A COMPARISON OF THE PERFORMANCE OF SELECTED CONCEPTUAL MODELS OF THE RAINFALL-RUNOFF PROCESS IN SEMI-ARID CATCHMENTS NEAR GRAHAMSTOWN

Dissertation

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PREFACE

A comparison of the performance of selected conceptual models of the rainfall-runoff process forms the central theme of this study and the comparison was conducted with three major objectives in mind. The first objective was to develop a conceptual model that could be used by practising hydrologists for the refinement and extension of historical streamflow records. The major requirements of the model were that it should be simple in structure and easy to operate and yet be flexible in terms of complexity of structure and input requirements as well as producing output at a level of accuracy that is competitive with that of the more complex models presently available. A comparison of the performance of the required model with that of other models formed an integral part of the development process.

The second objective of the comparative study was to contribute to current knowledge of the criteria used in the selection of a suitable model for a particular application. There are, at present, no reliable guidelines to assist the hydrologist in selecting a suitable model from the wide range of models available and a comparative study would indicate the merits of various forms of model structure.

The third objective is associated with the problems that arise when no streamflow data are available for model calibration. One approach is to calibrate the model in a nearby gauged catchment that the hydrologist regards as being 'hydrologically similar' and transferring the model parameter values to the ungauged catchment. Little is known about the feasibility of this parameter transfer process or about the choice of a model for such an application. The third objective was to test the feasibility of the parameter transfer process and to make use of the comparison of model performance to determine the model characteristics that are most suitable for the purpose.

In order to fully achieve the three objectives, it would be necessary to test the performance of a large number of models in a wide range of hydrological regimes. Unfortunately the requirement is beyond the scope of an individual study and must be regarded as a long term objective that is best reached by contributions from a number of investigators working in different areas. Consequently the degree to which the developed model (model DALT described in Chapter 3) can be refined and the contribution made to the development of general guidelines to model selection are necessarily limited in this thesis by the number of catchment areas used and the number of models tested.

A comparison of mathematical catchment models is an expensive and time consuming process that involves the collection and processing of a large amount of data, the development of computer programs to operate models described in the literature, numerous calibration runs for each model and a great deal of calculation to statistically assess the quality of the model output provided by each run. It is important that the rainfall and streamflow data used for calibration should be accurate since the testing of a model involves the assumption that the errors in the simulated streamflow are due to inadequacy of model structure rather than errors in the calibration data. In order to reduce the errors in the rainfall data it is necessary to utilize a relatively high density of sophisticated instrumentation (especially when fine time-intervals are used) in the monitored catchment and the large bulk of data obtained requires the development of a comprehensive data control system.

The author was fortunate in being able to select and instrument suitable catchment areas (in the Ecca Pass area near Grahamstown) under the auspices of the Hydrological Research Unit at Rhodes University (South Africa). The establishment of the data collection network took approximately three years and involved the design and construction of weirs and flumes in the stream channels, the location of autographic raingauges and evaporation pans and the development of the data control system. Although no work could be done on model calibration during this period it was possible to make substantial progress with the analysis of the physical features of the catchments as well as the development of the computer programs for the models.

Data collected in the catchments over a period of approximately two years have formed the basis of the study and as in the case of other highly instrumented catchments, the data are of good quality but cover a relatively short time-span. It was felt that much benefit could be derived by extending the comparison of model performance to at least one more catchment area for which long records were available despite the fact that the records would necessarily be of poorer quality. The additional catchment chosen was the Mareetsane catchment (in the North West Cape Province) primarily in view of the fact that the catchment has a similar climate to the Ecca catchments and because the necessary rainfall and concomitant streamflow records were already available at the Unit in a suitable format (processed for model input by Mr. P.S. Stickells). The use of the data for the Mareetsane catchment in Chapter 6 not only provided a means of investigating possible influences of record length on the pattern of results obtained for the Ecca catchments but also provided a test of the developed model (DALT) with data not used in the development process.

