the flows are identified and the distribution is selected, the modeler must next select a generating scheme for the synthetic flows. As we saw in the previous section the form of such scheme is

$$q_i = d_i + e_i \quad (5)$$

With d_i the deterministic part and e_i the random part of the synthetic flow. After several modifications with some reasonable assumptions [2] lognormal Markov monthly synthetic flow generating scheme has taken the form of

$$q_{i,j} = \mu_j + \rho_j \frac{\sigma_j}{\sigma_{j-1}} (q_{i-1,j-1} - \mu_{j-1}) + n_i \sigma_j \sqrt{1 - \rho_j^2} \quad (6)$$

where

i = the sequence index

j = the monthly index

q = flow (log values of depth over the catchment area)

ρ_j = correlation coefficient between months j and $j-1$

n = unit normal deviate

To preserve the historical statistics of the flows rather than of their logarithms, mathematically corrected approach is used. In this approach the monthly parameters μ_j , σ_j , ρ_j (they are not population parameters) are defined as

$$\bar{X}_j = \exp\left(\mu_j + \frac{\sigma_j^2}{2}\right) \quad (7)$$

$$\sigma_{xj}^2 = \exp(2\sigma_j^2 + 2\mu_j) - \exp(\sigma_j^2 + 2\mu_j) \quad (8)$$

$$R_{0j} = \frac{\exp(\sigma_{j-1}\sigma_j\rho_j) - 1}{[\exp(\sigma_{j-1}^2) - 1]^{1/2}[\exp(\sigma_j^2) - 1]^{1/2}} \quad (9)$$

Where \bar{X}_j , σ_{xj}^2 , R_{0j} are the observed means, variance, and serial correlation for month j (R_{0j} is the correlation of month j with $j-1$)

Lognormal Markovian monthly model is selected in this study because of the following reasons.

1. Monthly flow generating scheme was needed.
2. This model can be adopted to lognormally distributed flows.
3. Latest studies show that this model leads to more precise estimates of

monthly flows by producing severe droughts than other available models [16].

3.3 Operation Study.

Operation study is nothing but means to determine required capacity for a river reservoir. In the past, operation study was used to analyze only for a selected critical period of very low flows. But now, availability of modern computers favor the use of long synthetic records. The past practice can only define the capacity required during the selected drought. In the case of synthetic data, it is possible to estimate even the reliability of reservoirs of various capacities. The most commonly used methods for this purpose are sequent-peak-algorithm and Ripple mass curve.

3.3.1 Sequent Peak Algorithm (SPA).

In the case of calculating reservoir capacity using SPA, values of the cumulative sum of inflow minus withdrawals (including average evaporation and seepage) are calculated (Figure (3.1)). The first peak (local maximum of cumulative net inflow) and the sequent peak (next following peak which is greater than the first peak) are identified. The required storage for the interval is the difference between the initial peak and the lowest trough in the interval. The procedure is repeated for all cases in the period under study

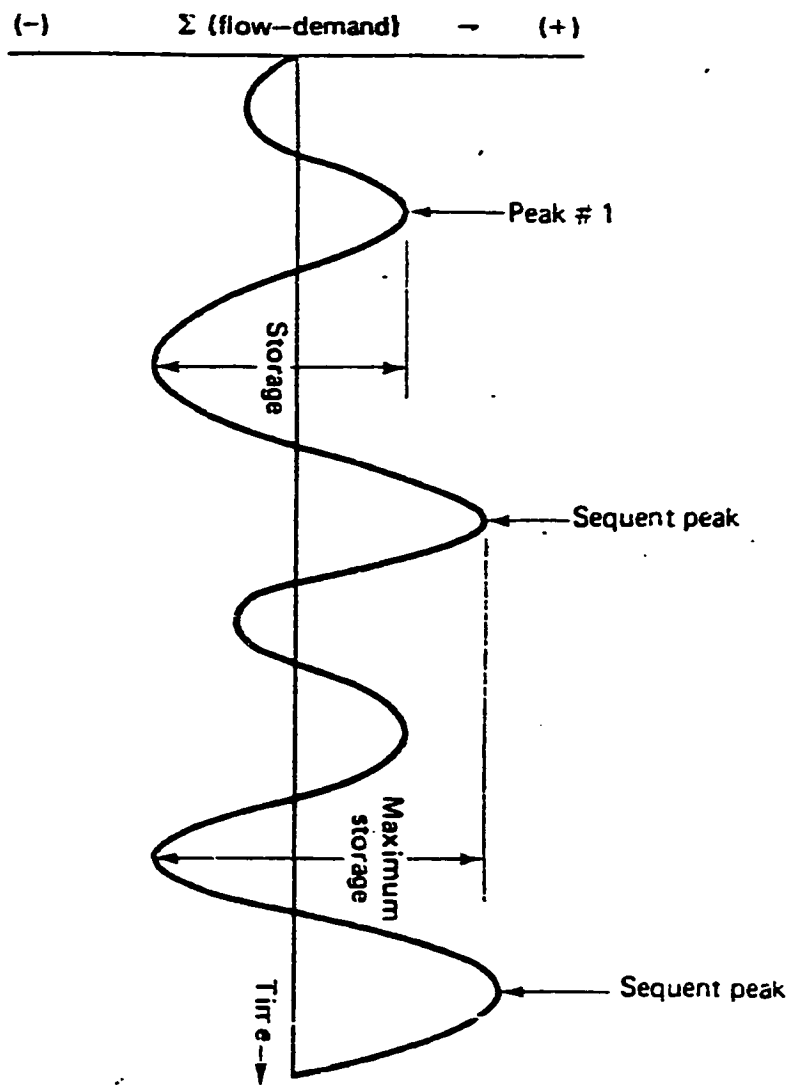


Figure 3.1: Illustration of the sequent-peak algorithm (From Water Resources Engineering Ray K.Linsey and Joseph B. Franzini).

and the largest value of required storage is determined. In the case of demand determination, with assumed initial demands the largest value of required storage is determined as mentioned above. Then, the calculated reservoir capacity and known reservoir capacity will be compared. This procedure will be repeated with iteratively changed demand until calculated reservoir and the known reservoir capacity are found to be the same. Since both capacities are the same, it can be said that the demands that satisfy the condition can be met by the reservoir under study. This procedure will be repeated for all traces and the demands obtained will be used for the reliability studies which is explained later in this chapter.

3.3.2 Ripple Mass Curve Analysis

Ripple mass curve is a cumulative plotting of net reservoir inflow. A sample plot is given in Figure (3.2). The slope of the mass curve at any time is a measure of inflow at that time. Demand curves representing uniform rate of demand are straight lines. Demand lines drawn tangent to the high points of the mass curve, (A,B) represent rates of withdrawal from the reservoir. Assuming the reservoir to be full wherever a demand line intersects the mass curve, the maximum departure between demand line and the mass curve represent the reservoir capacity required to satisfy the demand. Mass curve may also may be used to determine yield which may be expected with the given reservoir capacity Figure (3.3). In this case tangents are drawn to the high points of the mass curve (A,B) in such a manner that their maximum

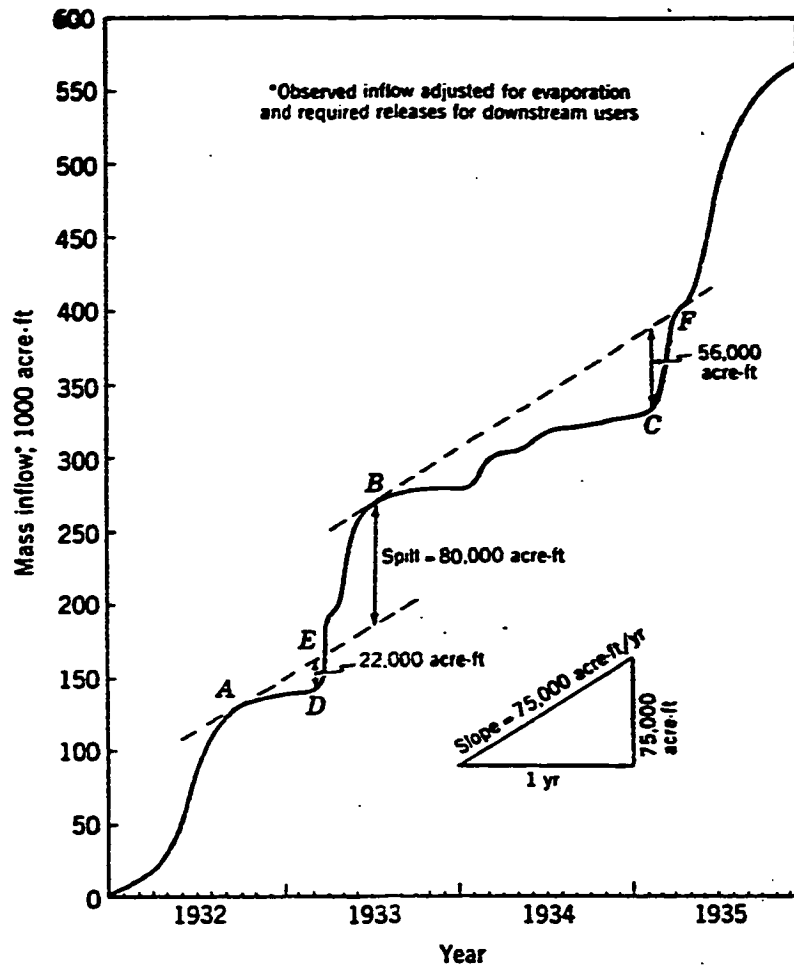


Figure 3.2: Use of mass curve to determine the reservoir capacity to meet a given demand (From Water Resources Engineering Ray K.Linsey and Joseph B. Franzini).

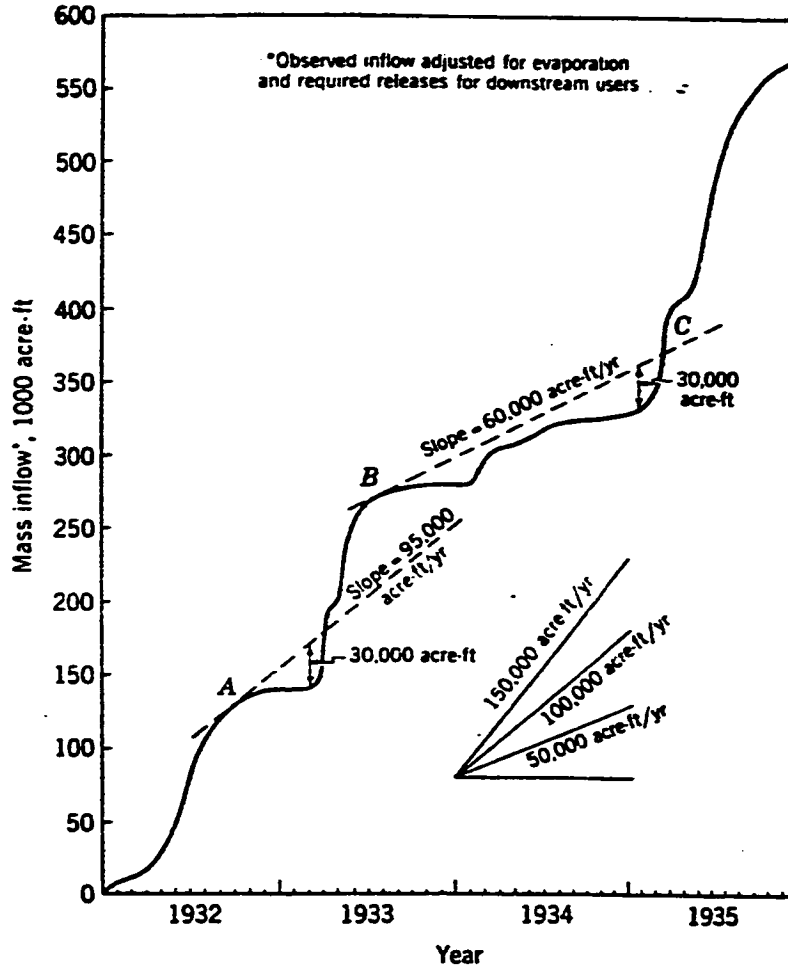


Figure 3.3: Use of mass curve to determine the possible demand from a reservoir of specified capacity (From Water Resources Engineering Ray K. Linsley and Joseph B. Franzin).

departure from the mass curve does not exceed the specified reservoir capacity. The minimum slope of the resulting lines indicate the yields that can be met from the specified storage capacity. A demand line must intersect the mass curve when extended forward. If it is not, then the reservoir will not refill.

