A COMPARISON OF THE PERFORMANCE OF THREE CONCEPTUAL MATHEMATICAL MODELS OF THE RAINFALL-RUNOFF PROCESS IN THE MAREETSANE CATCHMENT

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by

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PREFACE

The objective of the thesis is to make a critical assessment of the performance of three relatively simple deterministic models of the rainfall-runoff process. The need to evaluate and compare deterministic models arises because of the large number of models which are available in the literature. A number of the available models would appear to be equally suitable for a given situation whereas many models are found to be valid only under the specific range of conditions for which they were developed. Therefore there is a need for guidelines to allow the most judicious selection of a model for a particular set of circumstances. The models used in the study will be tested in a semi-arid catchment to determine their applicability under ephemeral flow conditions.

In addition to the great number of models available, the hydrologist also has a wide range of models of different structural complexity from which to make a choice. Many models have been found to be unnecessarily complex for a given application and hence there is a need for indications as to the minimum level of complexity required for acceptable model output. These indications would allow the selection of a model which is just sufficiently complex to be compatible with the intended application. Structurally simple models are used in the study to determine the extent to which simple models can produce output at an acceptable level of accuracy. Furthermore, the models chosen for study are of different levels of structural complexity and a comparison of model performance will provide indications as to the minimum level of complexity required for acceptable output.

The development of mathematical models in hydrology has come about largely in response to a lack of streamflow data. Practising hydrologists frequently have to make predictions regarding the frequency and magnitude of flood events and the expected yield of a particular catchment when designing structures such as dams and reservoirs as components of water resource systems. Predictions as to the sizes of floods and the volume of water available may be made with a measure of confidence if the river concerned has been gauged for a long period of time. Projected information about the nature of the flow regime is based upon an analysis of the long record and the assumption that trends observed in the recorded runoff data will continue into the future.

The hydrologist, however, is usually confronted by the situation where the existing flow record is either too short or, as is generally the case, the data are completely lacking. Runoff data which are of short duration do not allow reliable predictions to be made because there is less likelihood of the more extreme flow events being included in the short record. If no runoff record whatsoever exists, any predictions as to the nature of the flow regime are likely to be even more unreliable.

In response to the lack of runoff records, various methods have been devised to overcome the problem and are discussed in Chapter I. The current approach to solving the problem of inadequate data is the use of simulation models of which there are two main types. Stochastic models make use of the existing runoff record to extend the data and so provide adequate information for design calculations. Deterministic models are based upon the observation that there is a causative relationship between rainfall and runoff. The models express the relationship mathematically and use recorded rainfall data to produce a runoff record for analysis. Rainfall data of adequate length are usually available but may be stochastically generated if of too short duration. Deterministic models were chosen for study for a number of reasons which are elaborated in Chapter I. The three models were selected from the range of models available and their structures are described in Chapter II in relation to examples of other deterministic models.

The models chosen for study will be tested by calibrating them according to three objective functions which were developed to represent three engineering applications. The use of objective functions in the calibration process ensures objective rather than subjective assessment of the calibration results. Chapter III deals with the objective functions used and the hypotheses arising out of a consideration of the model structures in the light of the objective functions selected.

The first stage in the research was the selection of a study catchment and the processing of the data into a form suitable for model input. Specific criteria regarding the choice of a catchment were laid down and are discussed in Chapter IV. The final choice of the Mareetsane Catchment was made after a lengthy process of elimination from the more than 600 gauged catchments in South Africa. In order to obtain the data, it was necessary to go to Pretoria as there are no facilities for getting the data on demand. Streamflow data for the catchment were obtained from the Department of Water Affairs in the form of computer print-out. The rainfall data were extracted manually from the original records of the South African Weather Bureau and had to be written out on computer format sheets. Both the rainfall and runoff data were not in a form compatible with the model input requirements and had to be processed. Data processing involved the writing and development of three computer programs and a great deal of manual calculation. In view of the time-consuming nature of the work involved in getting the data into the correct form, a single catchment was chosen for study and is described in Chapter IV.

The next stage in the research was to write and develop the computer programs to operate the models. It is very rare that models are published in the form of computer programs and the development of the programs had to begin from first principles using the descriptions of the models in the literature. Once the models were operating satisfactorily, the calibration process could begin. The method of calibration used was trial and error manipulation of the model parameters and was necessitated by the limitations of computer core-space and time. Trial and error calibration is a lengthy procedure even for relatively simple models with few parameters because of the interaction of parameters of different sensitivities. Each model had to be calibrated three times, once for each objective function and the nature of one of the objective functions necessitated the writing of two separate programs in order to calculate the value of the function. In view of the time-consuming process involved in developing the objective functions and model calibration, the combination of three models and three objective functions provided the limit of the research within the time available.

The results of the calibration process are discussed in Chapter V and each hypothesis is examined as to its validity in the light of the calibration results. The final chapter contains an assessment of the overall results of the study and makes recommendations for further research.

Terminology: Throughout the text the terms evaporation and evapotranspiration are used synonymously.

Errata: Throughout the text the use of the word data should be in the plural.

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CHAPTER I

INTRODUCTION

The major portion of the total water consumption in South Africa is derived from surface resources. Midgley and Pitman (1969) estimated that surface water utilization amounted to one-seventh of the average annual flow of South African rivers. The figure of one-seventh was expected to rise to a third by the time all projects then under construction had been completed and continue to rise sharply as the economy expanded. In view of the increasing demand on surface water resources and South Africa's extremely erratic rainfall and high evaporation, there is an urgent need to efficiently plan for the optimum development and utilization of the country's water resources. With this need in mind, many water resource systems consisting of dams and reservoirs linked by canals, tunnels and pipelines have been planned and constructed to meet the water demand of the nation.

Hydrologists involved in the design of water resource systems are concerned generally with the magnitude and duration of streamflow over time from any particular catchment (Wilson, 1974). Reliable information as to the nature of the flow regime for a particular area may be obtained readily from an analysis of historical runoff data if these are available for a sufficient length of record. Historic data comprise any record of the flow of a river or the amount of rainfall regardless of the data length as distinct from artificial or synthetic data which are generated by a model.

The hydrologist is, however, usually confronted by the lack of reliable streamflow records which are vital for the design and operation of water resource systems (Bonne, 1970). More often than not, historic rainfall data are available for an adequate period of record, but runoff data have been gathered at relatively few locations and usually these records are of short duration (Midgley and Pitman, 1969). Fahlbusch and Muir (1973) point out that recent investigations have shown runoff records of inadequate length to be of little use in the design of water resource systems because such data cannot provide an adequate assessment of the risks involved. For example, "... risk is involuntarily involved in using a design flood having the return period greater than the number of years of record" (Pinkayan and Premchun, 1972, p. 334). In the case of design storage capacity, inadequate length of data usually leads to an overestimation of the required storage capacity and a consequent, unnecessary, increase in the construction costs.

According to Fleming (1975), a number of techniques of mathematical hydrology have been developed in attempting to overcome the problem of inadequate runoff data and so provide sufficient information for analysis in design calculations. The techniques may be grouped into two broad categories, namely stochastic and deterministic methods. Within the group of deterministic methods, two approaches are important. The first is the empirical approach which is non-process orientated and the second is the conceptual approach which considers the component processes and their interrelationships. The empiric, stochastic and deterministic methods are discussed with reference to their applications.

Empirical methods have been devised in order to provide design estimates for catchments which lack the necessary historic runoff data required for analysis. The empiric approach to solving the problem of inadequate runoff data involves the derivation of mathematical equations which given a specified input, yield an output. The mathematical equations are derived with little consideration of the relationship between the parameters used and the processes which the equation represents. An example of the empirical approach is the Rational Formula which has been applied by the Hydrological Research Unit, University of the Witwatersrand (Report 1/72, 1972) to determine the peak discharge rate from small catchments. The formula relates the peak rate of discharge to the catchment area and the intensity of rainfall by means of a regionalised parameter. The value of the parameter used for each catchment is based largely upon the hydrologist's judgement and experience (Fleming, 1975). While the formula is still used by engineers to design culverts and other minor structures, the estimates obtained can be highly misleading because of the use of the regionalised parameter which has such imprecise values.

As an alternative approach to solving the problem of inadequate runoff data, the hydrologist increasingly has been making use of simulation techniques to provide the data upon which to base design calculations. The trend towards simulation modelling has been identified by Ward (1974) as one of the major trends in hydrology at present. The use of simulation models has been facilitated to a great extent by the development of high-speed digital computers which handle the considerable computational effort involved (Phatarfod 1976; Bugliarello and Gunther 1974). The other two methods besides the empirical approach which attempt to overcome the problem of inadequate runoff data, make use of either the stochastic or the deterministic conceptual approach in simulation model development.

Simulation may be defined as "... the development and application of mathematical models to represent the time-variant interaction of physical processes" (Moore and Claborn, 1971, p. 296). A mathematical model is taken to be "... a collection of quantitative hydrologic concepts which are given mathematical representations" (Crawford and Linsley, 1966, p. 7). In general terms, simulation models may be grouped into the two broad categories referred to above, as being predominantly stochastic or predominantly deterministic in structure. The two types of model have different characteristics and as Delleur (1971a) states, the nature of the problem to be solved is the deciding criterion when choosing between the two types of model because one is more suitable for a given situation than the other. Within the general problem of inadequate runoff data, two specific situations may arise.

The first situation which may face the hydrologist is that where some historic streamflow data are available but the record is of inadequate length for reliable analysis. To overcome this problem, either a stochastic or a deterministic model may be selected. Stochastic models treat the existing runoff record as a sequence of events which is time dependent. The existing runoff record is used to determine statistical parameters which describe the characteristics of the data. These parameters and a source of stochastic elements (random number generator) are used to produce any required length of record (Pitman, 1973). The data which is generated in this way is known as synthetic data as opposed to artificial data which is produced by a deterministic model. The synthetic output from a stochastic model is non-unique because of the random generator which produces a different output for each run of the model.

According to Bonne (1970), many stochastic models for the generation of data either forward or backward in time are based upon regression models. These stochastic models usually make use of a Markovian process and relate the streamflow for the current time interval to that of the previous time interval. The Markovian technique treats the existing runoff data as nonpure random data, that is, data which are composed of random and ~~causal~~ deterministic elements. Alternatively, another stochastic method known as the Monte Carlo technique considers the data to be purely random, that is, the data is composed of totally [illegible]ependent events. The model defines the probability distribution of the existing runoff data and by means of a selected random generator, produces the synthetic output of the required length for analysis.

Stochastic models do have their limitations and it must be remembered that, as Yevjevich (1972) states, the information contained in the large generated record is no greater than that contained in the small sample from which it was derived. Further, the actual physical processes occuring in the catchment are ignored in stochastic simulation (Eagleson, 1971). The only requirement is that the statistical characteristics of the small sample be preserved in the generated record (Raudkivi and Lawgun, 1974). Because the actual physical processes occuring in nature are not represented in stochastic models, the model parameters have no physical interpretation. The lack of physically based parameters precludes the use of stochastic models in ungauged catchments where model parameters have to be estimated from the physical features of the watershed. Another reason why stochastic models cannot be applied in ungauged catchments is because they have no data whatsoever from which to generate a long runoff record for analysis. The fact that stochastic models cannot be applied in ungauged catchments therefore severely limits their usefulness.

Despite these disadvantages, the case for using stochastic models for the extension of existing runoff records is convincing and many stochastic models have been devised, for example, Chow (1971) and Chow and Kareliotis (1970). One of the foremost proponents of stochastic methods is Yevjevich who points out that most hydrological variables are random in time and space or are the result of past random processes (Yevjevich, 1974). For example, rainfall may be considered to be a purely random variable over time and space and the infiltration capacity of a catchment is also random with respect to time and space. Therefore, it would appear to be more logical to use stochastic simulation because of the strong random component in hydrological processes. However, in spite of the random nature of hydrological variables and processes, many hydrological simulation methods are deterministic in structure. It must be borne in mind, however, that "... a deterministic function among a set of random variables does not mean a deterministic explanation of hydrologic processes" (Yevjevich, 1974, p. 233).

When dealing with a catchment which has some historic runoff data but of inadequate length, the hydrologist alternatively may use a deterministic model to extend the runoff record. The deterministic approach is directed towards identifying and studying the components of the hydrological cycle and their interrelationships (Chaudhry, 1975). The components of the hydrological cycle are then combined conceptually and the interrelationships expressed mathematically to represent the time-variant interaction of the processes which make up the hydrological cycle. In using the deterministic approach, the hydrologist views the hydrological cycle as a system with specific inputs and outputs. Kostrowicki (1976, p. 29) defines a system as "... an ordered set of mutually interacting elements constituting a definite uniform structure". With regard to the hydrological cycle, the elements of the system include rainfall input, evaporation losses, soil moisture storage and runoff output. The deterministic model itself is an abstract system which is an approximation of the real hydrological system. Deterministic models will always be abstractions or simplifications of the real system because the real system cannot be fully understood or measured. Indeed, Chow (1971) emphasizes that the natural hydrological system is so complex that no exact laws have yet been devised that can fully explain the natural hydrological phenomena. Further, it is not feasible nor practicable to adequately monitor the spatial and temporal variations of even the known variables in the hydrological cycle. For example, it is not practicable to measure the infiltration capacity of the soil over even a small catchment. In view of the lack of a full understanding and adequate measurement of hydrological processes, deterministic models can only approximate the complicated hydrological system. An approximation of the hydrological cycle is achieved by making use of assumptions and simplifications such as "lumped" parameters to represent the relationship between variables which cannot be measured practicably and which also vary spatially (Chow, 1971; Delleur, 1971b; Dawdy, Lichty and Bergman, 1972). Furthermore, as Moore (1971) states, these simplifications and assumptions are necessary in order to achieve a workable simulation process.

Essentially, the deterministic model represents the relationship between the rainfall input of the catchment and the runoff output. In the situation where rainfall data is available but the runoff record is of short duration, the model may be calibrated against the historic runoff data by using the appropriate sequence of rainfall data as model input. Once the model is calibrated, the remainder of the rainfall data may be used to generate an extended runoff record. If adequate rainfall data are not available, the rainfall record may be generated stochastically and the synthetic data used as input to the deterministic model. In the calibration process, optimum parameter values are determined by matching the simulated output with the available runoff data. However, Crawford and Linsley (1966) state that finding optimum parameter values for a given mathematical representation does not mean that the mathematical representation is itself optimum. While this statement is true, "... the broader the range of conditions for which the streamflow output can be simulated by a particular program, the greater the confidence that the parameters and processes utilized have realistic physical meaning" (Moore and Claborn, 1971, p. 297).

The first specific situation within the general problem of a lack of runoff data was considered to be that where some historic runoff data was available but was of inadequate length. The other specific problem which may confront the hydrologist or engineer is that of the ungauged catchment which has no historic runoff data at all. Stochastic models cannot be used to overcome this specific problem because the model parameters have no physical interpretation and hence the values of the parameters cannot be ascertained. On the other hand, deterministic models are based upon the physical processes occurring in the catchment and the parameters used to express the relationship between variables have physical meaning. Parameters which have physical interpretation allow the use of deterministic models in the ungauged catchment where the values of the model parameters may be estimated from the physical features of the catchment. In addition, parameters which have realistic physical meaning allow the model to be adjusted to take account of physical changes in the catchment, for example, the reduction of vegetation cover. Using the available rainfall data as model input, which may be stochastically generated if not of adequate length, and suitable model parameter values, an artificial runoff record may be generated. Although it is not possible to determine accurately the validity of such a runoff sequence, the artificial record is based upon the causative rainfall. Therefore deterministic models represent the most suitable method of overcoming the problem of the ungauged catchment.

Deterministic models were chosen for the purposes of this study for two reasons. Firstly, deterministic models attempt to simulate the actual physical processes taking place in the catchment (Dawdy and O'Donnell, 1965). In this respect, deterministic models have an important heuristic property which enables the user to gain a clearer understanding of the processes taking place (Fleming, 1975). Secondly, deterministic models have parameters which have physical interpretation hence allowing the models to be used in ungauged catchments. It is this attribute of deterministic models which makes them more useful for engineering application because ungauged catchments are more common than those for which adequate records exist.

Research Needs and the Choice of Three Deterministic Models

In response to the need to overcome the problem of firstly, runoff data of inadequate length and secondly, the ungauged catchment, there has been a rapid proliferation of conceptual mathematical models in recent years (Dooge, 1971). Indeed, Ward (1974) has identified the development and refinement of conceptual models as one of the major trends in hydrology at present. Theoretically, there is no limit to the number of conceptual models which can be devised and the need for new models must surely have been satisfied to a large extent. The practising hydrologist is therefore presented with a wide variety of conceptual models from which he may choose for either specfic or general applications. For example, models have been built for urban water planning (Wood, 1975; Watt and Kidd, 1975), reservoir management (Pitman, 1976), groundwater management (Marino, 1975; Nutbrown et al, 1975), assessing water resources (Pitman, 1973) and flood control (Todini, 1975; Dawdy et al, 1972). Just as the range of uses of models is very wide, so the range of structural complexity of models is likewise extensive. According to Dawdy and O'Donnell (1965), quantitative models of catchment behaviour must inevitably be complex in order to be acceptably accurate. Such a conclusion would at first appear to be valid in view of the highly complex nature of the hydrological cycle. However, the more sophisticated models should be more accurate to justify their existence and the accuracy of sophisticated models must be measured in terms of their ultimate uses (Dawdy, Lichty and Bergman, 1972). Further, "... if a model is to be used in engineering practice, costs incurred for computer time and data gathering will be important considerations. Hence other factors being equal, the simplest model should be selected" (Watt and Kidd, 1975, p. 226), provided that the output from the model is at an acceptable level of accuracy. A further consideration with regard to the complexity of the model chosen is that the degree of complexity of the model selected should be consistent with the accuracy and representativeness of the primary input, that is, the rainfall data (Pitman, 1977). It is not logical to use a model such as the highly complex Stanford Watershed Model IV (Crawford and Linsley, 1966) to achieve output at great cost when the same output for a particular engineering application can be achieved with a comparable level of accuracy using a simple model at a fraction of the costs involved (Diskin and Simon, 1977). In view of the large number of models of different levels of structural complexity which are available to the user for a wide range of engineering applications, there is a great need for research to test and evaluate the different models. It is necessary to compare the merits of the different models because many models are valid only under very limited conditions or range of conditions (Delleur, 1971c). Further, Dooge (1971) correctly proposes that research is required to develop criteria for the best choice of a model in a given situation and it is towards these research needs that this study is directed. In this research three deterministic models will be selected, tested and then evaluated with respect to three specific engineering applications using data from a semi-arid catchment.

In view of Diskin and Simon's (1977) argument to use the simplest model which is compatible with the intended application, structurally simple models will be chosen in order to assess the extent to which they can produce acceptable output. Specifically three models were chosen so as to keep the research within manageable limits. In addition, the three models chosen had to be structurally different in order to be able to examine the merits of different model structures. The three models also had to have different levels of structural complexity so that the models could be examined to determine if the increase in structural complexity is justified in terms of their output. By using models of different structural complexities, a guide as to the minimum level of structural complexity required for acceptable output could be obtained. Three models which meet the above requirements are the Dalton Watershed Model (Diskin, Buras and Zamir, 1973), Model 15 (Diskin and Simon, 1977) and Model 12

(Simon and Diskin, 1975). The detailed structures of the three models are discussed in Chapter II. These three models are structurally simple in that of the three, only Model 12 has two storages, the other two models consisting of single storages only. The models have different structures and represent a range of structural complexity from the Dalton Watershed Model through Model 15 to Model 12. An added advantage of these three models is that they form part of a range of simple models developed in Israel thus providing a continuous series of models of increasing structural complexity. The models will be tested with South African data to assess their performance under South African conditions. In addition, the three models will be presented in the form of computer programs thereby facilitating their application by potential users.

Aims of the Research

The broad aim of this study is to assess critically and evaluate the three deterministic models chosen. Within the bounds of this general objective three specific aims have been identified. Firstly, any deficiencies that may exist in the three models will be illustrated by calibrating the three models with respect to three objective functions chosen to represent three common engineering applications. The objective functions and engineering applications are discussed in Chapter III. The models will be calibrated using daily rainfall data from a semi-arid catchment and estimates of daily evaporation as model input. In the calibration process, daily iterations of the models will be used to produce an artificial daily runoff record for the same period as the recorded rainfall and runoff data. The second aim is to compare the performance of the three models in terms of the derived values of the objective functions, to assess whether or not the increase in structural complexity is justified in terms of an improvement in the values of the objective functions. The results of the calibration process and a comparison of model performance are discussed in Chapter V. Lastly, suggested ways of overcoming deficiencies in the models will be proposed and set out in Chapter VI along with the overall results of the study and recommendations for further research.

The three models chosen for study were selected from the range of models available in the literature for reasons which have been discussed. The models were not published in the form of computer programs and the programs to operate the models had to be written and developed from first principles using the descriptions of the models in the literature. Before the model programs could be written and developed, the structures of the models were studied in detail in relation to other examples of deterministic conceptual models.

CHAPTER II

THE STRUCTURES OF DETERMINISTIC MODELS

The variety of deterministic conceptual models, in terms of their uses and structures, is extensive and models range from the highly complex to the relatively simple. Three models have been selected for study from those available and represent examples of the more simple type of model. The models chosen are discussed in relation to examples of other deterministic models as well as the concepts which underly deterministic modelling.

The basic concept which underlies the structure of deterministic models is that of the linear moisture storage. Conceptually, the land-phase of the hydrological cycle may be divided into one or more storages which interlink to represent the various processes occuring in the catchment. The concept of the moisture storage arises from the assumption that certain components of the land-phase of hydrological cycle have a finite capacity to absorb moisture. For example, it is assumed that the soil profile of any catchment is capable of absorbing a fixed quantity of moisture before saturation level is attained. The maximum capacity of the soil will not remain constant over time and space due to spatial and temporal changes in the characteristics of the soil profile. However, an average maximum capacity may be defined for any particular catchment.

Conceptually, the maximum capacity of the soil to absorb moisture is represented by the maximum ~~size~~ capacity of the conceptual soil storage. At any particular time, the ability of the soil to absorb additional moisture is determined by the level of moisture already in storage and the storage level conceptually represents the wetness of the soil profile in the catchment. Alternatively, some moisture storages in a deterministic model may be considered to be of infinite size. An example of a storage of infinite size is that for inactive groundwater loss from the catchment where deep percolating moisture is permanently lost from the catchment.

The number of storages into which the land-phase of the hydrological cycle may be divided is variable and several components may be grouped into a single storage element. The particular application for which the model was developed usually determines the number of storages of which the model is composed. For example, the Stanford Watershed Model IV (Crawford and Linsley, 1966) is probably the most comprehensive representation of the hydrological cycle and is a general purpose model of great structural complexity. The Stanford Model has seven storages including interception, upper and lower zone soil storages, active and inactive groundwater storages and snow-melt storages. The functions expressing the relationship between the variables of the processes represented, require the optimisation of thirty-four physically-based parameters. Another general purpose model which is a conceptual representation of the hydrological cycle is that produced by Dawdy and O'Donnell (1965). The model incorporates surface, soil moisture, channel and active groundwater storages and has thirteen parameters. The structure combines the interception and depression storage components into a single surface storage whereas the Stanford Model separates the two processes having a storage for each process. In addition, the Stanford Model has two groundwater storages. The first or active groundwater storage contributes to the total streamflow as base flow. The second or inactive groundwater storage accumulates moisture lost from the catchment by deep percolation. The inactive groundwater storage is omitted in the Dawdy and O'Donnell model and the only groundwater storage is decayed as base flow contribution. A further difference between the two models lies in the division of the soil moisture storage into two components in the Stanford Model. The model produced by Dawdy and O'Donnell alternatively groups the two soil moisture storages into a single storage element. The decision to combine or separate two processes in a model usually is dictated by the relative importance of the individual processes in the catchment concerned.

Another example of a general purpose model is that developed by Porter and McMahon (1971) which combines several structural features of the two models discussed previously. The interception and depression storages are separated into two elements similarly to the Stanford Watershed Model IV while the soil moisture storage is considered to be a single storage as in the model by Dawdy and O'Donnell. Porter and McMahon's model includes a channel storage and a single active groundwater storage which simulates the base flow component of the runoff. In these two aspects the model is similar to that of Dawdy and O'Donnell.

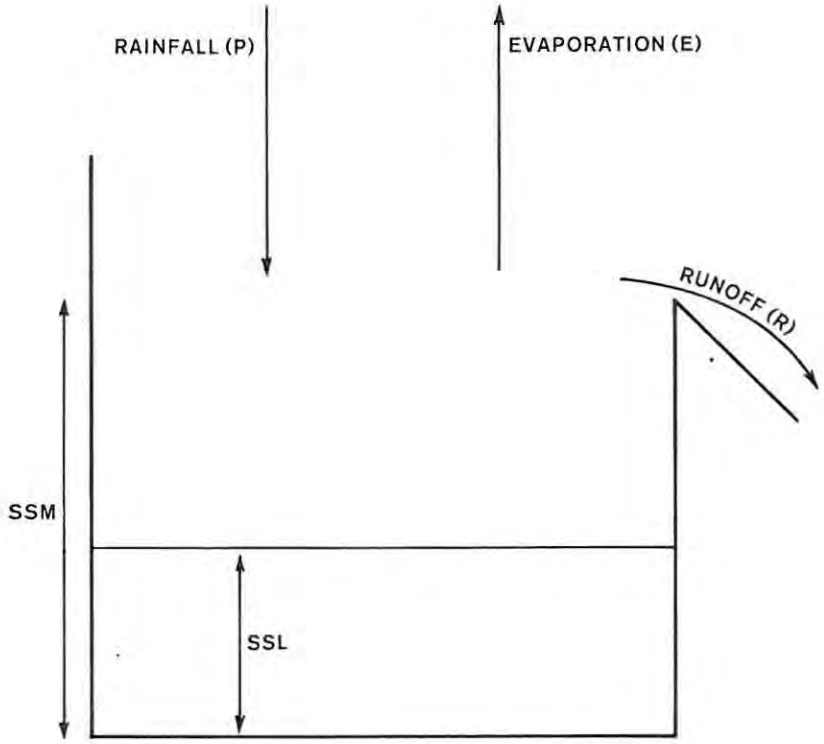
By way of contrast to the general purpose models, the model developed by Dawdy, Lichty and Bergman (1972) was specifically designed for predicting flood volumes and peak runoff rates for small catchments. In view of the specific purpose, the model is relatively less complex in structure and incorporates only a two layer soil moisture storage. The components of snow, interflow and base flow are excluded because the model is intended for flood predictions and not continuous simulation of the rainfall - runoff process over long periods. Hence the model represents only the surface runoff processes which are considered to be of greater importance for purposes of flood prediction than the processes which contribute to streamflow during non-rainfall periods.

A further example of a specific purpose model for design flood determination is discussed by Fleming (1975) and is known as the Hyreun Model (Schultz, 1968). The model input is in the form of individual storm rainfall data and the output is the simulated flood hydrograph of surface runoff. A number of processes such as groundwater, interflow, evaporation and snow-melt are omitted as being irrelevant to the specific purpose of the model. In this respect the model is similar to that of Dawdy, Lichty and Bergman (1972) and both these models serve to illustrate the fundamental difference between specific and general purpose models. Specific and general purpose models will also differ with respect to the model inputs and output. For example, general purpose models usually produce a continuous runoff series with an hourly, daily or monthly time interval whereas specific purpose models usually produce only that part of the hydrograph which is of relevance to the specific application. A further difference between general and specific purpose models also lies in the number of parameters which are used to express the relationship between the variables. General purpose models usually incorporate more parameters than specific purpose models because they are a more comprehensive representation of hydrological processes. Hence general purpose models are usually more difficult to calibrate because of the greater number of possible combinations of parameter values. In addition, the more parameters which a model requires to represent the relationship between variables, the greater the tendency for the parameters, especially the less sensitive parameters, to lack realistic physical meaning (Dawdy and O'Donnell, 1965).

The models chosen for study are relatively simple models in comparison to the comprehensive catchment models and the specific purpose models discussed above. Their simplicity is expressed in the number of storages in the models, the number of individual hydrological processes they represent and in the number of parameters which have to be optimised in the calibration process. The most complex of the three models chosen is Model 12 (Simon and Diskin, 1975) which has two storage elements and requires the optimisation of eight parameters. Model 15 (Diskin and Simon, 1977) and the Dalton Watershed Model (Diskin et al, 1973) are both single storage models but are structurally distinct and are of different levels of structural complexity. The difference in complexity of structure lies in the number of individual processes represented by the models and as a result, also in the number of model parameters. Model 15 is defined with respect to four parameters whereas the Dalton Model has a single parameter. The structures of the models were studied in detail before the commencement of the calibration process.

The Dalton Watershed Model

The Dalton Model was developed in Israel by Diskin, Buras and Zamir (1973) for reservoir management purposes. The model is of the simplest, single linear storage type and may be represented by a container of finite size as in Figure 1. The model is represented by a single operator and is defined completely with respect to one independent parameter, SSM. Parameter SSM corresponds to the maximum soil moisture deficiency averaged over the catchment. The current state of the model is completely defined by the current value of one dependent variable, SSL. Physically, SSL represents the amount of moisture in the catchment and the



THE STRUCTURE OF THE DALTON MODEL

(After Diskin, Buras and Zamir, 1973, p. 931)

FIGURE 1

difference (SSM-SSL), represents the moisture deficiency at any time. The level of moisture in the storage, SSL, is increased by the addition of daily rainfall in millimetres (P_i) and decreased by the subtraction of an estimate of daily free water surface evaporation in millimetres (E_i). The level of SSL is calculated for each time interval and compared to the parameter SSM. If SSL exceeds SSM, runoff (R_i) occurs on the day when the excess was produced and all the excess accrues to runoff (Diskin et al, 1973).

At the beginning of computation for each day, a trial value of depth, SSL'_i, for the current day, is calculated by the following equation;

$$SSL'_i = SSL_{i-1} + P_i - E_i. \qquad \text{(Equation 1)}$$

The value of runoff, R_i, for the current day and the state of the storage, SSL_i, for the current day are determined as follows:

$$\text{IF } SSL'_i > SSM; \quad R_i = SSL'_i - SSM \text{ and } SSL_i = SSM. \qquad \text{(Equation 2)}$$

$$\text{IF } 0 < SSL'_i < SSM; \quad R_i = 0 \text{ and } SSL_i = SSL'_i. \qquad \text{(Equation 3)}$$

$$\text{IF } SSL'_i < 0; \quad R_i = 0 \text{ and } SSL_i = 0. \qquad \text{(Equation 4)}$$

Computation proceeds from i=0 to i=M where M is the number of days in the simulation period and runoff first occurs when;

$$\sum P_i > SSM + \sum E_i. \qquad \text{(Equation 5)}$$

The grouping of the surface and sub-surface storage capacities into one storage represented by one parameter SSM and a single variable SSL, appears to be an oversimplification of the processes occurring in a catchment. Hence the Dalton Model may prove to be too simple for most engineering applications.

A computer program called DAWM (Appendix) was written in Fortran IV to operate a model using the principles of the Dalton Watershed Model.