The Hydrological Research Unit of the Department of Geography at Rhodes University was established in November 1973 in order to fulfil the terms of a contract between the Water Research Commission of South Africa and Rhodes University. Similar research units, financed by the Water Research Commission, were subsequently established in the

Department of Agricultural Engineering at the University of Natal (Pietermaritzburg) and the Department of Geography at the University of Zululand. The three research programmes have mathematical modelling as the basis of their hydrological investigations and are complimentary both in terms of objectives and the types of catchment areas used for data collection. One of the objectives in establishing the units was to create centres of expertise at the universities that would not only undertake hydrological research but also facilitate the training of new hydrologists by interaction with the departments to which they are attached.

One of the aims of the research programme at the Rhodes Unit was to provide hydrological data for relatively small, well instrumented catchments that could be used for developing and testing mathematical models of the rainfall-runoff process under relatively stable 'virgin' conditions. Having developed the models with data from a high density raingauge network, the models could be tested in a variety of hydrological regimes using data collected from the national network. Much of the research reported in this thesis was undertaken by the author to meet the aims of the first 5 year contract which is part of an on-going research programme with long term objectives. While much of the research was financed by the Water Research Commission, it should be stressed that the views expressed in this thesis are those of the author and do not in any way, either explicitly or by implication, represent any official view or policy of either signatory to the contract.

A note on terminology.

In the following text the term 'watershed' will refer to the divide separating one drainage basin from another but it should be pointed out that the term 'watershed' is considered by many authors as being synonymous with the terms 'drainage basin' and 'catchment'. It should also be stressed that the term 'program' has been used with specific reference to a programme of sequential commands to be executed by a computer.

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CHAPTER 1

THEORETICAL FRAMEWORK

1.1 Introduction

In the field of water resource planning, one of the biggest problems facing research workers is the lack of suitable data on which to base projections of patterns in the spatial and temporal distribution of water resources. Measurements of flow in river channels at various points in river systems constitute the basic form of data used and there is a need to refine and extend historical records of river flow, to generate records in ungauged catchments and to predict the effects on water supply of man-induced environmental changes. In order to achieve these objectives, it is necessary to simulate the rainfall-runoff process under a variety of conditions.

In recent years there has been a proliferation of mathematical models in hydrological literature. The models described vary widely in complexity and have been developed to cater for an extensive range of applications. Techniques used in water resource management and particularly techniques used in simulation modelling are developing so rapidly that "It is now quite impossible for the average hydrologist, or for that matter any scientist or engineer to read all the published matter even in his narrow field of specialization". (Fleming, 1975, 14). Simulation modelling of hydrological processes involves a great deal of computation and the growth of techniques is associated with the increasing availability of high speed digital computers.

The choice of a model for a particular application is complicated by the rapid development of new techniques and by the fact that hydrologists are faced with a wide range of models, many of which may appear to be equally suitable. Once a model has been chosen, it is usually necessary to spend time gaining a clear understanding of the internal workings of the model and developing a computer program that is compatible with the available facilities.

The problems presented by the complexity of conceptual models (sometimes referred to as explicit soil moisture accounting models (ESMA)) have been clearly stated by Todini and Wallis (1977, 150); "Reliably to estimate the parameters for an ESMA-type model needs skill, as well as experience, and, in fact, it is not at all unknown for would be practitioners to require several days of carefully guided specialized training before being able to use a specified model. How much of this slow and perhaps painfully acquired experience is transferable from one ESMA model to the next is unknown and the relative merits of the current bewildering array of ESMA models are largely unknown". The calibration of a model may involve substantial costs in terms of computer time and unfortunately there is no guarantee that the chosen model will be able to produce output at a level of accuracy that is acceptable in terms of the engineering application in mind. A judicious choice of model is therefore most important particularly for the practising hydrologists who pay commercial rates for computer time.