In this study, sequent-peak algorithm method has been chosen for operational study. This method was selected because of the Fiering's [5] clear explanation of the algorithm and its use. He has stated:

"sequent- peak algorithm differs from mass curve analysis in that the formalism of locating the correct starting storage is avoided; moreover, it precludes the ambiguous results frequently observed when mass curve analysis is applied to reservoir design. It specifies a sequence of calculations that elucidates the concept of mass analysis and is equivalent to a linear programming solution for the optimal waste pattern"

3.3.3 Flow generation

Once the synthetic generating scheme is chosen, then, flows can be generated. Stochastic analysis should be used to generate a number of synthetic flow traces usually between 500 and 1000 of length equal to the expected useful life usually between 50 and 100 years of the project under study. The restriction on the number of traces is the outcome of a research project done by Burges [2] . In his research, groups of 50, 100, 250, 500, and 1000 data point were plotted on extreme value paper. It can be seen from

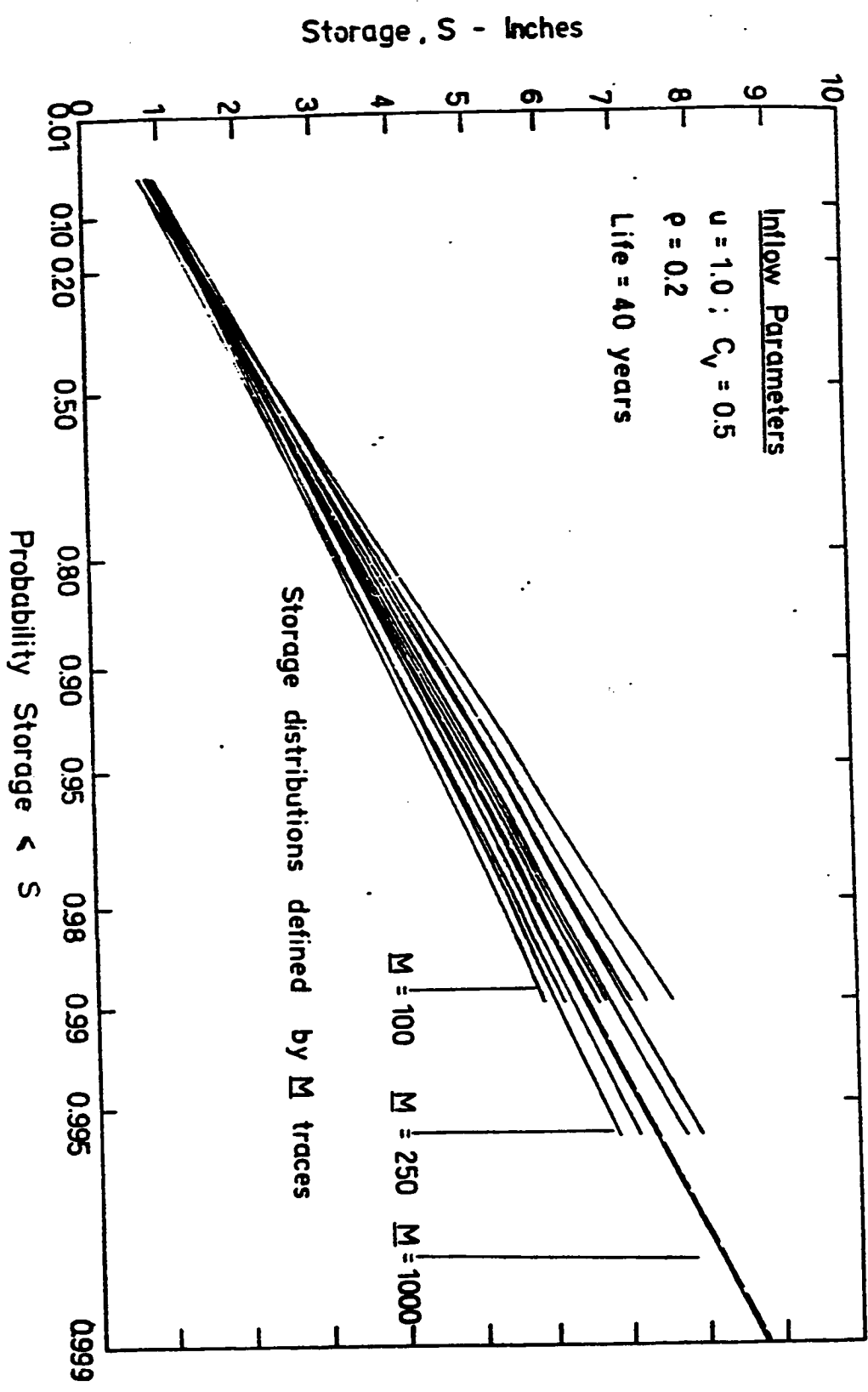


Figure 3.4a Influence of the number of traces used to define the distribution of storage (From Use of Stochastic Hydrology to Determine Storage requirements for Reservoirs Stephen J. Burges)

Figure 3.4a that increase in number of traces brings the distribution line closer to the true line. Furthermore, it shows that the line defined by two separate groups of 1000 values are virtually identical. From the results of this study he concluded that the exact distribution (Gumbel Extreme-value Distribution) is well defined by 1000 storage values (traces) and for most purposes 500 values (traces) would probably suffice. In the latter case the largest 4 or 5 values should be deleted because of the influence of these values (if they are assigned probabilities that are significantly in error) on the parameters of the extreme value distribution. The restriction on the expected life of the project is also explained and concluded in the same way as restriction on number of traces. In this study, 700 synthetic traces have been generated for each reservoir and the life of the reservoir is taken as 50 years. In each trace 612 flows were generated and the first 12 flows were discarded to eliminate the starting bias. The remaining 600 flows from each trace are now ready for the operational studies.

3.4 Reliability Studies

Information on the reliability of a reservoir is of crucial importance in the operational study in water resource engineering. The reliability of a reservoir is defined as the probability that it will deliver the expected demand throughout its life time without incurring a deficiency. In this sense, life time is taken as the economic life, which is usually between 50 and 100 years. We may estimate the reliability by generating statistically 500 to 1000 traces.

each trace equal in length to the adopted project life. Each trace then may be said to represent one possible example of what might occur during the project life time, and all traces are equally likely representatives of this future period. If the storage required to deliver a specified demand is calculated for each trace, the resulting values of storage can be ranked in order of magnitude and plotted as a frequency curve, or theoretical curve can be calculated from the data. There are several distributions available for this purpose but there is no real proof of their validity. Since the primary objective of this study is to find the maximum demand (extreme value) Gumbel extreme-value distribution appears to be the most appropriate distribution than others [12]. The result is a reliability curve which indicates the probability that the demands during the project life can be met as a function of reservoir capacity.

Alternatively, the same techniques can be adopted for determining the demand that can be met by a given capacity of a reservoir. As explained earlier in this chapter, demands will be calculated, using sequent-peak algorithm, from each trace. The resulting demands then can be described by an appropriate distribution. In this study, Gumbel extreme-value distribution is used. An illustration of reliability curve, using Gumbel extreme-value distribution, is given in Figure (3.4). Theoretical aspects of Gumbel extreme value distribution is discussed below.

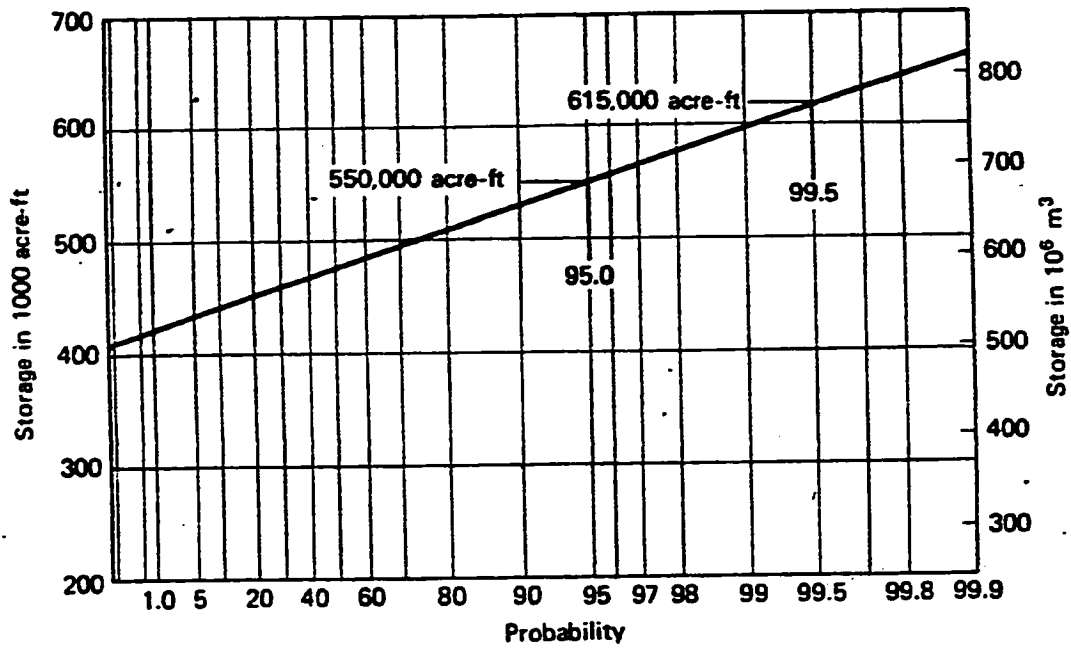


Figure 3.4: Illustration of Reliability curve (From Water Resources Engineering Ray K. Linsley and Joseph B. Franzini).

3.5 Gumbel Extreme-Value Distribution

Several distribution have been suggested as appropriate for streamflow out there is no real proof of their validity. Fischer and Tippett (1928) showed that if one selected the largest event from each of many large samples, the distribution of these extreme values was independent of the original distribution and conformed to a limiting function. Gumbel suggested that this distribution of extreme values was appropriate for flood analysis since the annual flood could be assumed to be the largest sample of 365 possible values each year. Based on the argument that the distribution of the floods is limited , i.e. that there is no physical limit to the maximum flood, he proposed that the probability P of the occurrence of a value equal to or greater than any value X be expressed as

$$P = 1 - e^{-e^y} \quad (10)$$

Where y is the reduced variate given by

$$y = \frac{1}{.7797\sigma}(x - \bar{x} + 0.45\sigma) \quad (11)$$

Where

x = flood magnitude with the probability P

\bar{x} = arithmetic mean

$$\sigma = \left[\frac{\sum (x - \bar{x})^2}{n-1} \right]^{1/2}$$

Where

n = The number of items in the series.

If t_p is the true recurrence interval, then the probability P that will be equal to or exceed X in any one year is:

$$P = \frac{1}{t_p} \quad (12)$$

The probability of an event can be obtained by the use of a plotting position. For example, when annual maximum values are being analyzed the recurrent interval t_p is defined as the mean time in years with N future trials, for the m^{th} largest values among the annual maxima to be exceeded once on the average. There are several plotting position formulas available. These formulas do not account for the sample size, that is the length of the record, except the general formula given by Gringorten (1963) which has the form

$$t_p = \frac{N+1-2a}{m-a} \quad (13)$$

where

N = The number of years of record

m = The rank

$a = 0 < a < 1$

The parameter "a" depends on the distribution and the number of years

of record. If the distribution is normal, Gumbel, or lognormal "a" is equal to 0.375, 0.44, or 0.40 respectively. The length of the record and the corresponding values of parameter "a" is given below.

N	10	20	30	40	50	60	70	80	90	100
a	.448	.443	.442	.441	.440	.440	.440	.440	.439	.439

When the number of years of record is very large then the effect of parameter "a" in the general formula will be very small. Therefore, for larger values of N, the general formula boils down to the form of Weibull plotting position which is the most common plotting position used in hydrology [22]. Hence, for larger values of N the recurrence interval t_p can be written as

$$t_p = \frac{N+1}{m}$$

It can be seen from the Equation (11) that when t_p is equal to 2.33 years x is equal to \bar{x} . This implies that in the Gumbel extreme-value distribution, at the return period of 2.33 years, or at the probability level of 42.97 percent, the flood magnitude will be equal to the arithmetic mean of the series.

Once the mean release (demand) and the releases at the probability level of 99 percent are calculated from the very first reservoir, statistics of the next reservoir should be updated according to the calculated mean. This can be done by using the following methods.

1. Mean inflow to the next reservoir can be calculated using

regression coefficients found from the historical data.

2. Standard deviation can be calculated by using the formula

$$\sigma = \sqrt{\frac{MSE}{N}} \quad (14)$$

where

MSE = Mean Standard Error in each month

N = Number of historical data in each month

3. Correlation coefficient can be calculated by using

$$\rho = \sqrt{R^2} \quad (15)$$

where

$$R^2 = \frac{SS_R}{S_{yy}}$$

where

R = Coefficient Determination.

$$SS_R = \sum(\hat{y}_i - \bar{y})^2$$

$$S_{yy} = \sum\{y_i - \bar{y}\}^2$$

Where

\hat{y}_i = Regression estimate of Y.

\bar{y} = Mean value of observations.

y_i = observation

CHAPTER 4

DATA ANALYSIS AND METHODOLOGY

4.1 Data Acquisition

Application of stochastic hydrology to a scheme of river reservoirs needs long historical record of streamflow data, downstream requirements when reservoir capacity is not known, or reservoir capacity when the operational policy is not known, and other related data such as catchment area, precipitation record, evaporation data, key maps of river basins etc.. In the case of Sri Lanka where operational policy is not known because of the change in demand, and the availability of all required data makes it an ideal place for this case study. As a result, it was decided to acquire all necessary data from Sri Lanka. Details of the data and the place where they were acquired are discussed below.

4.1.1 Historical Monthly Flow Data

Historical monthly flow data, given in Appendix (1), were obtained from Mahaweli Authority of Sri Lanka, 500 T. B. Jaya Mawatha, Colombo 10, Sri Lanka. Historical flow data were acquired for five reservoirs and a barrage namely Kotmale, Victoria, Randenigale, Rantembe, Bowatenne, and Polgolla respectively. Each data set, for each reservoir, consists of 36 years of

monthly flow data starting from 1949 up to 1985. These are incremental inflow into the reservoirs. All flow data are given in Million Cubic Meters (MCM). Precipitation data was also acquired from the same place. Also the location of the gauging station and drainage area are given. All rainfall data are given in millimeters (mm).

4.1.2 Key Maps of River Basins

Key maps of river basins were acquired from Ceylon Electricity Board prepared by Lahmeyer International - DECON Consulting Engineers, Frankfurt (M), F.R. Germany under the project: Master Plan for Electricity Supply of Sri Lanka. The key maps consist of catchment boundaries of rivers, location of stream gauges and precipitation stations.

4.1.3 Reservoir Configuration and Power Flow Data

Reservoir configuration and power flow data were acquired from Mahaweli Water Resource Management, 500 T. B. Jaya Mawatha, Colombo 10, Sri Lanka This was prepared and submitted to Mahaweli Water Resource Management by Canadian International Development Agency. Reservoir characteristics, area capacity tables, power station characteristics, and turbine efficiency tables are given in this report for each reservoir in the river basin.

4.2 Model Development

Stochastic monthly streamflow models are often used in simulation

studies to evaluate the likely future performance of water resource system. In general, the development and use of a stochastic streamflow model may involve the following steps [20]:

1. Obtain streamflow records and other information.
2. Select models to describe the marginal probability distribution of flows in different seasons and estimate the model's parameters.
3. Select an appropriate model of the special and temporal dependence of the streamflows.
4. Verify the computer implementation of the model performance as specified.
5. Validate the model for water resource system simulation.
6. Usage of the model.

With these steps in mind, a program has been developed. In this program, markov monthly streamflow model was used as a stochastic generator. The flow chart of the program is given in Figure (4.1). Input to this program is the mathematically corrected statistics of historical streamflow data and the output is a set of release (demands).

First phase of the program reads and writes the input. Second phase of the program calculates the deterministic component, which is denoted by $DCOMP(K)$, of Markov's model. $DCOMP(K)$ is calculated by the equation given below.