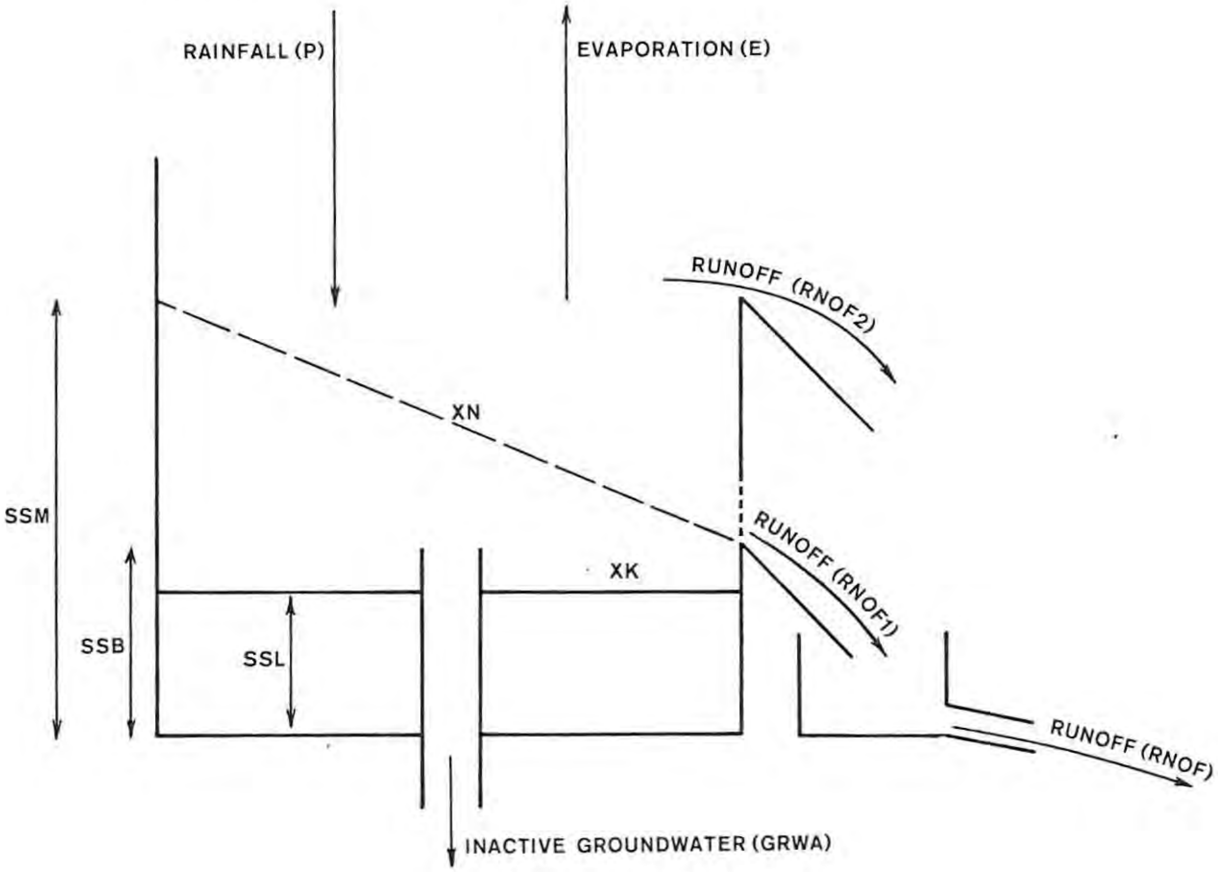
Model 15

Model 15 (Diskin and Simon, 1977) represents a slight increase in structural complexity over the Dalton Watershed Model but retains the single linear storage as shown in Figure 2. Model 15 differs from the Dalton Model by the incorporation of an inactive groundwater loss function and an infiltration function thereby allowing runoff to occur under unsaturated catchment conditions.

The parameter SSM represents the maximum interception, depression and soil storage capacities of the catchment. The level of moisture in the storage for the current day, SSL_i', is increased by the addition of daily rainfall in millimetres (P_i) and decreased by the subtraction of an estimate of actual daily evaporation (E_i) in millimetres as follows :

$$SSL_i' = SSL_{i-1} + P_i - E_i. \qquad \text{(Equation 6)}$$

It is assumed that evaporation occurs at the estimated free water surface rate only when the storage is full and the daily rainfall is less than 1,0 mm. If the storage is full and the daily rainfall is greater than 1,0 mm, the evaporation value to be subtracted is reduced by a half. Under conditions when the storage is not full, that is when SSL_i' is less than SSM, and the daily rainfall is less than 1,0 mm the evaporation value is reduced in proportion to $(SSL_i' + P_i)/SSM$. If the storage is not full and the rainfall for the current day is above 1,0 mm, the evaporation value is reduced by half. This process of reduced evaporation loss under higher rainfall conditions and/or drier catchment conditions, appears to be a more realistic procedure than simply extracting evaporation at the estimated free surface rate under all conditions as in the case of the Dalton Model. However, the reduction of the extracted evaporation value by a half when rainfall is



THE STRUCTURE OF MODEL 15

(After Diskin and Simon, 1977, p. 137)

FIGURE 2

above 1,0 mm appear to be somewhat arbitrary criteria.

The inactive groundwater loss component of Model 15 is based on the parameter SSB which represents the threshold storage below which no runoff occurs. The temporary level of moisture in the storage, SSL'_i, is compared to the value of the storage threshold SSB, to determine if runoff occurs. If SSL'_i, is less than SSB, runoff, RNOFl, is zero and in addition there is no flow to inactive groundwater, GRWA. The final value of storage for the current day, SSL_i, is then taken to be equal to SSL'_i in this case. If SSL'_i is above the storage threshold SSB, but below the maximum, SSM, some surface runoff, RNOFl, and some flow to inactive groundwater, GRWA, is produced by the model. The value of surface runoff is determined by the following equation:

$$RNOFl = \frac{XN}{XN + 1} \quad (SSL'_i - SSB)\ (SSL'_i - SSB/SSM - SSB)^{1/XN}$$

(Equation 7)

where XN is the parameter describing the variability of infiltration capacity over the catchment. The equation for surface runoff is based upon a spatially variable infiltration concept and the value of surface runoff depends upon the storage ratio above SSB, the level of moisture in storage above SSB and the parameter XN. Parameter XN represents the proportion of the catchment area over which infiltration is active and the shape of this function is illustrated in Figure 3. The graph was plotted for increasing values of XN from 0,2 to 3,0, (the recommended range of values of Diskin and Simon, (1977)) and the values of RNOFl were expressed as a percentage of the storage level above the threshold SSB. The relationship between RNOFl and the storage level above SSB appears to be curvilinear. For values of XN below 1,0, the effective infiltration capacity is high, that is, a relatively large part of the catchment is pervious, and consequently a relatively small proportion of the rainfall accrues to runoff. Values of XN above 1,0 produce a reduced infiltration capacity, that is a relatively large part

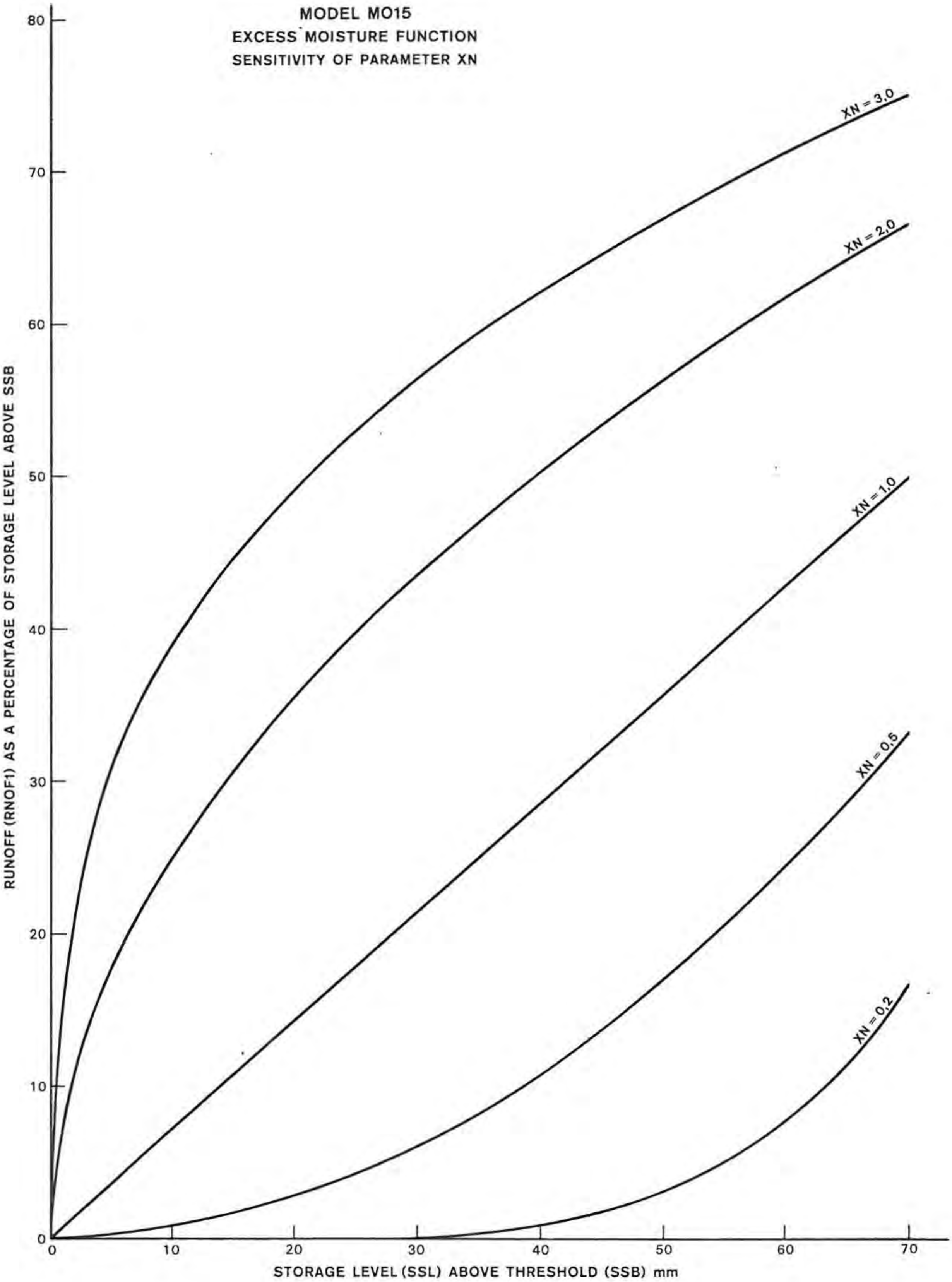

MODEL MO15
EXCESS MOISTURE FUNCTION
SENSITIVITY OF PARAMETER XN
XN = 3.0
XN = 2.0
XN = 1.0
XN = 0.5
XN = 0.2
RUNOFF (RNOF1) AS A PERCENTAGE OF STORAGE LEVEL ABOVE SSB
STORAGE LEVEL (SSL) ABOVE THRESHOLD (SSB) mm
0
10
20
30
40
50
60
70
80

FIGURE 3

of the catchment is impervious, with a resultant larger proportion of the rainfall occurring as runoff. Hence this function allows some runoff to occur from any volume of rainfall after a minimum amount has infiltrated as represented by the threshold SSB, that is, under unsaturated conditions. The infiltration concept incorporated in Model 15 is similar to that used in the Stanford Watershed Model IV (Crawford and Linsley, 1966) and the model developed by Dawdy et al (1972).

When the storage level $SSL_i^!$ exceeds the threshold SSB, some flow to inactive groundwater, GRWA, is produced by the model in addition to surface runoff, RNOF1. The flow to inactive groundwater, GRWA, is considered as a loss from the catchment and does not contribute to streamflow. Inactive groundwater loss is calculated by the following equation:

$$GRWA = XK\ (SSL_i^! - SSB - RNOF1). \qquad \text{(Equation 8)}$$

The equation governing groundwater loss is a linear function and parameter XK has a range of values from zero to unity (Diskin and Simon, 1977). The effect of parameter XK is to control the rate of percolation to inactive groundwater and the higher the value of XK, the higher the rate of percolation loss from the storage above SSB. After the surface runoff and the flow to inactive groundwater have been extracted from the storage, the final value of storage for the current day is given by;

$$SSL_i = SSL_i^! - (RNOF1 + GRWA). \qquad \text{(Equation 9)}$$

The second case when runoff occurs is under saturated catchment conditions, that is when $SSL_i^!$ is greater than the maximum capacity SSM. In this case the additional runoff, RNOF2, is calculated as the excess above SSM:

$$RNOF2 = SSL_i^! - SSM. \qquad \text{(Equation 10)}$$

The value of RNOF1 under saturated conditions is calculated by the following equation derived from Equation 7 by the substitution of SSM for SSL_i' :

$$RNOF1 = \frac{XN}{XN + 1} \quad (SSM - SSB). \qquad \text{(Equation 11)}$$

The calculation of RNOF1 under these conditions is related to the maximum capacity of the storage above the threshold SSB and the concept behind parameter XN remains the same as in the case of Equation 7. The total value of runoff for the current day is given by the sum of RNOF1 and RNOF2. In addition, there is some loss to inactive groundwater, the value of which is calculated by Equation 8. The final value of storage for the day, SSL_i, under saturated conditions is determined as follows:

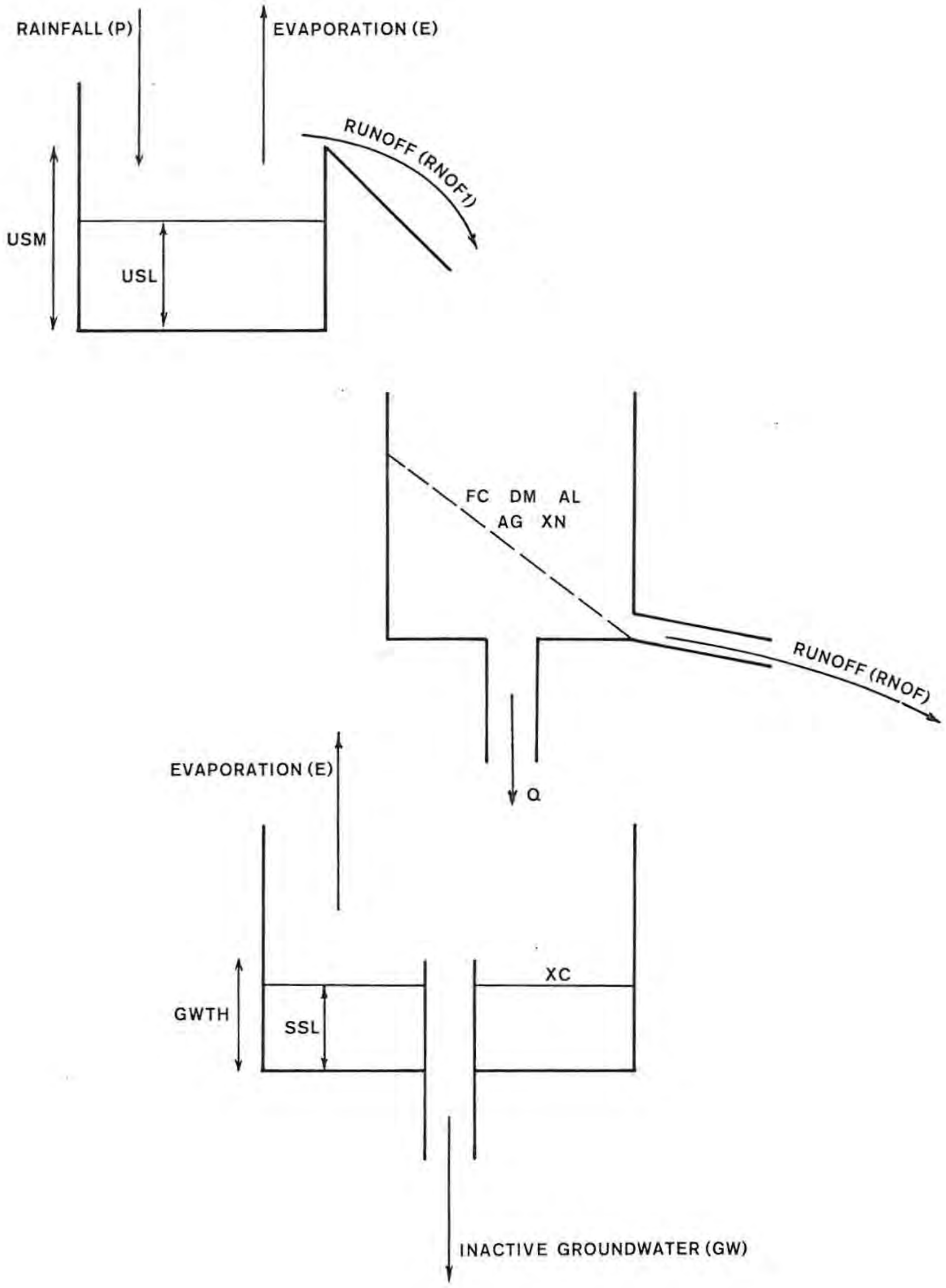
$$SSL_i = SSL_i' - (RNOF1 + RNOF2 + GRWA). \qquad \text{(Equation 12)}$$

The final value of storage, SSL_i, is then used as the starting value SSL, for computations on the following day.

A computer program called MO15 (Appendix) was developed to operate a model based upon the principles of Model 15 (Diskin and Simon, 1977).

Model 12

Model 12 (Simon and Diskin, 1975) represents a further increase in structural complexity by incorporating an additional storage and more parameters than Model 15. Both storages in Model 12 are linear and the excess moisture from the first storage is divided by a distributing element as shown in Figure 4. The first storage represents the interception and depression storages and the second represents the upper zone of the soil layer which is effected by evaporation losses. Regarding the surface storages, Model 12 differs from other models, for example those developed by Porter and McMahon (1971) and Boughton (1968), which have separate storages for the interception and depression components and have one or two storages



THE STRUCTURE OF MODEL 12

(After Simon and Diskin, 1975, fig. 3)

FIGURE 4

representing the soil layer. Model 12 does however, resemble the model produced by Nielsen and Hansen (1973) which groups the interception and depression components with the uppermost cultivated soil layer as a surface storage. The amalgamation of the interception and depression storages does not appear to be a serious oversimplification because both components operate above the soil surface and both are relatively small storages. At the beginning of computation for the current day, rainfall in millimetres (P) is added to the contents in the first storage, USL, and evaporation (E) in millimetres is subtracted. Evaporation is assumed to occur at the potential free water surface rate if the daily rainfall is less than 1,0 mm and enough moisture is available in the upper storage. If insufficient moisture is available in the upper storage, the balance of the potential evaporation is extracted from the contents of the second storage above the threshold, GWTH, which controls losses to inactive groundwater. Should there be insufficient moisture in the second storage above GWTH to meet the remaining evaporation demand, some of the remaining deficiency may be extracted below GWTH at the rate defined by;

$$AE = PE\ (SSL/GWTH) \qquad \text{(Equation 13)}$$

where AE is the extracted evaporation and PE is the remaining potential free water surface evaporation. Whenever the daily rainfall is above 1,0 mm, the calculated values of actual evaporation are reduced by half under all conditions (Simon and Diskin, 1975). The extraction of evaporation appears to be a generally realistic procedure with the initial losses coming from the first storage and then from the second storage. However, as in the case of Model 15 (Diskin and Simon, 1977), the criteria for reduced evaporation losses under rainfall conditions appear to be somewhat arbitrary but are probably adequate approximations.

The addition of daily rainfall and the extraction of daily evaporation continues until the level in the first storage, USL, exceeds the maximum capacity of the storage, USM, and runoff, RNOF1, is produced. The value of RNOF1 is calculated by;

$$\mathrm{RNOF1} = (\mathrm{USL} + P - E) - \mathrm{USM}. \qquad \text{(Equation 14)}$$

The runoff, RNOF1, enters the distributing element which divides it into a soil moisture component, Q, and a surface runoff component, RNOF. The soil moisture component, Q, is added to the level of moisture, SSL, in the second storage. When SSL becomes larger than GWTH (the threshold governing loss to inactive groundwater), flow to inactive groundwater occurs. The threshold GWTH is equivalent to SSB in Model 15 (Diskin and Simon, 1977) and represents the amount of moisture the soil can absorb without loss to inactive groundwater. The contribution to inactive groundwater, GW, is calculated as a loss from the catchment which does not contribute to streamflow and is determined as follows:

$$\mathrm{GW} = \mathrm{XC}\ (\mathrm{SSL} - \mathrm{GWTH}) \qquad \text{(Equation 15)}$$

where XC is the parameter controlling the percolation process. The groundwater loss equation is a linear function and parameter XC has a positive value less than or equal to unity. Hence parameter XC controls the rate of percolation and is equivalent to parameter XK in Model 15 (Diskin and Simon, 1977). The level of moisture in the second storage is therefore depleted by flow to inactive groundwater, GW, and by evaporation losses.

The moisture distributing element in effect represents the infiltration process and has five parameters, FC, DM, AL, AG and XN. Parameters FC, DM and AL define the maximum infiltration capacity of the watershed while FC alone defines the conceptual minimum watershed infiltration capacity. The infiltration function given in Equation 16 below, bears a marked resemblance to the Philip infiltration formula as applied by Porter and McMahon (1971).

In both Model 12 and the model developed by Porter and McMahon (1971), the infiltration capacity of the catchment depends on the contents of the soil moisture storage, that is the wetness of the soil. The only difference between the infiltration functions used in Model 12 and the model by Porter and McMahon (1971), is that Model 12 lacks the aspect of time-dependent recovery of infiltration capacity. The infiltration component used in Model 15 (Diskin and Simon, 1977) is similar to that used in Model 12 in two aspects. Firstly, both functions are dependent upon the wetness of the soil as represented by the storage level and both incorporate a parameter representing the variation of infiltration capacity over the catchment. The infiltration capacity of the watershed, WINCP is determined as follows:

$$\mathrm{WINCP} = \mathrm{FC} + \mathrm{DM}\ (\exp\ (-\mathrm{AL.}\ \mathrm{SSL})\ ). \qquad \text{(Equation 16)}$$

The above function was plotted in order to illustrate the curvilinear relationship between WINCP and the storage level SSL. The infiltration function was also plotted to obtain an indication of the sensitivity of the parameters. Parameter sensitivity was investigated by allowing one parameter to vary within set limits while keeping the other two parameters constant. The graphs are shown in Figures 5, 6 and 7. Parameter FC is the conceptual minimum infiltration capacity as shown in Figure 5. The influence of parameters DM and AL is that they determine the rate of infiltration to the second storage element in the model as shown in Figures 6 and 7. No guides as to the range of values for FC, DM and AL were provided by Simon and Diskin (1975) but all are positive, real values. The calibrated parameter values were obtained by trial and error manipulation with respect to chosen objective functions.

The ratio of the watershed infiltration capacity, WINCP, to the infiltration capacity of the stream network, SINCP, is defined by parameter AG

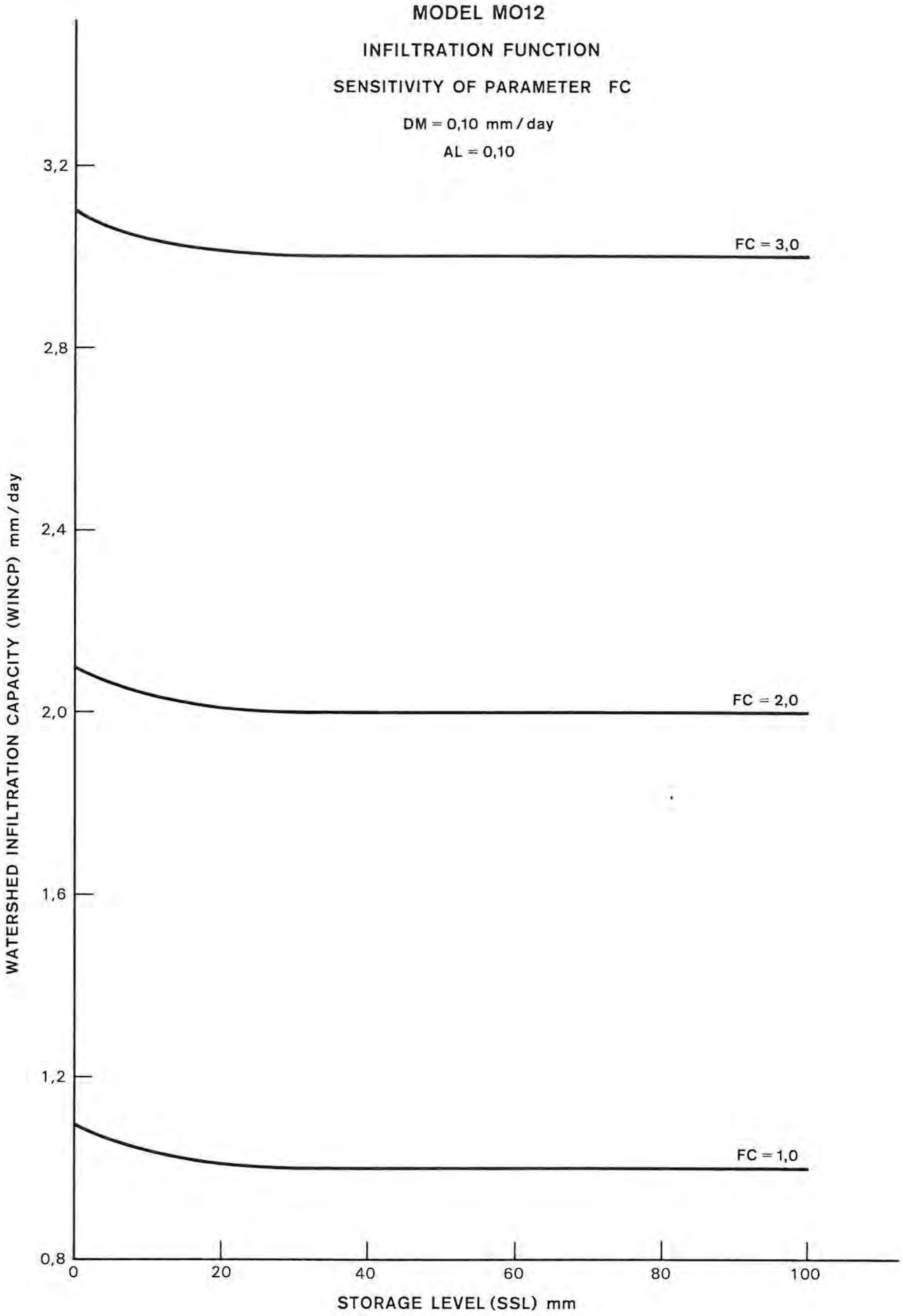

MODEL MO12
INFILTRATION FUNCTION
SENSITIVITY OF PARAMETER FC
DM = 0,10 mm / day
AL = 0,10
FC = 3,0
FC = 2,0
FC = 1,0
WATERSHED INFILTRATION CAPACITY (WINCP) mm / day
3,2
2,8
2,4
2,0
1,6
1,2
0,8
0
20
40
60
80
100
STORAGE LEVEL (SSL) mm

FIGURE 5

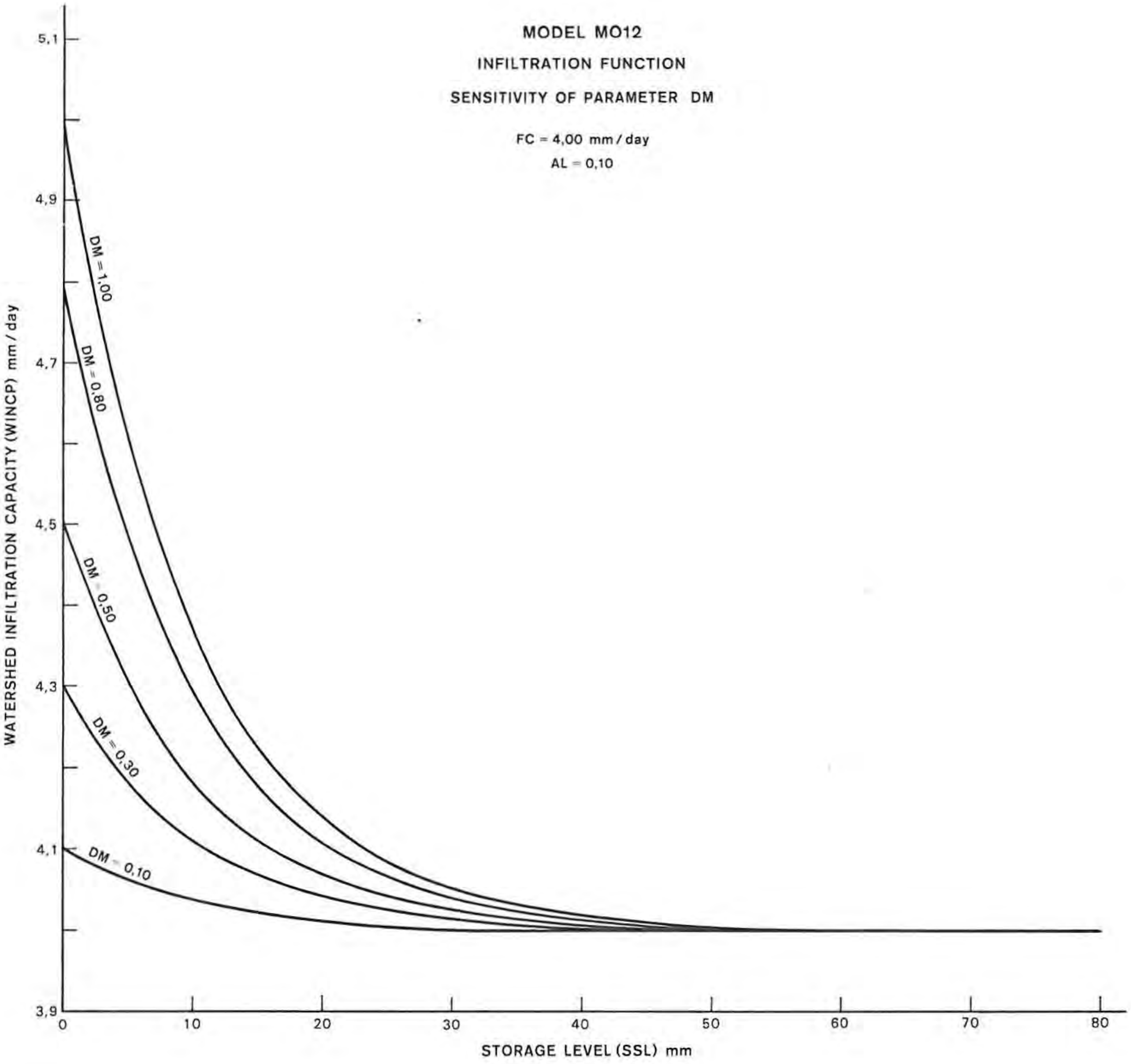
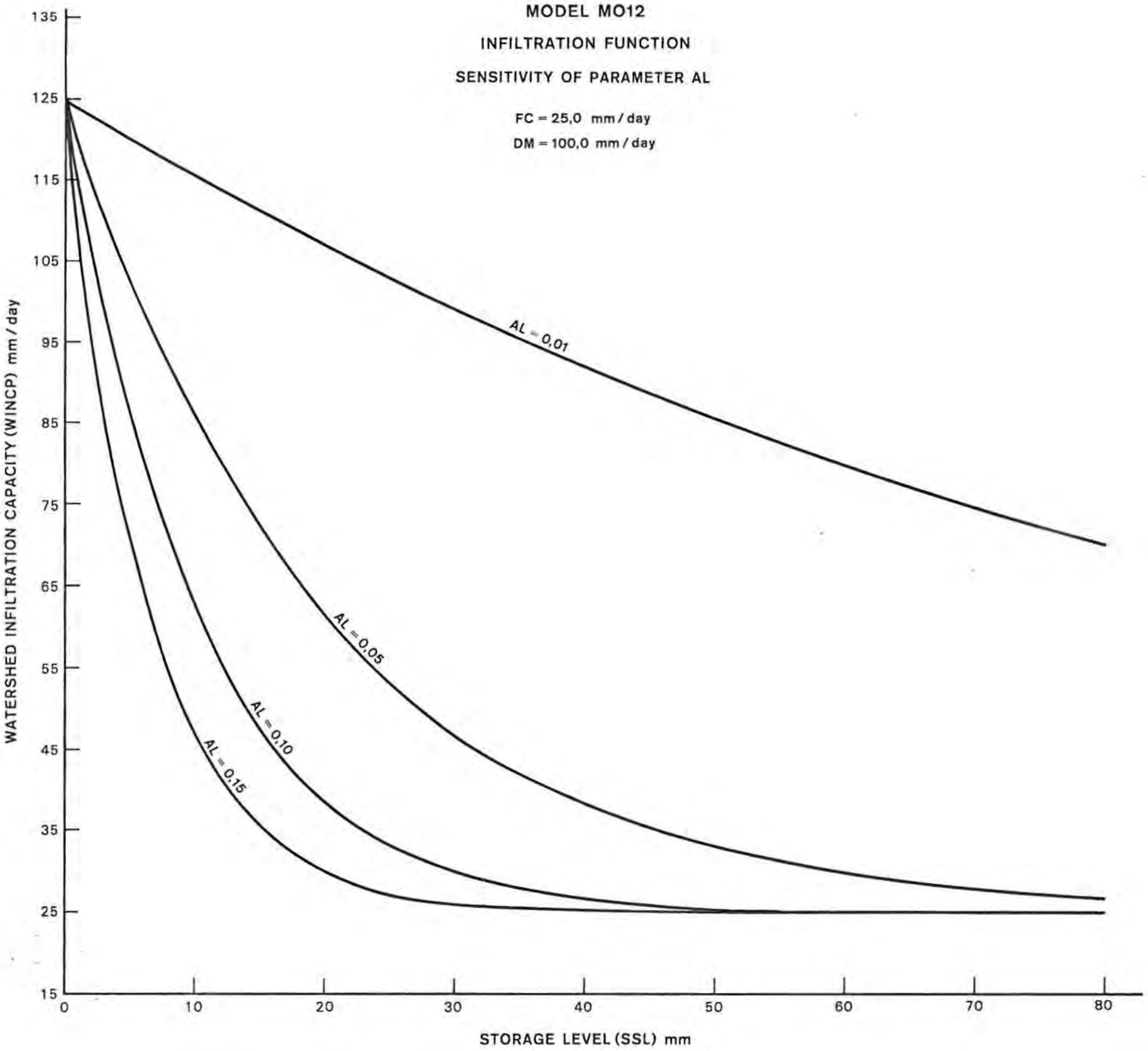

MODEL MO12
INFILTRATION FUNCTION
SENSITIVITY OF PARAMETER DM
FC = 4,00 mm / day
AL = 0,10
DM = 1,00
DM = 0,80
DM = 0,50
DM = 0,30
DM = 0,10
WATERSHED INFILTRATION CAPACITY (WINCP) mm / day
5,1
4,9
4,7
4,5
4,3
4,1
3,9
0
10
20
30
40
50
60
70
80
STORAGE LEVEL (SSL) mm

FIGURE 6



MODEL MO12

INFILTRATION FUNCTION

SENSITIVITY OF PARAMETER AL

FC = 25,0 mm / day

DM = 100,0 mm / day

FIGURE 7

as below:

$$\mathrm{SINCP} = \mathrm{WINCP}/\mathrm{AG}. \qquad \text{(Equation 17)}$$

Parameter AG is likely to be largely insensitive as evidenced by the recommended range of values which are of the order of 10^2 to 10^4 (Simon and Diskin, 1975).