The need for research that will lead to the development of guidelines for the model selection process has been stressed by Dooge (1977, 72); "There is no limit to the number of conceptual models that can be devised. Indeed, a grave defect in hydrological research in recent years has been the proliferation of conceptual models without a corresponding effort to devise methods of objectively comparing models and developing criteria for the best choice of model in a given situation."

The aims of the research (discussed later in this chapter) are orientated to a comparison of performance of selected conceptual models that will contribute to knowledge of criteria used in the model selection process for applications in both gauged and ungauged catchments. The comparison of model performance will also provide guidelines for the development of a simple, flexible model and an additional benefit of the research will be the presentation of the models studied in the form of readily useable computer programs.

1.2 Simulation of Hydrological Processes

Hydrological systems are so complex that hydrologists are unable to explain completely the natural hydrological phenomena, and as a result complex hydrological systems can only be approximated by simulation (Chow, 1971). In modelling the response of a catchment the physical processes involved may be conceptualized and expressed in mathematical terms. "These conceptualizations may be deterministic or stochastic, linear or non-linear, lumped or distributed, time independent or time varying, stationary or non-stationary or some combination of these." (Delleur, 1971(a), 454). In practice, however, "...the many natural phenomena that hydrologists attempt to model are more often non-linear than linear, usually more unsteady than in equilibrium, probably more stochastic than deterministic, certainly more non-uniformly distributed in time and space than homogeneous." (Delleur, 1971(b), 462).

The interrelationships between individual processes are also complex and unfortunately many of the processes of the land phase of the hydrological cycle cannot be observed directly and those that can be observed are often difficult to monitor over even relatively small areas. For example, the process of interflow (lateral movement of water through upper soil layers to the stream channel) cannot be observed directly and its presence is inferred from the fact that hydrograph analyses often indicate the existence of a third flow component intermediate (in terms of decay rate) between overland flow and base flow. However, for any individual hydrograph, the proportion of the intermediate flow component that is actually derived from soil moisture above the zone of saturation cannot be accurately determined and the process itself is not well understood. As a result of the complexity of hydrological systems, assumptions and simplifications are necessary to provide workable mathematical solutions and numerous mathematical models have been proposed, many of which are valid only under limited conditions.

The terminology associated with the various methods adopted in mathematical modelling of hydrological processes can be confusing. In this thesis, the classification of the methods proposed by Fleming (1975) will be adopted because of its clarity but Fleming (1975, 28) has cautioned that "The proposed classification of these methods will not satisfy everyone's concepts or definitions. They represent a personal viewpoint." All of the methods associated with catchment models may be regarded as parametric and may be subdivided into two main groups, namely the physical (deterministic) that regard hydrological processes as being chance-independent as opposed to the statistical that treat the processes as chance-dependent. The physical methods include the conceptual (based on processes) and empirical methods (not related to processes) that provide the same output for any particular input, whereas the statistical methods include the probabilistic and stochastic methods which treat the processes as either pure random (Monte Carlo method) or non-pure random (Markov process). The physical and statistical methods are sometimes combined in model formulation to give 'quasi-deterministic' models such as the model proposed by Wood (1976) which is dominantly deterministic in structure but treats the infiltration process as stochastic. Alternately some models are dominantly stochastic but contain deterministic functions as part of their structure to treat the processes as non-pure random. A good example is the model proposed by Chow and Kareliotis (1970) which considers runoff as a product of three dominantly stochastic processes, namely rainfall, watershed storage and moisture loss. Each process is modelled in terms of a deterministic part and a stochastic part that is uncorrelated to the deterministic part.

In view of the variations in the degree to which system structure is represented in modelling techniques, mathematical models used in response hydrology may be conveniently divided into three categories (Eagleson, 1971):

(1) Black box models. No attempt is made to model the system structure with the result that this type of model contributes little to the understanding of system structure and the nature of the processes taking place. However, the black box approach is valuable for making predictions in the absence of knowledge of system structure for "...the solutions to many problems involving hydrology, in whole or in part, require little knowledge or understanding of the physical processes taking place." (Steele, 1971, 457). Empirical and stochastic models are regarded as black box models.