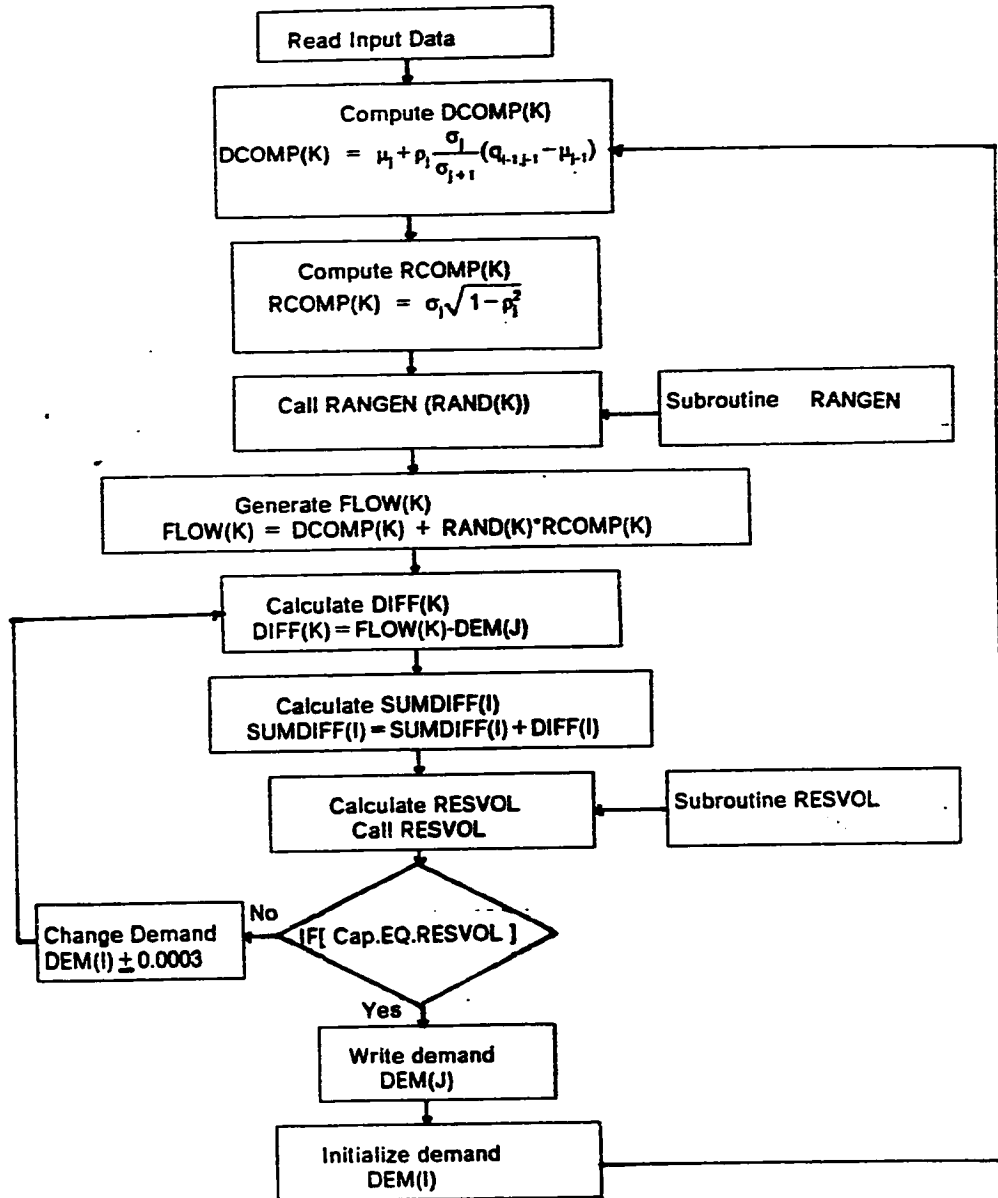


Figure 4.1: Flow chart of the program developed for the study.

Reservoir location	Reservoir capacity(MCM)	Catchment area(sq.Km)	Power flow(m/s)	Power (MWH)
Kotmale	172.9	544.0	38.0	67.0
Victoria	721.2	629.0	46.7	70.0
Randenigale	864.4	444.4	90.0	63.0
Randembe	22.0	747.1	90.0	24.5
Bowatenne	52.0	505.7	94.9	40.0

Table 4.1 : Required data for power calculation

$$DCOMP(K) = \mu_j + \rho_j \frac{\sigma_j}{\sigma_{j-1}} (q_{t-1,j-1} - \mu_{j-1})$$

In the next phase random component, which is denoted by RCOMP(K), of the Markov's model is calculated using the equation given below.

$$RCOMP(K) = \sigma_j \sqrt{1 - \rho_j^2}$$

Random number denoted by RAND(K) is produced by a subroutine with zero mean and unit standard deviation. This subroutine, written by D.Knuth [11], is available in the IBM scientific subroutine package. Random numbers from this subroutine is directly used without taking the logarithmic value of them, because the model requires random numbers with zero mean and unit standard deviation. With these three components (DCOMP(K), RCOMP(K), and RAND(K)) synthetic streamflow , denoted by FLOW(K), are generated using the equation of:

$$FLOW(K) = DCOMP(K) + RAND(K) \times RCOMP(K)$$

In this study 600 (50X12) streamflows were generated for each trace and this procedure was repeated for 700 traces.

The next phase of program deals with reservoir volume calculation using subroutine RESVOL. This subroutine follows Sequent Peak Algorithm method to calculate reservoir volume. Assuming the mean of the historical data as the initial demand the difference between the flow and the demand (DIFF(K)) for each month is calculated. The cumulative values of DIFF(K) known as SUMDIFF(K) is the primary input to the subroutine RESVOL. The reservoir

added or subtracted to the demand computed previously. Then, the new capacity required to meet this demand is obtained using the sequent-peak algorithm. This procedure is continued until the computed capacity is very nearly equal to the capacity of the reservoir in question and the corresponding demand is now chosen as the release from the reservoir. The same procedure is carried out for the other traces as well and the corresponding releases are obtained for each of the traces.

4.3 Data Analysis

Historical monthly flows and yearly flows were plotted against time to determine any possible trend. No visible trends were found in these plots and the data was considered to be random. After a careful check for the disturbance of the data, several tests were made to determine the probability distribution so that the most suitable synthetic scheme may be selected. To perform this exercise the STATGRAF package was used. Chi square values indicate at the significant level of 0.002 all historical flow at all locations follow lognormal distribution. These are shown in Figures(4.2-4.6) and Tables (4.2-4.6).

In view of this result the lognormal Markov monthly flow model was selected for generating synthetic flows. Input parameters to this model were

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency	Chisquare
at or bellow	18.52	35	25	4.10559
18.52	37.04	78	84	.40521
37.04	55.56	75	83	.83389
55.56	74.07	46	64	5.22795
74.07	92.59	49	47	.12647
92.59	111.11	45	33	4.14760
111.11	129.63	24	24	.00125
129.63	148.15	28	17	6.71825
148.15	166.67	16	13	.90565
166.67	185.19	10	9	.04494
185.19	203.70	4	7	1.29476
203.70	222.22	9	5	2.54587
222.22	259.26	7	7	.00771
259.26	314.81	4	6	.64374

Chisquare = 30.774 With 12 d.f. Sig. Level = 2.12244E-3

Table 4.2 : Chisquare test for the historical data of Kotmale rservoir

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency	Chisquare
at or bellow	18.52	59	64	.4051
18.52	37.04	92	110	.2.9484
37.04	55.56	94	80	2.5604
55.56	74.07	55	53	.0955
74.07	92.59	45	35	2.8180
92.59	111.11	28	24	.7376
111.11	129.63	14	17	.3959
129.63	148.15	21	12	7.2114
148.15	166.67	9	9	.0231
166.67	185.19	5	6	.2783
185.19	222.22	5	8	1.3647
222.22	277.78	2	7	3.3174
277.78		3	8	3.3203

Chisquare = 25.4762 With 10 d.f. Sig. Level = 4.51231E-3

Table 4.3 : Chisquare test for the historical data of Victoria rervoir

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency	Chisquare
at or bellow	18.52	133	136	0.0705
18.52	37.04	124	116	0.5174
37.04	55.56	52	66	2.1900
55.56	74.07	42	37	0.6562
74.07	92.59	25	23	0.1865
92.59	111.11	17	15	0.2852
111.11	129.63	7	10	0.9712
129.63	148.15	9	7	0.4993
148.15	166.67	6	5	0.1461
166.67	203.70	7	7	0.0187
203.70	259.26	6	5	0.1124
259.26		4	7	1.0441

Chisquare = 6.69764 With 9 d.f. Sig. Level = 0.668566

Table 4.4: Chisquare test for the historical data of Randenigale rservoir

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency	Chisquare
at or bellow	22.22	33	44	2.80972
22.22	44.44	191	175	1.42736
44.44	66.67	117	118	0.00473
66.67	88.89	57	54	0.20388
88.89	111.11	14	23	3.45490
111.11	133.33	8	10	0.35490
133.33		12	8	1.46445

Chisquare = 9.71844 With 4 d.f. Sig. Level = 0.0454473

Table 4.5 : Chisquare test for the historical data of Rantambe rservoir

Lower Limit	Upper Limit	Observed Frequency	Expected Frequency	Chisquare
at or bellow	14.81	120	112	0.6118
14.81	29.63	124	133	0.5461
29.63	44.44	65	75	1.3144
44.44	59.26	45	42	0.2392
59.26	74.07	27	24	0.2727
74.07	88.89	19	15	1.1132
88.89	103.70	8	9	0.2359
103.70	118.52	7	6	0.0888
118.52	148.15	12	7	3.2113
148.15		5	9	1.5820

Chisquare = 9.21522 With 12 d.f. Sig. Level = 0.237571

Table 4.6: Chisquare test for the historical data of Bowatenne rervoir

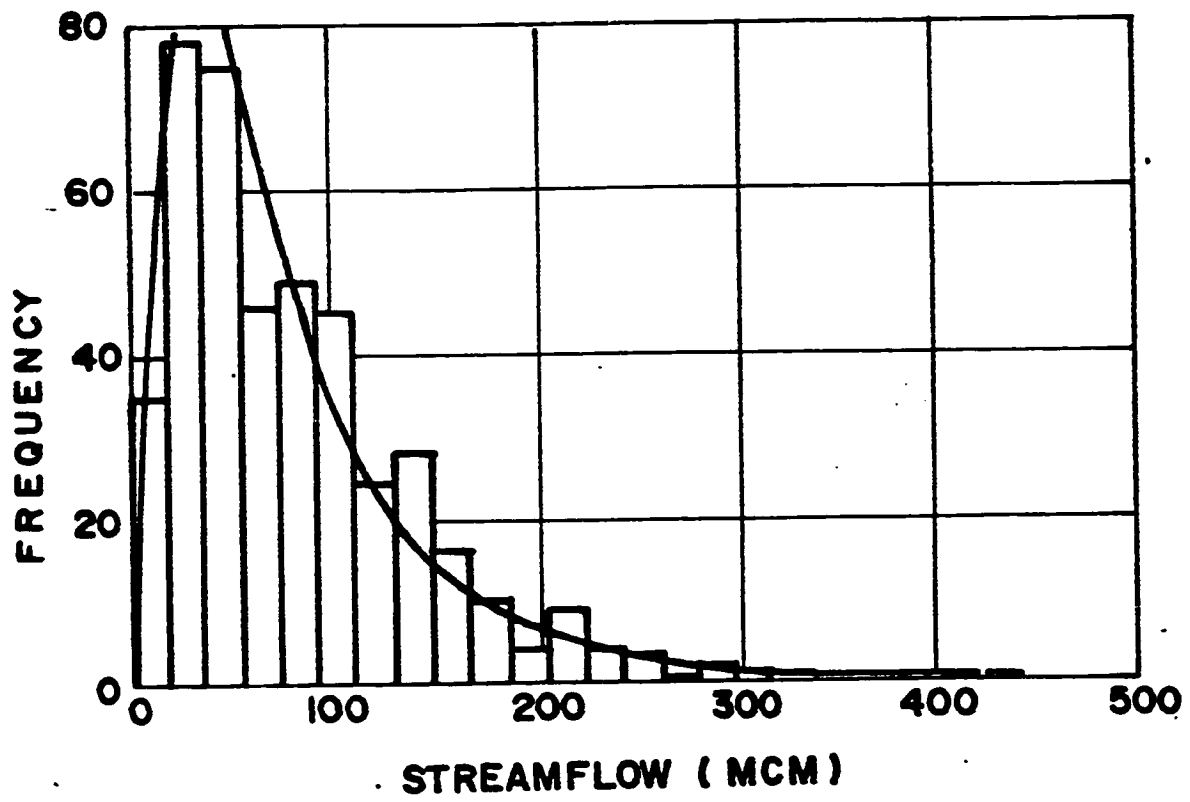
FREQUENCY HISTOGRAM KOTMALE RESERVOIR

Figure 4.2: Lognormally fitted frequency histogram for Kotmale reservoir.