The excess moisture from the first storage, RNOF1, enters the distributing element and is divided into a surface runoff component, RNOF, and a contribution to soil moisture, Q. If RNOF1 is large in comparison to the estimated infiltration capacities WINCP and SINCP, the value of Q is calculated as follows;

$$\text{for RNOF1} > \text{WINCP}; \qquad Q = \left[\mathrm{WINCP}/(\mathrm{XN} + 1)\right] (1 - {}^{1}/\mathrm{AG}). \qquad \text{(Equation 18)}$$

Parameter XN is analogous to the parameter XN in Model 15 (Diskin and Simon, 1977) and represents the variation of infiltration capacity over the catchment. The quantity of surface runoff, RNOF, is computed as the difference between the excess, RNOF1, and Q as below:

$$\mathrm{RNOF} = \mathrm{RNOF1} - \left[\mathrm{WINCP}/(\mathrm{XN} + 1)\right] (1 - {}^{1}/\mathrm{AG}). \qquad \text{(Equation 19)}$$

If however, RNOF1 is smaller than the estimated infiltration capacity of the watershed, WINCP, an intermediate value of surface runoff, RNOF2, is calculated.

$$\text{For RNOF1} < \text{WINCP};$$

$$\mathrm{RNOF2} = (\mathrm{XN}/(\mathrm{XN} + 1)) (\mathrm{RNOF1}) ((\mathrm{RNOF1}/\mathrm{WINCP})^{1/\mathrm{XN}}). \qquad \text{(Equation 20)}$$

The intermediate value of runoff, RNOF2, represents the surface runoff which occurs as a result of the relatively impervious areas of the catchment and is controlled by parameter XN above. RNOF2 is then compared to SINCP, the stream infiltration capacity, to determine the final value of surface runoff, RNOF.

For $\mathrm{RNOF2} < \mathrm{SINCP}$;

$$\mathrm{RNOF} = (\mathrm{XN}/(\mathrm{XN} + 1))\ (\mathrm{RNOF2})\ (\ (\mathrm{RNOF2}/\mathrm{SINCP})^{1/\mathrm{XN}})$$

(Equation 21)

and for $\mathrm{RNOF2} > \mathrm{SINCP}$;

$$\mathrm{RNOF} = \mathrm{RNOF2} - (\mathrm{SINCP}/(\mathrm{XN} + 1)\ ). \qquad \text{(Equation 22)}$$

Under both the conditions above, the value of Q is calculated as the difference;

$$Q = \mathrm{RNOF1} - \mathrm{RNOF}. \qquad \text{(Equation 23)}$$

In the situation where the excess from the first storage, RNOF1, is greater than the catchment infiltration capacity, WINCP, the influence of the stream network infiltration capacity upon the soil moisture contribution, Q, was relatively insignificant. When the excess, RNOF1, is less than the infiltration capacity, WINCP, some surface runoff from impermeable areas, RNOF2, is produced by the model. When RNOF1 is less than WINCP, the infiltration capacity of the stream network becomes relatively more important in determining the amount of surface runoff, RNOF, and soil moisture contribution, Q. The relationship between RNOF2 and the final value of surface runoff, RNOF, is illustrated in Figure 8. The graph shows that when RNOF2 is less than the stream infiltration capacity, SINCP, relatively more surface runoff occurs and relatively less moisture infiltrates to soil moisture, Q, than when RNOF2 is greater than SINCP. The use of an estimation of the stream

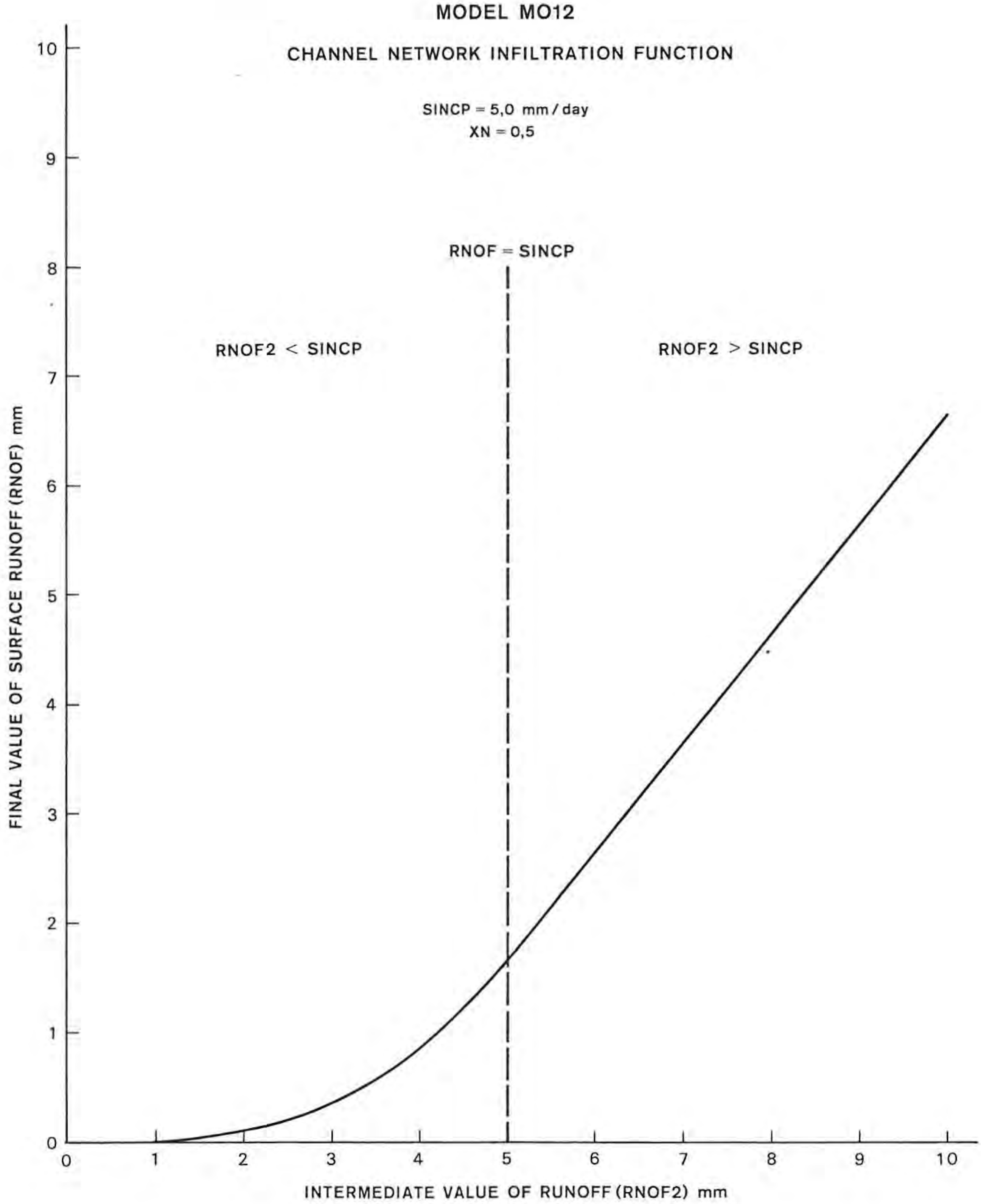

MODEL MO12
CHANNEL NETWORK INFILTRATION FUNCTION
SINCP = 5,0 mm / day
XN = 0,5
RNOF = SINCP
RNOF2 < SINCP
RNOF2 > SINCP
FINAL VALUE OF SURFACE RUNOFF (RNOF) mm
INTERMEDIATE VALUE OF RUNOFF (RNOF2) mm
0
1
2
3
4
5
6
7
8
9
10

FIGURE 8

infiltration capacity appears to be a rather unusual component in a model as none of the other models referred to have such a component. When SINCP does come into operation, the actual volumes involved are likely to be relatively small and so this aspect of Model 12 appears to be an unnecessary addition to the structure of the model.

Model 12 was used as the basis of a model operated by a computer program called MO12 (Appendix). Model MO12 and the other two models were calibrated with respect to the three objective functions which are set out in the following chapter.

CHAPTER III

OBJECTIVE FUNCTIONS AND HYPOTHESES

The performance of the three models chosen for study will be assessed by calibrating each of the models with respect to each of three objective functions devised to represent three common engineering applications. An objective function takes the form of a mathematical formulation which is used to express the criterion of accuracy of the model output in relation to the observed runoff data. Usually the objective function is formulated so as to represent the requirements of the model output for a specific engineering application. Different model applications have different requirements of model output and the use of objective functions which represent the output requirements ensures objective rather than subjective model calibration. The model is calibrated by optimisation of the model parameters so as to minimise the value of the objective function concerned. In this way, the output at the requisite level of accuracy is achieved for the application in question. However, as Diskin and Simon (1977) have indicated, the optimal set of parameter values obtained in the calibration process is optimal only with respect to the objective function used and a different parameter set may be expected for each objective function.

According to Fleming (1975) there are three common methods for arriving at an optimum parameter set for a particular objective function. The first method is by trial and error adjustment of the model parameters until the best value of the objective function being used in the calibration is attained. A second technique is that of automatic parameter adjustment which makes use of programming internal to the model program. The program automatically compares the derived value of the objective function used in the calibration against the optimum value of the function and adjusts the value of the parameters within set limits. The process is repeated until the optimum value of the objective function is achieved or some specified cut-off limit is exceeded. Automatic adjustment techniques are usually used only when there is unlimited access to computer facilities and cost is not a limiting factor. The third method of model calibration is a combination of these two techniques. The model parameters are adjusted by trial and error until a near-optimal set is achieved and then automatic adjustment is used to refine and finalise the parameter set. In this study, the models were calibrated by trial and error adjustment of the model parameters with respect to the objective functions because of the small number of parameters involved and because of the limitations on computer core-space and time.

The objective functions used in the calibration of the three models and the engineering applications which they represent are discussed. In view of the different structures of the models chosen, three hypotheses arising from a consideration of the model structures in the light of the objective functions were formulated.

Objective Functions and Engineering Applications

Objective function U1

The general requirement of any model output for reservoir management and water resources planning, is the accurate reproduction of the mean monthly volume as well as the accurate reproduction of the standard deviation of monthly volumes (Pitman, 1973). In the absence of an adequate period of recorded runoff, the model may be used to generate monthly volumes to give an indication of the amount of water available each month, that is the monthly yield of the catchment (Porter and McMahon, 1971). The objective function to be minimised, U1, which expresses these requirements of a model, is composed of two statistics, S1 and S2, and S1 is:

$$S1 = \frac{\dfrac{\sum Y}{N} - \dfrac{\sum X}{N}}{\dfrac{\sum X}{N}} \quad X\ 100 \qquad \text{(Equation 24)}$$

where S1 is the percentage error in the mean monthly volume, X is the observed monthly volume and Y is the simulated monthly volume and where the units used are thousands of cubic metres. The second statistic, S2, is calculated as;

$$S2 = \frac{\sqrt{\frac{\sum(Y - \bar{Y})^2}{N - 1}} - \sqrt{\frac{\sum(X - \bar{X})^2}{N - 1}}}{\sqrt{\frac{\sum(X - \bar{X})^2}{N - 1}}} \times 100$$

(Equation 25)

where S2 is the percentage error in the standard deviation of monthly volumes, $\bar{X}$ is the mean of the observed monthly volumes and $\bar{Y}$ is the mean of the simulated monthly volumes and where the units used are thousands of cubic metres. As both S1 and S2 have an optimum value of zero, they may be combined into one objective function, U1, which also has an optimum value of zero as follows;

$$U1 = /S1/ + /S2/$$ (Equation 26)

where U1 is the combined percentage error in the mean and standard deviation of monthly volume. The absolute values of S1 and S2 are used to avoid the value of U1 becoming zero when the average of the errors in the mean and standard deviation of monthly volume becomes zero. The objective function, U1, has been developed by the Hydrological Research Unit, Rhodes University. In the calibration process for objective function U1, " ... the purpose for which a sequence of runoff data is simulated should be borne in mind when selecting criteria for acceptance or rejection" (Pitman, 1973, p 3.1). Further, in deciding upon an acceptable level of accuracy, such a level must be commensurate with the level of error in the primary input data, namely the rainfall (Pitman, 1973). With these two considerations in mind, a combined error of ten percent for objective function U1 is considered to be an acceptable level of accuracy and calibration will cease if this level is attained.

Objective function U2

For the purpose of structural design, "... the more common engineering applications of hydrologic data are normally concerned with extreme and infrequent conditions which might be expected to occur within the life of a structure" (Huggins, 1966, p 4). In this case the model must be able to reproduce the peak daily volume of streamflow in order to give an indication of the size of the flood peaks which a structure such as a bridge will have to withstand. While the highest peak flow is the cause of damage to structures, instantaneous peak flows are rarely available. However, recent work by Boughton (1976) has shown that the daily mean flow, that is, the total daily volume divided by 24 hours, is highly correlated with the instantaneous peak flow during the day for flood events. Hence the second objective function, U2, is a measure of the ability of the model to reproduce peak daily volumes above a pre-set base level. The pre-set base level is defined in order to discount minor fluctuations in base flow which cannot be regarded as flood events. For the purposes of this study, the base level was set at 160 000 cubic metres after an examination of most of the runoff events in the observed record.

The objective function chosen to express the one-to-one correspondence between observed and simulated peak daily volumes, ideally, has to be sensitive to the presence of systematic error in the simulated data. One method of providing an indication of the one-to-one correspondence between two sets of data but which is insensitive to systematic error, is the product moment correlation coefficient. If the correlation coefficient was to be used as an objective function, some way of incorporating both the regression coefficient and the base constant would have to be found so as to make the objective function sensitive to systematic error. On the other hand, Aitken (1973) has proposed the use of the coefficient of efficiency as a way of expressing the one-to-one correspondence between two data sets and which is sensitive to the presence of systematic error in the simulated data set. The coefficient of efficiency has been applied by Pitman (1977) to show the degree of correspondence between observed and simulated flows. It was decided to use the coefficient of efficiency, Ep, in the objective function U2, with respect to this engineering application where;

$$Ep = \frac{\sum(q_c - \bar{q}_c)^2 - \sum(q_c - q_e)^2}{\sum(q_c - \bar{q}_c)^2} \qquad \text{(Equation 27)}$$

and q_c is the observed peak daily volume above a pre-set base level, q_e is the simulated peak daily volume above the same base level and the units used are millions of cubic metres. The optimum value of Ep is unity and hence the objective function to be minimised has the form;

$$U2 = 1{,}0 - Ep \qquad \text{(Equation 28)}$$

where Ep is the coefficient of efficiency between observed and simulated peak daily volumes above a pre-set base level. As in the case of the previous objective function, U1, an acceptable level of accuracy has to be decided upon. Judging by the results obtained by Pitman (1977), a value of U2 of 0,15 or less will be deemed to be acceptable. However this cut-off value may have to be revised upon inspection of the results obtained from the most efficient of the three models and a new cut-off level defined.

Objective function U3

The third engineering application arises from the need to reproduce floods and droughts at the correct times for purposes of forecasting, that is, the timing of the wet and dry periods must be accurately reproduced by a model (Todini, 1975; Mehrotra, 1976). The information gained from the accurate reproduction of wet and dry periods has uses in the design and operation of dams and reservoirs and in the management of water resources. Because the timing of peak and low runoff volumes is critical for this engineering application, the objective function U3, chosen to represent this application must show the degree of one-to-one correspondence between observed and simulated daily runoff volumes. As in the case of the second objective function, U2, the coefficient of efficiency, Ev, will be used as it is sensitive to systematic error in the model output. The equation for the coefficient of efficiency, Ev, is;

$$Ev = \frac{\sum (q_c - \bar{q}_c)^2 - \sum (q_c - q_e)^2}{\sum (q_c - \bar{q}_c)^2} \qquad \text{(Equation 29)}$$

where q_c is the observed daily volume, q_e is the simulated daily volume and the units used are millions of cubic metres. The optimum value of Ev is unity and hence the objective function to be minimised, U3, which represents this engineering application has the form;

$$U3 = 1{,}0 - Ev \qquad \text{(Equation 30)}$$

where Ev is the coefficient of efficiency between simulated and observed daily volumes. As in the case of U2, the acceptable level of accuracy for objective function U3 will be taken as a value of 0,15 or less.

The anticipated results of the calibration process for each engineering application are expressed in terms of three hypotheses. Each hypothesis is based upon a study of the structures of the three models in the light of the objective function concerned.

Hypotheses

Hypothesis H1

With respect to the first objective function, U1, the simulation of runoff after the peak has occurred, that is the contribution of base flow to runoff, is not regarded to be of great importance in the chosen study catchment. In a perennial catchment where base flow continues for long periods after the peak, the accurate simulation of the base flow contribution would be of great importance. If the base flow contribution were not simulated by a model for a perennial catchment, the absent base flow volume would have to be incorporated into the runoff peak in order to achieve the correct mean volume. The incorporation of base flow into the peak would produce a greatly exaggerated peak with a consequent exaggeration in the standard deviation. An examination of the flow record for the semi-arid catchment chosen for study (described in Chapter IV) shows that the contribution of base flow to the runoff is of short duration in comparison to the time interval of one month. Therefore it may be assumed that the inability of a model to produce base flow after the runoff peak, will not seriously affect the derived value for U1. Any difference in the ability of the three models to minimise U1 must therefore be due mainly to the ability of the models to accurately represent the generation of excess moisture. The prime factor involved with regard to the reproduction of the mean monthly volume and standard deviation of monthly volumes hence depends upon the model's ability to accurately represent the variability of soil moisture conditions.

The Dalton Watershed Model (Diskin et al, 1973) has a single linear storage with no percolation function and does not take into account losses to active or inactive groundwater. Both Models 12 and 15 incorporate a percolation function thereby simulating an additional process in the watershed and are hence seen as being more realistic models than the Dalton Model. On the other hand, Model 12 divides the soil storage element into two parts representing the surface storages of interception and depression and a second storage representing the upper zone soil moisture storage. Model 12, compared to Model 15, appears to be able to simulate more accurately the hydrological processes occurring in nature and therefore appears to be more able to represent soil moisture conditions than Model 15. Assuming that the ability of a model to produce base flow after the runoff peak is not of prime importance in this case and that the ability of a model to accurately portray the variability of soil moisture conditions is the important consideration, the first hypothesis, H1, takes the form:

> H1 "The mean and standard deviation of monthly runoff volumes will be reproduced most accurately by Model 12 followed by Model 15 and be reproduced least accurately by the Dalton Watershed Model."

Hypothesis H2

With respect to the peak daily discharge volumes according to the requirements of the second objective function U2, the accurate reproduction of peak values is highly dependent on the antecedent moisture conditions. A model which is more representative of soil moisture conditions prior to the peak would be expected to produce the peak volume more accurately than a less representative model. Model 12 appears to be more representative of hydrological processes than the other two models by virtue of the additional storage in Model 12. Hence Model 12 is regarded as being able to simulate more accurately antecedent soil moisture conditions and is proposed as being the best of the three models with respect to U2. Model 15 seems to be more representative of antecedent moisture conditions than the Dalton Model by reason of its percolation function and is regarded as being the better model for objective function U2.

If two runoff peaks occur within a short time interval, a model which produces flow on succeeding non-rain days after the first peak would have realistic decay of soil moisture and hence a more representative soil moisture state by the time the second peak occurred. Of the three models, only Model 15 appears to be able to produce runoff on succeeding rainless days after the peak because of the threshold of storage and the infiltration function in the model. However, an examination of the flow record for the study catchment reveals few instances of two runoff peaks in quick succession and therefore this consideration is assumed to be of minor importance with regard to U2.

In view of the models having apparent differences in their ability to represent soil moisture conditions prior to the runoff peak, it may be hypothesised that:

> H2 "The peak daily discharge volume above a pre-set base level will be reproduced most accurately by Model 12 followed by Model 15 and be reproduced least accurately by the Dalton Model."

Hypothesis H3

With regard to the one-to-one correspondence between daily discharge volumes for objective function U3, the important factor involved is the accurate simulation of runoff due to base flow on non-rain days after the peak. A model which produces only surface runoff would be expected to produce a very poor one-to-one correspondence between daily volumes. Model 15 appears to have the ability to produce runoff after a threshold governing the loss to inactive groundwater has been exceeded. The ability of Model 15 to produce runoff before the maximum storage capacity has been reached, seems to allow runoff to occur before the peak as well as on days succeeding the peak until the level of moisture in the storage falls to the level of the storage threshold. In contrast, the Dalton Model and Model 12 both depend entirely upon excess moisture above the maximum storage capacity in order to produce runoff. The Dalton Model and Model 12 therefore appear to be unable to simulate the base flow contribution to the runoff and are considered inferior to Model 15 with respect to objective function U3. However, Model 12 does have an additional storage and simulates more hydrological processes than the Dalton Model and is considered to be the more representative of catchment processes of the two models. Therefore Model 12 should be able to reproduce the daily volumes more accurately than the simple

Dalton Model. However, the more representative structure of Model 12 does not fully overcome the inability to simulate the base flow after the peak has occurred.

On the basis of the above reasoning, the final hypothesis, H3, is proposed:

> H3 "The daily discharge volumes will be reproduced most accurately by Model 15 followed by Model 12 and be reproduced least accurately by the Dalton Model."

In order to aid interpretation of the results of the calibration process, the study catchment will be described in detail. The rainfall and runoff data for the catchment used in the model calibration were not available conveniently in a form suitable for model input. Hence the raw data had to be processed until in a form compatible with the simulation requirements. A method of processing the raw data was devised and is discussed.

CHAPTER IV

STUDY CATCHMENT AND DATA PROCESSING

Rainfall and runoff data are available for a large number of catchments in South Africa and in order to select a suitable study catchment, a number of criteria were laid down. These criteria were established after a consideration of the data required for the critical assessment of the three models. In order to assess critically the three conceptual mathematical models chosen for study, three sets of data were necessary;

(1) Daily rainfall data in millimetres averaged over the catchment.

(2) Assessments of daily pan evaporation in millimetres.

(3) Daily runoff data in cubic metres for the same period as recorded rainfall.

The choice of a study catchment was made with respect to two main criteria. Firstly, the period of recorded runoff was an important consideration in the choice of a catchment because the longer the period of record, the more rigorously the model may be tested. According to Pitman (1973), a minimum of fifty years of record is required for the sample statistics to begin to approach the statistics of the population. Therefore, it was considered desirable to choose a catchment which has been recorded for approximately fifty years so as to be able to fully test the performance of the models under a wide range of runoff conditions.

The second criterion was that the catchment selected should be adequately covered by raingauges. The large catchments, that is, those in excess of 800 square kilometres, were discarded because of the prohibitively large computational effort involved in obtaining adequate areal assessments of daily rainfall due to the large number of raingauges which would be involved. Few of the smaller catchments were found to be suitable either because the coverage by raingauges was inadequate or because they had been gauged to produce monthly data whereas daily data were required. Further considerations were the reliability of the data and the period of recorded rainfall had to be the same as the period of recorded runoff. Regarding the reliability of the rainfall and runoff data, it is not possible to ascertain the accuracy of the records. However, it must be emphasized that the data used are typical of that available in South Africa except for a few recently instrumented catchments where the records are too short.

A suitable catchment which adequately fulfilled the above requirements was found to be that of the Mareetsane River (Figure 9), catchment number D4M02 (Department of Water Affairs, 1964) which was gauged at Neverset, North-East of Vryburg in the Northern Cape. The catchment has an area of 342 square kilometres and the river which is ephemeral, has an estimated mean annual runoff of $3324{,}21 \times 10^3 m^3$ (calculated from data obtained from Department of Water Affairs). The period of recorded daily runoff is from 1927 to 1964 inclusive which provides 38 years of record. The area has an average rainfall range of 530 to 490 millimetres (Department of Water Affairs, 1964) and daily rainfall data have been recorded at three stations covering the same period as recorded runoff. An added advantage of this catchment is that it occurs in a semi-arid region and has a climate characteristic of the larger part of South Africa.