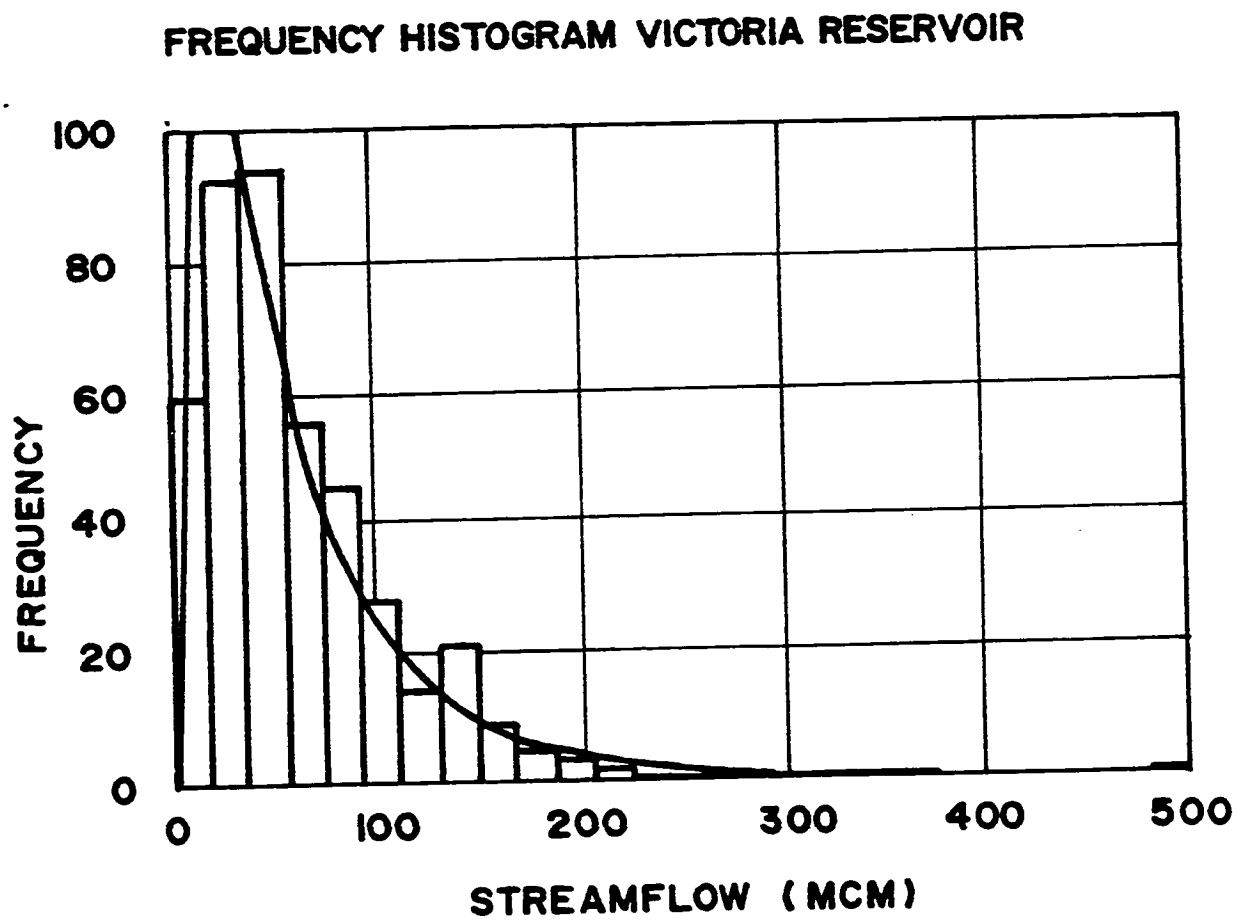


Figure 4.3: Lognormally fitted frequency histogram for Victoria reservoir.

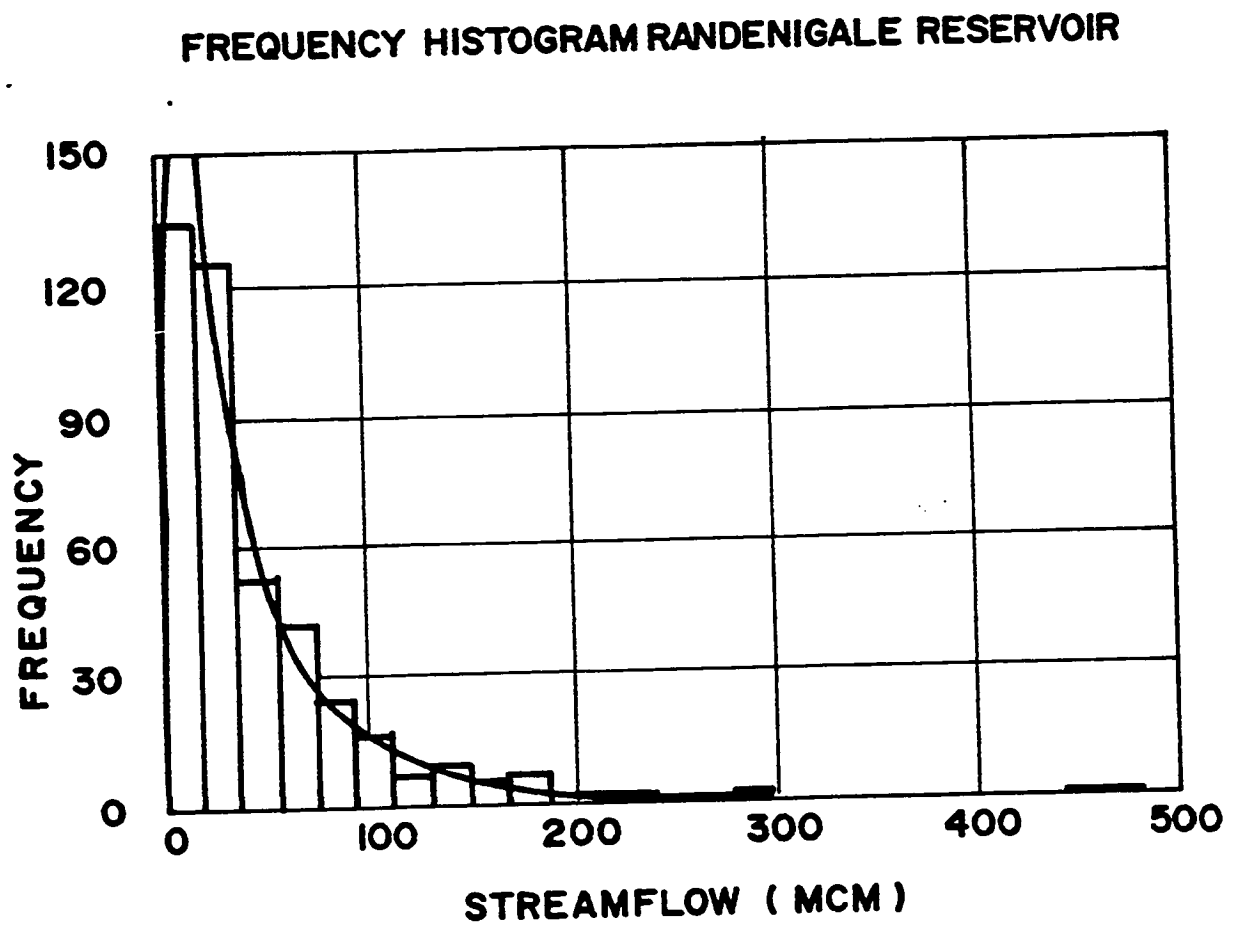


Figure 4.4: Lognormally fitted frequency histogram for Randenigale reservoir

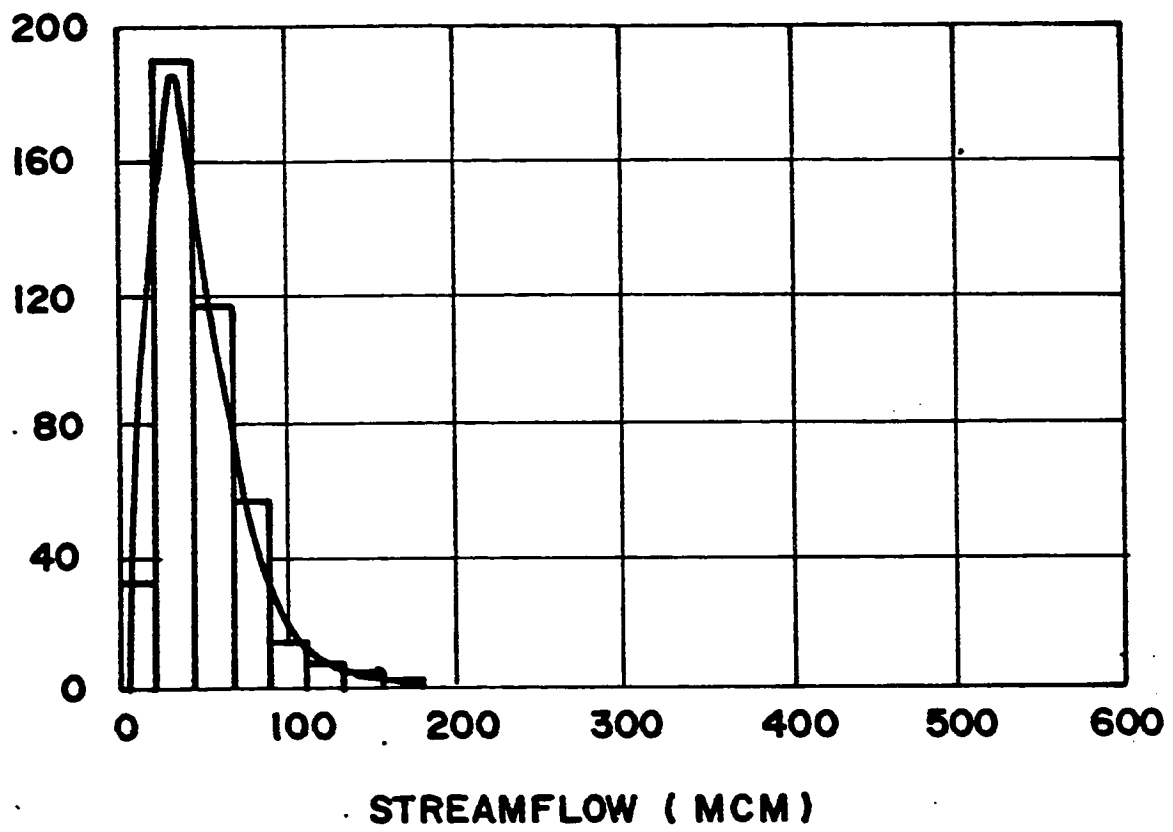
FREQUENCY HISTOGRAM RANTAMBE RESERVOIR

Figure 4.5: Lognormally fitted frequency histogram for Rantembe reservoir.

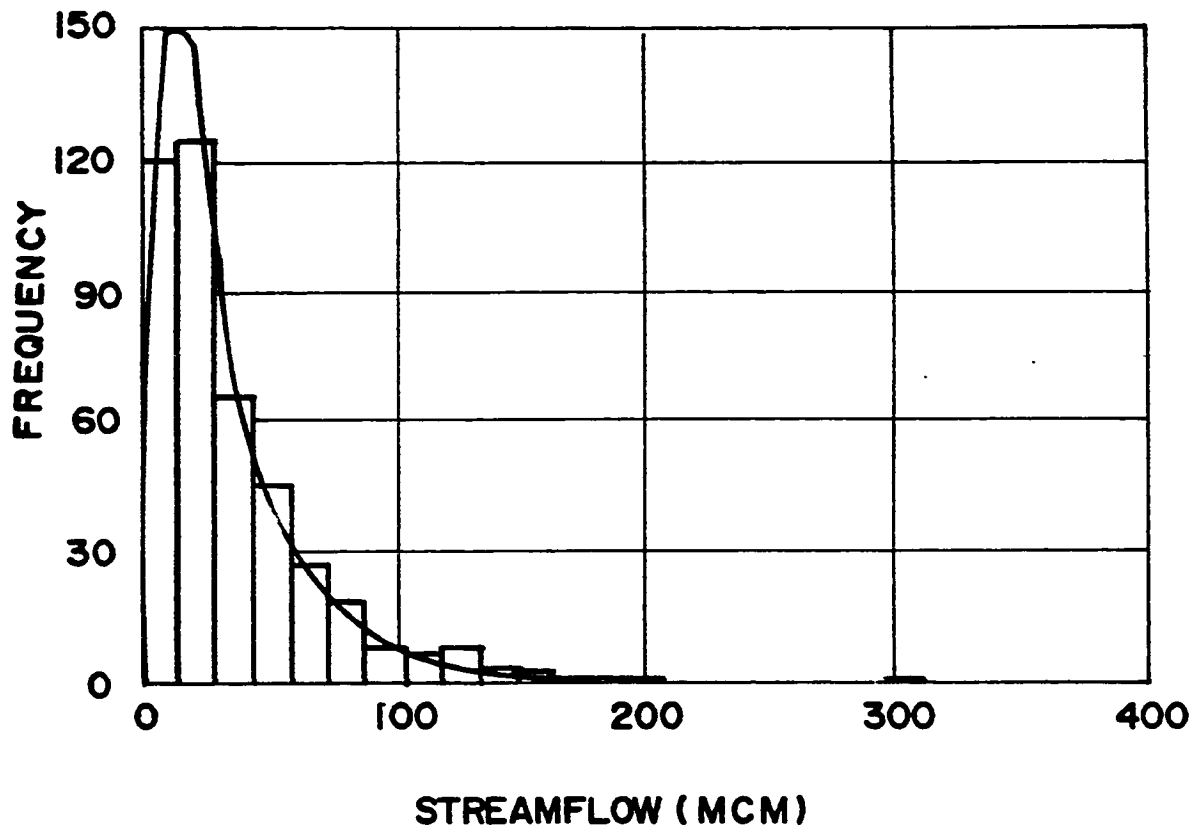
FREQUENCY HISTOGRAM BOWATENNA RESERVOIR

Figure 4.6: Lognormally fitted frequency histogram for Bowatenna reservoir.

the mean, the standard deviation, and the serial correlation coefficient of historical data. The statistics were found using SAS regression packages. These statistics were used in equations (7,8,9) to calculate mathematically corrected input to the Markov model explained in Chapter 3. Mathematically corrected input data are given in tables (4.7-4.11).

As one can see in the use of the Markov model necessitates the generation of random numbers with zero mean and unit standard deviation. After making sure of the zero mean and standard deviation using goodness of fit, IBM's Random number generator package was selected and used in the model to generate the synthetic streamflow. With the random number generator package and statistics of historical data, synthetic data were generated. Next, statistics of synthetic data and the statistics of historical data were compared in order to make sure that the statistics of the historical data were preserved. These comparisons are shown in Tables (4.7-4.11). It was concluded, from the results given in Tables (4.7-4.11), that the model generates flows which have the same statistics as the historical flows. Having ascertained that the synthetic flows preserved the statistics of the historical flows, the next stage of operation was the application of the model to flows at Kotmale, the first reservoir in the scheme. Output from the model is a set of releases (demands) which can be met from this reservoir capacity. As explained earlier, Gumbel extreme value distribution was employed to study the reliability of these releases. As explained earlier in Chapter 3, values corresponding to the probability level of 42.97 percent as mean releases and the releases at the probability level of 99 percent were chosen

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
HISTORICAL MEAN	3.037	2.835	2.525	2.077	1.494	1.393	1.797	2.234	2.839	3.104	3.001	2.861
SYNTHETIC MEAN	3.036	2.833	2.525	2.078	1.495	1.394	1.797	2.238	2.842	3.104	3.002	2.861
HISTORICAL STAND.DIVIAION	0.116	0.204	0.202	0.163	0.188	0.146	0.170	0.483	0.454	0.170	0.212	0.222
SYNTHETIC STAND.DIVIAION	0.116	0.203	0.201	0.162	0.186	0.145	0.168	0.477	0.450	0.169	0.211	0.221
HISTORICAL CORR.COEFFICIENT	0.000	0.479	0.225	0.430	0.765	0.678	0.389	0.218	0.203	0.334	0.460	0.280
SYNTHETIC CORR.COEFFICIENT	0.005	0.468	0.227	0.426	0.759	0.674	0.378	0.220	0.197	0.328	0.458	0.274

Table 4.7 : Statistics of historical and synthetic flow data of Kotmale reservoir.