Geologically the catchment is relatively homogeneous, being covered mostly by superficial deposits which are frequently of considerable thickness (du Toit, 1907). The area (Figure 10) is a rather monotonous, slightly undulating plain interupted by isolated ridges and low outcrops to produce a typical inselberg terrain. The superficial deposits consist of red sand mainly with smaller areas of surface quartzite, limestone and calcareous tufa. Beneath this superficial layer old schists occur set in massive granite and granitic gneiss. The granites and gneisses are exposed along the length of the Mareetsane River where the infrequent runoff events

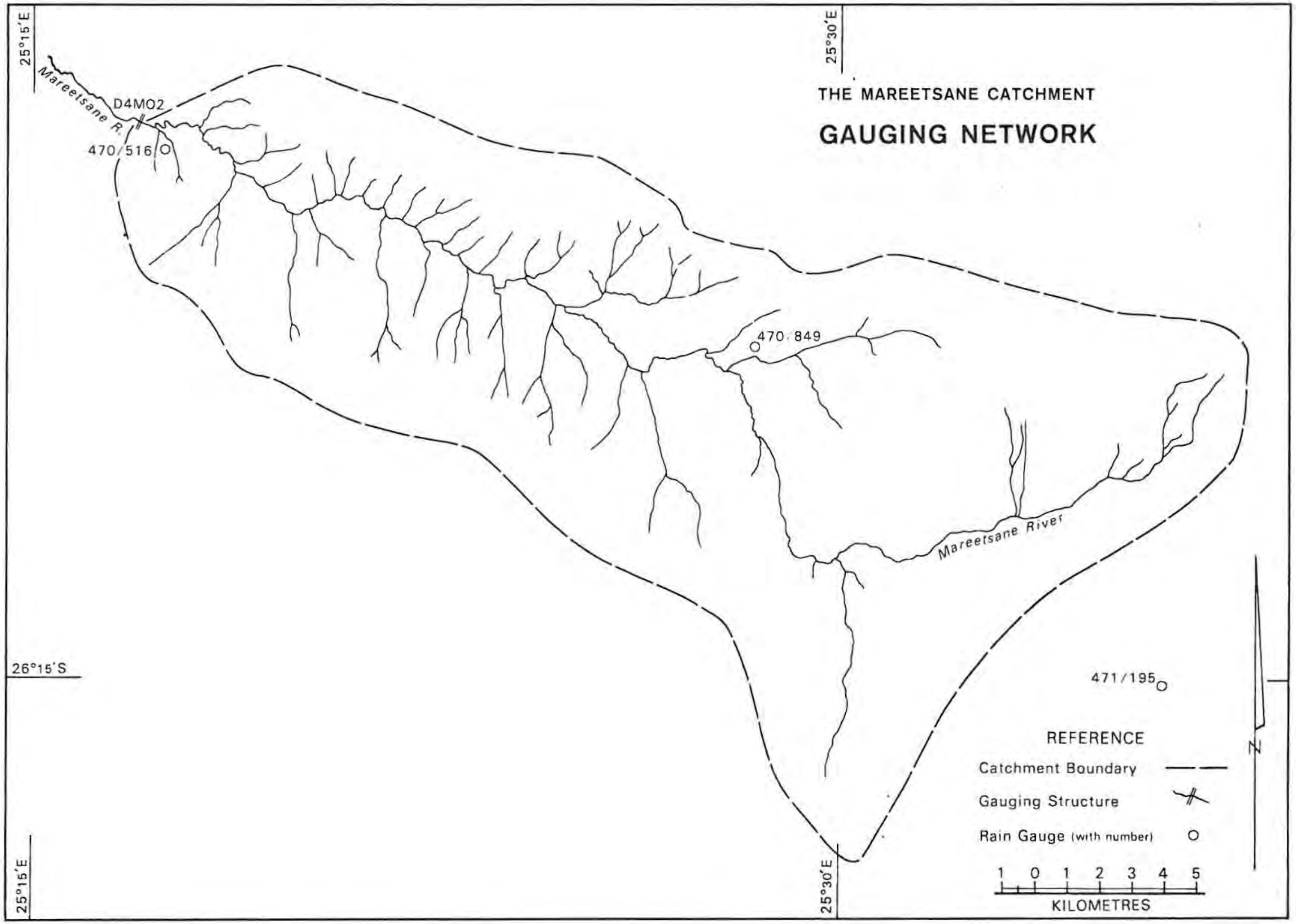

25°15'E
25°30'E
THE MAREETSANE CATCHMENT
GAUGING NETWORK
Mareetsane R.
D4M02
470/516
470/849
Mareetsane River
26°15'S
471/195
REFERENCE
Catchment Boundary
Gauging Structure
Rain Gauge (with number)
1 0 1 2 3 4 5
KILOMETRES
N
25°15'E
25°30'E

FIGURE 9

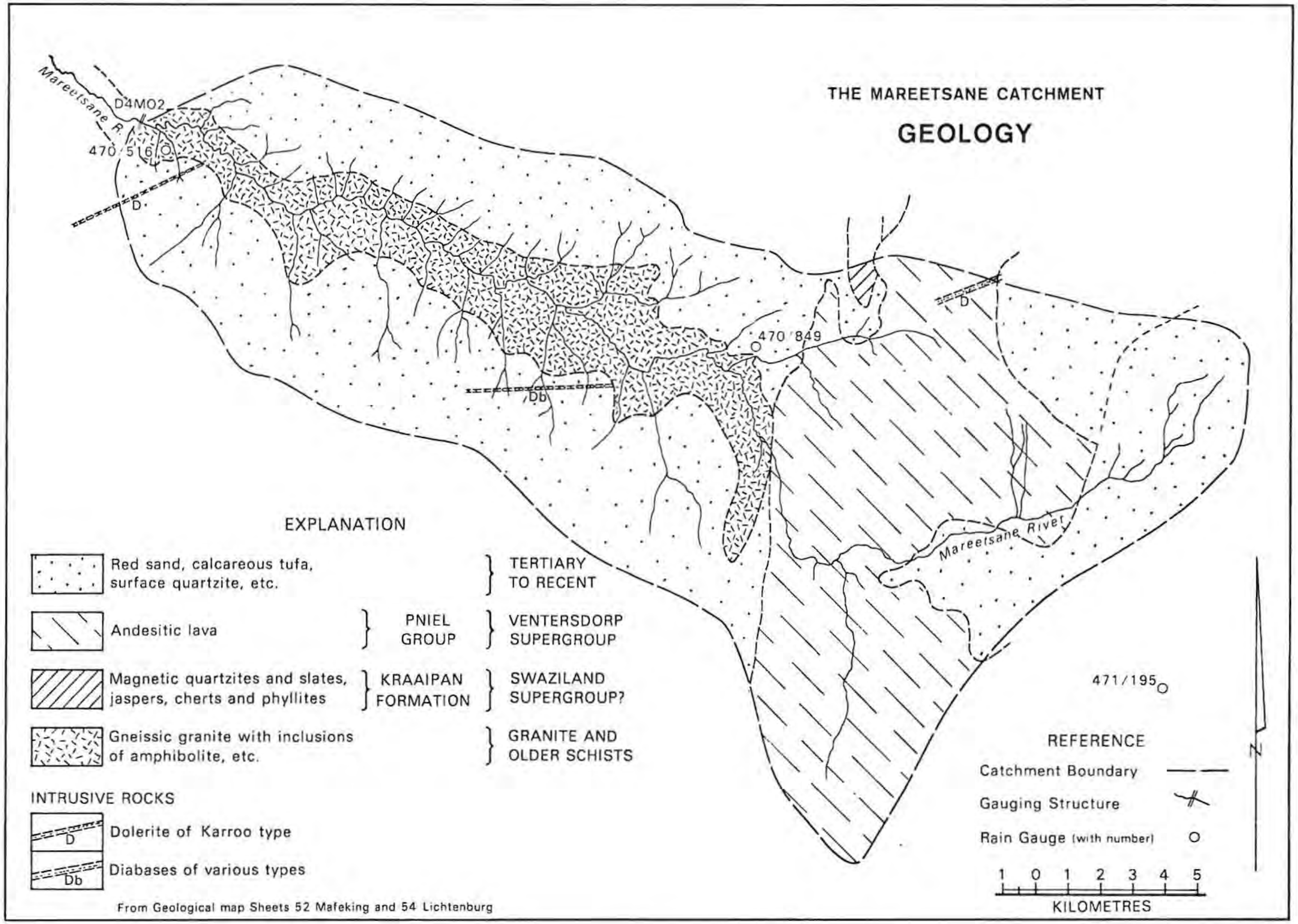

THE MAREETSANE CATCHMENT
GEOLOGY
Mareetsane R.
D4M02
470/516
D
Db
470/849
D
Mareetsane River
471/195
N
EXPLANATION
Red sand, calcareous tufa, surface quartzite, etc.
TERTIARY TO RECENT
Andesitic lava
PNIEL GROUP
VENTERSDORP SUPERGROUP
Magnetic quartzites and slates, jaspers, cherts and phyllites
KRAAIPAN FORMATION
SWAZILAND SUPERGROUP?
Gneissic granite with inclusions of amphibolite, etc.
GRANITE AND OLDER SCHISTS
INTRUSIVE ROCKS
D
Dolerite of Karroo type
Db
Diabases of various types
From Geological map Sheets 52 Mafeking and 54 Lichtenburg
REFERENCE
Catchment Boundary
Gauging Structure
Rain Gauge (with number)
1 0 1 2 3 4 5
KILOMETRES

FIGURE 10

have cut through the surface deposits. In the extreme East of the catchment occurs the Kraaipan Formation which includes hard magnetic quartzite and cherty rock interbedded with sheared volcanics, quartzites and calcareous schists (Haughton, 1969).

The vegetation of the area (Figure 11) consists of open Kalahari Thornveld of dense, tall grassland interupted by trees, dominantly Acacia giraffae with other trees and shrubs being rare occurances (Acocks, 1953). The general lack of trees and the mean annual precipitation of 487 mm (calculated from data obtained from the South African Weather Bureau) indicate that the catchment lies in a semi-arid area.

The rainfall data until 1953 were recorded by daily observations in units of inches and thereafter the units used were 0,1 mm. Data from the three stations which cover the catchment area were collected from the South African Weather Bureau and extend over the same period as the runoff record. The data were first converted to uniform units of 0,1 mm by means of program CONV (Appendix) and expressed as integer values of tenths of a millimetre because of the limitations of storage space in the computer. Due to the areal variability of rainfall, it was necessary to convert the several point measurements of rainfall to areal assessments of rainfall averaged over the catchment. Fleming (1975) and Gilman (1964) have discussed three commonly used methods for determining the average depth of rainfall over an area using the existing data at several point gauges. The first method is known as the arithmetic mean method and equal weight is assigned to each raingauge. The average rainfall depth over the catchment area is simply the total rainfall at all the gauges divided by the number of gauges, irrespective of the location of the gauges in the catchment. The method should be used only when the catchment has an even distribution of raingauges. Another technique of determining the average depth of rainfall over a catchment is the isohyetal method and is suitable for use in physically dissected areas. Lines of equal rainfall (isohyets) are drawn for the catchment using

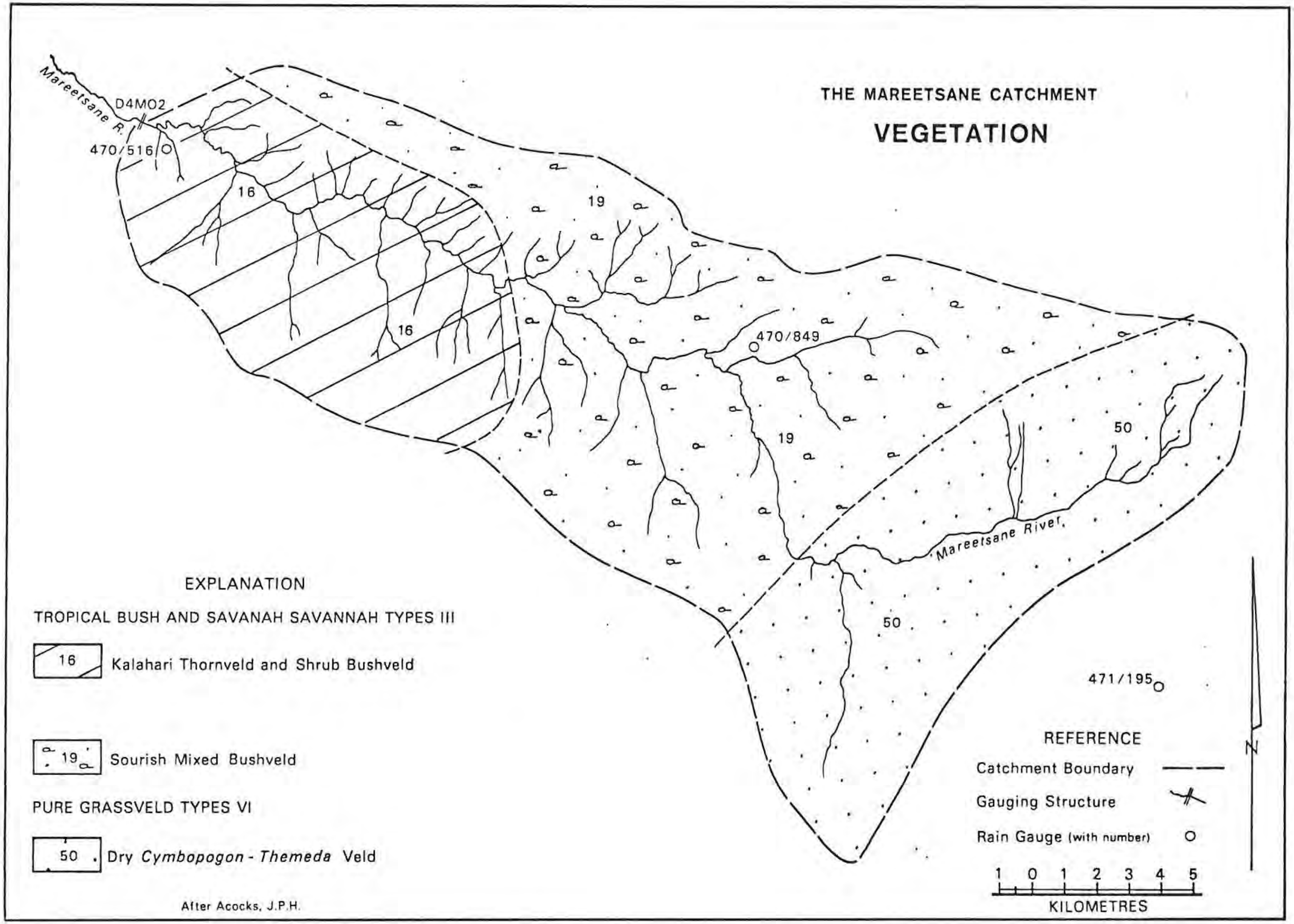

THE MAREETSANE CATCHMENT
VEGETATION
Mareetsane R.
D4M02
470/516
16
16
19
19
470/849
50
50
Mareetsane River
471/195
EXPLANATION
TROPICAL BUSH AND SAVANAH SAVANNAH TYPES III
16 Kalahari Thornveld and Shrub Bushveld
19 Sourish Mixed Bushveld
PURE GRASSVELD TYPES VI
50 Dry Cymbopogon - Themeda Veld
After Acocks, J.P.H.
REFERENCE
Catchment Boundary
Gauging Structure
Rain Gauge (with number)
1 0 1 2 3 4 5
KILOMETRES
N

FIGURE 11

the existing point rainfall data. The average precipitation is computed as the sum of the average rainfall between two isohyets multiplied by the ratio of the area between the isohyets and the total catchment area. By making use of isohyets, this method attempts to take into account the influence of topography on the variability of rainfall. The third proceedure is known as the Thiessen method and is generally used for catchments which have an uneven distribution of raingauges. The method attempts to overcome the uneven distribution by adjusting the weight given to each gauge by the ratio of the area represented by the gauge to the total catchment area. The subarea around each gauge is determined by constructing Thiessen polygons about the location of each gauge. Polygons are formed by the perpendicular bisectors of the lines joining nearby stations and the average rainfall is computed as the sum of each point rainfall multiplied by the ratio of the subarea to the total catchment area. The influence of topography upon the variability of rainfall is ignored in the Thiessen method. Of the three methods discussed, the Thiessen method was considered to be the most suitable for two reasons. Firstly, the catchment area is extremely flat and therefore did not warrant the use of the isohyetal method. Secondly, the distribution of the raingauges is uneven thereby precluding the use of the arithmetic mean method and necessitating the use of a form of weighting each point measurement. The several point measurements of rainfall were converted to areal assessments of rainfall by means of computer program POLY (Appendix). These areal assessments of rainfall were then inserted into their correct positions in a matrix of zeros created by program PROG (Appendix) with the correct year, month and card codes.

The other form of model input required was daily assessments of pan evaporation in millimetres. Daily evaporation data is not generally available and to overcome this problem, average pan evaporation data for each month were used (obtained from Pitman, 1973) and distributed over the month to give approximate daily values. This is the most common procedure for arriving at daily pan evaporation data. These daily approximations of pan evaporation were then converted to estimates of free water surface evaporation in each model by means of standard conversion factors used by the Department of Water Affairs.

Runoff was recorded by daily observation at a gauging weir with gauge plates in the river channel (Department of Water Affairs, 1964). The level of the river was measured several times in a 24 hour period during flow events and therefore to arrive at a value for daily discharge, a method of averaging the several daily readings was devised. The mean flow between successive readings was multiplied by the time interval in hours between the successive readings to obtain an average flow for each hour of the day. These hourly average flows were totalled and divided by 24 to obtain the mean flow value for the day. This mean flow for the day in cubic feet per second (cusecs) was converted to tens of cubic metres, the desired units of discharge and expressed as integer values. The use of integer values of runoff in tens of cubic metres was necessitated by the limitation on storage space in the computer. The daily discharge volumes obtained were inserted into their correct positions in a zero matrix similar to that created by program PROG (Appendix) for the rainfall data.

Using the data in the form set out above, each model was calibrated with respect to the three objective functions and the results are discussed in the following chapter. The performances of the models are compared and the hypotheses are examined in the light of the results to test their validity.

CHAPTER V

CALIBRATION RESULTS

Each of the three models was calibrated with respect to the three objective functions by trial and error manipulation of the model parameters. The performance of each model was assessed in terms of nine statistical indices calculated by means of a statistical sub-routine in each model program and a separate program EFFP (Appendix) for calculating the indices for peak daily discharges. These statistical indices and the results of the calibration process are discussed and assessed.

Statistical Indices

Of the nine statistical indices mentioned above, seven have been dealt with previously as part of the objective functions (Chapter III). In the case of any one objective function which is minimised, the other objective functions are calculated as indices of model performance. The statistical indices and objective functions are:

1) Percentage error in the mean of monthly volumes (S1).
2) Percentage error in the standard deviation of monthly volumes (S2).
3) U1 = /S2/+/S2/ (Objective Function 1).
4) Coefficient of efficiency of peak daily volume above a pre-set base level (Ep).
5) U2 = 1,0 - Ep (Objective Function 2).
6) Coefficient of determination for peak daily volumes above a pre-set base level (Dp) as given below;

$$Dp = \frac{\sum (q_c - \bar{q}_c)^2 - \sum (q_c - q_e)^2}{\sum (q_c - \bar{q}_c)^2} \qquad \text{(Equation 31)}$$

where q_c is the observed peak daily volumes above the base level, q_e is the simulated peak daily volume above the same base level and where the units used are millions of cubic metres.

7) Coefficient of efficiency of daily volumes (Ev).

8) U3 = 1,0 - Ev (Objective Function 3).

9) Coefficient of determination for daily volumes (Dv) where;

$$Dv = \frac{\sum(q_c - \bar{q}_c)^2 - \sum(q_c - q_e)^2}{\sum(q_c - \bar{q}_c)^2} \qquad \text{(Equation 32)}$$

and where q_c is the observed daily volumes, q_e is the estimated daily volume and the units used are millions of cubic metres.

The only two of the above list which remain statistics and are not part of the objective functions throughout the calibration process, are the coefficients of determination which are calculated as the squares of the respective product moment correlation coefficients, "r" (Aitken, 1973). While the coefficient of determination is generally used to show the association between two sets of data, it does not distinguish between random and systematic error in the simulated output should systematic error exist. It was for this reason that the coefficient of efficiency was used in objective functions U2 and U3 because it is sensitive to systematic error. In order to show the extent to which the values of the coefficients of efficiency Ep and Ev have been depressed by systematic error, the respective coefficients of determination Dp and Dv are calculated. The presence of strong bias in the simulated output is revealed by the values of Ep and Ev being lower than the respective values of Dp and Dv (Aitken, 1973).

In the calculation of the coefficients of efficiency and determination for daily volumes for objective function U3, that is, Ev and Dv, logarithmic values of daily runoff were used. The use of logarithmic values was deemed necessary because of the nature of the flow regime in the study catchment where low or zero flows predominate, interspersed with a relatively few large flood peaks. The influence of these flood peaks was found to be out of proportion in relation to the low flows and therefore the logarithmic values of daily runoff volumes were used to achieve more realistic values of Ev and Dv by giving more equal weight to each daily value. In the case of objective function U2, it was not considered to be necessary to use logarithmic values of runoff to calculate Ep and Dp because the flood peak values were more normally distributed than the daily values which were polarized into two groups.

Using the information gained from plotting the shapes of the various functions in the models (Chapter II), suitable parameter values and sizes of storage elements were used and adjusted to calibrate the models so as to minimise the values of the three objective functions. The results of the calibration of all three models are discussed in terms of each objective function.

Calibration Results and Testing of Hypotheses

Objective function U1

All three models were calibrated so as to minimise the first objective function U1 and the results are set out in Table 1. Included in the table are the values of the other objective functions and statistics, as indices of model performance. The results contained in Table 1 indicate that the errors involved are probably too large to be acceptable for most engineering applications. The model MO15 produced the lowest combined error in the mean and standard deviation of monthly volume, that is 28,5%. The value for U1 produced by MO12 was approximately double this figure and that produced by DAWM was approximately three times the error produced by MO15. In terms of the first hypothesis H1, these results show that H1 only partially holds true with DAWM being least able to minimise U1. However with respect to MO15 and MO12, the two models have been transposed. A possible explanation for this

MODEL INDEX	DAWM	MO15	MO12
OBJECTIVE FUNCTION U1	87,63	28,53	62,66
ERROR IN MEAN MONTHLY VOLUME S1 (%)	-87,09	- 1,03	-62,55
ERROR IN STANDARD DEVIATION S2 (%)	- 0,54	27,50	- 0,11
OBJECTIVE FUNCTION U2	5,03	3,09	5,66
COEFFICIENT OF EFFICIENCY Ep	- 4,03	- 2,09	- 4,66
COEFFICIENT OF DETERMINATION Dp	0,01	0,00	0,00
OBJECTIVE FUNCTION U3	1,07	1,06	1,08
COEFFICIENT OF EFFICIENCY Ev	- 0,07	- 0,06	- 0,08
COEFFICIENT OF DETERMINATION Dv	0,00	0,28	0,01

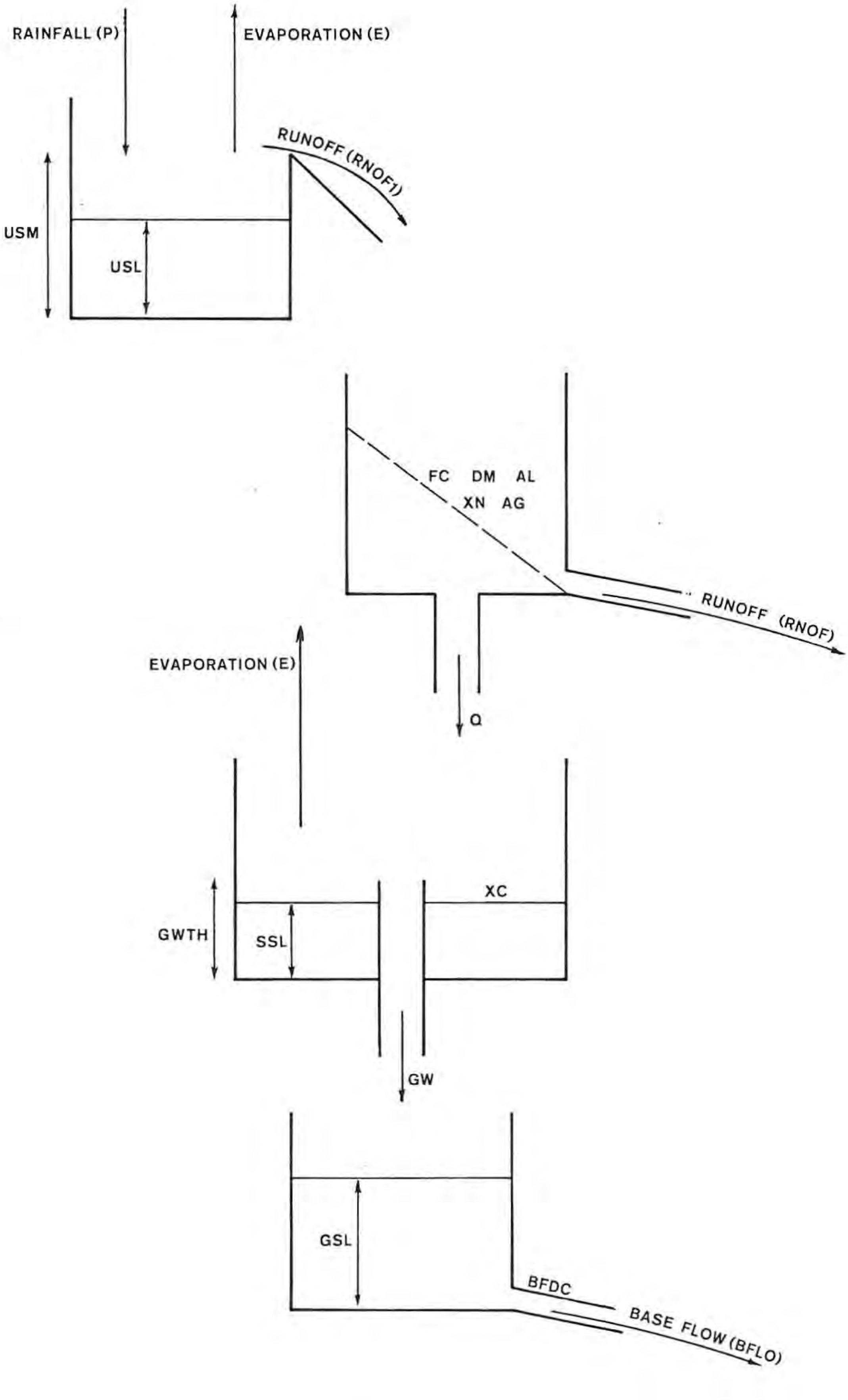
TABLE 1

CALIBRATION RESULTS FOR OBJECTIVE FUNCTION U1 result will be discussed in a later section of this chapter in the light of the other results.

In terms of the other statistics of model performance, MO15 produced lower values for U2 than the other two models, that is, 3,09 as opposed to 5,03 for DAWM and 5,66 for MO12. With regard to U3, MO15 was marginally better than the other two models. An examination of the values for Dv and Dp relative to Ep and Ev, shows the presence of strong systematic error in the simulated data for all three models. However in all three cases, the values of U2 and U3 do not even approach acceptable limits of error, that is a value of 0,15. Hence it may be concluded that all three models appear to be unable to produce reasonable mean monthly volumes and at the same time give reasonably accurate simulated peak daily flows and daily volumes.

One possible cause for the inability of MO12 to minimise objective function U1 appears to be that MO12 is capable only of producing surface runoff with no flow after the peak for successive non-rain days. This deficiency is partially overcome by calibrating MO12 to produce a greatly exaggerated hydrograph peak to compensate for the lack of base flow after the peak. Because it was hypothesized that MO12 would be the most efficient of the three models in terms of the first two objective functions, it was decided to modify MO12 to include a base flow component in order to assess the extent to which the results could be improved. The modified version of Model MO12, called EX12, is illustrated in Figure 12.

There appear to be mainly two ways by which the contribution to base flow is simulated by other models. The first is to direct part of the infiltrating moisture directly to an active groundwater storage which is then decayed exponentially as base flow. Two examples of this method are to be found in the Stanford Watershed Model IV (Crawford and Linsley, 1966) and in the model produced by Porter and McMahon (1971). The second and possibly the more common method of simulating base flow in a model is to directly relate the contribution to base flow to the level of moisture in a



THE STRUCTURE OF MODEL EX12

FIGURE 12

lower zone storage. Base flow contribution may then take the form of moisture extraction from the lower zone storage and decayed as in the case of the models by Nielsen and Hansen (1973), Bowles and Riley (1976), Dawdy and O'Donnell (1965) and Claborn and Moore (1970). Alternatively the contribution to base flow may be determined by an exponential function based upon the contents of the lower zone storage without the use of a separate groundwater storage as in the model by Pitman (1973). With respect to model MO12, the second storage represents the upper zone soil storage and the model's structure does not incorporate a lower zone soil storage. It was therefore decided to direct the calculated inactive groundwater losses to a base flow storage of infinite size, that is, an active groundwater storage, and to decay the storage as base flow. The amount of base flow occuring in each time interval is determined using a constant, BFDC, where BFDC is the Base Flow Decay Constant for the 24 hour period as determined from the observed runoff record. The base flow decay function used in model EX12 is;

$$\mathrm{BFLO} = \mathrm{GSL}\ (1{,}0 - \mathrm{BFDC}) \qquad \text{(Equation 33)}$$

where GSL is the level of moisture in the base flow storage and BFLO is the contribution to base flow during the current time interval. The shape of the base flow decay function is illustrated in Figure 13 and the graph shows that the base flow function produces exponential decay of the base flow storage even though the function itself is linear. The addition of a base flow component to MO12 has changed the concept of the losses from the upper zone storage and this change of concept will have to be compensated for by a change in the values of the parameter set which controls the variation of the soil moisture level, SSL. The results obtained by calibration of EX12 represent an improvement over those obtained from MO12 and are set out in Table 2 along with the results from MO15 in order to aid

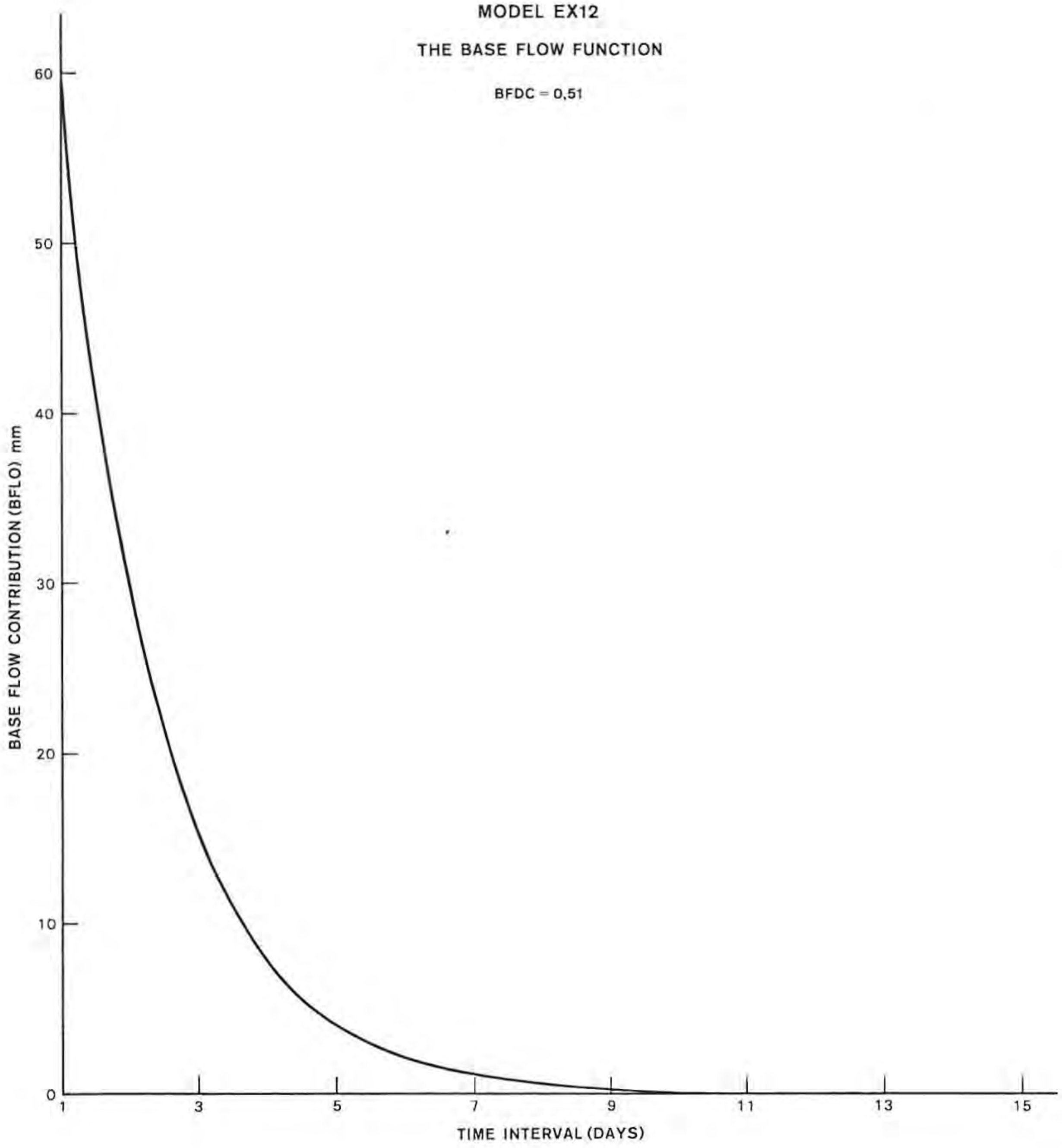

MODEL EX12
THE BASE FLOW FUNCTION
BFDC = 0,51
BASE FLOW CONTRIBUTION (BFLO) mm
60
50
40
30
20
10
0
1
3
5
7
9
11
13
15
TIME INTERVAL (DAYS)

FIGURE 13

INDEX / MODEL	MO15	MO12	EX12
OBJECTIVE FUNCTION U1	28,53	62,66	31,94
ERROR IN MEAN MONTHLY VOLUME S1 (%)	- 1,03	-62,55	-23,72
ERROR IN STANDARD DEVIATION S2 (%)	27,50	- 0,11	8,21
OBJECTIVE FUNCTION U2	3,09	5,66	2,28
COEFFICIENT OF EFFICIENCY Ep	- 2,09	- 4,66	- 1,28
COEFFICIENT OF DETERMINATION Dp	0,00	0,00	0,00
OBJECTIVE FUNCTION U3	1,06	1,08	1,68
COEFFICIENT OF EFFICIENCY Ev	- 0,06	- 0,08	- 0,68
COEFFICIENT OF DETERMINATION Dv	0,28	0,01	0,31

TABLE 2

COMPARISON OF RESULTS FOR MODELS
MO15, MO12, EX12

comparison of the three models.