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
HISTORICAL MEAN	3.098	2.325	1.810	1.504	0.877	0.388	1.595	2.129	2.955	3.295	3.015	2.904
SYNTHETIC MEAN	3.098	2.325	1.810	1.504	0.876	0.388	1.595	2.130	2.955	3.294	3.016	2.904
HISTORICAL STAD.DIVIAATION	0.004	0.019	0.029	0.005	0.013	0.034	0.016	0.022	0.016	0.004	0.003	0.005
SYNTHETIC STAD.DIVIAATION	0.003	0.019	0.028	0.004	0.014	0.034	0.015	0.021	0.014	0.004	0.003	0.003
HISTORICAL CORR.COEFFICIENT	0.254	0.586	0.849	0.737	0.745	0.821	0.560	0.694	0.417	0.538	0.638	0.695
SYNTHETIC CORR.COEFFICIENT	0.254	0.589	0.846	0.734	0.744	0.819	0.564	0.699	0.419	0.541	0.640	0.697

Table 4.8 : Statistics of historical and synthetic flow data of Victoria reservoir.

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
HISTORICAL MEAN	3.553	3.008	2.419	2.456	2.489	2.503	3.006	3.172	3.954	4.243	3.903	3.790
SYNTHETIC MEAN	3.553	3.008	2.419	2.456	2.489	2.503	3.006	3.172	3.954	4.243	3.903	3.790
HISTORICAL STAND.DIVIAATION	0.015	0.045	0.044	0.103	0.033	0.023	0.010	0.025	0.007	0.007	0.014	0.011
SYNTHETIC STAND.DIVIAATION	0.014	0.044	0.043	0.101	0.033	0.023	0.009	0.024	0.004	0.004	0.013	0.009
HISTORICAL CORR.COEFFICIENT	0.909	0.809	0.989	0.849	0.980	0.920	0.969	0.903	0.954	0.879	0.853	0.942
SYNTHETIC CORR.COEFFICIENT	0.909	0.814	0.987	0.849	0.977	0.918	1.022	0.911	0.957	0.912	0.849	0.950

Table 4.9 : Statistics of historical and synthetic flow data of Randenigale reservoir.

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
HISTORICAL MEAN	2.580	2.413	2.793	2.785	2.263	1.773	1.476	1.641	0.784	3.088	3.772	2.931
SYNTHETIC MEAN	2.580	2.412	2.793	2.785	2.263	1.773	1.476	1.642	0.785	3.088	3.772	2.931
HISTORICAL STAND.DIVATION	0.034	0.069	0.097	0.096	0.118	0.083	0.077	0.087	0.135	0.011	0.005	0.017
SYNTHETIC STAND.DIVATION	0.034	0.069	0.097	0.095	0.117	0.082	0.076	0.086	0.134	0.010	0.003	0.017
HISTORICAL CORR.COEFFICIENT	0.280	0.241	0.469	0.625	0.362	0.352	0.294	0.227	0.001	0.334	0.611	0.253
SYNTHETIC CORR.COEFFICIENT	0.278	0.231	0.470	0.622	0.352	0.351	0.283	0.230	-.001	0.366	0.609	0.257

Table 4.10: Statistics of historical and synthetic flow data of Rantembe reservoir.

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
HISTORICAL MEAN	3.950	3.627	2.761	2.247	2.407	2.575	2.981	3.639	4.466	4.593	4.230	4.423
SYNTHETIC MEAN	3.950	3.626	2.760	2.247	2.407	2.575	2.981	3.639	4.466	4.593	4.230	4.423
HISTORICAL STAND.DIVIAATION	0.033	0.055	0.104	0.046	0.028	0.036	0.040	0.040	0.033	0.023	0.024	0.025
SYNTHETIC STAND. DIVIATION	0.033	0.055	0.104	0.046	0.028	0.038	0.039	0.039	0.032	0.022	0.023	0.024
HISTORICAL CORR. COEFFICIENT	0.409	0.365	0.754	0.637	0.811	0.639	0.579	0.713	0.509	0.434	0.320	0.597
SYNTHETIC CORR. COEFFICIENT	0.387	0.341	0.752	0.635	0.811	0.638	0.568	0.707	0.492	0.405	0.284	0.570

Table 4.11: Statistics of historical and synthetic flow data of Bowatenne reservoir.

from this distribution and recorded. Having obtained this releases, statistics of the next reservoir were updated according to these releases. This has been done as explained in Chapter 3. Then, the new statistics were used as input to the model for the next reservoir. This procedure was continued until all reservoirs are taken into consideration. Finally, mean releases and the releases at the probability level of 99 percent from each reservoir were recorded and an operating policy for the system was prepared.

CHAPTER 5

ANALYSIS OF RESULTS

Since this study deals with a multi reservoir system, a proper way to analyse the results is to consider a single reservoir in the system initially and then to consider the other cases wherever necessary. Some of the results are already shown in chapter 4. A more detailed analysis of the results of the operation and reliability studies are presented here.

As discussed in chapter 4 , historical data was tested for possible trends and appeared to be random. Next, several test were made to determine the probability distribution of the historical flow to select the most suitable synthetic scheme. All historical flows at all reservoir sites best fitted the lognormal distribution. Thus, the lognormal Markov monthly flow model was selected as the synthetic flow generator. A key requirement in the synthetic flow generation is that "the statistics of the historical data" must be preserved. Therefore, statistics of the historical flow and the statistics of the synthetic flow were compared to make sure that the statistics of the historical flow data were preserved. From the results given in tables (4.7-4.11) it may be concluded that the model preserves the statistics of the historical flow

data. After having drawn this conclusion, the model was applied to the first (Kotmale) reservoir in the system.

5.1 Results of Operation Study

The outcome of the application of the model to the Kotmale reservoir is a set of maximum possible releases (demands) that can be met from the known reservoir capacity. These demands (releases) for each month represent the largest event (release) for that month that is possible using the given capacity of the reservoir. Thus, each trace provides 12 values of releases for the life of the reservoir. 700 such traces will provide a matrix of 700 X 12 entries, which is in fact 700 maximum possible values for each of the 12 months.

As one can see from this theoretical plot given in Appendix 2, for certain months, the releases appear to remain constant. This is because of the following constraints being placed in the iterative process.

1. To economize the power generation the turbine must be run as efficiently as possible. There is a given minimum supply required to do this. Wherever the release from the reservoir falls this minimum it is set at the minimum requirement level.
2. To prevent negative releases during the iterative process.

In operation studies the primary objective is to determine either the capacity of the reservoir that can meet a given demand or to determine the demand (release) that can be met by the reservoir of a given capacity The

study undertaken in this research pertains to the later case. Having predetermined releases (demands) for certain months does not interfere in the synthetic flow generation.

In view of the demand being fixed for the months of dry season, reliability curves obtained by the process explained earlier should be a straight line, as shown in Figure (5.1).

5.2 Results of Reliability Studies

As shown earlier there are 700 maximum possible releases for each month for a given reservoir. All these releases have the same likelihood of occurrence. Thus, these values may be ranked in the order of magnitude and plotted as a frequency curve. As pointed by Burges (1975), and Linsley(1979), the Gumbel extreme value distribution appears to be the appropriate one for this purpose. The result, therefore, should be the reliability curve for each month of the year for the reservoir. In this study, Weibull plotting position formula with the Gumbel probability paper were used to obtain the reliability curve. In order to have this plot, selected probability levels and the corresponding releases (demands) were taken and plotted on Gumbel extreme value distribution paper. The results of this plot is a set of straight lines. Each line represents the reliability distribution of that particular month. This plot can be used as to select releases (demands) with certain reliability according to the necessity of the requirement. For example, from the Figure 5.1, it will be 91 (MCM) if one needed the demand for the month of July with the reliability of 95 percent. It means that 91 (MCM) can be met as demand

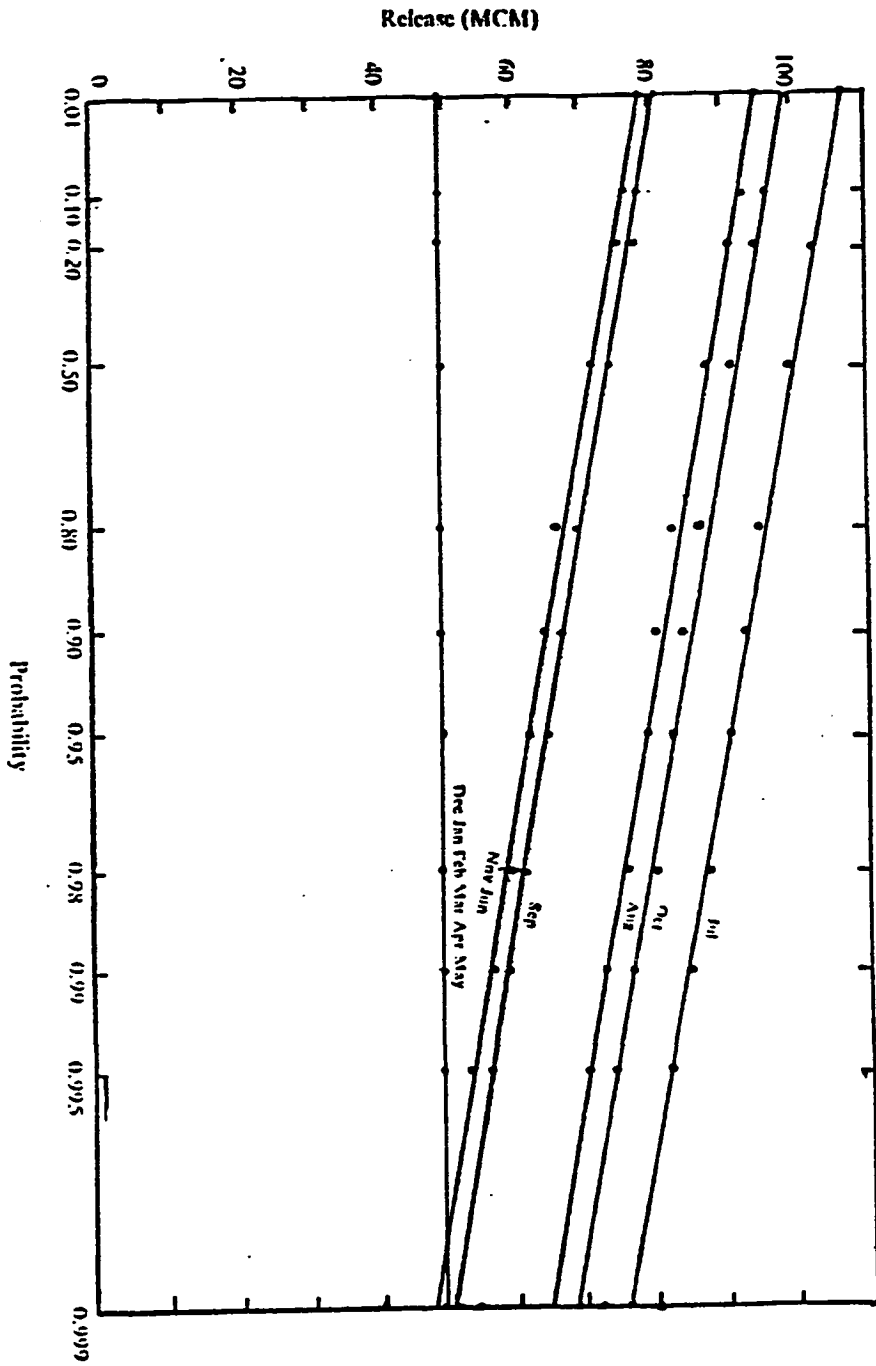


Figure 5.1: Reliability Curve of Kotmale reservoir

from the reservoir with the reliability of 95 percent. In this study, the mean releases were chosen as the required demands at the probability level of 42.97 percent. This is because of the reason that usually engineers consider the mean values for their studies in power generation schemes or in irrigation projects. If the reservoir is used for water supply then, it is better to choose higher level of probability.

The release obtained from the reliability curve is the release that is going to be maintained for the rest of the life of that reservoir. As explained in chapter 3 next reservoir inflow statistics were updated corresponding to the above release. This procedure was continued for all cases in the study and the releases were tabulated. These are shown in Tables(5.1,5.2). From this information and the information given in Table (4.1), total power that can be generated from the watershed for each month was calculated using the equation given below,

$$P = \eta \frac{\gamma H Q}{102}$$

Where

P = Power (KWH)

η = efficiency of the turbine

γ = Specific gravity of water (Kg/ m^3)

H = Design head (m)

Q = Discharge (m^3 /sec)

These are given in tables (5.3,5.4). The total average monthly power requirement in SriLanka and the power that can be generated from Mahaweli

Reservoir	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Kotmale	92.5	71.9	49.3	49.3	49.3	49.3	49.3	49.3	72.2	100.4	88.5	74.3
Victoria	104.8	60.5	60.5	60.5	60.5	60.5	60.5	60.5	86.3	135.1	93.7	80.4
Randenlgale	131.8	89.5	89.5	89.5	89.5	89.5	89.5	89.5	208.3	285.9	197.0	173.3
Rnantembe	98.6	83.4	122.0	121.0	71.8	44.0	32.7	38.5	16.4	163.8	324.7	140.0
Bowatenne	224.6	161.0	64.3	41.7	43.4	52.4	81.5	163.0	380.3	432.7	299.1	365.9

Table 5.1: Final releases at the probability level of 42.92 percent (mean)
from all reservoirs after simulation (values are in MCM).

Reservoir	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Kotmale	77.6	57.0	49.3	49.3	49.3	49.3	49.3	49.3	57.3	85.4	73.6	59.4
Victoria	127.8	57.6	45.3	45.3	45.3	45.3	45.3	45.3	114.5	168.6	118.4	112.6
Randenlgale	129.0	89.5	89.5	89.5	89.5	89.5	89.5	89.5	205.4	283.0	194.0	170.0
Rnantembe	99.1	57.9	44.1	81.9	81.2	32.1	29.1	29.1	29.1	123.0	280.9	98.4
Bowatenne	217.3	153.6	57.0	41.7	41.7	45.0	74.2	155.6	373.0	425.3	291.7	358.5

Table 5.2: Final releases at the probability level of 99 percent from all reservoirs after simulation (values are in MCM).

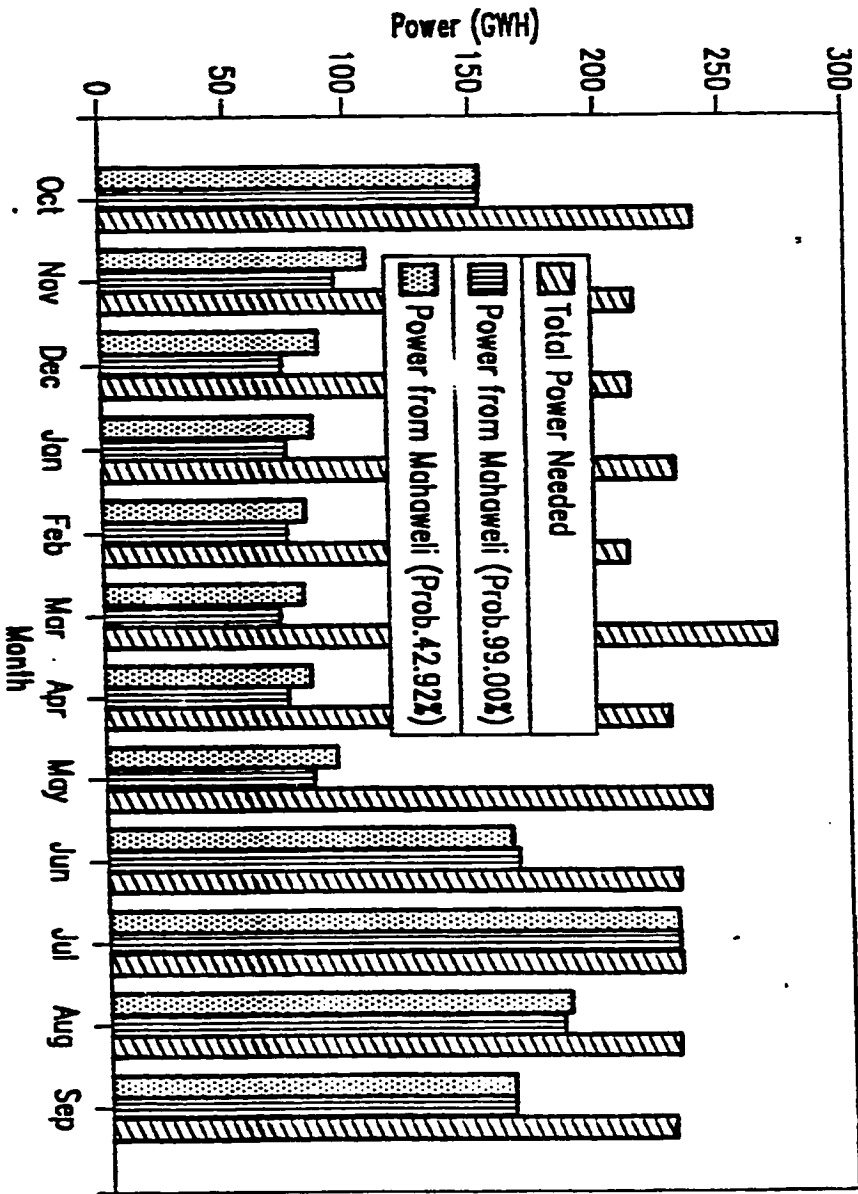
Reservoir	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Kotmale	45.3	35.2	24.1	24.1	24.1	24.1	24.1	24.1	35.4	49.2	43.3	36.4
Victoria	26.3	18.9	7.5	4.9	5.1	6.1	9.5	19.1	44.5	50.7	35.0	42.8
Randenigale	25.6	17.4	17.4	17.4	17.4	17.4	17.4	17.4	40.5	55.6	38.3	33.7
Rantembe	43.6	25.2	25.2	25.2	25.2	25.2	25.2	25.2	35.9	56.3	39.0	33.5
Bowatenne	7.5	6.3	9.2	9.1	5.4	3.3	2.5	2.9	1.2	12.4	24.6	10.6
Polgolla	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Total	153.1	107.8	88.2	85.5	82.0	80.9	83.5	93.5	162.3	229.0	185.0	161.8

Table 5.3: Total power that can be generated from all hydropower stations in Mahaweli scheme at the probability level of 42.92 percent (GWH).

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Reservoir												
Kotmale	38.0	27.9	24.1	24.1	24.1	24.1	24.1	24.1	28.1	41.8	36.1	29.1
Victoria	53.2	24.0	18.8	18.8	18.8	18.8	18.8	18.8	47.7	70.1	49.3	46.8
Randenigale	25.1	17.4	17.4	17.4	17.4	17.4	17.4	17.4	39.9	55.0	37.7	33.1
Rantembe	7.5	4.4	3.3	6.2	6.2	2.4	2.2	2.2	2.2	9.3	21.2	7.4
Bowatenne	25.4	18.0	6.7	4.9	4.9	5.3	8.7	18.2	43.7	49.8	34.1	42.0
Polgolla	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Total	152.6	95.1	73.7	74.8	74.8	71.4	74.6	84.1	165.0	229.4	181.8	161.8

Table 5.4: Total power that can be generated from all hydropower stations in Mahaweli scheme at the probability level of 99 percent (GWH).

Figure 5.2: Comparison of total power requirement and the power can be generated from Mahaweli scheme for each month at the probability level of 42.92 percent and 99 percent (Giga Watt Hour).



scheme are compared in figure 5.2. From the figure, it is clear that nearly 55 percent at the probability level of 42.92 percent and 52 percent at the probability level of 99 percent respectively, of the total power requirement can be met from Mahaweli scheme alone.

CHAPTER 6

CONCLUSION

Subject to the constraints concerning the usage of the Markov model and the Sequent-peak analysis the following broad based conclusions may be drawn.

1. Monthly streamflows at all reservoir locations of Mahaweli scheme of Sri Lanka fit the lognormal distribution.
2. Stochastic approach is not only useful in determining reservoir capacities but also in determining probable releases given the reservoir capacities.
3. Lag-one lognormal monthly Markov model appears to be suitable model for performing operation studies in multi-reservoir system.
4. Reliability studies of reservoirs can be successfully performed using stochastic techniques combined with either the Ripple mass curve or the sequent-peak algorithm and the Fischer-Tippet Type 1 (Gumbel) extreme value distribution
5. At 99 percent reliability, nearly 52 percent of the total power requirements of Sri Lanka may be met from Mahaweli watershed alone, if the suggested operating policy in this study is maintained, however, at reliability level of 42.92 percent (mean monthly flow) this requirement may be reached to approximately 55 percent.

RECOMMENDATION

This study has come up with operating regulation pertaining to maximizing power generation only. However, the reservoir system investigated in Sri Lanka has yet another important purpose of providing water for irrigation requirements in the developed lands in the system. Thus, it is recommended that further studies be conducted to come up with a set of operating regulations where benefits from power generation and irrigation are maximized. A possible approach for optimizing the benefits from irrigation and power generation is to use Chance-Constrained programming (Duffaa,1991) reach to an overall operating policy. The study in this thesis can be extended for the purpose of forecasting future releases from the reservoirs and time series analysis is recommended for such study.

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Appendix 1

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949/1950	98.6	30.1	79.3	42.1	24.0	25.9	18.7	39.8	85.8	139.3	17.6	207.5
1950/1951	62.4	42.2	28.0	75.6	44.1	28.7	37.1	44.4	429.7	176.3	2.2	86.8
1951/1952	135.5	135.4	57.7	72.3	32.9	22.3	61.7	226.4	178.0	138.8	17.8	112.5
1952/1953	158.9	53.1	36.1	33.8	15.0	35.6	75.7	33.7	76.8	128.0	14.6	91.3
1953/1954	102.3	101.5	73.5	83.7	48.0	33.9	48.3	48.6	55.7	100.9	12.9	85.5
1954/1955	180.6	51.6	79.5	71.2	41.2	17.6	48.6	107.5	352.4	136.2	1.6	87.0
1955/1956	87.5	81.3	33.3	13.0	11.1	14.3	13.3	37.7	129.7	127.1	13.7	113.9
1956/1957	144.2	106.4	76.2	40.1	28.8	25.1	19.8	39.4	140.5	151.1	1.8	93.0
1957/1958	79.0	110.0	218.3	89.6	38.8	53.8	49.3	17.5	106.1	108.5	13.2	50.2
1958/1959	155.1	118.8	55.4	29.1	17.1	11.6	39.8	42.0	211.1	239.0	6.6	80.3
1959/1960	107.7	93.6	54.1	39.2	57.1	36.7	49.1	64.7	103.9	131.9	17.4	217.8
1960/1961	184.4	162.0	58.2	34.2	28.8	23.4	28.3	112.6	88.9	91.3	19.9	79.4
1961/1962	61.0	79.7	61.5	40.9	22.3	19.2	28.5	114.4	69.7	136.6	4.3	154.5
1962/1963	128.7	78.5	49.7	51.4	29.8	19.6	41.8	35.3	61.8	97.4	3.5	71.2
1963/1964	131.1	103.0	109.8	73.2	44.7	33.0	18.0	23.1	34.8	112.3	12.9	139.9
1964/1965	61.8	136.4	46.4	18.8	15.5	13.4	49.5	204.0	114.3	48.4	8.7	109.3
1965/1966	102.7	93.0	82.0	50.0	20.2	27.0	41.9	24.0	33.4	54.7	2.0	105.2
1966/1967	139.1	104.6	49.3	34.4	25.5	24.4	17.5	18.9	47.6	82.3	0.1	43.1
1967/1968	162.7	117.9	142.1	36.2	15.2	21.1	18.0	47.5	80.7	260.1	20.2	166.3
1968/1969	144.6	96.3	57.3	33.2	15.9	13.3	45.3	92.1	155.5	84.8	7.4	104.1
1969/1970	98.0	62.4	71.4	72.2	44.2	27.1	43.1	41.7	77.1	92.4	16.5	59.9
1970/1971	111.3	94.9	119.0	65.8	27.1	23.6	56.8	57.9	101.9	149.9	14.9	239.9
1971/1972	132.7	70.4	103.8	31.2	14.6	9.3	27.5	109.2	33.5	180.0	12.9	77.0
1972/1973	172.4	141.0	95.8	44.6	23.6	17.8	22.7	16.4	36.9	67.7	17.0	62.0
1973/1974	53.0	79.5	88.8	53.6	24.7	26.5	49.2	71.0	147.3	250.1	31.0	140.4
1974/1975	129.8	62.3	47.1	56.2	31.0	32.6	46.3	57.2	188.1	100.5	12.4	154.7
1975/1976	214.5	256.1	80.2	54.8	22.0	17.6	44.5	19.8	15.1	59.4	6.6	44.9
1976/1977	81.7	83.4	53.4	23.0	17.0	17.2	28.5	85.2	113.8	54.3	3.6	47.8
1977/1978	176.4	96.8	57.5	29.2	21.0	24.5	18.2	179.5	95.5	219.1	25.2	107.5
1978/1979	142.2	245.1	87.5	33.2	21.1	16.3	32.9	62.6	102.1	185.2	15.7	144.2
1979/1980	186.1	190.2	114.4	37.9	18.0	16.7	32.4	40.2	47.5	104.3	14.2	57.9
1980/1981	112.0	78.8	60.7	44.2	19.5	19.2	25.1	23.0	140.1	86.9	8.7	216.8
1981/1982	66.7	100.3	50.4	16.3	11.6	19.3	24.4	82.1	141.5	112.8	4.9	45.6
1982/1983	74.5	81.9	79.0	47.9	18.4	15.0	10.6	24.1	25.4	49.0	5.6	52.9
1983/1984	52.2	89.4	96.7	78.5	51.4	44.2	53.7	49.3	100.3	228.5	4.5	102.6
1984/1985	116.5	63.0	53.0	45.3	16.9	21.6	22.0	54.9	278.6	164.2	16.5	73.1

Historical flow data for KOTMALE reservoir (Million Cubic Meters)