The results shown in Table 2 illustrate that EX12 produced an error of 31,94% for objective function U1 compared with an error of 62,66% produced by MO12. While the error of 31,94% produced by EX12 is probably too large to be of use for most applications, it does represent a marked improvement over MO12 but is still not as good as that produced by MO15, that is, 28,53%. In terms of the other statistics of model performance, EX12 produced a better value for U2 than MO12, in fact the lowest value for U2 for all the models. However systematic error exists in the simulation as shown in Table 2 by Ep being lower than Dp. With respect to U3, EX12 did not improve on the value obtained by MO12 and indeed produced the worst result of all the models with strong systematic error present. Hence in terms of U1, the modifications to MO12 appear to be valid for most statistics.

Objective function U2

The three original models were recalibrated so as to minimise objective function U2 and the results are set out in Table 3. The results given in Table 3 indicate that the errors involved in reproducing the peak daily volumes above a pre-set base level of 160 000m^3 are large, probably too large for practical application. Models MO15 and DAWM produced values for U2 of 2,02 while that of MO12 was 2,16. These values of U2 do not approach the accepted level of 0,15 for calibration. In addition, the value of Dp relative to Ep reveals the presence of strong bias in the model output. In view of these results, the second hypothesis, H2, is conclusively disproved in all respects and a possible explanation of these results will be put forward in a later section of this chapter.

A comparison of the three models on the basis of all the statistics of model performance shows that MO15 was the most efficient of the three models. Model MO15 produced a lower combined error in the mean and standard deviation of monthly volumes and a better value for U3 than DAWM or MO12. However, the errors in the simulation are still large, being 36%

MODEL INDEX	DAWM	MO15	MO12	EX12
OBJECTIVE FUNCTION U2	2,02	2,02	2,16	1,60
COEFFICIENT OF EFFICIENCY Ep	- 1,02	- 1,02	- 1,16	- 0,60
COEFFICIENT OF DETERMINATION Dp	0,00	0,00	0,00	0,00
OBJECTIVE FUNCTION U1	198,31	36,42	169,59	64,71
ERROR IN MEAN MONTHLY VOLUME S1 (%)	-99,81	-34,57	-96,51	9,67
ERROR IN STANDARD DEVIATION S2 (%)	-98,50	- 1,86	-73,09	55,04
OBJECTIVE FUNCTION U3	1,07	0,96	1,07	1,18
COEFFICIENT OF EFFICIENCY Ev	- 0,07	0,04	- 0,07	- 0,18
COEFFICIENT OF DETERMINATION Dv	0,00	0,27	0,00	0,36

TABLE 3

RESULTS OF CALIBRATION FOR
OBJECTIVE FUNCTION U2

for U1 and there is a marked systematic error in the simulated daily discharge volumes. Hence it would appear not to be possible to reproduce the peak daily volumes accurately as well as producing accurate monthly and daily volumes with the models in their present forms.

Model EX12 was also calibrated for objective function U2 and represents an improvement over M012. The value for U2 was 1,60 as compared to 2,16 for M012 and 2,02 for M015 and this value produced by EX12 represents the lowest value achieved by all the models. There is however systematic error present and the value of 1,60 is still poor in comparison to the cut-off value of 0,15. In terms of the other statistics, EX12 produced a value for U1 much lower than that produced by M012, again representing an improvement over M012 but not over M015. However, the value for U3 obtained from EX12 of 1,18 is the worst of all the models and strong bias is also present. As in the calibration for objective function U1, it has been shown that EX12 provides improved results in comparison to M012 for most statistics but not for all of them.

Objective function U3

The calibration process was repeated a third time so as to minimise the third objective function U3 which represents the models ability to reproduce the daily discharge volumes. The results of this calibration are set out in Table 4 and demonstrate that none of the models minimised U3 to within the acceptable level of accuracy of 0,15. Model M015 produced the lowest value for U3 of 0,88 while the value for DAWM was 1,05 and that for M012 was 1,07. The relative values of Dv and Ev reveal the presence of systematic error in the simulated data. These results show that the third hypothesis, H3, is partially true with M015 being the most efficient of the three models but DAWM being marginally more efficient than M012. As with the previous two hypotheses, a possible explanation will be offered in the following section.

MODEL INDEX	DAWM	MO15	MO12	EX12
OBJECTIVE FUNCTION U3	1,05	0,88	1,07	0,78
COEFFICIENT OF EFFICIENCY Ev	- 0,05	0,12	- 0,07	0,22
COEFFICIENT OF DETERMINATION Dv	0,02	0,21	0,00	0,38
OBJECTIVE FUNCTION U1	208,53	90,95	157,95	70,53
ERROR IN MEAN MONTHLY VOLUME S1 (%)	- 0,18	-62,75	-91,78	-68,26
ERROR IN STANDARD DEVIATION S2 (%)	208,35	-23,20	-66,17	2,27
OBJECTIVE FUNCTION U2	2,02	2,02	2,16	2,24
COEFFICIENT OF EFFICIENCY Ep	- 1,02	- 1,02	- 1,16	- 1,24
COEFFICIENT OF DETERMINATION Dp	0,00	0,00	0,00	0,00

TABLE 4

CALIBRATION RESULTS FOR
OBJECTIVE FUNCTION U3

A consideration of the other indices of model performance shows MO15 to be the most efficient of the three models but that the errors involved are probably too large to be acceptable for most practical applications. The value for the combined error in the mean and standard deviation of monthly volumes is 91% compared with 209% for DAWM and 158% for MO12. With regard to the reproduction of peak daily volumes, the strong systematic error present is illustrated by the value for Ep being much less than Dp. Hence the errors involved in producing the daily discharge volumes in terms of all the indices of model performance, are too large for the output to be of practical use.

The results obtained by calibrating EX12 indicate that not only is the model an improvement over MO12 with respect to U3 but that EX12 achieved the best results of all the models. The improvement in the results for this objective function might be expected because of the incorporation of a base flow function in EX12. The value for U3 produced by EX12 was 0,78 as opposed to 1,07 for MO12 and 0,88 for MO15. In addition, the systematic error involved in the simulation using EX12 does not appear to be as marked as in any previous case because Ev has a value of 0,22 compared to a Dv value of 0,38. Further in terms of the other statistics, EX12 produced the lowest U1 value of the four models, that is, 70,5%. Although the error is too large to be acceptable, this value for U1 was lower than the 91% produced by MO15. However, EX12 was not capable of producing a comparable value for U2, the value of 2,24 being the worst of all the models.

In the light of the above results and the partial rejection of the first and third hypotheses and the total rejection of the second hypothesis, some explanation is necessary as to the reason for the hypotheses being found to be invalid.

Assessment of Simulation Results

The results obtained from the original three models and the modified version of MO12 are extremely poor and none of the calibrations produced output at an acceptable level of accuracy. The reasons for such poor results probably lie in three directions although it is not possible to assess the precise influence of each source of error. In view of the recommendations by Wilson (1974) regarding rain-gauge densities for reservoired areas, it is recognised that the recorded rainfall data represents one of the possible sources of error in the simulation. As a result, the causative rainfall producing some of the highest runoff is probably inadequately represented in the rainfall record and this is supported by visual comparison of some of the major runoff events with their causative rainfalls. The second source of error probably lies in the recorded runoff data because of the relatively low capacity of the gauging structure and the lack of autographic instrumentation. These two factors could give rise to inaccurate measurement of the peak runoff events. However it should be noted that the rainfall and runoff data is typical of that available to the user in South Africa.

The third source of error could lie in the structure of the models themselves. It has already been demonstrated that the model EX12 can produce a substantial improvement in results by incorporating a base flow function. However, a clue as to a further aspect of model structure which could be at fault can be obtained from work done by Pitman (1973). Pitman's work on fifty catchments in South Africa indicated that in humid climates (as defined by Pitman (1973)) the catchment output is highly dependent upon the soil moisture conditions. Alternatively, in arid climates it was found that soil moisture state had little influence on the output and that the function relating runoff to soil moisture could be omitted from the model. In areas which are transitional between these two types, both functions are required to produce runoff with acceptable accuracy. The character of all of the models studied is such that all are very dependent upon the soil moisture state to produce runoff. Under dry conditions, the nature of the functions which produce runoff in the models studied is that more rainfall is absorbed by the model than actually occurs in the catchment. Conversely, under wet conditions, the model absorbs less rainfall than it should. The dependence upon soil moisture should be seen in relation to the fact that the study catchment probably lies in an arid zone as evidenced by the presence of wind-blown sand. The presence of sand makes the runoff in the catchment less dependent upon antecedent moisture conditions than would normally be the case. It seems that an excess precipitation function that is more sensitive to the precipitation volume than antecedent conditions for the current time interval, is the most important component missing from the models in their present form.

All three of the models studied are to a greater or lesser extent dependent upon soil moisture content to produce runoff. Model DAWM is the most dependent upon the level of moisture in the single storage to produce runoff. Model MO12 depends on the overflow from the relatively small first storage and the amount of runoff depends upon the level of moisture in the second storage element. Alternatively, MO15 appears to be less dependent upon soil moisture state to produce runoff than the other two models because runoff is produced after the threshold for inactive groundwater has been exceeded. Once the threshold has been exceeded, runoff can occur depending upon the value of the parameter XN and consequently runoff can be produced before saturated catchment conditions have been reached, that is, before the storage level has reached the maximum capacity. It is this feature of MO15 which is proposed as the explanation for the results produced by MO15 being relatively more accurate than MO12 with respect to all three objective functions despite the fact that it is a single storage model.

The research has revealed a number of defects in the models tested and possible ways of overcoming these deficiencies are proposed in order that the models be made more widely applicable under South African conditions. In terms of the aims of the study, indications as to the minimum level of structural complexity required for acceptable output have been gained.

However, further research into this aspect is needed and a number of recommendations are put forward.

CHAPTER VI

CONCLUSION

For the purposes of this research project, three conceptual mathematical models of the rainfall-runoff process were calibrated for a semi-arid catchment using data which is typical of that available in South Africa. The three models were calibrated with respect to three objective functions devised to represent three common engineering applications. During the calibration process, Model MO12 was refined by the incorporation of a base flow component in the model structure to produce Model EX12.

The results of the calibration process indicate that the performance of the three models is in general very poor and this led to the partial or total rejection of the three hypotheses which were put forward. The reasons for such poor performance are thought to be mainly in four areas although it is not possible to determine the precise contribution of each source to the total error in the simulated output. Firstly, it is proposed that error is probably inherent in the accuracy of the rainfall data because of an inadequate coverage of raingauges in relation to the shape of the catchment. Secondly, errors in the recorded runoff data are probably due to the lack of autographic records of the flow events. Thirdly, a general inadequacy of all three models was demonstrated to be the lack of a base flow component. Model EX12 was calibrated in the same way as the three models and showed that it was capable of improved results for most statistics but not for all. Finally, while the inclusion of a base flow component eliminates some of the inadequacy of model structure, a major deficiency in all three models was found to be their high degree of dependence upon antecedent moisture conditions to produce runoff. It is proposed that the high dependence upon soil moisture conditions can be overcome by incorporating an excess precipitation function which is more dependent upon the precipitation volume than upon the soil moisture state.

The results of the study therefore support the conclusions reached by Pitman (1973) concerning the use of models in semi-arid and arid regions.

The coefficient of efficiency was used to show the degree of one-to-one correspondence between two sets of data with respect to objective functions U2 and U3. This statistic was used primarily because of its sensitivity to systematic error in model output. However, it was found that the value of the statistic is highly dependent upon the units used to express the input data. The dependence upon the units of the input data does not affect relative comparison of values because the same units were used throughout, but caution should be exercised when comparing the values determined by different investigators.

In the calibration process, it was found that the values of the model parameters changed with the objective function being minimised. Further, none of the models was capable of minimising all three objective functions in one calibration process. This observation supports the current trend towards the use of suitable objective functions in the calibration process if reliable simulated output is to be achieved.

One of the aims of this study was to determine if the increase in structural complexity from DAWM through MO15 to MO12 was justified in terms of an improvement in the derived values of the objective functions. The results of the calibration process conclusively show that the complexity of MO12 compared to the other two models is not justified with respect to the catchment studied and that the incorporation of the stream network infiltration capacity is probably superfluous. Alternatively, model DAWM is too simple to provide reasonably accurate output for most practical applications. Model MO15 seems to possess the approximate minimum level of structural complexity necessary to provide acceptable output, provided that the model can be made less dependent upon antecedent soil moisture conditions for use in semi-arid regions.

Recommendations For Future Research

This study has revealed two major structural defects in the models chosen and further research is necessary to refine the models and overcome these inadequacies. Firstly, if models are to be useful generally under South African conditions, their structures should be improved so as to make the models less dependent upon antecedent moisture conditions. Secondly, there is a need for models to include a base flow component in their structure especially when the model is to be used for simulating discharge volumes over relatively short time intervals. Further, there is a need for research to improve the statistics available which can be used to show the degree of one-to-one correspondence between two sets of data, for example, between observed and simulated daily volumes.

For reasons stated previously, it was necessary to limit this research to three models and three objective functions in the calibration process. Therefore further research is required for more rigorous testing of the models using a wider range of objective functions. In addition, this study was based upon one catchment in a semi-arid area and further testing of the models in other semi-arid catchments (preferably with more accurate data) is necessary to examine the performance of the models under a wider range of catchment conditions. Finally, it would be desirable to use more models of the type used in this study to gain more knowledge of the structural requirements of a model under semi-arid catchment conditions.

REFERENCES

Acocks, J.P.H., 1953: "Veld Types of South Africa". *Botanical Survey Memoir*, 28, Pretoria, Department of Agriculture, Government Printer.

Aitken, A.P., 1973: "Assessing Systematic Errors in Rainfall-Runoff Models". *Journal of Hydrology*, 20, 121-136.

Bonne, J., 1970: *Stochastic Simulation of Monthly Streamflow by a Multiple Regression Model Utilizing Precipitation Data.* Ph.D. Thesis, University of Nevada. Ann Arbor, University Microfilms International.

Boughton, W.C., 1968: "A Mathematical Catchment Model for Estimating Runoff". *Journal of Hydrology (New Zealand)*, 7, 75-100.

Boughton, W.C., 1976: "Flood Estimation from Short Records". *Proceedings American Society of Civil Engineers : Journal of the Hydraulics Division*, 102 (HY3), 241-251.

Bowles, D.S. and Riley, J.P., 1976: "Low Flow Modelling in Small Steep Watersheds". *Proceedings American Society of Civil Engineers: Journal of the Hydraulics Division*, 102 (HY9), 1225-1239.

Bugliarello, G. and Gunther, F., 1974: *Computer Systems and Water Resources.* New York, Elsevier Publishing Company.

Chaudhry, A., 1975: *Development of a Version of Stanford Model and its Evaluation for Streamflow Synthesis from Small Watersheds in West Virginia.* Ph.D. Thesis, West Virginia University. Ann Arbor, University Microfilms International.

Chow, Ven Te and Kareliotis, S.J., 1970: "Analysis of Stochastic Hydrologic Systems". *Water Resources Research*, 6 (6), 1569-1582.

Chow, Ven Te, 1971: "Stochastic Hydrologic Systems". *Systems Approach to Hydrology*, 1-23. Fort Collins, Water Resources Publications.

Crawford, N.H. and Linsley, R.K., 1966: *Digital Simulation in Hydrology: Stanford Watershed Model IV.* Technical Report 39, Stanford, Stanford University.

Dawdy, D.R., Lichty, R.W. and Bergman, J.M., 1972: "A Rainfall-Runoff Simulation Model for Estimation of Flood Peaks for Small Drainage Basins". *U.S. Geological Survey Professional Paper 50 6-B*, Washington, U.S. Government Printing Office.

Dawdy, D.R. and O'Donnell, T., 1965: "Mathematical Models of Catchment Behavior". *Proceedings American Society of Civil Engineers : Journal of the Hydraulics Division*, 91 (HY4), 123-137.

Delleur, J.W., 1971a: General Discussion on Relevant Future Hydrologic Research Areas, in *Systems Approach to Hydrology*, 462-464. Fort Collins, Water Resources Publications.

Delleur, J.W., 1971b: General Discussion on Response Hydrology, in *Systems Approach to Hydrology*, 454-458. Fort Collins, Water Resources Publications.

Delleur, J.W., 1971c: General Discussion on Bridge Between Scientific and Applied Hydrology, in *Systems Approach to Hydrology*, 459-461. Fort Collins, Water Resources Publications.

Department of Water Affairs, 1964: Hydrographic Survey Publication, 8, 1. Pretoria, Government Printer.

Diskin, M.H., Buras, N. and Zamir, S., 1973: "Application of a Simple Hydrologic Model for Rainfall-Runoff Relations of the Dalton Watershed". Water Resources Publications, 9, 4, 927-936.

Diskin, M.H. and Simon, E., 1977: "A Procedure for the Selection of Objective Functions for Hydrologic Simulation Models". Journal of Hydrology, 34, 129-149.

Dooge, J.C.I., 1977: "Problems and Methods of Rainfall-Runoff Modelling". Mathematical Models for Surface Water Hydrology, Ciriani, T.A., Maidne, U. and Wallis, J.R. (eds), London, Wiley.

Du Toit, A.L., 1907: "Geological Survey of Portions of Mafeking and Vryberg". Twelfth Annual Report of the Geological Commission, Cape Town, Government Printer, 125-157.

Eagleson, P.S., 1971: Discussion of paper by Chow, Ven Te, in Systems Approach to Hydrology, 20. Fort Collins, Water Resources Publications.

Fahlbusch, F. and Muir, T.C., 1973: "Experience with a Monthly Rainfall-Runoff Transfer Function Model". Decisions with Inadequate Hydrological Data, Woolhiser, D.A. (ed), Fort Collins, Water Resources Publications.

Fleming, G., 1975: Computer Simulation Techniques in Hydrology. New York, American Elsevier Publishing Company.

Gilman, C.S., 1964: Rainfall, in Handbook of Applied Hydrology, Chow, Ven Te (ed), Section 9. New York, McGraw-Hill.

Haughton, S.H., 1969: Geological History of Southern Africa. Cape Town, Geological Society of South Africa.

Huggins, L.F., 1966: The Mathematical Simulation of the Hydrology of Small Watersheds. Ph.D. Thesis, Purdue University. Ann Arbor, University Microfilms International.

Hydrological Research Unit, Report No 1/72, 1972: Design Flood Determination in South Africa. Johannesburg, Department of Civil Engineering, University of the Witwatersrand.

Kostrowicki, A.S., 1976: "A System-based Approach to Research Concerning the Geographical Environment". Geographia Polonica, 33, 27-37.

Marino, M.A., 1975: "Digital Simulation Model of Aquifer Response to Stream Storage Fluctuation". Journal of Hydrology, 25, 51-58.

Mehrotra, S.C., 1976: "Some Theoretical Considerations in Reservoir Design". Journal of Hydrology, 29, 115-120.

Midgley, D.C. and Pitman, W.V., 1969: "Surface Water Resources of South Africa". Hydrological Research Unit Report 2/69, Johannesburg, Department of Civil Engineering, University of Witwatersrand.

Moore, W.L. and Claborn, B.J., 1971: "Numerical Simulation of Watershed Hydrology". Systems Approach to Hydrology, 296-324, Fort Collins, Water Resources Publications.

Moore, W.L., 1971: General Discussion on Response Hydrology in Systems Approach to Hydrology, 454-458, Fort Collins, Water Resources Publications.

Nielsen, S.A. and Hansen, E., 1973: "Numerical Simulation of the Rainfall-Runoff Process on a Daily Basis". Nordic Hydrology, 4, 171-190.

Nutbrown, D.A., Downing, R.A. and Monkhouse, R.A., 1975: "The Use of a Digital Model in the Management of the Chalk Aquifer in the South Downs, England". Journal of Hydrology, 27, 127-142.

Phatarfod, R.M., 1976: "Some Aspects of Stochastic Reservoir Theory". Journal of Hydrology, 30, 199-217.

Pinkayan, S. and Premchun, P., 1972: "Risks from Using Inadequate Flood Records". Floods and Draughts, 334-342. Schulz, E.F., Koelzer, V.A. and Mahmood, K. (eds), Fort Collins, Water Resources Publications.

Pitman, W.V., 1973: A Mathematical Model for Generating Monthly River Flows from Meteorological Data in South Africa. Report 2/73, Hydrological Research Unit, Johannesburg, University of the Witwatersrand.

Pitman, W.V., 1976: A Mathematical Model for Generating Daily River Flows from Meteorological Data in South Africa. Report 2/76, Hydrological Research Unit, Johannesburg, University of the Witwatersrand.

Pitman, W.V., 1977: Flow Generation by Catchment Models of Differing Complexity - A Comparison of Performance. Report 1/77, Hydrological Research Unit, Johannesburg, University of the Witwatersrand.

Porter, J.W. and McMahon, T.A., 1971: "A Model for the Simulation of Streamflow Data from Climatic Records". Journal of Hydrology, 13, 297-324.

Raudkivi, A.J. and Lawgun, N., 1974: "Simulation of Rainfall Sequences". Journal of Hydrology, 22, 271-294.

Schultz, G.A., 1968: "Digital Computer Solutions for Flood Hydrograph Prediction from Rainfall Data". Proceedings of the Symposium on the Use of Analogue and Digital Computers in Hydrology, Vol 1, 125-237. Tucson, IASH/UNESCO.

Simon, E. and Diskin, M.H., 1975: Objective Function Formulation and Their Effect on Hydrologic Simulation Models. Faculty of Civil Engineering Publication No. 216, Haifa, Technion - Israel Institute of Technology.

Todini, E., 1975: "The Arno River Model : Problems, Methodologies and Techniques". Computer Simulation of Water Resources Systems, 199-207, Vansteenkiste, G.C. (ed), Amsterdam, North-Holland Publishing Company.

Ward, R.C., 1974: Principles of Hydrology (2nd ed.), London, McGraw-Hill.

Watt, W.E. and Kidd, C.H.R., 1975: "QUURM - A Realistic Urban Runoff Model". Journal of Hydrology, 27, 225-235.

Wilson, E.M., 1974: Engineering Hydrology. London, Macmillan.

Wood, S.R., 1975: "A Catchment Simulation Model Developed for Urban and Urbanising Catchments with particular reference to the use of Automatic Optimisation Techniques". Computer Simulation of Water Resources Systems, 209-218. Vansteenkiste, G.C. (ed), Amsterdam, North-Holland Publishing Company.

Yevjevich, V., 1972: Stochastic Processes in Hydrology. Fort Collins, Water Resources Publications.

Yevjevich, V., 1974: "Determinism and Stochasticity in Hydrology". Journal of Hydrology, 22, 225-238.

APPENDIX

COMPUTER PROGRAMS

APPENDIX

Computer Programs

The programs used in this study are all written in standard Fortran IV for the ICL 1900T computer and are presented in the form of computer printouts to facilitate their application by potential users. In addition, all programs include detailed comment blocks setting out the format of the model inputs and output and other information relevant to the user.

The model programs

The four model programs DAWM, MO15, MO12 and EX12 may be divided conveniently into four segments, namely input, model structure, output and statistical subroutine. The input segment requires three sets of data which are read by way of three separate input channels and all the data is in card format. The first set of data, called the parameter set, contains the catchment name and simulation period, the catchment area, number of months in the simulation period, model parameters and storage values, program flags, monthly pan evaporation values and factors for pan to free water surface conversion. All four programs were written so as to use the same input data except for the small parameter section which is unique to each model. The model parameters and storage values were included in the first data set so as to facilitate the changing of parameter and storage values during the calibration process. In order to achieve flexibility, two control flags (ISTAT and IFLAG) have been built into the model programs. The flag "ISTAT" enables the user to initiate or suppress the statistical subroutine. The subroutine would be suppressed, for example, when the model is being used without observed runoff data to generate an artificial record. The other flag, "IFLAG" is used to initiate or suppress the printing of the simulated and observed daily volumes, and has uses in the model calibration process when only the output from the subroutine is required.

The other two sets of data required are areal assessments of rainfall and observed runoff data and both sets of data are in the form of three cards per month. In view of the considerable length of data used in this study, it was decided to express the rainfall data as integer values in tenths of a millimetre and the runoff data as integer values of tens of cubic metres. The use of integer values for the input data was necessitated by the limitations on storage space in the computer.

Three separate input channels were used as being the most efficient method for the system available. However, the programs were written so as to be capable of being run with a single data set if only one input channel is available. If the programs are to be run with a single input channel, the peripheral channel codes used in the model programs would have to be changed to a single code throughout. In this case, the single data set would have to be arranged as follows. The first section of the data would consist of the parameter set referred to above, followed by the first month's rainfall data of three cards, followed by the three cards for the first month's observed runoff data. Thereafter alternate rainfall and runoff data would follow for the entire simulation period.

The output from each model program is in two sections and either of the two sections may be suppressed by means of the program control flags. If both flags are set to initiate output, the output consists of, firstly the parameter set and catchment name used in the run so as to uniquely identify each run. The parameter values are followed by the simulated and observed daily volumes (6 lines per month) and the monthly totals. The second output section consists of the output from the statistical subroutine and provides the values of the objective functions used, indices of model performance, the final values of storage and a flow component summary generated by the model in the simulation process. The final values of storage are given so as to provide starting values for additional simulation if more data becomes available and to provide continuous simulation.

Data processing and accessory programs

The other programs included in the appendix are those for manipulating the data into a form suitable for model input and the additional programs used in the study.

The three data manipulation programs are relatively simple and require little comment except for program PROG. With regard to any arid or semi-arid catchment, days of zero flow and zero rainfall are likely to predominate over flow and rainfall days. To facilitate the creation of the rainfall and runoff data sets, program PROG was written to generate a zero matrix of the required length. The flow and rainfall values were then inserted into their correct positions in the matrix. PROG reads a sample zero matrix representing one month (3 cards) in the correct format and duplicates the sample, correcting for leap years and adding the correct data identification, year, month and card codes.

The calculation of the value of the coefficient of efficiency (Ev) for objective function U3 in the subroutine in each model program, requires the value of the sum of the squares of the deviations from the mean observed daily volume. To achieve the value of this constant, two programs were written. LEF1 calculates the mean observed daily volume and LEF2 uses the mean volume to calculate the sum of the squares of the deviations for the observed data.