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949/1950	78.9	70.6	78.1	33.6	24.1	36.2	19.4	71.2	132.9	154.7	19.5	207.7
1950/1951	92.2	108.1	9.9	79.6	18.3	3.8	86.7	34.4	181.9	95.2	4.5	60.3
1951/1952	114.5	190.9	48.6	49.8	12.5	12.4	34.3	188.5	168.5	118.2	18.3	40.4
1952/1953	259.1	81.3	30.4	13.3	8.6	5.1	8.5	8.9	69.8	93.3	9.4	45.2
1953/1954	90.9	60.5	56.3	13.7	3.0	4.29	88.3	127.0	102.2	76.8	11.5	83.7
1954/1955	194.9	85.5	131.3	48.1	39.2	62.4	43.8	277.5	434.8	192.4	17.7	137.7
1955/1956	171.9	135.2	50.0	24.1	4.0	13.4	10.3	35.7	280.0	73.4	16.6	126.3
1956/1957	186.5	301.3	73.2	28.6	41.2	20.9	34.6	89.1	260.4	281.7	0.5	35.9
1957/1958	64.3	212.4	478.2	55.2	20.8	39.3	68.1	114.8	86.1	186.4	10.8	64.1
1958/1959	227.3	133.3	74.2	25.7	16.3	6.9	52.9	74.0	231.8	254.7	12.6	115.0
1959/1960	156.1	126.3	70.3	59.3	75.5	45.2	103.5	99.6	134.9	157.7	12.7	144.9
1960/1961	176.2	227.8	80.0	35.8	21.1	16.4	33.5	132.5	112.0	107.1	22.9	97.7
1961/1962	102.6	112.9	70.4	53.3	30.8	30.6	54.4	142.9	89.6	142.3	19.3	163.5
1962/1963	179.4	114.0	62.2	48.6	28.0	28.7	53.8	59.4	93.0	135.8	17.0	110.5
1963/1964	189.5	121.0	150.8	50.1	36.3	44.6	45.7	82.5	93.9	156.6	18.7	156.4
1964/1965	123.9	231.9	60.6	15.9	15.6	7.2	73.0	225.4	185.1	56.7	18.9	65.8
1965/1966	178.9	116.0	94.7	33.0	18.8	22.8	61.6	36.1	35.8	63.1	4.8	219.6
1966/1967	198.2	156.5	73.9	34.7	32.0	33.6	26.8	26.3	103.3	109.4	7.1	42.4
1967/1968	222.5	128.7	142.7	19.3	3.7	19.1	40.7	100.7	134.4	252.2	14.1	145.1
1968/1969	124.2	114.4	63.2	25.1	17.0	12.3	65.0	136.2	182.0	72.6	7.4	107.2
1969/1970	120.3	82.3	75.1	57.9	44.0	28.3	71.5	69.0	115.0	118.2	11.2	88.9
1970/1971	149.6	150.1	140.3	67.5	28.1	30.5	88.3	124.1	170.2	193.8	12.4	373.8
1971/1972	189.3	86.2	108.6	21.0	4.5	2.0	38.2	209.2	40.7	165.1	13.4	77.7
1972/1973	245.8	188.5	136.7	10.4	6.6	10.7	8.0	12.8	35.9	42.2	7.0	26.1
1973/1974	21.7	67.6	71.6	34.9	22.8	24.0	101.0	155.3	233.6	311.4	29.3	288.4
1974/1975	208.7	77.2	94.0	33.8	14.6	13.8	31.2	65.0	264.5	80.2	26.6	174.4
1975/1976	191.5	302.6	120.5	46.6	16.2	3.0	38.5	20.4	11.3	77.7	2.6	57.1
1976/1977	125.3	141.3	85.8	23.3	9.4	12.1	36.1	146.4	157.1	102.0	5.5	51.7
1977/1978	171.2	143.3	64.1	22.1	13.4	16.7	10.7	162.7	85.9	151.3	18.0	107.4
1978/1979	148.9	317.8	119.9	44.2	27.9	21.5	18.3	51.2	79.5	97.9	5.7	136.4
1979/1980	153.2	162.2	126.0	38.7	16.4	11.2	44.9	34.4	40.9	100.4	6.0	246.4
1980/1981	95.7	101.2	70.9	37.4	11.7	8.3	22.5	21.4	153.7	115.0	0.8	64.4
1981/1982	107.9	152.7	61.3	29.2	16.1	7.2	35.3	75.8	323.7	183.2	10.0	41.5
1982/1983	90.5	137.4	121.3	47.4	19.1	8.8	13.5	23.8	37.8	60.3	18.1	86.8
1983/1984	60.5	180.7	190.7	74.7	62.4	86.0	115.9	85.4	150.3	289.0	5.4	91.2
1984/1985	165.5	90.5	41.0	41.5	5.1	4.3	27.5	61.1	391.4	329.4	17.9	78.3

Historical flow data for POLGOLLE reservoir (Million Cubic Meters)

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949/1950	69.3	88.0	144.3	67.8	72.3	44.8	29.8	34.4	63.6	27.6	9.3	82.0
1950/1951	55.4	64.5	22.7	282.5	55.5	24.7	47.8	24.8	44.0	72.7	0.1	59.3
1951/1952	45.5	115.0	79.6	133.2	57.6	16.2	51.6	118.0	126.9	74.0	13.4	26.3
1952/1953	98.0	73.7	45.0	46.3	19.8	24.6	45.4	15.3	33.1	49.7	8.3	6.0
1953/1954	59.0	45.4	42.4	45.8	38.8	58.3	35.0	52.9	36.6	29.5	0.7	47.8
1954/1955	95.4	71.6	181.8	181.2	100.0	47.9	81.4	52.7	41.7	44.7	4.2	57.3
1955/1956	50.3	52.0	45.0	46.2	15.1	29.1	30.9	40.5	163.8	47.4	5.0	4.0
1956/1957	51.3	104.5	82.2	492.0	81.4	37.6	25.5	26.9	102.2	119.3	3.9	22.8
1957/1958	39.3	191.3	492.0	170.1	40.4	33.2	92.0	117.2	108.0	52.2	15.0	22.3
1958/1959	30.1	90.3	68.3	43.6	17.2	11.6	47.3	35.3	43.5	84.1	6.2	30.0
1959/1960	134.6	140.4	105.6	134.0	230.7	61.8	54.3	57.5	69.6	100.9	3.4	150.0
1960/1961	71.9	144.2	45.8	55.2	37.1	26.6	28.9	93.1	47.4	58.4	7.1	38.9
1961/1962	45.5	127.5	116.3	106.4	62.7	24.5	61.3	157.1	78.9	88.0	9.5	140.6
1962/1963	135.6	91.7	111.0	141.3	83.1	37.5	54.8	34.0	55.9	67.4	6.1	49.5
1963/1964	83.1	111.1	169.8	196.6	139.6	73.0	34.6	49.2	26.3	82.3	2.5	58.1
1964/1965	46.3	113.2	78.4	49.8	127.3	31.1	83.3	130.2	39.5	10.8	1.1	24.9
1965/1966	66.4	116.9	124.4	80.1	35.7	41.3	50.4	20.3	25.0	39.3	4.1	98.8
1966/1967	67.5	106.3	58.9	79.3	104.1	52.5	37.5	21.5	50.3	71.0	2.5	34.2
1967/1968	89.4	185.5	217.2	62.6	25.1	36.3	40.7	52.5	21.6	123.7	0.0	68.3
1968/1969	108.4	154.5	146.0	61.9	22.3	19.1	87.3	80.2	94.7	39.7	8.1	69.3
1969/1970	129.7	87.9	140.0	102.6	163.0	31.0	60.4	39.4	57.8	53.8	9.3	39.1
1970/1971	123.2	108.7	195.2	141.3	29.4	29.5	49.0	56.4	60.3	51.8	10.9	149.2
1971/1972	66.8	13.7	244.0	63.2	20.4	8.7	28.3	73.3	13.6	80.4	6.9	15.4
1972/1973	86.3	157.6	302.9	24.9	11.8	3.7	17.9	4.0	17.3	48.4	4.9	21.0
1973/1974	27.6	75.8	122.2	26.3	11.2	10.5	22.3	26.6	25.1	49.7	13.0	75.6
1974/1975	31.9	98.0	70.9	44.9	13.0	24.0	20.8	55.1	92.9	16.0	4.4	64.5
1975/1976	43.9	141.0	88.3	83.5	21.6	8.5	20.5	3.7	4.7	15.3	4.6	24.6
1976/1977	72.2	92.0	59.8	12.2	9.4	12.9	24.6	82.7	55.2	35.9	6.7	7.3
1977/1978	141.2	91.7	76.0	34.4	27.3	36.8	15.9	96.4	21.9	69.5	9.7	14.6
1978/1979	83.6	205.3	98.5	35.0	5.3	16.6	14.4	17.3	13.5	12.4	1.9	23.0
1979/1980	39.7	166.8	83.1	24.1	1.5	0.8	15.2	23.0	16.7	35.6	7.3	19.0
1980/1981	54.6	96.5	50.5	40.5	24.9	13.0	21.3	20.4	53.9	35.0	0.9	52.3
1981/1982	35.4	64.3	28.9	18.7	3.4	7.2	14.8	37.8	39.1	9.1	2.5	7.3
1982/1983	50.6	83.7	155.9	29.7	4.3	11.8	11.1	16.9	5.2	8.8	2.0	9.6
1983/1984	52.0	105.0	141.2	136.3	77.7	78.2	81.6	80.4	51.3	78.5	6.4	47.4
1984/1985	70.2	69.2	52.5	62.9	30.0	18.2	22.0	41.3	63.9	64.3	0.4	34.0

Historical flow data for VICTORIA reservoir (Million Cubic Meters)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1949/1950	40.9	74.2	143.2	80.5	67.1	44.9	17.3	18.7	16.5	8.9	0.2	27.1
1950/1951	28.4	33.7	23.0	282.5	37.4	19.6	34.5	23.0	17.8	27.4	7.1	28.0
1951/1952	23.6	82.6	93.7	174.7	52.0	12.8	33.0	58.4	37.5	34.1	9.7	22.2
1952/1953	43.0	63.5	58.9	72.6	24.0	21.1	31.9	4.3	13.8	22.2	8.9	3.0
1953/1954	34.4	40.1	62.5	64.7	40.2	44.2	22.9	14.6	6.6	9.4	9.4	18.5
1954/1955	65.1	66.0	175.1	240.2	121.5	37.4	52.6	17.3	11.2	13.1	8.7	28.7
1955/1956	27.1	32.1	67.4	73.2	26.4	20.8	13.2	11.4	67.6	13.2	4.4	1.1
1956/1957	28.3	23.2	107.3	97.4	78.5	41.0	14.5	14.0	28.7	43.3	9.7	15.4
1957/1958	26.0	151.8	447.0	470.8	65.8	65.4	59.1	65.7	42.1	17.5	3.8	21.6
1958/1959	46.2	62.2	82.3	57.3	22.3	9.6	27.7	20.4	19.0	25.6	0.2	16.3
1959/1960	92.6	121.7	123.0	142.7	243.0	71.2	26.8	23.5	17.0	54.9	9.7	49.8
1960/1961	50.0	88.6	54.0	67.7	42.4	27.9	19.9	33.3	15.5	19.1	9.0	17.6
1961/1962	31.2	132.7	130.2	167.3	89.0	30.6	40.7	74.2	25.4	25.4	7.9	51.1
1962/1963	73.9	92.3	123.0	140.3	106.9	27.3	40.0	33.3	18.8	28.5	1.3	32.8
1963/1964	50.8	95.6	160.5	229.2	175.6	76.6	23.9	26.4	7.6	41.8	4.9	22.5
1964/1965	25.8	63.8	82.3	63.3	141.6	20.6	55.1	96.3	10.7	6.0	2.5	9.5
1965/1966	47.4	99.1	129.0	110.4	46.9	35.0	42.7	31.3	10.9	12.3	5.5	44.3
1966/1967	50.4	87.2	57.6	87.6	105.4	42.4	26.1	11.9	18.2	17.5	4.8	20.5
1967/1968	57.4	153.7	167.4	81.9	17.4	30.6	19.5	28.9	6.7	32.9	7.6	25.5
1968/1969	73.3	104.3	144.7	79.0	35.3	19.1	64.8	33.9	26.6	20.0	9.7	35.2
1969/1970	84.5	70.4	140.2	166.9	155.3	25.8	36.4	26.6	15.1	15.4	7.3	17.4
1970/1971	58.3	78.1	206.3	209.1	26.1	23.5	29.6	35.8	22.0	21.2	8.9	63.1
1971/1972	44.3	14.5	230.7	81.8	46.1	7.1	16.7	39.2	4.5	28.0	1.8	12.5
1972/1973	72.6	145.9	295.2	49.5	16.4	3.3	11.0	2.3	7.2	17.6	1.4	15.7
1973/1974	24.3	68.2	116.2	40.5	10.6	8.8	12.4	12.6	7.7	18.4	7.5	28.6
1974/1975	18.2	28.7	85.3	67.9	12.4	16.5	13.6	31.9	34.2	7.3	7.2	29.7
1975/1976	15.7	65.8	98.3	109.7	31.2	8.2	13.5	6.8	1.6	5.3	9.9	8.8
1976/1977	36.5	63.5	50.6	18.9	10.9	10.3	13.2	38.2	13.8	18.8	8.3	7.1
1977/1978	92.0	59.9	95.1	65.0	27.1	29.2	11.8	44.6	4.4	27.1	7.0	4.1
1978/1979	56.8	108.5	113.3	46.7	5.3	10.6	8.8	7.4	5.3	5.5	3.7	11.2
1979/1980	31.0	109.4	81.9	53.2	7.5	1.1	10.9	14.7	4.3	9.3	5.5	8.2
1980/1981	40.3	79.5	50.5	48.4	34.8	10.9	16.5	17.0	14.1	17.2	7.6	23.0
1981/1982	20.9	42.3	32.9	30.5	5.6	5.8	9.3	17.4	11.7	4.6	1.2	3.1
1982/1983	31.9	60.1	164.2	53.3	11.5	7.2	7.0	3.8	1.8	4.6	1.0	4.7
1983/1984	32.4	74.4	160.3	170.1	87.7	106.1	45.9	43.4	14.8	27.6	4.7	24.6
1984/1985	43.4	55.2	60.3	79.8	34.1	15.8	13.5	20.4	19.7	22.5	6.3	18.1

Historical flow data for RANDENIGALE reservoir (Million Cubic Meter)