The value of the second objective function U2 was calculated by program EFFP as the peak values above the pre-set base level were extracted manually from the observed and simulated records. Similarly to objective function U3, the value of the sum of the squares of the deviations from the mean observed peak daily volume above the base level was required for the calculation of the coefficient of efficiency (Ep). The value of the constant was calculated by program EFPK which first calculates the mean peak volume and uses the mean peak volume to calculate the sum of the squares of the deviations used in EFFP.

```
-------------------------------------------------------------------------
      DATE 31/10/78   TIME 15/52/58                         LISTING FOR:=

FILE:   HRPSMAXIMOP     SUBFILE DAWM IN CARD MODE

      LIST
      PROGRAM(DAWM)
      INPUT 5=CR0
      INPUT 6=ED1/FORMATTED(HRPSDATA01  )
      INPUT 7=ED2/FORMATTED(HRPSDATA02  )
      OUTPUT 8=LP0
      TRACE 2
      END
      MASTER DAWM
C#######################################################################
C THIS PROGRAM GENERATES DAILY DISCHARGE VOLUMES IN TENS OF CUBIC
C METRES FROM DAILY RAINFALL IN TENTHS OF A MILLIMETRE AND DAILY
C EVAPORATION IN MILLIMETRES.
C THE STRUCTURE OF THE MODEL IS BASED UPON THAT OF THE DALTON
C WATERSHED MODEL (DISKIN, BURAS AND ZAMIR, 1973).
C THE PROGRAM WAS DEVELOPED BY PETER S. STICKELLS, RHODES
C UNIVERSITY, 1978.
C#######################################################################
      DIMENSION LAST(12),EVAP(12),CONV(12),IRAIN(31)
      DIMENSION IRUN(31),IVOL(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C***********************************************************************
C READ IN CATCHMENT NAME, SIMULATION PERIOD (32 COLUMNS), CATCHMENT
C AREA (SQ. KM.) AND NUMBER OF MONTHS IN SIMULATION PERIOD (NMON).
C***********************************************************************
      READ(5,1)H1,H2,H3,H4,AREA,NMON
    1 FORMAT(4A8,F8.2,I6)
C***********************************************************************
C READ IN STORAGE VALUES (SSL, SSM) IN MM, FLAG TO INITIATE
C STATISTICAL SUBROUTINE, ISTAT, ( 1 = INITIATE, 0 = SUPPRESS)
C AND FLAG TO INITIATE PRINTING OF DAILY VALUES, IFLAG, ( 1 = PRINT,
C 0 = SUPPRESS).
C***********************************************************************
      READ(5,2)SSL,SSM,ISTAT,IFLAG
    2 FORMAT(F8.2,F8.2,1X,I1,1X,I1)
C***********************************************************************
C READ IN TWELVE AVERAGE MONTHLY PAN EVAPORATION VALUES (EVAP) IN MM
C AND TWELVE CONVERSION FACTORS, PAN EVAPORATION TO FREE WATER
C SURFACE (CONV).
C***********************************************************************
      READ(5,3)(EVAP(K),K=1,12),(CONV(L),L=1,12)
    3 FORMAT(12F5.0,/,12F5.2)
C-----------------------------------------------------------------------
C WRITE HEADING FOR OUTPUT AND STORAGE VALUES FOR RUN IDENTIFICATION.
C-----------------------------------------------------------------------
      WRITE(8,4)H1,H2,H3,H4
    4 FORMAT(1H1,1H ,4A8,//)
      WRITE(8,5)AREA,NMON,SSL,SSM
    5 FORMAT(1H ,17HCATCHMENT AREA = ,F8.2,/,1H ,13HNO. MONTHS = ,I6,/,
     11H ,6HSSL = ,F8.2,5X,6HSSM = ,F8.2,///)
C-----------------------------------------------------------------------
C IF THE DAILY VALUES ARE NOT WRITTEN (IFLAG=0), THE FOLLOWING "WRITE"
C STATEMENT IS OMITTED.
C-----------------------------------------------------------------------
      IF(IFLAG.NE.1)GO TO 52
      WRITE(8,8)
```

```
    8 FORMAT(1H ,47HDAILY DISCHARGE VOLUMES IN TENS OF CUBIC METRES,//)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C TPPT = TOTAL RAINFALL IN MM.
C TPE  = TOTAL POTENTIAL EVAPORATION IN MM.
C TRUN = TOTAL SIMULATED RUNOFF IN MM.
C TAE  = TOTAL ACTUAL EVAPORATION EXTRACTED IN MM.
C-----------------------------------------------------------------------
   52 TPPT=0.0
      TPE=0.0
      TRUN=0.0
      TAE=0.0
C-----------------------------------------------------------------------
C START OF MONTH LOOP.
C-----------------------------------------------------------------------
      DO 10 IMON=1,NMON
C***********************************************************************
C READ IN THE FIRST CARD OF THE CURRENT MONTH'S RAINFALL DATA IN UNITS
C OF INTEGER VALUES OF TENTHS OF A MILLIMETRE.
C      7X   = DATA IDENTIFICATION NOT READ BY PROGRAM.
C      2I2  = YEAR AND MONTH (64 FOR 1964, 06 FOR JUNE).
C      1X   = 1 FOR CARD 1 FOR DAYS 1 - 10.
C           = 2 FOR CARD 2 FOR DAYS 11 - 20.
C           = 3 FOR CARD 3 FOR DAYS 21 - END.
C      10I6 = TEN INTEGER VALUES OF RAINFALL.
C***********************************************************************
      READ(6,6)IYR,MON,(IRAIN(J),J=1,10)
    6 FORMAT(7X,2I2,1X,10I6)
C***********************************************************************
C CHECK FOR LEAP YEARS, SET NUMBER OF DAYS IN THE MONTH AND READ IN
C THE REST OF THE CURRENT MONTH'S RAINFALL DATA (2 CARDS).
C***********************************************************************
      NEND=LAST(MON)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(MON.EQ.2))NEND=NEND+1
      READ(6,7)(IRAIN(I),I=11,NEND)
    7 FORMAT(12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C CALCULATE DAILY FREE SURFACE EVAPORATION FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      AVAP=(EVAP(MON)*CONV(MON))/FLOAT(NEND)
C-----------------------------------------------------------------------
C START OF DAY LOOP.
C-----------------------------------------------------------------------
      DO 20 IDAY=1,NEND
C-----------------------------------------------------------------------
C CONVERT RAINFALL TO REAL VALUES IN MILLIMETRES AND ADD TO STORAGE
C LEVEL.
C-----------------------------------------------------------------------
      RAIN=FLOAT(IRAIN(IDAY))/10.0
      TPPT=TPPT+RAIN
      TPE=TPE+AVAP
      SSL=SSL+RAIN
      IF(SSL.GT.AVAP)GO TO 100
C-----------------------------------------------------------------------
C IF TEMPORARY STORAGE LEVEL IS INSUFFICIENT FOR FULL EVAPORATION
C DEMAND, REDUCE SSL TO ZERO.
C-----------------------------------------------------------------------
      TAE=TAE+SSL
      SSL=0.0
      RNOF=0.0
      IVOL(IDAY)=0.0
```

```
      GO TO 20
C-----------------------------------------------------------------------
C IF TEMPORARY STORAGE LEVEL IS SUFFICIENT FOR FULL EVAPORATION
C DEMAND SUBTRACT EVAPORATION DEMAND AND REDUCE STORAGE LEVEL.
C-----------------------------------------------------------------------
  100 SSL=SSL-AVAP
      TAE=TAE+AVAP
      IF(SSL.GE.SSM)GO TO 102
      IVOL(IDAY)=0.0
      GO TO 20
C-----------------------------------------------------------------------
C IF TEMPORARY STORAGE LEVEL IS ABOVE THE MAXIMUM CAPACITY,
C CALCULATE RUNOFF IN MILLIMETRES, CONVERT TO VOLUME IN TENS OF
C CUBIC METRES AND SET STORAGE LEVEL TO MAXIMUM CAPACITY.
C-----------------------------------------------------------------------
  102 RNOF=SSL-SSM
      TRUN=TRUN+RNOF
      IVOL(IDAY)=RNOF*AREA*100.0
      SSL=SSM
   20 CONTINUE
C-----------------------------------------------------------------------
C END OF DAY LOOP.
C-----------------------------------------------------------------------
      IF(ISTAT.EQ.0)GO TO 24
C***********************************************************************
C READ IN ONE MONTH'S OBSERVED RUNOFF (3 CARDS) IN SAME FORMAT AS THE
C RAINFALL DATA. THE OBSERVED RUNOFF DATA IS REQUIRED ONLY IF ISTAT=1.
C
C      12X  = DATA IDENTIFICATION, YEAR, MONTH & CARD CODE NOT READ.
C      10I6 = TEN INTEGER VALUES IN TENS OF CUBIC METRES.
C***********************************************************************
      READ(7,12)(IRUN(KK),KK=1,NEND)
   12 FORMAT(12X,10I6,/,12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH.
C MTOT = TOTAL SIMULATED RUNOFF FOR THE MONTH.
C NTOT = TOTAL OBSERVED RUNOFF FOR THE MONTH.
C-----------------------------------------------------------------------
   24 MTOT=0
      NTOT=0
C-----------------------------------------------------------------------
C CALCULATE MONTHLY TOTAL OBSERVED AND SIMULATED RUNOFF.
C-----------------------------------------------------------------------
   25 DO 30 IK=1,NEND
      MTOT=MTOT+IVOL(IK)
      IF(ISTAT.EQ.0)GO TO 30
      NTOT=NTOT+IRUN(IK)
   30 CONTINUE
      IF(IFLAG.NE.1)GO TO 51
   26 NE=0
C-----------------------------------------------------------------------
C WRITE OBSERVED AND SIMULATED DAILY VOLUMES AND MONTHLY TOTALS.
C-----------------------------------------------------------------------
      DO 60 LK=1,3
      NE=NE+10
      NB=NE-9
      IF(LK.EQ.3)NE=NEND
      WRITE(8,13)IYR,MON,(IVOL(IK),IK=NB,NE)
   13 FORMAT(1H ,10HSIMULATED ,2I2,1X,11I7)
      IF(ISTAT.EQ.0)GO TO 60
      WRITE(8,17)IYR,MON,(IRUN(NK),NK=NB,NE)
```

```
   17 FORMAT(1H ,10HOBSERVED  ,2I2,1X,11I7,)
      IF(LK.NE.3)GO TO 60
      WRITE(8,14)MTOT,NTOT
   14 FORMAT(1H0,1H ,15HSIMULATED TOTAL,I10,5X,14HOBSERVED TOTAL,I10,/,
     195(1H=),/)
   60 CONTINUE
   51 IF(ISTAT.NE.1)GO TO 10
C-----------------------------------------------------------------------
C CALL STATISTICAL SUBROUTINE (STAT) IF ISTAT=1.
C-----------------------------------------------------------------------
      CALL STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
   10 CONTINUE
C-----------------------------------------------------------------------
C END OF MONTH LOOP.
C WRITE THE FINAL VALUE OF STORAGE AND THE FLOW COMPONENT SUMMARY.
C-----------------------------------------------------------------------
      WRITE(8,31)SSL
   31 FORMAT(5X,19HFINAL STORAGE LEVEL,33X,F8.2,///)
      WRITE(8,32)TPPT,TRUN,TPE,TAE
   32 FORMAT(1H ,50HFLOW COMPONENT SUMMARY - ALL VALUES IN MILLIMETRES,
     1/,1X,50(1H=),//,5X,25HTOTAL RAINFALL FOR PERIOD,18X,F8.2,//,
     25X,33HTOTAL SIMULATED RUNOFF FOR PERIOD,10X,F8.2,//,
     35X,38HTOTAL POTENTIAL EVAPORATION FOR PERIOD,5X,F8.2,//,
     45X,35HTOTAL ACTUAL EVAPORATION FOR PERIOD,8X,F8.2)
      STOP
      END
      SUBROUTINE STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
C#######################################################################
C THIS SUBROUTINE CALCULATES THE VALUES OF OBJECTIVE FUNCTIONS U1 & U3
C AND THE COEFFICIENT OF DETERMINATION ACCOMPANYING U3.
C NOTE: LOGARITHMIC VALUES OF RUNOFF ARE USED TO CALCULATE THE VALUES
C       OF THE COEFFICIENTS OF EFFICIENCY AND DETERMINATION FOR
C       OBJECTIVE FUNCTION U3.
C#######################################################################
      DIMENSION IRUN(31),IVOL(31)
      IF(IMON.GT.1)GO TO 21
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C-----------------------------------------------------------------------
      YSUM=0.0
      XSUM=0.0
      TOYSQ=0.0
      TOXSQ=0.0
      TDFSQ=0.0
      TOSXY=0.0
      TMTSQ=0.0
      TOMSQ=0.0
      NDAY=0.0
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH.
C-----------------------------------------------------------------------
   21 SIGMY=0.0
      SIGMX=0.0
      SDFSQ=0.0
      SPRXY=0.0
      STOT=FLOAT(MTOT)/100000.0
      YSUM=YSUM+STOT
      SMTSQ=STOT*STOT
      TMTSQ=TMTSQ+SMTSQ
      OTOT=FLOAT(NTOT)/100000.0
      XSUM=XSUM+OTOT
```

```
      OMTSQ=OTOT*OTOT
      TOMSQ=TOMSQ+OMTSQ
      NDAY=NDAY+NEND
C-----------------------------------------------------------------------
C CALCULATE TOTALS FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      DO 40 ICON=1,NEND
      SSSS=FLOAT(IVOL(ICON)+1)
      SVAL=ALOG10(SSSS)
      SIMSQ=SVAL*SVAL
      SIGMY=SIGMY+SIMSQ
      OOOO=FLOAT(IRUN(ICON)+1)
      OVAL=ALOG10(OOOO)
      OBSSQ=OVAL*OVAL
      SIGMX=SIGMX+OBSSQ
      DIFXY=OVAL-SVAL
      DIFSQ=DIFXY*DIFXY
      SDFSQ=SDFSQ+DIFSQ
      PRXY=SVAL*OVAL
      SPRXY=SPRXY+PRXY
   40 CONTINUE
C-----------------------------------------------------------------------
C ADD MONTH TOTALS TO TOTALS FOR SIMULATION PERIOD.
C-----------------------------------------------------------------------
      TOYSQ=TOYSQ+SIGMY
      TOXSQ=TOXSQ+SIGMX
      TDFSQ=TDFSQ+SDFSQ
      TOSXY=TOSXY+SPRXY
      IF(IMON.NE.NMON)RETURN
      IF((YSUM.NE.0).AND.(XSUM.NE.0))GO TO 50
      WRITE(8,55)
   55 FORMAT(1H ,46HARRAY EQUAL TO ZERO - NO STATISTICS CALCULATED)
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      WRITE(8,54)EV,U3
   54 FORMAT(1H0,4X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,
     14X,F8.2,//,5X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//)
      RETURN
C-----------------------------------------------------------------------
C CALCULATE THE VALUES OF S1, S2, U1, EV, DV, AND U3.
C-----------------------------------------------------------------------
   50 A=YSUM/(FLOAT(NMON))
      B=XSUM/(FLOAT(NMON))
      TYR=FLOAT(NMON)/12.0
      AMSR=YSUM/TYR
      AMOR=XSUM/TYR
      S1=((A-B)/B)*100.0
      C=TMTSQ/FLOAT(NMON-1)
      D=A*A
      E=(C-D)**0.5
      F=TOMSQ/FLOAT(NMON-1)
      G=B*B
      H=(F-G)**0.5
      S2=((E-H)/H)*100.0
      U1=ABS(S1)+ABS(S2)
C-----------------------------------------------------------------------
C THE VALUE OF THE CONSTANT 11531.844 IS OBTAINED FROM TWO SEPARATE
C PROGRAMS (APPENDIX) WHERE THE CONSTANT IS THE SUM OF THE SQUARES OF
C THE DEVIATIONS FRON THE MEAN FOR OBSERVED RUNOFF DATA.
C-----------------------------------------------------------------------
      EV=(11531.844-TDFSQ)/11531.844
```

```
      U3=1.0-EV
      P=YSUM*XSUM
      Q=P/FLOAT(NDAY)
      R=TOSXY-Q
      AX=(XSUM*XSUM)/FLOAT(NDAY)
      BX=TOXSQ-AX
      CY=(YSUM*YSUM)/FLOAT(NDAY)
      DY=TOYSQ-CY
      EXY=(BX*DY)**0.5
      CCOE=R/EXY
      DV=CCOE*CCOE
C-----------------------------------------------------------------------
C WRITE HEADING AND OUTPUT FROM SUBROUTINE.
C-----------------------------------------------------------------------
      WRITE(8,22)
   22 FORMAT(1H1,1X,62HVALUES OF INDICES OF MODEL PERFORMANCE AND OBJECT
     1IVE FUNCTIONS,/,1X,62(1H-),//)
      WRITE(8,23)A,B,S1,E,H,S2,U1,EV,U3,DV
   23 FORMAT(5X,34HMEAN OF SIMULATED MONTHLY VOLUMES ,18X,F8.2,//,
     15X,33HMEAN OF OBSERVED MONTHLY VOLUMES ,19X,F8.2,//,
     25X,40H% ERROR IN MEAN OF MONTHLY VOLUMES (S1) ,12X,F8.2,//,
     35X,39HSTD. DEV. OF SIMULATED MONTHLY VOLUMES ,13X,F8.2,//,
     45X,38HSTD. DEV. OF OBSERVED MONTHLY VOLUMES ,14X,F8.2,//,
     55X,45H% ERROR IN STD. DEV. OF MONTHLY VOLUMES (S2) ,7X,F8.2,//,
     65X,22HOBJECTIVE FUNCTION U1 ,30X,F8.2,//,
     75X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,4X,F8.2,//,
     85X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//,
     95X,52HCOEFFICIENT OF DETERMINATION FOR DAILY VOLUMES (DV) ,F8.2)
      WRITE(8,29)YSUM,XSUM,AMSR,AMOR
   29 FORMAT(1H0,4X,45HTOTAL SIMULATED RUNOFF (MILLION CUBIC METRES),
     17X,F8.2,//,5X,44HTOTAL OBSERVED RUNOFF (MILLION CUBIC METRES),
     28X,F8.2,//,5X,28HMEAN ANNUAL SIMULATED RUNOFF,24X,F8.2,//,
     35X,27HMEAN ANNUAL OBSERVED RUNOFF,25X,F8.2,//)
      RETURN
      END
      FINISH
```

```
------------------------------------------------------------------------
       DATE 31/10/78   TIME 15/53/34                         LISTING FOR:- H

FILE:   HRPSMAXIMOP    SUBFILE M015 IN CARD MODE

      LIST
      PROGRAM(M015)
      INPUT 5=CR0
      INPUT 6=ED1/FORMATTED(HRPSDATA01   )
      INPUT 7=ED2/FORMATTED(HRPSDATA02   )
      OUTPUT 8=LP0
      TRACE 2
      END
      MASTER M015
C#######################################################################
C THIS PROGRAM GENERATES DAILY DISCHARGE VOLUMES IN TENS OF CUBIC
C METRES FROM DAILY RAINFALL IN TENTHS OF A MILLIMETRE  AND DAILY
C EVAPORATION IN MILLIMETRES.
C THE STRUCTURE OF THE MODEL IS BASED UPON THAT OF MODEL 15 (SIMON
C AND DISKIN, 1975).
C THE PROGRAM WAS DEVELOPED BY PETER S. STICKELLS, RHODES
C UNIVERSITY, 1978.
C#######################################################################
      DIMENSION LAST(12),EVAP(12),CONV(12),IRAIN(31)
      DIMENSION IRUN(31),IVOL(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C***********************************************************************
C READ IN CATCHMENT NAME, SIMULATION PERIOD (32 COLUMNS), CATCHMENT
C AREA (SQ. KM.) AND NUMBER OF MONTHS IN SIMULATION PERIOD (NMON).
C***********************************************************************
      READ(5,1)H1,H2,H3,H4,AREA,NMON
    1 FORMAT(4A8,F8.2,I6)
C***********************************************************************
C READ IN STORAGE VALUES (SSL,SSM,SSB) IN MM, MODEL PARAMETER
C VALUES (XN,XK), FLAG TO INITIATE STATISTICAL SUBROUTINE, ISTAT,
C (1 = INITIATE, 0 = SUPPRESS) AND FLAG TO INITIATE PRINTING OF
C DAILY VALUES OF RUNOFF, IFLAG, (1 = PRINT, 0 = SUPPRESS).
C***********************************************************************
      READ(5,2)SSL,SSM,SSB,XN,XK,ISTAT,IFLAG
    2 FORMAT(5F8.2,1X,I1,1X,I1)
C***********************************************************************
C READ IN TWELVE AVERAGE MONTHLY PAN EVAPORATION VALUES (EVAP) IN MM
C AND TWELVE CONVERSION FACTORS, PAN EVAPORATION TO FREE WATER
C SURFACE (CONV).
C***********************************************************************
      READ(5,3)(EVAP(K),K=1,12),(CONV(L),L=1,12)
    3 FORMAT(12F5.0,/,12F5.2)
C-----------------------------------------------------------------------
C WRITE HEADING FOR OUTPUT, STORAGE AND PARAMETER VALUES FOR RUN
C IDENTIFICATION.
C-----------------------------------------------------------------------
      WRITE(8,4)H1,H2,H3,H4
    4 FORMAT(1H1,1H ,4A8,//)
      WRITE(8,5)AREA,NMON,SSL,SSM,SSB,XN,XK
    5 FORMAT(1H ,17HCATCHMENT AREA = ,F8.2,/,1H ,13HNO. MONTHS = ,I6,/,
     11H ,6HSSL = ,F8.2,3X,6HSSM = ,F8.2,3X,6HSSB = ,F8.2,//,
     21H ,22HRUNOFF PARAMETER XN = ,F8.2,/,1H ,
     327HGROUNDWATER PARAMETER XK = ,F8.2,///)
C-----------------------------------------------------------------------
C IF DAILY VOLUMES ARE NOT WRITTEN (IFLAG=0), THE FOLLOWING "WRITE"
C STATEMENT IS OMITTED.
```

```
C-----------------------------------------------------------------------
      IF(IFLAG.NE.1)GO TO 52
      WRITE(8,8)
    8 FORMAT(1H ,47HDAILY DISCHARGE VOLUMES IN TENS OF CUBIC METRES,//)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C TPPT  = TOTAL RAINFALL IN MM.
C TPE   = TOTAL POTENTIAL EVAPORATION IN MM.
C TRUN  = TOTAL ACTUAL EVAPORATION EXTRACTED IN MM.
C TGRW  = TOTAL LOSS TO GROUNDWATER IN MM.
C TRUN1 = TOTAL RUNOFF UNDER UNSATURATED CONDITIONS IN MM.
C TRUN2 = TOTAL RUNOFF UNDER SATURATED CONDITIONS IN MM.
C-----------------------------------------------------------------------
   52 TPPT=0.0
      TPE=0.0
      TRUN=0.0
      TAE=0.0
      TGRW=0.0
      TRUN1=0.0
      TRUN2=0.0
C-----------------------------------------------------------------------
C START OF MONTH LOOP.
C-----------------------------------------------------------------------
      DO 10 IMON=1,NMON
C***********************************************************************
C READ IN THE FIRST CARD OF THE CURRENT MONTH'S RAINFALL DATA IN UNITS
C OF INTEGER VALUES OF TENTHS OF A MILLIMETRE.
C      7X     = DATA IDENTIFICATION NOT READ BY PROGRAM.
C      2I2    = YEAR AND MONTH (64 FOR 1964, 06 FOR JUNE).
C      1X     = 1 FOR CARD 1 FOR DAYS  1 - 10.
C             = 2 FOR CARD 2 FOR DAYS 11 - 20.
C             = 3 FOR CARD 3 FOR DAYS 21 - END.
C      10I6   = TEN INTEGER VALUES OF RAINFALL.
C***********************************************************************
      READ(6,6)IYR,MON,(IRAIN(J),J=1,10)
    6 FORMAT(7X,2I2,1X,10I6)
C***********************************************************************
C CHECK FOR LEAP YEARS, SET NUMBER OF DAYS IN THE MONTH AND READ IN
C THE REST OF THE CURRENT MONTH'S RAINFALL DATA (2 CARDS).
C***********************************************************************
      NEND=LAST(MON)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(MON.EQ.2))NEND=NEND+1
      READ(6,7)(IRAIN(I),I=11,NEND)
    7 FORMAT(12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C CALCULATE DAILY FREE SURFACE EVAPORATION FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      AVAP=(EVAP(MON)*CONV(MON))/FLOAT(NEND)
C-----------------------------------------------------------------------
C START OF DAY LOOP.
C-----------------------------------------------------------------------
      DO 20 IDAY=1,NEND
C-----------------------------------------------------------------------
C CONVERT RAINFALL TO REAL VALUES IN MILLIMETRES AND DETERMINE CURRENT
C TEMPORARY STATE OF STORAGE.
C-----------------------------------------------------------------------
      RAIN=FLOAT(IRAIN(IDAY))/10.0
      TPPT=TPPT+RAIN
      TPE=TPE+AVAP
      IF((SSL.GE.SSM).AND.(RAIN.LT.1.0))EVAPT=AVAP
      IF((SSL.GE.SSM).AND.(RAIN.GT.1.0))EVAPT=AVAP*0.5
```

```
      IF(SSL.LT.SSM)EVAPT=AVAP*((SSL+RAIN)/SSM)
      IF((SSL.LT.SSM).AND.(RAIN.GT.1.0))EVAPT=EVAPT*0.5
      IF(EVAPT.GT.AVAP)EVAPT=AVAP
      SSL=SSL+RAIN
      IF(SSL.GT.EVAPT)GO TO 100
      TAE=TAE+SSL
      SSL=0.0
      RNOF1=0.0
      IVOL(IDAY)=0.0
      GO TO 20
  100 SSL=SSL-EVAPT
      TAE=TAE+EVAPT
      IF((SSL.GE.SSB).AND.(SSL.LE.SSM))GO TO 101
      IF(SSL.GT.SSM)GO TO 102
      IVOL(IDAY)=0.0
      GRWA=0.0
      GO TO 20
C-----------------------------------------------------------------------
C CALCULATE RUNOFF UNDER UNSATURATED CONDITIONS.
C-----------------------------------------------------------------------
  101 RNOF1=(XN/(XN+1.0))*(SSL-SSB)*(((SSL-SSB)/(SSM-SSB))**(1.0/XN))
      TRUN=TRUN+RNOF1
      TRUN1=TRUN1+RNOF1
      IVOL(IDAY)=RNOF1*AREA*100.0
      GRWA=(XK*(SSL-SSB-RNOF1))
      TGRW=TGRW+GRWA
      SSL=SSL-(RNOF1+GRWA)
      GO TO 20
C-----------------------------------------------------------------------
C CALCULATE RUNOFF UNDER SATURATED CONDITIONS
C-----------------------------------------------------------------------
  102 RNOF2=(SSL-SSM)+((XN/(XN+1.0))*(SSM-SSB))
      RNOF1=(XN/(XN+1.0))*(SSM-SSB)
      TRUN=TRUN+RNOF2
      TRUN2=TRUN2+(SSL-SSM)
      IVOL(IDAY)=RNOF2*AREA*100.0
      GRWA=(XK*(SSL-SSB-RNOF1))
      TGRW=TGRW+GRWA
      SSL=SSL-(RNOF2+GRWA)
   20 CONTINUE
C-----------------------------------------------------------------------
C END OF DAY LOOP.
C-----------------------------------------------------------------------
      IF(ISTAT.EQ.0)GO TO 24
C***********************************************************************
C READ IN ONE MONTH'S OBSERVED RUNOFF (3 CARDS) IN SAME FORMAT AS THE
C RAINFALL DATA. OBSERVED RUNOFF DATA ONLY REQUIRED IF ISTAT=1.
C      12X  = DATA IDENTIFICATION, YEAR, MONTH & CARD CODE NOT READ.
C      10I6 = TEN INTEGER VALUES IN TENS OF CUBIC METRES.
C***********************************************************************
      READ(7,12)(IRUN(KK),KK=1,NEND)
   12 FORMAT(12X,10I6,/,12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH AND CALCULATE MONTHLY TOTALS.
C MTOT = TOTAL SIMULATED RUNOFF FOR MONTH.
C NTOT = TOTAL OBSERVED RUNOFF FOR MONTH.
C-----------------------------------------------------------------------
   24 MTOT=0
      NTOT=0
   25 DO 30 IK=1,NEND
      MTOT=MTOT+IVOL(IK)
```

```
      IF(ISTAT.EQ.0)GO TO 30
      NTOT=NTOT+IRUN(IK)
   30 CONTINUE
      IF(IFLAG.NE.1)GO TO 51
   26 NE=0
C-----------------------------------------------------------------------
C WRITE SIMULATED AND OBSERVED DAILY VOLUMES AND MONTHLY TOTALS.
C-----------------------------------------------------------------------
      DO 60 LK=1,3
      NE=NE+10
      NB=NE-9
      IF(LK.EQ.3)NE=NEND
      WRITE(8,13)IYR,MON,(IVOL(IK),IK=NB,NE)
   13 FORMAT(1H ,10HSIMULATED ,2I2,1X,11I7)
      IF(ISTAT.EQ.0)GO TO 60
      WRITE(8,17)IYR,MON,(IRUN(NK),NK=NB,NE)
   17 FORMAT(1H ,10HOBSERVED  ,2I2,1X,11I7,)
      IF(LK.NE.3)GO TO 60
      WRITE(8,14)MTOT,NTOT
   14 FORMAT(1H0,1H ,15HSIMULATED TOTAL,I10,5X,14HOBSERVED TOTAL,I10,/,
     195(1H-),/)
   60 CONTINUE
   51 IF(ISTAT.NE.1)GO TO 10
C-----------------------------------------------------------------------
C CALL STATISTICAL SUBROUTINE (STAT) IF ISTAT = 1.
C-----------------------------------------------------------------------
      CALL STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
   10 CONTINUE
C-----------------------------------------------------------------------
C END OF MONTH LOOP.
C WRITE FINAL VALUE OF STORAGE AND FLOW COMPONENT SUMMARY.
C-----------------------------------------------------------------------
      WRITE(8,31)SSL
   31 FORMAT(5X,19HFINAL STORAGE LEVEL,33X,F8.2,///)
      WRITE(8,32)TPPT,TRUN,TPE,TAE,TGRW,TRUN1,TRUN2
   32 FORMAT(1H ,50HFLOW COMPONENT SUMMARY - ALL VALUES IN MILLIMETRES,
     1/,1X,50(1H-),//,5X,25HTOTAL RAINFALL FOR PERIOD,18X,F8.2,//,
     25X,33HTOTAL SIMULATED RUNOFF FOR PERIOD,10X,F8.2,//,
     35X,38HTOTAL POTENTIAL EVAPORATION FOR PERIOD,5X,F8.2,//,
     45X,35HTOTAL ACTUAL EVAPORATION FOR PERIOD,8X,F8.2,//,
     55X,36HTOTAL FLOW TO GROUNDWATER FOR PERIOD,7X,F8.2,//,
     65X,26HTOTAL RUNOFF R1 FOR PERIOD,17X,F8.2,//,
     75X,26HTOTAL RUNOFF R2 FOR PERIOD,17X,F8.2)
      STOP
      END
      SUBROUTINE STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
C#######################################################################
C THIS SUBROUTINE CALCULATES THE VALUES OF OBJECTIVE FUNCTIONS U1 & U3
C AND THE COEFFICIENT OF DETERMINATION ACCOMPANYING U3
C NOTE: LOGARITHMIC VALUES OF RUNOFF ARE USED TO CALCULATE THE VALUES
C       OF THE COEFFICIENTS OF EFFICIENCY AND DETERMINATION FOR
C       OBJECTIVE FUNCTION U3.
C#######################################################################
      DIMENSION IRUN(31),IVOL(31)
      IF(IMON.GT.1)GO TO 21
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C-----------------------------------------------------------------------
      YSUM=0.0
      XSUM=0.0
      TOYSQ=0.0
```

```
      TOXSQ=0.0
      TDFSQ=0.0
      TOSXY=0.0
      TMTSQ=0.0
      TOMSQ=0.0
      NDAY=0.0
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH.
C-----------------------------------------------------------------------
   21 SIGMY=0.0
      SIGMX=0.0
      SDFSQ=0.0
      SPRXY=0.0
      STOT=FLOAT(MTOT)/100000.0
      YSUM=YSUM+STOT
      SMTSQ=STOT*STOT
      TMTSQ=TMTSQ+SMTSQ
      OTOT=FLOAT(NTOT)/100000.0