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949/1950	45.6	67.6	54.1	59.5	33.8	26.5	46.4	45.5	29.3	30.3	2.8	28.7
1950/1951	54.1	100.7	174.4	122.7	73.2	58.0	64.1	69.7	43.3	27.6	6.0	19.3
1951/1952	67.5	127.0	161.2	122.1	166.5	80.2	82.9	66.2	35.9	47.3	1.0	26.2
1952/1953	50.4	59.6	28.1	81.0	54.9	35.1	66.9	72.2	41.5	35.6	5.1	28.6
1953/1954	43.8	73.2	77.4	82.3	60.6	47.9	45.6	52.6	23.4	26.8	4.7	29.4
1954/1955	31.6	133.1	524.7	275.5	149.3	125.2	84.6	69.8	42.7	37.1	1.6	22.4
1955/1956	39.5	40.4	20.8	20.4	15.4	6.8	10.5	20.0	21.9	40.5	8.0	39.5
1956/1957	40.9	65.1	52.3	52.6	47.9	35.0	39.0	43.4	31.0	27.0	8.8	23.5
1957/1958	67.2	149.7	333.6	166.4	70.6	66.4	76.8	70.8	33.6	31.2	1.7	19.9
1958/1959	47.2	64.5	63.8	47.7	28.4	15.7	50.8	51.1	42.3	35.0	9.5	22.3
1959/1960	57.1	60.2	60.1	86.7	145.5	72.8	80.0	55.3	28.9	47.3	6.3	35.7
1960/1961	53.4	53.5	34.5	75.4	60.0	49.4	59.9	77.1	37.7	29.5	8.8	28.9
1961/1962	31.0	65.6	32.7	40.3	47.6	37.4	43.2	58.7	27.0	25.5	4.3	28.7
1962/1963	49.3	42.6	54.0	83.7	59.9	40.5	53.1	45.3	29.9	24.9	9.4	22.4
1963/1964	56.1	84.3	107.1	110.3	61.2	68.2	37.6	35.4	26.4	26.8	3.9	24.6
1964/1965	45.3	69.7	55.1	79.1	53.6	35.5	58.7	50.7	31.1	28.7	2.6	25.5
1965/1966	49.3	83.1	92.0	64.1	53.4	35.6	46.1	35.3	21.5	30.4	2.7	29.5
1966/1967	41.3	52.9	37.8	64.6	53.6	38.4	38.0	40.3	24.5	32.0	1.4	29.3
1967/1968	47.5	72.7	73.7	43.0	31.5	18.8	32.7	40.5	27.6	34.7	3.3	25.4
1968/1969	50.1	72.2	104.7	85.3	68.0	44.7	45.5	43.7	26.3	30.8	9.6	28.8
1969/1970	52.9	89.1	135.8	110.4	68.4	49.3	64.9	67.7	31.8	29.4	6.4	24.6
1970/1971	73.2	94.7	151.8	108.6	106.7	62.2	126.7	72.5	45.0	47.0	9.8	35.2
1971/1972	41.5	53.9	52.8	52.5	45.7	25.6	42.1	58.2	25.2	27.0	1.3	23.0
1972/1973	51.9	73.2	61.7	94.0	116.6	63.1	74.7	79.6	48.1	36.3	9.3	24.4
1973/1974	39.8	65.9	131.6	100.4	60.4	30.6	104.2	74.8	47.8	45.6	1.3	27.1
1974/1975	49.5	54.9	44.7	95.7	66.0	51.9	67.0	53.2	39.3	34.3	6.6	28.8
1975/1976	40.0	40.2	33.4	62.9	27.2	23.7	43.1	45.1	22.1	17.1	8.0	19.3
1976/1977	46.0	62.6	45.8	64.7	39.7	34.5	40.8	43.5	25.1	28.3	9.4	24.7
1977/1978	58.9	79.7	32.0	80.5	70.8	50.0	65.9	74.3	36.6	36.6	0.1	28.9
1978/1979	48.0	70.4	84.4	85.5	48.6	38.3	30.7	32.4	23.4	28.1	1.3	26.9
1979/1980	39.1	50.1	39.1	73.1	76.4	45.7	61.9	46.4	34.1	28.1	0.3	23.4
1980/1981	43.4	68.3	53.1	39.9	24.4	14.6	19.9	27.9	18.6	35.2	9.6	38.5
1981/1982	40.7	64.3	42.6	45.8	37.0	25.7	32.9	39.1	27.7	28.7	0.6	25.9
1982/1983	48.2	73.1	80.6	74.5	56.1	33.2	29.8	37.8	24.1	25.4	9.0	25.7
1983/1984	43.4	62.5	60.8	81.4	61.4	51.4	66.4	58.9	32.7	35.6	6.2	26.4
1984/1985	44.2	63.3	35.5	50.4	39.4	28.1	37.1	37.5	26.7	28.1	9.8	25.7

Historical flow data for RANTEMBE reservoir (Million Cubic Meters)

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949/1950	18.0	48.0	129.9	76.7	33.0	54.3	16.5	15.2	13.2	16.4	5.0	23.8
1950/1951	24.2	25.2	30.4	204.7	41.3	21.1	33.5	18.1	28.6	19.3	8.9	26.5
1951/1952	44.5	74.9	86.5	127.5	49.4	26.2	30.2	39.3	44.5	33.3	9.4	19.3
1952/1953	84.4	76.8	53.3	43.7	35.2	35.2	47.3	3.3	6.5	22.1	7.1	11.8
1953/1954	50.4	54.9	75.2	112.3	63.3	57.9	60.9	30.9	22.9	22.2	9.8	11.7
1954/1955	52.0	52.3	141.2	151.4	85.3	48.2	61.9	60.6	47.1	33.6	0.3	37.5
1955/1956	36.8	37.9	49.0	35.6	9.7	11.3	10.9	7.7	24.3	10.7	7.1	7.0
1956/1957	21.6	87.4	75.9	64.2	62.0	43.5	22.3	31.6	45.3	29.2	1.0	8.1
1957/1958	48.1	115.3	308.2	118.7	26.7	64.7	58.2	46.3	14.6	11.6	0.3	6.8
1958/1959	31.7	35.0	62.8	36.2	14.5	6.8	20.6	26.7	18.3	29.2	0.2	12.6
1959/1960	38.8	55.3	76.9	70.5	145.0	48.3	39.9	23.8	16.9	33.0	8.9	11.1
1960/1961	32.5	97.4	54.3	86.7	40.9	23.9	22.8	29.9	17.0	16.5	2.5	8.6
1961/1962	12.7	64.0	84.4	87.7	44.2	19.5	34.8	54.3	16.2	15.6	5.6	17.7
1962/1963	60.9	49.5	85.6	131.0	77.0	22.7	34.3	17.6	11.0	10.7	9.8	7.4
1963/1964	13.7	57.9	135.1	142.9	92.1	49.4	24.5	21.2	12.5	17.7	3.1	12.2
1964/1965	13.7	41.1	75.5	40.6	58.5	19.1	41.2	53.0	17.6	8.1	7.0	6.3
1965/1966	33.7	63.9	101.4	60.9	33.2	38.4	27.2	11.7	8.8	6.2	3.5	14.9
1966/1967	36.7	93.1	56.8	59.3	71.7	23.7	17.2	12.5	9.4	6.9	8.5	4.1
1967/1968	38.6	105.6	156.3	63.9	18.3	37.4	20.3	11.2	7.7	18.7	9.7	6.3
1968/1969	28.8	65.8	112.0	79.3	46.1	25.1	36.1	21.8	16.5	8.3	6.2	13.3
1969/1970	55.1	41.8	105.2	92.0	119.3	26.4	41.1	25.0	11.9	8.7	5.9	9.4
1970/1971	22.7	38.8	81.6	97.8	33.8	23.9	37.4	30.3	19.9	11.7	4.9	42.5
1971/1972	32.1	28.7	188.8	39.5	19.4	4.7	14.9	44.1	11.4	14.3	7.3	5.8
1972/1973	53.1	57.3	123.4	21.1	20.7	10.5	12.6	9.3	7.1	6.0	5.2	4.4
1973/1974	7.3	23.4	101.2	47.3	8.8	7.2	20.6	10.6	9.8	14.5	8.7	27.4
1974/1975	17.6	13.0	55.8	45.8	21.7	25.4	12.3	13.1	15.9	12.7	6.7	15.7
1975/1976	23.5	58.2	64.3	28.4	7.8	34.1	20.6	16.7	10.2	25.4	7.2	9.2
1976/1977	30.9	68.5	65.1	15.7	18.1	14.0	23.9	10.9	10.6	11.6	4.6	5.0
1977/1978	30.4	64.5	90.9	26.5	44.6	22.7	29.3	5.6	11.3	3.9	3.6	5.7
1978/1979	38.3	61.9	44.1	39.6	74.2	23.4	29.0	31.0	15.6	15.8	2.1	32.7
1979/1980	42.5	40.0	24.1	25.9	39.8	24.2	29.2	9.7	14.3	6.1	5.5	6.6
1980/1981	31.4	49.9	104.4	62.7	38.3	25.5	12.5	10.6	2.7	7.1	9.1	15.0
1981/1982	26.3	29.2	53.3	17.8	17.4	14.7	14.5	10.1	11.9	22.7	1.2	11.0
1982/1983	30.2	62.3	132.7	16.5	15.0	17.5	13.9	11.3	10.4	6.5	7.3	3.7
1983/1984	16.8	26.3	74.8	123.4	113.3	58.9	61.3	21.0	14.5	15.3	3.1	28.7
1984/1985	50.6	55.3	63.9	55.2	42.9	50.7	24.8	12.6	13.3	27.3	4.3	7.3

Historical flow data for BOWATTENNE reservoir (Million Cubic Meters)

Appendix 2

PROBABILITY AND CALCULATED DEMANDS FOR KOTMALE RESERVOIR

PROB	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
0.14	101.999	81.299	56.642	49.286	49.286	49.286	49.286	49.286	81.668	109.856	97.990	83.723
0.29	100.564	79.873	55.216	49.286	49.286	49.286	49.286	49.286	80.242	108.421	96.555	82.298
0.43	100.279	79.590	54.933	49.286	49.286	49.286	49.286	49.286	79.959	108.136	96.270	82.015
0.57	100.181	79.493	54.835	49.286	49.286	49.286	49.286	49.286	79.861	108.038	96.171	81.917
0.71	100.148	79.460	54.802	49.286	49.286	49.286	49.286	49.286	79.829	108.005	96.139	81.884
0.86	100.038	79.351	54.693	49.286	49.286	49.286	49.286	49.286	79.720	107.895	96.029	81.775
1.00	99.775	79.090	54.432	49.286	49.286	49.286	49.286	49.286	79.459	107.632	95.766	81.514
1.14	99.709	79.024	54.367	49.286	49.286	49.286	49.286	49.286	79.393	107.566	95.700	81.449
1.28	99.655	78.970	54.312	49.286	49.286	49.286	49.286	49.286	79.339	107.512	95.645	81.394
1.43	99.315	78.633	53.975	49.286	49.286	49.286	49.286	49.286	79.001	107.172	95.306	81.057
1.57	99.304	78.622	53.964	49.286	49.286	49.286	49.286	49.286	78.991	107.161	95.295	81.046
1.71	98.964	78.284	53.627	49.286	49.286	49.286	49.286	49.286	78.653	106.821	94.835	80.709
1.85	98.844	78.165	53.507	49.286	49.286	49.286	49.286	49.286	78.533	106.701	94.835	80.589
2.00	98.778	78.099	53.442	49.286	49.286	49.286	49.286	49.286	78.468	106.635	94.769	80.524
2.14	98.745	78.067	53.409	49.286	49.286	49.286	49.286	49.286	78.436	106.602	94.736	80.447
2.28	98.701	78.023	53.365	49.286	49.286	49.286	49.286	49.286	78.392	106.558	94.692	80.404
2.43	98.658	77.969	53.311	49.286	49.286	49.286	49.286	49.286	78.348	106.515	94.648	80.393
2.57	98.647	77.958	53.300	49.286	49.286	49.286	49.286	49.286	78.338	106.504	94.637	80.382
2.71	98.636	77.958	53.300	49.286	49.286	49.286	49.286	49.286	78.327	106.493	94.626	80.382
2.85	98.636	77.958	53.300	49.286	49.286	49.286	49.286	49.286	78.327	106.493	94.626	80.382
3.00	98.581	77.903	53.246	49.286	49.286	49.286	49.286	49.286	78.272	106.438	94.572	80.328
3.14	98.340	77.664	53.006	49.286	49.286	49.286	49.286	49.286	78.033	106.197	94.331	80.088
3.28	98.318	77.642	52.984	49.286	49.286	49.286	49.286	49.286	78.011	106.175	94.309	80.066
3.42	98.186	77.512	52.854	49.286	49.286	49.286	49.286	49.286	77.880	106.043	94.177	79.936
3.57	98.175	77.501	52.843	49.286	49.286	49.286	49.286	49.286	77.870	106.033	94.166	79.925
3.71	98.165	77.490	52.832	49.286	49.286	49.286	49.286	49.286	77.859	106.022	94.155	79.914
3.85	98.132	77.457	52.799	49.286	49.286	49.286	49.286	49.286	77.826	105.989	94.122	79.881
3.99	98.033	77.359	52.701	49.286	49.286	49.286	49.286	49.286	77.728	105.890	94.024	79.783
4.14	97.989	77.316	52.658	49.286	49.286	49.286	49.286	49.286	77.684	105.846	93.980	79.740
4.28	97.945	77.272	52.614	49.286	49.286	49.286	49.286	49.286	77.641	105.802	93.936	79.696
4.42	97.923	77.250	52.593	49.286	49.286	49.286	49.286	49.286	77.619	105.780	93.914	79.675
4.56	97.923	77.250	52.593	49.286	49.286	49.286	49.286	49.286	77.619	105.780	93.914	79.675
4.71	97.913	77.239	52.582	49.286	49.286	49.286	49.286	49.286	77.608	105.770	93.903	79.664
4.85	97.891	77.218	52.560	49.286	49.286	49.286	49.286	49.286	77.587	105.748	93.881	79.642
4.99	97.891	77.218	52.560	49.286	49.286	49.286	49.286	49.286	77.587	105.748	93.881	79.642
5.14	97.880	77.207	52.547	49.286	49.286	49.286	49.286	49.286	77.499	105.660	93.761	79.631
5.28	97.803	77.131	52.440	49.286	49.286	49.286	49.286	49.286	77.467	105.627	93.750	79.522
5.42	97.770	77.098	52.410	49.286	49.286	49.286	49.286	49.286	77.456	105.616	93.750	79.511
5.56	97.759	77.087	52.429	49.286	49.286	49.286	49.286	49.286	77.456	105.616	93.750	79.511
5.71	97.759	77.087	52.429	49.286	49.286	49.286	49.286	49.286	77.456	105.616	93.750	79.511
5.85	97.639	76.967	52.299	49.286	49.286	49.286	49.286	49.286	77.336	105.496	93.629	79.392
5.99	97.628	76.956	52.288	49.286	49.286	49.286	49.286	49.286	77.325	105.485	93.618	79.381
6.13	97.617	76.946	52.277	49.286	49.286	49.286	49.286	49.286	77.314	105.474	93.607	79.370
6.28	97.606	76.935	52.277	49.286	49.286	49.286	49.286	49.286	77.304	105.463	93.597	79.359
6.42	97.595	76.924	52.266	49.286	49.286	49.286	49.286	49.286	77.293	105.452	93.586	79.348
6.56	97.518	76.848	52.190	49.286	49.286	49.286	49.286	49.286	77.216	105.375	93.509	79.272
6.70	97.485	76.815	52.157	49.286	49.286	49.286	49.286	49.286	77.184	105.342	93.476	79.239
6.85	97.463	76.793	52.135	49.286	49.286	49.286	49.286	49.286	77.162	105.320	93.454	79.217
6.99	97.463	76.793	52.135	49.286	49.286	49.286	49.286	49.286	77.162	105.320	93.454	79.217