      XSUM=XSUM+OTOT
      OMTSQ=OTOT*OTOT
      TOMSQ=TOMSQ+OMTSQ
      NDAY=NDAY+NEND
C-----------------------------------------------------------------------
C CALCULATE TOTALS FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      DO 40 ICON=1,NEND
      SSSS=FLOAT(IVOL(ICON)+1)
      SVAL=ALOG10(SSSS)
      SIMSQ=SVAL*SVAL
      SIGMY=SIGMY+SIMSQ
      OOOO=FLOAT(IRUN(ICON)+1)
      OVAL=ALOG10(OOOO)
      OBSSQ=OVAL*OVAL
      SIGMX=SIGMX+OBSSQ
      DIFXY=OVAL-SVAL
      DIFSQ=DIFXY*DIFXY
      SDFSQ=SDFSQ+DIFSQ
      PRXY=SVAL*OVAL
      SPRXY=SPRXY+PRXY
   40 CONTINUE
C-----------------------------------------------------------------------
C ADD MONTH TOTALS TO TOTALS FOR SIMULATION PERIOD.
C-----------------------------------------------------------------------
      TOYSQ=TOYSQ+SIGMY
      TOXSQ=TOXSQ+SIGMX
      TDFSQ=TDFSQ+SDFSQ
      TOSXY=TOSXY+SPRXY
      IF(IMON.NE.NMON)RETURN
      IF((YSUM.NE.0).AND.(XSUM.NE.0))GO TO 50
      WRITE(8,55)
   55 FORMAT(1H ,46HARRAY EQUAL TO ZERO - NO STATISTICS CALCULATED)
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      WRITE(8,54)EV,U3
   54 FORMAT(1H0,4X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,
     14X,F8.2,//,5X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//)
      RETURN
C-----------------------------------------------------------------------
C CALCULATE VALUES OF S1, S2, U1, EV, DV AND U3.
C-----------------------------------------------------------------------
   50 A=YSUM/(FLOAT(NMON))
```

```
      B=XSUM/(FLOAT(NMON))
      TYR=FLOAT(NMON)/12.0
      AMSR=YSUM/TYR
      AMOR=XSUM/TYR
      S1=((A-B)/B)*100.0
      C=TMTSQ/FLOAT(NMON-1)
      D=A*A
      E=(C-D)**0.5
      F=TOMSQ/FLOAT(NMON-1)
      G=B*B
      H=(F-G)**0.5
      S2=((E-H)/H)*100.0
      U1=ABS(S1)+ABS(S2)
C-----------------------------------------------------------------------
C THE VALUE OF THE CONSTANT 11531.844 IS OBTAINED FROM TWO SEPARATE
C PROGRAMS (APPENDIX) WHERE THE CONSTANT IS THE SUM OF THE SQUARES
C OF THE DEVIATIONS FROM THE MEAN FOR THE OBSERVED RUNOFF DATA.
C-----------------------------------------------------------------------
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      P=YSUM*XSUM
      Q=P/FLOAT(NDAY)
      R=TOSXY-Q
      AX=(XSUM*XSUM)/FLOAT(NDAY)
      BX=TOXSQ-AX
      CY=(YSUM*YSUM)/FLOAT(NDAY)
      DY=TOYSQ-CY
      EXY=(BX*DY)**0.5
      CCOE=R/EXY
      DV=CCOE*CCOE
C-----------------------------------------------------------------------
C WRITE HEADING AND OUTPUT FROM SUBROUTINE.
C-----------------------------------------------------------------------
      WRITE(8,22)
   22 FORMAT(1H1,1X,62HVALUES OF INDICES OF MODEL PERFORMANCE AND OBJECT
     1IVE FUNCTIONS,/,2X,62(1H-),//)
      WRITE(8,23)A,B,S1,E,H,S2,U1,EV,U3,DV
   23 FORMAT(5X,34HMEAN OF SIMULATED MONTHLY VOLUMES ,18X,F8.2,//,
     15X,33HMEAN OF OBSERVED MONTHLY VOLUMES ,19X,F8.2,//,
     25X,40H% ERROR IN MEAN OF MONTHLY VOLUMES (S1) ,12X,F8.2,//,
     35X,39HSTD. DEV. OF SIMULATED MONTHLY VOLUMES ,13X,F8.2,//,
     45X,38HSTD. DEV. OF OBSERVED MONTHLY VOLUMES ,14X,F8.2,//,
     55X,45H% ERROR IN STD. DEV. OF MONTHLY VOLUMES (S2) ,7X,F8.2,//,
     65X,22HOBJECTIVE FUNCTION U1 ,30X,F8.2,//,
     75X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,4X,F8.2,//,
     85X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//,
     95X,52HCOEFFICIENT OF DETERMINATION FOR DAILY VOLUMES (DV) ,F8.2)
      WRITE(8,29)YSUM,XSUM,AMSR,AMOR
   29 FORMAT(1H0,4X,45HTOTAL SIMULATED RUNOFF (MILLION CUBIC METRES),
     17X,F8.2,//,5X,44HTOTAL OBSERVED RUNOFF (MILLION CUBIC METRES),
     28X,F8.2,//,5X,28HMEAN ANNUAL SIMULATED RUNOFF,24X,F8.2,//,
     35X,27HMEAN ANNUAL OBSERVED RUNOFF,25X,F8.2,//)
      RETURN
      END
      FINISH
```

```
--------------------------------------------------------------------------------
       DATE 31/10/78   TIME 15/53/55                              LISTING FOR:= H

FILE:   HRPSMAXIMOP     SUBFILE M012 IN CARD MODE

      LIST
      PROGRAM(M012)
      INPUT 5=CR0
      INPUT 6=ED1/FORMATTED(HRPSDATA01   )
      INPUT 7=ED2/FORMATTED(HRPSDATA02   )
      OUTPUT 8=LP0
      TRACE 2
      END
      MASTER M012
C#######################################################################
C THIS PROGRAM GENERATES DAILY DISCHARGE VOLUMES IN TENS OF CUBIC
C METRES FROM DAILY RAINFALL IN TENTHS IF A MILLIMETRE AND DAILY
C EVAPORATION IN MILLIMETRES
C THE STRUCTURE OF THE MODEL IS BASED UPON THAT OF MODEL 12 (SIMON
C AND DISKIN, 1975).
C THE PROGRAM WAS DEVELOPED BY PETER S. STICKELLS, RHODES
C UNIVERSITY, 1978.
C#######################################################################
      DIMENSION LAST(12),EVAP(12),CONV(12),IRAIN(31)
      DIMENSION IRUN(31),IVOL(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C***********************************************************************
C READ IN CATCHMENT NAME, SIMULATION PERIOD (32 COLUMNS), CATCHMENT
C AREA (SQ. KM.) AND NUMBER OF MONTHS IN SIMULATION PERIOD (NMON).
C***********************************************************************
      READ(5,1)H1,H2,H3,H4,AREA,NMON
    1 FORMAT(4A8,F8.2,I6)
C***********************************************************************
C READ IN STORAGE VALUES (USL,USM,SSL,GWTH) IN MM, FLAG TO
C INITIATE STATISTICAL SUBROUTINE, ISTAT, (1 = INITIATE, 0 = SUPPRESS)
C AND FLAG TO INITIATE PRINTING OF DAILY RUNOFF VALUES, IFLAG,
C (1 = PRINT, 0 = SUPPRESS).
C***********************************************************************
      READ(5,2)USL,USM,SSL,GWTH,ISTAT,IFLAG
    2 FORMAT(4F8.2,2X,I1,2X,I1)
C***********************************************************************
C READ IN MODEL PARAMETERS (FC,DM,AL,AG,XN,XC).
C***********************************************************************
      READ(5,3)FC,DM,AL,AG,XN,XC
    3 FORMAT(5F8.2,F8.3)
C***********************************************************************
C READ IN TWELVE AVERAGE MONTHLY PAN EVAPORATION VALUES (EVAP) IN MM
C AND TWELVE CONVERSION FACTORS, PAN EVAPORATION TO FREE WATER
C SURFACE (CONV).
C***********************************************************************
      READ(5,4)(EVAP(K),K=1,12),(CONV(L),L=1,12)
    4 FORMAT(12F5.0,/,12F5.2)
C-----------------------------------------------------------------------
C WRITE HEADING FOR OUTPUT, STORAGE AND PARAMETER VALUES FOR RUN
C IDENTIFICATION.
C-----------------------------------------------------------------------
      WRITE(8,5)H1,H2,H3,H4
    5 FORMAT(1H1,1H ,4A8,//)
      WRITE(8,6)AREA,NMON,USL,USM,SSL,GWTH
    6 FORMAT(1H ,14HCATCHMENT AREA,6X,F8.2,/,
     11H ,16HNUMBER OF MONTHS,4X,I8,///,
```

```
     21H ,20HMODEL STORAGE VALUES,/,1X,20(1H=),//,
     31H ,17HUP. STORAGE LEVEL,3X,F8.2,/,
     41H ,16HUP. STORAGE MAX.,4X,F8.2,/,
     51H ,17H2ND STORAGE LEVEL,3X,F8.2,/,
     61H ,19HGRNDWATER THRESHOLD,1X,F8.2,//)
      WRITE(8,7)FC,DM,AL,AG,XN,XC
    7 FORMAT(1H ,16HMODEL PARAMETERS,/,1X,16(1H=),//,
     11H ,5HFC = ,F8.2,/,1H ,5HDM = ,F8.2,/,1H ,5HAL = ,F8.2,/,
     21H ,5HAG = ,F8.2,/,1H ,5HXN = ,F8.2,/,1H ,5HXC = ,F8.3,///)
C-----------------------------------------------------------------------
C IF DAILY VOLUMES ARE NOT WRITTEN (IFLAG=0), THE FOLLOWING "WRITE"
C STATEMENT IS OMITTED.
C-----------------------------------------------------------------------
      IF(IFLAG.NE.1)GO TO 52
      WRITE(8,8)
    8 FORMAT(1H ,47HDAILY DISCHARGE VOLUMES IN TENS OF CUBIC METRES,//)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C TPPT  = TOTAL RAINFALL IN MM.
C TPE   = TOTAL POTENTIAL EVAPORATION IN MM.
C TAE   = TOTAL ACTUAL EVAPORATION EXTRACTED IN MM.
C TRUN  = TOTAL SURFACE RUNOFF IN MM.
C TOTQ  = TOTAL CONTRIBUTION TO SOIL MOISTURE IN MM.
C TGWA  = TOTAL FLOW TO GROUNDWATER IN MM.
C-----------------------------------------------------------------------
   52 TPPT=0.0
      TPE=0.0
      TAE=0.0
      TRUN=0.0
      TOTQ=0.0
      TGWA=0.0
C-----------------------------------------------------------------------
C START OF MONTH LOOP.
C-----------------------------------------------------------------------
      DO 10 IMON=1,NMON
C***********************************************************************
C READ IN THE FIRST CARD OF THE CURRENT MONTH'S RAINFALL DATA IN UNITS
C OF INTEGER VALUES OF TENTHS OF A MILLIMETRE.
C     7X    = DATA IDENTIFICATION NOT READ BY PROGRAM.
C     2I2   = YEAR AND MONTH (64 FOR 1964, 06 FOR JUNE).
C     1X    = 1 FOR CARD 1 FOR DAYS   1 - 10.
C           = 2 FOR CARD 2 FOR DAYS  11 - 20.
C           = 3 FOR CARD 3 FOR DAYS  21 - END.
C     10I6  = TEN INTEGER VALUES OF RAINFALL.
C***********************************************************************
      READ(6,9)IYR,MON,(IRAIN(J),J=1,10)
    9 FORMAT(7X,2I2,1X,10I6)
C***********************************************************************
C CHECK FOR LEAP YEARS, SET NUMBER OF DAYS IN THE MONTH AND READ IN
C THE REST OF THE CURRENT MONTH'S RAINFALL DATA (2 CARDS).
C***********************************************************************
      NEND=LAST(MON)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(MON.EQ.2))NEND=NEND+1
      READ(6,11)(IRAIN(I),I=11,NEND)
   11 FORMAT(12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C CALCULATE DAILY FREE SURFACE EVAPORATION FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      VAPT=(EVAP(MON)*CONV(MON))/FLOAT(NEND)
C-----------------------------------------------------------------------
C START OF DAY LOOP.
```

```
C----------------------------------------------------------------------
      DO 20 IDAY=1,NEND
C----------------------------------------------------------------------
C CONVERT RAINFALL TO REAL VALUES IN MILLIMETRES AND DETERMINE CURRENT
C TEMPORARY STATE OF STORAGE.
C----------------------------------------------------------------------
      RAIN=FLOAT(IRAIN(IDAY))/10.0
      TPPT=TPPT+RAIN
      TPE=TPE+VAPT
      USL=USL+RAIN
      AVAP=VAPT
      IF(RAIN.GT.1.0)AVAP=AVAP*0.5
      IF(USL.LT.AVAP)GO TO 101
      USL=USL-AVAP
      TAE=TAE+AVAP
      AVAP=0.0
      GO TO 105
  101 AVAP=AVAP-USL
      TAE=TAE+USL
      USL=0.0
      DIFF=SSL-GWTH
      IF(DIFF.LT.AVAP)GO TO 102
      SSL=SSL-AVAP
      TAE=TAE+AVAP
      AVAP=0.0
      GO TO 105
  102 IF(SSL.LE.GWTH)GO TO 103
      AVAP=AVAP-DIFF
      TAE=TAE+DIFF
      SSL=GWTH
  103 AVAP=AVAP*(SSL/GWTH)
      IF(SSL.LT.AVAP)GO TO 104
      SSL=SSL-AVAP
      TAE=TAE+AVAP
      AVAP=0.0
      GO TO 105
  104 AVAP=SSL
      TAE=TAE+AVAP
      SSL=0.0
  105 IF(USL.GT.USM)GO TO 106
      RNOF=0.0
      GO TO 112
C----------------------------------------------------------------------
C CALCULATE WATERSHED INFILTRATION CAPACITY, SURFACE RUNOFF AND SOIL
C MOISTURE CONTRIBUTION.
C----------------------------------------------------------------------
  106 RNOF1=USL-USM
      USL=USM
      WINCP=FC+DM*EXP(-AL*SSL)
      SINCP=WINCP/AG
      IF((RNOF1.LE.WINCP).AND.(RNOF1.LE.SINCP))GO TO 107
      Q=(WINCP/(XN+1.0))*(1.0+(1.0/AG))
      IF(Q.GT.RNOF1)Q=RNOF1
      TOTQ=TOTQ+Q
      RNOF=RNOF1-Q
      TRUN=TRUN+RNOF
      GO TO 108
C----------------------------------------------------------------------
C CALCULATE INTERMEDIATE VALUE OF SURFACE RUNOFF AND RESULTING VALUES
C FOR SURFACE RUNOFF AND SOIL MOISTURE CONTRIBUTION.
C----------------------------------------------------------------------
```

```
  107 RNOF2=(XN/(XN+1.0))*RNOF1*((RNOF1/WINCP)**(1.0/XN))
      IF(RNOF2.GE.SINCP)GO TO 110
      RNOF=(XN/(XN+1.0))*RNOF2*((RNOF2/SINCP)**(1.0/XN))
      GO TO 113
  110 RNOF=RNOF2-(SINCP/(XN+1.0))
  113 Q=RNOF1-RNOF
      TRUN=TRUN+RNOF
      TOTQ=TOTQ+Q
C-----------------------------------------------------------------------
C ADD SOIL MOISTURE CONTRIBUTION TO SECOND STORAGE LEVEL AND CALCULATE
C INACTIVE GROUNDWATER LOSS.
C-----------------------------------------------------------------------
  108 SSL=SSL+Q
  109 IF(SSL.GT.GWTH)GO TO 111
      GW=0.0
      GO TO 112
  111 GW=XC*(SSL-GWTH)
      IF(GW.GT.(SSL-GWTH)) GW=SSL-GWTH
      TGWA=TGWA+GW
      SSL=SSL-GW
  112 IVOL(IDAY)=RNOF*AREA*100.0
   20 CONTINUE
C-----------------------------------------------------------------------
C END OF DAY LOOP.
C-----------------------------------------------------------------------
      IF(ISTAT.EQ.0)GO TO 24
C***********************************************************************
C READ IN ONE MONTH'S OBSERVED RUNOFF (3 CARDS) IN SAME FORMAT AS THE
C RAINFALL DATA. OBSERVED RUNOFF DATA REQUIRED ONLY IF ISTAT=1.
C      12X   = DATA IDENTIFICATION, YEAR ,MONTH & CARD CODE NOT READ.
C      10I6  = TEN INTEGER VALUES IN TENS OF CUBIC METRES.
C***********************************************************************
      READ(7,12)(IRUN(KK),KK=1,NEND)
   12 FORMAT(12X,10I6,/,12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH AND CALCULATE MONTHLY TOTALS.
C MTOT = TOTAL SIMULATED RUNOFF FOR MONTH.
C NTOT = TOTAL OBSERVED RUNOFF FOR MONTH.
C-----------------------------------------------------------------------
   24 MTOT=0
      NTOT=0
   25 DO 30 IK=1,NEND
      MTOT=MTOT+IVOL(IK)
      IF(ISTAT.EQ.0)GO TO 30
      NTOT=NTOT+IRUN(IK)
   30 CONTINUE
      IF(IFLAG.NE.1)GO TO 51
   26 NE=0
C-----------------------------------------------------------------------
C WRITE SIMULATED AND OBSERVED DAILY VOLUMES AND MONTHLY TOTALS.
C-----------------------------------------------------------------------
      DO 60 LK=1,3
      NE=NE+10
      NB=NE-9
      IF(LK.EQ.3)NE=NEND
      WRITE(8,13)IYR,MON,(IVOL(IK),IK=NB,NE)
   13 FORMAT(1H ,10HSIMULATED ,2I2,1X,11I7)
      IF(ISTAT.EQ.0)GO TO 60
      WRITE(8,17)IYR,MON,(IRUN(NK),NK=NB,NE)
   17 FORMAT(1H ,10HOBSERVED  ,2I2,1X,11I7,)
      IF(LK.NE.3)GO TO 60
```

```
      WRITE(8,14)MTOT,NTOT
   14 FORMAT(1H0,1H ,15HSIMULATED TOTAL,I10,5X,14HOBSERVED TOTAL,I10,/,
     195(1H=),/)
   60 CONTINUE
   51 IF(ISTAT.NE.1)GO TO 10
C-----------------------------------------------------------------------
C CALL STATISTICAL SUBROUTINE (STAT) IF ISTAT=1.
C-----------------------------------------------------------------------
      CALL STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
   10 CONTINUE
C-----------------------------------------------------------------------
C END OF MONTH LOOP.
C WRITE FINAL VALUE OF STORAGES AND FLOW COMPONENT SUMMARY.
C-----------------------------------------------------------------------
      WRITE(8,31)USL,SSL
   31 FORMAT(1H ,4X,18HFINAL VALUE OF USL,34X,F8.2,/,
     11H ,4X,18HFINAL VALUE OF SSL,34X,F8.2,///)
      WRITE(8,32)TPPT,TPE,TAE,TOTQ,TGWA,TRUN
   32 FORMAT(1H ,48HFLOW COMPONENT SUMMARY-ALL VALUES IN MILLIMETERS,
     1/,1X,48(1H=),//,5X,25HTOTAL RAINFALL FOR PERIOD,18X,F8.2,//,
     25X,38HTOTAL POTENTIAL EVAPORATION FOR PERIOD,5X,F8.2,//,
     35X,35HTOTAL ACTUAL EVAPORATION FOR PERIOD,8X,F8.2,//,
     45X,32HTOTAL FLOW TO LOWER ZONE STORAGE,11X,F8.2,//,
     55X,25HTOTAL FLOW TO GROUNDWATER,18X,F8.2,//,
     65X,33HTOTAL SIMULATED RUNOFF FOR PERIOD,10X,F8.2)
      STOP
      END
      SUBROUTINE STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
C#######################################################################
C THIS SUBROUTINE CALCULATES THE VALUES OF OBJECTIVE FUNCTIONS U1 & U3
C AND THE COEFFICIENT OF DETERMINATION ACCOMPANYING U3.
C NOTE: LOGARITHMIC VALUES OF RUNOFF ARE USED TO CALCULATE THE VALUES
C       OF THE COEFFICIENTS OF EFFICIENCY AND DETERMINATION FOR
C       OBJECTIVE FUNCTION U3.
C#######################################################################
      DIMENSION IRUN(31),IVOL(31)
      IF(IMON.GT.1)GO TO 21
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C-----------------------------------------------------------------------
      YSUM=0.0
      XSUM=0.0
      TOYSQ=0.0
      TOXSQ=0.0
      TDFSQ=0.0
      TOSXY=0.0
      TMTSQ=0.0
      TOMSQ=0.0
      NDAY=0.0
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH.
C-----------------------------------------------------------------------
   21 SIGMY=0.0
      SIGMX=0.0
      SDFSQ=0.0
      SPRXY=0.0
      STOT=FLOAT(MTOT)/100000.0
      YSUM=YSUM+STOT
      SMTSQ=STOT*STOT
      TMTSQ=TMTSQ+SMTSQ
      OTOT=FLOAT(NTOT)/100000.0
```

```
      XSUM=XSUM+OTOT
      OMTSQ=OTOT*OTOT
      TOMSQ=TOMSQ+OMTSQ
      NDAY=NDAY+NEND
C-----------------------------------------------------------------------
C CALCULATE TOTALS FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      DO 40 ICON=1,NEND
      SSSS=FLOAT(IVOL(ICON)+1)
      SVAL=ALOG10(SSSS)
      SIMSQ=SVAL*SVAL
      SIGMY=SIGMY+SIMSQ
      OOOO=FLOAT(IRUN(ICON)+1)
      OVAL=ALOG10(OOOO)
      OBSSQ=OVAL*OVAL
      SIGMX=SIGMX+OBSSQ
      DIFXY=OVAL-SVAL
      DIFSQ=DIFXY*DIFXY
      SDFSQ=SDFSQ+DIFSQ
      PRXY=SVAL*OVAL
      SPRXY=SPRXY+PRXY
   40 CONTINUE
C-----------------------------------------------------------------------
C ADD TOTALS TO TOTALS FOR SIMULATION PERIOD.
C-----------------------------------------------------------------------
      TOYSQ=TOYSQ+SIGMY
      TOXSQ=TOXSQ+SIGMX
      TDFSQ=TDFSQ+SDFSQ
      TOSXY=TOSXY+SPRXY
      IF(IMON.NE.NMON)RETURN
      IF((YSUM.NE.0).AND.(XSUM.NE.0))GO TO 50
      WRITE(8,55)
   55 FORMAT(1H ,46HARRAY EQUAL TO ZERO - NO STATISTICS CALCULATED)
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      WRITE(8,54)EV,U3
   54 FORMAT(1H0,4X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,
     14X,F8.2,//,5X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//)
      RETURN
C-----------------------------------------------------------------------
C CALCULATE VALUES OF S1, S2, U1, EV, DV AND U3.
C-----------------------------------------------------------------------
   50 A=YSUM/(FLOAT(NMON))
      B=XSUM/(FLOAT(NMON))
      TYR=FLOAT(NMON)/12.0
      AMSR=YSUM/TYR
      AMOR=XSUM/TYR
      S1=((A-B)/B)*100.0
      C=TMTSQ/FLOAT(NMON-1)
      D=A*A
      E=(C-D)**0.5
      F=TOMSQ/FLOAT(NMON-1)
      G=B*B
      H=(F-G)**0.5
      S2=((E-H)/H)*100.0
      U1=ABS(S1)+ABS(S2)
C-----------------------------------------------------------------------
C THE VALUE OF THE CONSTANT 11531.844 IS OBTAINED FROM TWO SEPARATE
C PROGRAMS (APPENDIX) WHERE THE CONSTANT IS THE SUM OF THE SQUARES OF
C THE DEVIATIONS FROM THE MEAN FOR THE OBSERVED RUNOFF DATA.
C-----------------------------------------------------------------------
```

```
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      P=YSUM*XSUM
      Q=P/FLOAT(NDAY)
      R=TOSXY-Q
      AX=(XSUM*XSUM)/FLOAT(NDAY)
      BX=TOXSQ-AX
      CY=(YSUM*YSUM)/FLOAT(NDAY)
      DY=TOYSQ-CY
      EXY=(BX*DY)**0.5
      CCOE=R/EXY
      DV=CCOE*CCOE
C-----------------------------------------------------------------------
C WRITE HEADING AND OUTPUT FROM SUBROUTINE.
C-----------------------------------------------------------------------
      WRITE(8,22)
   22 FORMAT(1H1,1X,62HVALUES OF INDICES OF MODEL PERFORMANCE AND OBJECT
     1IVE FUNCTIONS,/,2X,62(1H-),//)
      WRITE(8,23)A,B,S1,E,H,S2,U1,EV,U3,DV
   23 FORMAT(5X,34HMEAN OF SIMULATED MONTHLY VOLUMES ,18X,F8.2,//,
     15X,33HMEAN OF OBSERVED MONTHLY VOLUMES ,19X,F8.2,//,
     25X,40H% ERROR IN MEAN OF MONTHLY VOLUMES (S1) ,12X,F8.2,//,
     35X,39HSTD. DEV. OF SIMULATED MONTHLY VOLUMES ,13X,F8.2,//,
     45X,38HSTD. DEV. OF OBSERVED MONTHLY VOLUMES ,14X,F8.2,//,
     55X,45H% ERROR IN STD. DEV. OF MONTHLY VOLUMES (S2) ,7X,F8.2,//,
     65X,22HOBJECTIVE FUNCTION U1 ,30X,F8.2,//,
     75X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,4X,F8.2,//,
     85X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//,
     95X,52HCOEFFICIENT OF DETERMINATION FOR DAILY VOLUMES (DV) ,F8.2)
      WRITE(8,29)YSUM,XSUM,AMSR,AMOR
   29 FORMAT(1H0,4X,45HTOTAL SIMULATED RUNOFF (MILLION CUBIC METRES),
     17X,F8.2,//,5X,44HTOTAL OBSERVED RUNOFF (MILLION CUBIC METRES),
     28X,F8.2,//,5X,28HMEAN ANNUAL SIMULATED RUNOFF,24X,F8.2,//,
     35X,27HMEAN ANNUAL OBSERVED RUNOFF,25X,F8.2,//)
      RETURN
      END
      FINISH
```

```
---------------------------------------------------------------------------
       DATE 31/10/78   TIME 15/54/13                          LISTING FOR:= HI

FILE:   HRPSMAXIMOP     SUBFILE EX12 IN CARD MODE

      LIST
      PROGRAM(EX12)
      INPUT 5=CR0
      INPUT 6=ED1/FORMATTED(HRPSDATA01   )
      INPUT 7=ED2/FORMATTED(HRPSDATA02   )
      OUTPUT 8=LP0
      TRACE 2
      END
      MASTER EX12
C####################################################################
C THIS PROGRAM GENERATES DAILY DISCHARGE VOLUMES IN TENS OF CUBIC
C METRES FROM DAILY RAINFALL IN TENTHS OF A MILLIMETRE AND DAILY
C EVAPORATION IN MILLIMETRES.
C THE STRUCTURE OF THE MODEL IS BASED UPON THAT OF MODEL 12 ( SIMON
C AND DISKIN, 1975) WHICH WAS MODIFIED TO INCLUDE A BASE FLOW FUNCTION
C BY PETER S. STICKELLS, RHODES UNIVERSITY, 1978.
C####################################################################
      DIMENSION LAST(12),EVAP(12),CONV(12),IRAIN(31)
      DIMENSION IRUN(31),IVOL(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C********************************************************************
C READ IN CATCHMENT NAME, SIMULATION PERIOD (32 COLUMNS), CATCHMENT
C AREA (SQ. KM.) AND NUMBER OF MONTHS IN SIMULATION PERIOD (NMON).
C********************************************************************
      READ(5,1)H1,H2,H3,H4,AREA,NMON
    1 FORMAT(4A8,F8.2,I6)
C********************************************************************
C READ IN STORAGE VALUES (USL,USM,SSL,GWTH,GSL) IN MM, FLAG TO
C INITIATE STATISTICAL SUBROUTINE, ISTAT, (1 = INITIATE, 0 = SUPPRESS)
C AND FLAG TO INITIATE PRINTING OF DAILY RUNOFF VALUES, IFLAG,
C (1 = PRINT, 0 = SUPPRESS).
C********************************************************************
      READ(5,2)USL,USM,SSL,GWTH,GSL,ISTAT,IFLAG
    2 FORMAT(5F8.2,2X,I1,2X,I1)
C********************************************************************
C READ IN MODEL PARAMETERS (FC,DM,AL,AG,XN,XC) AND BASE FLOW DECAY
C CONSTANT (BFDC).
C********************************************************************
      READ(5,3)FC,DM,AL,AG,XN,XC,BFDC
    3 FORMAT(5F8.2,F8.3,F5.2)
C********************************************************************
C READ IN TWELVE AVERAGE MONTHLY PAN EVAPORATION VALUES (EVAP) IN MM
C AND TWELVE CONVERSION FACTORS, PAN EVAPORATION TO FREE WATER
C SURFACE (CONV).
C********************************************************************
      READ(5,4)(EVAP(K),K=1,12),(CONV(L),L=1,12)
    4 FORMAT(12F5.0,/,12F5.2)
C--------------------------------------------------------------------
C WRITE HEADING FOR OUTPUT, STORAGE AND PARAMETER VALUES FOR RUN
C IDENTIFICATION.
C--------------------------------------------------------------------
      WRITE(8,5)H1,H2,H3,H4
    5 FORMAT(1H1,1H ,4A8,//)
      WRITE(8,6)AREA,NMON,USL,USM,SSL,GWTH,GSL
    6 FORMAT(1H ,14HCATCHMENT AREA,6X,F8.2,/,
     11H ,16HNUMBER OF MONTHS,4X,I8,///,
```

```
     21H ,20HMODEL STORAGE VALUES,/,1X,20(1H-),//,
     31H ,17HUP. STORAGE LEVEL,3X,F8.2,/,
     41H ,16HUP. STORAGE MAX.,4X,F8.2,/,
     51H ,17H2ND STORAGE LEVEL,3X,F8.2,/,
     61H ,19HGRNDWATER THRESHOLD,1X,F8.2,/,
     71H ,18HGRNDWATER S. LEVEL,2X,F8.2,//)
      WRITE(8,7)FC,DM,AL,AG,XN,XC,BFDC
    7 FORMAT(1H ,16HMODEL PARAMETERS,/,1X,16(1H-),//,
     11H ,5HFC = ,F8.2,/,1H ,5HDM = ,F8.2,/,1H ,5HAL = ,F8.2,/,
     21H ,5HAG = ,F8.2,/,1H ,5HXN = ,F8.2,/,1H ,5HXC = ,F8.3,/,
     31H ,7HBFDC = ,F6.2,///)
C-----------------------------------------------------------------------
C IF DAILY VOLUMES ARE NOT WRITTEN (IFLAG=0), THE FOLLOWING "WRITE"
C STATEMENT IS OMITTED.
C-----------------------------------------------------------------------
      IF(IFLAG.NE.1)GO TO 52
      WRITE(8,8)
    8 FORMAT(1H ,47HDAILY DISCHARGE VOLUMES IN TENS OF CUBIC METRES,//)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C TPPT  = TOTAL RAINFALL IN MM.
C TPE   = TOTAL POTENTIAL EVAPORATION IN MM.
C TAE   = TOTAL ACTUAL EVAPORATION EXTRACTED IN MM.
C TRUN  = TOTAL SURFACE RUNOFF IN MM.
C TOTQ  = TOTAL CONTRIBUTION TO SOIL MOISTURE IN MM.
C TGWA  = TOTAL FLOW TO BASE FLOW STORAGE IN MM.
C TBFL  = TOTAL BASE FLOW CONTRIBUTION IN MM.
C TOTR  = TOTAL RUNOFF IN MM.
C-----------------------------------------------------------------------
   52 TPPT=0.0
      TPE=0.0
      TAE=0.0
      TRUN=0.0
      TOTQ=0.0
      TGWA=0.0
      TBFL=0.0
      TOTR=0.0
C-----------------------------------------------------------------------
C START OF MONTH LOOP.
C-----------------------------------------------------------------------
      DO 10 IMON=1,NMON
C***********************************************************************
C READ IN THE FIRST CARD OF THE CURRENT MONTH'S RAINFALL DATA IN UNITS
C OF INTEGER VALUES OF TENTHS OF A MILLIMETRE.
C     7X   = DATA IDENTIFICATION NOT READ BY PROGRAM.
C     2I2  = YEAR AND MONTH (64 FOR 1964, 06 FOR JUNE).
C     1X   = 1 FOR CARD 1 FOR DAYS  1 - 10.
C          = 2 FOR CARD 2 FOR DAYS 11 - 20.
C          = 3 FOR CARD 3 FOR DAYS 21 - END.
C     10I6 = TEN INTEGER VALUES OF RAINFALL.
C***********************************************************************
      READ(6,9)IYR,MON,(IRAIN(J),J=1,10)
    9 FORMAT(7X,2I2,1X,10I6)
C***********************************************************************
C CHECK FOR LEAP YEARS, SET NUMBER OF DAYS IN THE MONTH AND READ IN
C THE REST OF THE CURRENT MONTH'S RAINFALL DATA (2 CARDS).
C***********************************************************************
      NEND=LAST(MON)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(MON.EQ.2))NEND=NEND+1
      READ(6,11)(IRAIN(I),I=11,NEND)
   11 FORMAT(12X,10I6,/,12X,11I6)
```

```
C-----------------------------------------------------------------------
C CALCULATE DAILY FREE SURFACE EVAPORATION FOR CURRENT MONTH.
C-----------------------------------------------------------------------
      VAPT=(EVAP(MON)*CONV(MON))/FLOAT(NEND)
C-----------------------------------------------------------------------
C START OF DAY LOOP.
C-----------------------------------------------------------------------
      DO 20 IDAY=1,NEND
C-----------------------------------------------------------------------
C CONVERT RAINFALL TO REAL VALUES IN MILLIMETRES AND DETERMINE CURRENT
C TEMPORARY STATE OF STORAGE.
C-----------------------------------------------------------------------
      RAIN=FLOAT(IRAIN(IDAY))/10.0
      TPPT=TPPT+RAIN
      TPE=TPE+VAPT
      USL=USL+RAIN
      AVAP=VAPT
      IF(RAIN.GT.1.0)AVAP=AVAP*0.5
      IF(USL.LT.AVAP)GO TO 101
      USL=USL-AVAP
      TAE=TAE+AVAP
      AVAP=0.0
      GO TO 105
  101 AVAP=AVAP-USL
      TAE=TAE+USL
      USL=0.0
      DIFF=SSL-GWTH
      IF(DIFF.LT.AVAP)GO TO 102
      SSL=SSL-AVAP
      TAE=TAE+AVAP
      AVAP=0.0
      GO TO 105
  102 IF(SSL.LE.GWTH)GO TO 103
      AVAP=AVAP-DIFF
      TAE=TAE+DIFF
      SSL=GWTH
  103 AVAP=AVAP*(SSL/GWTH)
      IF(SSL.LT.AVAP)GO TO 104
      SSL=SSL-AVAP
      TAE=TAE+AVAP
      AVAP=0.0
      GO TO 105
  104 AVAP=SSL
      TAE=TAE+AVAP
      SSL=0.0
  105 IF(USL.GT.USM)GO TO 106
      RNOF=0.0
      GO TO 112
C-----------------------------------------------------------------------
C CALCULATE WATERSHED INFILTRATION CAPACITY, SURFACE RUNOFF AND SOIL
C MOISTURE CONTRIBUTION.
C-----------------------------------------------------------------------
  106 RNOF1=USL-USM
      USL=USM
      WINCP=FC+DM*EXP(-AL*SSL)
      SINCP=WINCP/AG
      IF((RNOF1.LE.WINCP).AND.(RNOF1.LE.SINCP))GO TO 107
      Q=(WINCP/(XN+1.0))*(1.0+(1.0/AG))
      IF(Q.GT.RNOF1)Q=RNOF1
      TOTQ=TOTQ+Q
      RNOF=RNOF1-Q
```

```
      TRUN=TRUN+RNOF
      GO TO 108
C-----------------------------------------------------------------------
C CALCULATE INTERMEDIATE VALUE OF SURFACE RUNOFF AND RESULTING VALUES
C FOR SURFACE RUNOFF AND SOIL MOISTURE CONTRIBUTION.
C-----------------------------------------------------------------------
  107 RNOF2=(XN/(XN+1.0))*RNOF1*((RNOF1/WINCP)**(1.0/XN))
      IF(RNOF2.GE.SINCP)GO TO 110
      RNOF=(XN/(XN+1.0))*RNOF2*((RNOF2/SINCP)**(1.0/XN))
      GO TO 113
  110 RNOF=RNOF2-(SINCP/(XN+1.0))
  113 Q=RNOF1-RNOF
      TRUN=TRUN+RNOF
      TOTQ=TOTQ+Q
C-----------------------------------------------------------------------
C ADD SOIL MOISTURE CONTRIBUTION TO SECOND STORAGE LEVEL AND CALCULATE
C LOSS TO ACTIVE GROUNDWATER.
C-----------------------------------------------------------------------
  108 SSL=SSL+Q
  109 IF(SSL.GT.GWTH)GO TO 111
      GW=0.0
      GO TO 112
  111 GW=XC*(SSL-GWTH)
      IF(GW.GT.(SSL-GWTH)) GW=SSL-GWTH
      TGWA=TGWA+GW
      SSL=SSL-GW
      GSL=GSL+GW
C-----------------------------------------------------------------------
C CALCULATE BASE FLOW CONTRIBUTION TO STREAMFLOW.
C-----------------------------------------------------------------------
  112 BFLO=GSL*(1.0-BFDC)
      GSL=GSL-BFLO
      TBFL=TBFL+BFLO
      RUN=RNOF+BFLO
      TOTR=TOTR+RUN
      IVOL(IDAY)=RUN*AREA*100.0
   20 CONTINUE
C-----------------------------------------------------------------------
C END OF DAY LOOP.
C-----------------------------------------------------------------------
      IF(ISTAT.EQ.0)GO TO 24
C***********************************************************************
C READ IN ONE MONTH'S OBSERVED RUNOFF (3 CARDS) IN SAME FORMAT AS THE
C RAINFALL DATA. OBSERVED RUNOFF DATA REQUIRED ONLY IF ISTAT = 1.
C     12X    = DATA IDENTIFICATION, YEAR, MONTH & CARD CODES NOT READ.
C     10I6   = TEN INTEGER VALUES IN TENS OF CUBIC METRES.
C***********************************************************************
      READ(7,12)(IRUN(KK),KK=1,NEND)
   12 FORMAT(12X,10I6,/,12X,10I6,/,12X,11I6)
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH AND CALCULATE MONTHLY TOTALS.
C MTOT = TOTAL SIMULATED RUNOFF FOR MONTH.
C NTOT = TOTAL OBSERVED RUNOFF FOR MONTH.
C-----------------------------------------------------------------------
   24 MTOT=0
      NTOT=0
   25 DO 30 IK=1,NEND
      MTOT=MTOT+IVOL(IK)
      IF(ISTAT.EQ.0)GO TO 30
      NTOT=NTOT+IRUN(IK)
   30 CONTINUE
```

```
      IF(IFLAG.NE.1)GO TO 51
   26 NE=0
C-----------------------------------------------------------------------
C WRITE SIMULATED AND OBSERVED DAILY VOLUMES AND MONTHLY TOTALS.
C-----------------------------------------------------------------------
      DO 60 LK=1,3
      NE=NE+10
      NB=NE-9
      IF(LK.EQ.3)NE=NEND
      WRITE(8,13)IYR,MON,(IVOL(IK),IK=NB,NE)
   13 FORMAT(1H ,10HSIMULATED ,2I2,1X,11I7)
      IF(ISTAT.EQ.0)GO TO 60
      WRITE(8,17)IYR,MON,(IRUN(NK),NK=NB,NE)
   17 FORMAT(1H ,10HOBSERVED  ,2I2,1X,11I7,)
      IF(LK.NE.3)GO TO 60
      WRITE(8,14)MTOT,NTOT
   14 FORMAT(1H0,1H ,15HSIMULATED TOTAL,I10,5X,14HOBSERVED TOTAL,I10,/,
     195(1H-),/)
   60 CONTINUE
   51 IF(ISTAT.NE.1)GO TO 10
C-----------------------------------------------------------------------
C CALL STATISTICAL SUBROUTINE (STAT) IF ISTAT = 1.
C-----------------------------------------------------------------------
      CALL STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
   10 CONTINUE
C-----------------------------------------------------------------------
C END OF MONTH LOOP.
C WRITE FINAL VALUE OF STORAGES AND FLOW COMPONENT SUMMARY.
C-----------------------------------------------------------------------
      WRITE(8,31)USL,SSL,GSL
   31 FORMAT(1H ,4X,18HFINAL VALUE OF USL,34X,F8.2,/,
     11H ,4X,18HFINAL VALUE OF SSL,34X,F8.2,/,
     21H ,4X,18HFINAL VALUE OF GSL,34X,F8.2,///)
      WRITE(8,32)TPPT,TPE,TAE,TOTQ,TRUN,TGWA,TBFL,TOTR
   32 FORMAT(1H ,48HFLOW COMPONENT SUMMARY-ALL VALUES IN MILLIMETERS,
     1/,1X,48(1H-),//,5X,25HTOTAL RAINFALL FOR PERIOD,18X,F8.2,//,
     25X,38HTOTAL POTENTIAL EVAPORATION FOR PERIOD,5X,F8.2,//,
     35X,35HTOTAL ACTUAL EVAPORATION FOR PERIOD,8X,F8.2,//,
     45X,32HTOTAL FLOW TO LOWER ZONE STORAGE,11X,F8.2,//,
     55X,31HTOTAL SURFACE RUNOFF FOR PERIOD,12X,F8.2,//,
     65X,33HTOTAL FLOW TO GROUNDWATER STORAGE,10X,F8.2,//,
     75X,26HTOTAL BASE FLOW FOR PERIOD,17X,F8.2,//,
     85X,33HTOTAL SIMULATED RUNOFF FOR PERIOD,10X,F8.2)
      STOP
      END
      SUBROUTINE STAT(IRUN,IVOL,NMON,NEND,MTOT,NTOT,IMON)
C#######################################################################
C THIS SUBROUTINE CALCULATES THE VALUES OF OBJECTIVE FUNCTIONS U1 & U3
C AND THE COEFFICIENT OF DETERMINATION ACCOMPANYING U3.
C NOTE: LOGARITHMIC VALUES OF RUNOFF ARE USED TO CALCULATE THE VALUES
C       OF THE COEFFICIENTS OF EFFICIENCY AND DETERMINATION FOR
C       OBJECTIVE FUNCTION U3.
C#######################################################################
      DIMENSION IRUN(31),IVOL(31)
      IF(IMON.GT.1)GO TO 21
C-----------------------------------------------------------------------
C INITIALISE VARIABLES FOR TOTAL SIMULATION PERIOD.
C-----------------------------------------------------------------------
      YSUM=0.0
      XSUM=0.0
      TOYSQ=0.0
```

```
      TOXSQ=0.0
      TDFSQ=0.0
      TOSXY=0.0
      TMTSQ=0.0
      TOMSQ=0.0
      NDAY=0.0
C----------------------------------------------------------------------
C INITIALISE VARIABLES FOR CURRENT MONTH.
C----------------------------------------------------------------------
   21 SIGMY=0.0
      SIGMX=0.0
      SDFSQ=0.0
      SPRXY=0.0
      STOT=FLOAT(MTOT)/100000.0
      YSUM=YSUM+STOT
      SMTSQ=STOT*STOT
      TMTSQ=TMTSQ+SMTSQ
      OTOT=FLOAT(NTOT)/100000.0
      XSUM=XSUM+OTOT
      OMTSQ=OTOT*OTOT
      TOMSQ=TOMSQ+OMTSQ
      NDAY=NDAY+NEND
C----------------------------------------------------------------------
C CALCULATE TOTALS FOR CURRENT MONTH.
C----------------------------------------------------------------------
      DO 40 ICON=1,NEND
      SSSS=FLOAT(IVOL(ICON)+1)
      SVAL=ALOG10(SSSS)
      SIMSQ=SVAL*SVAL
      SIGMY=SIGMY+SIMSQ
      OOOO=FLOAT(IRUN(ICON)+1)
      OVAL=ALOG10(OOOO)
      OBSSQ=OVAL*OVAL
      SIGMX=SIGMX+OBSSQ
      DIFXY=OVAL-SVAL
      DIFSQ=DIFXY*DIFXY
      SDFSQ=SDFSQ+DIFSQ
      PRXY=SVAL*OVAL
      SPRXY=SPRXY+PRXY
   40 CONTINUE
C----------------------------------------------------------------------
C ADD TOTALS TO TOTALS FOR SIMULATION PERIOD.
C----------------------------------------------------------------------
      TOYSQ=TOYSQ+SIGMY
      TOXSQ=TOXSQ+SIGMX
      TDFSQ=TDFSQ+SDFSQ
      TOSXY=TOSXY+SPRXY
      IF(IMON.NE.NMON)RETURN
      IF((YSUM.NE.0).AND.(XSUM.NE.0))GO TO 50
      WRITE(8,55)
   55 FORMAT(1H ,46HARRAY EQUAL TO ZERO - NO STATISTICS CALCULATED)
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      WRITE(8,54)EV,U3
   54 FORMAT(1H0,4X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,
     14X,F8.2,//,5X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//)
      RETURN
C----------------------------------------------------------------------
C CALCULATE VALUES OF S1, S2, U1, EV, DV AND U3.
C----------------------------------------------------------------------
   50 A=YSUM/(FLOAT(NMON))
```

```
      B=XSUM/(FLOAT(NMON))
      TYR=FLOAT(NMON)/12.0
      AMSR=YSUM/TYR
      AMOR=XSUM/TYR
      S1=((A-B)/B)*100.0
      C=TMTSQ/FLOAT(NMON-1)
      D=A*A
      E=(C-D)**0.5
      F=TOMSQ/FLOAT(NMON-1)
      G=B*B
      H=(F-G)**0.5
      S2=((E-H)/H)*100.0
      U1=ABS(S1)+ABS(S2)
C----------------------------------------------------------------------
C THE VALUE OF THE CONSTANT 11531.844 IS OBTAINED FROM TWO SEPARATE
C PROGRAMS (APPENDIX) WHERE THE CONSTANT IS THE SUM OF THE SQUARES OF
C THE DEVIATIONS FROM THE MEAN FOR THE OBSERVED RUNOFF DATA.
C----------------------------------------------------------------------
      EV=(11531.844-TDFSQ)/11531.844
      U3=1.0-EV
      P=YSUM*XSUM
      Q=P/FLOAT(NDAY)
      R=TOSXY-Q
      AX=(XSUM*XSUM)/FLOAT(NDAY)
      BX=TOXSQ-AX
      CY=(YSUM*YSUM)/FLOAT(NDAY)
      DY=TOYSQ-CY
      EXY=(BX*DY)**0.5
      CCOE=R/EXY
      DV=CCOE*CCOE
C----------------------------------------------------------------------
C WRITE HEADING AND OUTPUT FROM SUBROUTINE.
C----------------------------------------------------------------------
      WRITE(8,22)
   22 FORMAT(1H1,1X,62HVALUES OF INDICES OF MODEL PERFORMANCE AND OBJECT
     1IVE FUNCTIONS,/,2X,62(1H-),//)
      WRITE(8,23)A,B,S1,E,H,S2,U1,EV,U3,DV
   23 FORMAT(5X,34HMEAN OF SIMULATED MONTHLY VOLUMES ,18X,F8.2,//,
     15X,33HMEAN OF OBSERVED MONTHLY VOLUMES ,19X,F8.2,//,
     25X,40H% ERROR IN MEAN OF MONTHLY VOLUMES (S1) ,12X,F8.2,//,
     35X,39HSTD. DEV. OF SIMULATED MONTHLY VOLUMES ,13X,F8.2,//,
     45X,38HSTD. DEV. OF OBSERVED MONTHLY VOLUMES ,14X,F8.2,//,
     55X,45H% ERROR IN STD. DEV. OF MONTHLY VOLUMES (S2) ,7X,F8.2,//,
     65X,22HOBJECTIVE FUNCTION U1 ,30X,F8.2,//,
     75X,48HCOEFFICIENT OF EFFICIENCY OF DAILY VOLUMES (EV) ,4X,F8.2,//,
     85X,22HOBJECTIVE FUNCTION U3 ,30X,F8.2,//,
     95X,52HCOEFFICIENT OF DETERMINATION FOR DAILY VOLUMES (DV) ,F8.2)
      WRITE(8,29)YSUM,XSUM,AMSR,AMOR
   29 FORMAT(1H0,4X,45HTOTAL SIMULATED RUNOFF (MILLION CUBIC METRES),
     17X,F8.2,//,5X,44HTOTAL OBSERVED RUNOFF (MILLION CUBIC METRES),
     28X,F8.2,//,5X,28HMEAN ANNUAL SIMULATED RUNOFF,24X,F8.2,//,
     35X,27HMEAN ANNUAL OBSERVED RUNOFF,25X,F8.2,//)
      RETURN
      END
      FINISH
```

```
-----------------------------------------------------------------------
       DATE 31/10/78   TIME 15/54/42                         LISTING FOR:- H

FILE:   HRPSMAXIMOP     SUBFILE CONV IN CARD MODE

      LIST
      PROGRAM(CONV)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER CONV
C#################################################################
C THIS PROGRAM CONVERTS RAINFALL IN INCHES TO RAINFALL IN UNITS
C OF INTEGER VALUES OF TENTHS OF A MILLIMETRE.
C#################################################################
      DIMENSION LAST(12),RAIN(12),IRAIN(12)
      DATA LAST/11,8,11,10,11,10,11,11,10,11,10,11/
      DO 10 ICARD=1,402
C*****************************************************************
C READ IN THE FIRST RAINFALL CARD.
C*****************************************************************
      READ(5,1)IYR,MON,ICODE,(RAIN(J),J=1,11)
    1 FORMAT(7X,2I2,I1,11F6.2)
      NEND=10
      IF(ICODE.LT.3) GO TO 30
C-----------------------------------------------------------------
C CHECK FOR LEAP YEARS AND SET NUMBER OF VALUES ON LAST CARD.
C-----------------------------------------------------------------
      NEND=LAST(MON)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(MON.EQ.2)) NEND=NEND+1
   30 DO 40 I=1,NEND
C-----------------------------------------------------------------
C CONVERT RAINFALL IN INCHES TO INTEGER VALUES IN TENTHS OF A MM.
C-----------------------------------------------------------------
   40 IRAIN(I)=RAIN(I)*254
      WRITE(6,2)IYR,MON,ICODE,(IRAIN(K),K=1,NEND)
    2 FORMAT(1H ,7H87RAIN ,2I2,I1,11I6)
   10 CONTINUE
      STOP
      END
      FINISH
```

```
-----------------------------------------------------------------------------------
       DATE 31/10/78   TIME 16/05/59                                   LISTING FOR:= H

FILE:   HRPSMAXIMOP     SUBFILE PROG IN CARD MODE

      LIST
      PROGRAM(PROG)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER PROG
C#######################################################################
C THIS PROGRAM CREATES A MATRIX OF ZEROS IN THE CORRECT FORMAT
C WITH THE CORRECT YEAR, MONTH AND CARD CODES FOR USE IN THE
C CREATION OF RAINFALL AND RUNOFF DATA FILES.
C#######################################################################
      DIMENSION LAST(12),IVAL(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C***********************************************************************
C READ IN ONE MONTH ZERO MATRIX IN CORRECT FORMAT.
C***********************************************************************
      READ(5,2)(IVAL(J),J=1,31)
    2 FORMAT(10I6,/,10I6,/,11I6)
      NYR=48
      MON=1
      DO 10 I=1,16
      IYR=NYR+I
      DO 40 IK=MON,12
      NEND=0
   20 DO 30 K=1,3
      NEND=NEND+10
      NBEG=NEND-9
      IF(K.NE.3)GO TO 7
C-----------------------------------------------------------------------
C CHECK FOR LEAP YEARS AND SET NUMBER OF DAYS IN THE MONTH.
C-----------------------------------------------------------------------
      NEND=LAST(IK)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(IK.EQ.2)) NEND=NEND+1
C-----------------------------------------------------------------------
C WRITE ZERO MATRIX WITH CORRECT DATA IDENTIFICATION, YEAR, MONTH
C AND CARD CODES.
C-----------------------------------------------------------------------
    7 WRITE(6,50)IYR,IK,K,(IVAL(JJ),JJ=NBEG,NEND)
   50 FORMAT(1H ,2H87,5HRAIN ,I2,I2,I1,11I6)
   30 CONTINUE
   40 CONTINUE
      MON=1
   10 CONTINUE
      STOP
      END
      FINISH
```

```
-----------------------------------------------------------------------------------
       DATE 31/10/78   TIME 15/55/00                                LISTING FOR:- H

FILE:   HRPSMAXIMOP     SUBFILE POLY IN CARD MODE

      LIST
      PROGRAM(POLY)
      INPUT 5=CR0
      INPUT 4=CR1
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER POLY
C###################################################################
C THIS PROGRAM CONVERTS TWO POINT MEASUREMENTS OF RAINFALL
C TO AREAL ASSESSMENTS OF RAINFALL USING THE THIESSEN
C POLYGON METHOD.
C###################################################################
      DIMENSION LAST(12),IRA5(12),IRA4(12),IRAIN(12)
      DATA LAST/11,8,11,10,11,10,11,11,10,11,10,11/
      DO 10 ICARD=1,549
C*******************************************************************
C READ IN ONE RAINFALL CARD FROM EACH OF THE TWO FILES
C REPRESENTING THE DATA FOR THE TWO POINT SOURCES.
C RAINFALL DATA IN UNITS OF INTEGER VALUES OF TENTHS OF A MM.
C*******************************************************************
      READ(5,1)IYR,MON,ICODE,(IRA5(J),J=1,11)
      READ(4,1)IIYR,IMON,IKODE,(IRA4(K),K=1,11)
    1 FORMAT(7X,2I2,I1,11I6)
      IF(IYR.NE.IIYR) GO TO 20
      IF(MON.NE.IMON) GO TO 20
      IF(ICODE.NE.IKODE) GO TO 20
      NEND=10
      IF(ICODE.LT.3) GO TO 30
C-------------------------------------------------------------------
C CHECK FOR LEAP YEARS AND SET NUMBER OF DAYS IN THE MONTH.
C-------------------------------------------------------------------
      NEND=LAST(MON)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(MON.EQ.2)) NEND=NEND+1
   30 DO 40 I=1,NEND
      RAIN5=FLOAT(IRA5(I))
      RAIN4=FLOAT(IRA4(I))
C-------------------------------------------------------------------
C CONVERT THE TWO POINT MEASUREMENTS TO AREAL ASSESSMENTS
C OF RAINFALL.
C-------------------------------------------------------------------
   40 IRAIN(I)=(RAIN5*0.444+RAIN4*0.556)
      WRITE(6,2)IYR,MON,ICODE,(IRAIN(K),K=1,NEND)
    2 FORMAT(1H ,7H87RAIN ,2I2,I1,11I6)
   10 CONTINUE
      GO TO 60
   20 WRITE(6,3)
    3 FORMAT(1H ,31HCARD IDENTIFIERS NOT COMPATIBLE)
   60 CONTINUE
      STOP
      END
      FINISH
```

```
-------------------------------------------------------------------------------
       DATE 31/10/78   TIME 16/06/52                             LISTING FOR:= H

FILE:   HRPSMAXIMOP    SUBFILE LEF1 IN CARD MODE

      LIST
      PROGRAM(LEF1)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER LEF1
C######################################################################
C THIS PROGRAM CALCULATES THE MEAN OBSERVED DAILY DISCHARGE VOLUME
C USING LOGARITHMIC VALUES OF RUNOFF. THE MEAN DAILY VOLUME IS USED
C IN PROGRAM "LEF2" TO CALCULATE THE VALUE OF THE CONSTANT IN THE
C COEFFICIENT OF EFFICIENCY FOR DAILY VOLUMES (EV) WHERE THE CONSTANT
C IS THE SUM OF THE SQUARES OF THE DEVIATIONS FROM THE MEAN FOR
C OBSERVED DAILY VOLUMES.
C######################################################################
      DIMENSION LAST(12),TOT(12),IRUN(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
      GTOT=0.0
      KY=26
      WRITE(6,5)
    5 FORMAT(1H1,42HMEAN DAILY VOLUME FOR MAREETSANE CATCHMENT,/,
     139HUNITS USED ARE MILLIONS OF CUBIC METRES,//)
      DO 10 I=1,38
      IYR=KY+I
      YRT=0.
      DO 20 K=1,12
C----------------------------------------------------------------------
C CHECK FOR LEAP YEARS AND SET NUMBER OF DAYS IN THE MONTH.
C----------------------------------------------------------------------
      NEND=LAST(K)
      IF(((IYR-4*(IYR/4)).EQ.0).AND.(K.EQ.2)) NEND=NEND+1
C**********************************************************************
C READ IN ONE MONTH'S OBSERVED RUNOFF DATA IN TENS OF CUBIC METRES.
C**********************************************************************
      READ(5,1)(IRUN(J),J=1,NEND)
    1 FORMAT(12X,10I6,/,12X,10I6,/,12X,11I6)
      TOT(K)=0.
      DO 30 N=1,NEND
C----------------------------------------------------------------------
C CALCULATE TOTAL RUNOFF FOR CURRENT MONTH.
C----------------------------------------------------------------------
      VVVV=FLOAT(IRUN(N)+1)
      OVAL=ALOG10(VVVV)
   30 TOT(K)=TOT(K)+OVAL
C----------------------------------------------------------------------
C CALCULATE TOTAL FOR YEAR.
C----------------------------------------------------------------------
      YRT=YRT+TOT(K)
   20 CONTINUE
      WRITE(6,2)IYR,(TOT(KK),KK=1,12),YRT
    2 FORMAT(2X,I3,2X,12F8.4,2X,F8.2,/)
C----------------------------------------------------------------------
C CALCULATE TOTAL FOR SIMULATION PERIOD AND CALCULATE MEAN DAILY
C DISCHARGE VOLUME.
C----------------------------------------------------------------------
      GTOT=GTOT+YRT
```

```
10 CONTINUE
   DMV=GTOT/13880.0
   WRITE(6,3)GTOT,DMV
 3 FORMAT(15HTOTAL RUNOFF = ,F10.3,/,20HMEAN DAILY VOLUME = ,F8.3,//)
   STOP
   END
   FINISH
```

```
----------------------------------------------------------------------------
       DATE 31/10/78   TIME 16/07/05                          LISTING FOR:= HF

FILE:   HRPSMAXIMOP     SUBFILE LEF2 IN CARD MODE

      LIST
      PROGRAM(LEF2)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER LEF2
C#####################################################################
C THIS PROGRAM CALCULATES THE VALUE OF THE CONSTANT IN THE
C COEFFICIENT OF EFFICIENCY FOR DAILY VOLUMES (EV) USING THE MEAN
C DAILY VOLUME CALCULATED BY PROGRAM "LEF1" AND LOGARITHMIC VALUES OF
C RUNOFF. THE CONSTANT IS THE SUM OF THE SQUARES OF THE DEVIATIONS
C FROM THE MEAN OF OBSERVED DAILY VOLUMES AND IS USED IN SUBROUTINE
C "STAT" IN EACH MODEL PROGRAM.
C#####################################################################
      DIMENSION LAST(12),ATOT(12),IRNOF(31)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
      STOT=0.0
      KYR=26
      WRITE(6,7)
    7 FORMAT(1H1,45HVALUES OF THE CONSTANT IN COEFF OF EFFICIENCY,/,
     139HUNITS USED ARE MILLIONS OF CUBIC METRES,//)
      DO 40 II=1,38
      IYEAR=KYR+II
      YRTOT=0.0
      DO 50 IK=1,12
C*********************************************************************
C CHECK FOR LEAP YEARS, SET NUMBER OF DAYS IN THE MONTH AND READ IN
C THE FIRST MONTH'S RUNOFF DATA.
C*********************************************************************
      NNEND=LAST(IK)
      IF(((IYEAR-4*(IYEAR/4)).EQ.0).AND.(IK.EQ.2)) NNEND=NNEND+1
      READ(5,4)(IRNOF(JJ),JJ=1,NNEND)
    4 FORMAT(12X,10I6,/,12X,10I6,/,12X,11I6)
      ATOT(IK)=0.0
      DO 60 NN=1,NNEND
      RUN=FLOAT(IRNOF(NN)+1)
      RLOG=ALOG10(RUN)
C---------------------------------------------------------------------
C CALCULATE THE DIFFERENCE BETWEEN EACH DAILY VALUE AND THE MEAN
C DAILY VALUE, SQUARE THE DIFFERENCE AND SUM THE DIFFERENCES.
C---------------------------------------------------------------------
      VAL=RLOG-0.2420
      SQVAL=VAL*VAL
      ATOT(IK)=ATOT(IK)+SQVAL
   60 CONTINUE
      YRTOT=YRTOT+ATOT(IK)
   50 CONTINUE
      WRITE(6,5)IYEAR,(ATOT(IK),IK=1,12)
    5 FORMAT(2X,I3,2X,12F8.2,/)
C---------------------------------------------------------------------
C CALCULATE THE SUM OF THE SQUARES OF THE DIFFERENCES FOR THE
C SIMULATION PERIOD.
C---------------------------------------------------------------------
      STOT=STOT+YRTOT
   40 CONTINUE
```

```
  WRITE(6,6)STOT
6 FORMAT(2X,22HSUM((Q-(Q/N))**2.0) = ,F18.8)
  STOP
  END
  FINISH
```

```
--------------------------------------------------------------------------------
      DATE 31/10/78   TIME 16/06/32                          LISTING FOR:= HF

FILE:   HRPSMAXIMOP     SUBFILE EFPK IN CARD MODE

      LIST
      PROGRAM(EFPK)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER EFPK
C###############################################################################
C THIS PROGRAM CALCULATES THE MEAN OBSERVED PEAK VOLUME ABOVE A PRE-SET
C BASE LEVEL AND THE VALUE OF THE CONSTANT IN THE COEFFICIENT OF
C EFFICIENCY OF PEAK DAILY VOLUMES (EP). THE VALUE OF THE CONSTANT IS
C USED IN PROGRAM "EFFP" AND IS THE SUM OF THE SQUARES OF THE DEVIATIONS
C FROM THE MEAN OBSERVED PEAK DAILY VOLUME ABOVE A PRE-SET BASE LEVEL.
C###############################################################################
      DIMENSION PEAK(100)
      READ(5,1)(PEAK(J),J=1,91)
    1 FORMAT(10F8.6)
      TOT=0.0
      DO 10 K=1,91
C-------------------------------------------------------------------------------
C CALCULATE THE TOTAL VOLUME AND THE MEAN.
C-------------------------------------------------------------------------------
      TOT=TOT+PEAK(K)
   10 CONTINUE
      AMEAN=TOT/91.0
      DFTOT=0.0
      DO 20 K=1,91
C-------------------------------------------------------------------------------
C CALCULATE THE DIFFERENCE BETWEEN EACH PEAK VALUE AND THE MEAN, SQUARE
C THE DIFFERENCE AND SUM THE SQUARES.
C-------------------------------------------------------------------------------
      DIFF=PEAK(K)-AMEAN
      DIFSQ=DIFF*DIFF
      DFTOT=DFTOT+DIFSQ
   20 CONTINUE
      WRITE(6,2)AMEAN,DFTOT
    2 FORMAT(1H1,1H ,47HMEAN OBSERVED PEAK VOLUME ABOVE 160000 CU.METRE,
     12X,F9.7,1X,13HMILLION  CU M,//,1H ,26HVALUE OF SUM(Q-(Q/N))**2.0,
     22X,F15.9)
      STOP
      END
      FINISH
```

```
----------------------------------------------------------------------------
      DATE 31/10/78   TIME 16/06/17                             LISTING FOR:= H

FILE:   HRPSMAXIMOP     SUBFILE EFFP IN CARD MODE

      LIST
      PROGRAM(EFFP)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER EFFP
C######################################################################
C THIS PROGRAM CALCULATES THE VALUES OF OBJECTIVE FUNCTION U2, THE
C COEFFICIENT OF EFFICIENCY OF PEAK DISCHARGE VOLUMES (EP) AND THE
C COEFFICIENT OF DETERMINATION FOR PEAK DISCHARGE VOLUMES (DP=R*R),
C######################################################################
      DIMENSION PKOB(100),PKSM(100)
C**********************************************************************
C READ IN THE OBSERVED AND SIMULATED PEAK ARRAYS,
C**********************************************************************
      READ(5,1)(PKOB(J),J=1,91)
    1 FORMAT(8F9.6)
      READ(5,2)(PKSM(K),K=1,91)
    2 FORMAT(8F9.6)
C----------------------------------------------------------------------
C INITIALISE VARIABLES,
C----------------------------------------------------------------------
      TOTX=0,0
      TOTY=0,0
      TOXSQ=0,0
      TOYSQ=0,0
      TOPXY=0,0
      TDFSQ=0,0
C----------------------------------------------------------------------
C CALCULATE TOTALS,
C----------------------------------------------------------------------
      DO 10 L=1,91
      TOTX=TOTX+PKOB(L)
      TOTY=TOTY+PKSM(L)
      XSQ=PKOB(L)*PKOB(L)
      YSQ=PKSM(L)*PKSM(L)
      TOXSQ=TOXSQ+XSQ
      TOYSQ=TOYSQ+YSQ
      PRXY=PKOB(L)*PKSM(L)
      TOPXY=TOPXY+PRXY
      DIFF=PKOB(L)-PKSM(L)
      DIFSQ=DIFF*DIFF
      TDFSQ=TDFSQ+DIFSQ
   10 CONTINUE
C----------------------------------------------------------------------
C CALCULATE VALUES OF EP, DP AND U2,
C----------------------------------------------------------------------
      EP=(32,1811774-TDFSQ)/32,1811774
      U2=1,0-EP
      A=TOTX*TOTY
      B=A/91,0
      C=TOPXY-B
      AX=(TOTX*TOTX)/91,0
      BX=TOXSQ-AX
      CY=(TOTY*TOTY)/91,0
```

```
  DY=TOYSQ-CY
  EXY=(BX*DY)**0.5
  CCOE=C/EXY
  DP=CCOE*CCOE
  WRITE(6,3)
3 FORMAT(1H1,49HVALUES OF INDICES FOR REPRODUCING PEAK DISCHARGES,
 1/,1X,49(1H=),//)
  WRITE(6,4)EP,U2,DP
4 FORMAT(5X,50HCOEFFICIENT OF EFFICIENCY FOR PEAK DISCHARGES (EP),
 16X,F8.2,//,5X,21HOBJECTIVE FUNCTION U2,35X,F8.2,//,5X,
 253HCOEFFICIENT OF DETERMINATION FOR PEAK DISCHARGES (DP),3X,F8.2)
  STOP
  END
  FINISH
```