(2) Grey box models. General, but not detailed structure of the system is known and parameter values for the model are obtained from observation of processes. With this approach the knowledge of the best conceptual structure for the system and the observation of appropriate parameter levels contribute to our understanding of the physical processes taking place. The majority of the conceptual (deterministic) catchment models fall into this category. Conceptual models in hydrology may be regarded as mathematical models of the hydrological system "...in which one or more of the naturally occuring moisture reservoirs is explicitly included in the formulation of the model." (Manley, 1977, 342).

(3) White box models. In this type of model the nature of the physical system is known and the system is represented exactly by the model in the form of mathematical equations. A hydrological process may be regarded as a combination of a signal and a noise and it is the hope of those in favour of the deterministic approach to simulation modelling that the ratio of the explained signal by physical or other laws to the unexplained noise will increase in time by improving the degree of physical analysis of hydrological phenomena. Hence the white box model

of the hydrological cycle forms the ultimate goal with complete explanation of the processes by cause-effect relationships. From a deterministic point of view the stochastic processes begin where the understanding of the physical phenomena end (Yevjevich, 1974).

Yevjevich (1974) regards continuous hydrological processes as periodic-stochastic processes in which deterministic periodic changes in the atmosphere give rise to the cyclicity in the parameters of the processes while stochasticity is introduced by various sources of randomness in the response by the environment to energy input. As a result of the periodic-stochastic nature of hydrological processes there has been some controversy as to whether the stochastic approach to the simulation of the rainfall-runoff process should be chosen in preference to the quasi-deterministic or deterministic approach. Those in favour of a stochastic approach have stressed that purely deterministic processes in nature are very rare. "Any hydrologic variable realistically conceived, and observed in nature, either as a chronological time series or as a survey across a line, across an area or over a space, is a random process." (Yevjevich, 1974, 235). Hence runoff, as a random variable, may be expressed as a deterministic function of many variables, such as rainfall, soil moisture, vegetation and topography but these are random variables with a deterministic component and "A deterministic function among a set of random variables does not mean a deterministic explanation of hydrologic processes." (Yevjevich, 1974, 233). Even the shape of a catchment, which may be regarded as a constant at a given time is the result of past random processes and is therefore a random variable since "variables which are a function of other random variables are random regardless that the function itself may be deterministic." (Yevjevich, 1974, 225). There is a sound basis for choosing stochastic models for the solution of many problems in hydrology.

The principle use of stochastic models involves the generation of very long synthetic streamflow sequences which can be expected to contain more of the critical flood and drought conditions than are contained in the historical record. Whereas the synthetic sequences retain the statistical characteristics (usually the mean, variance and autocorrelation structure) of the historical record, the synthetic sequences are chronologically different and "Because of the very nature of the systems being studied it is an unfortunate fact that the conclusions reached by synthetic hydrological methods can rarely be subjected to scientific test against observation." (Clark, 1977, 17). Perhaps the major disadvantage of the stochastic models is that the reasonably well understood dynamics of catchment behaviour are ignored and as a result the physical processes involved are obscured. Water development schemes are planned in the long term and it is likely that physical changes will occur in the catchment during that time. A model chosen for planning purposes should allow for incorporation of physical changes, that is, parameters of the model should have physical meaning and be capable of being related to anticipated physical changes. A deterministic model with parameters that have physical meaning would be more capable of adjustment to changing catchment conditions and it is therefore necessary to utilize in a deterministic manner all the data and knowledge about physical processes that are available (Moore, 1971). The physical interpretation of model parameter values also gives rise to the possibility of utilizing the model in ungauged catchments by estimating parameter values from the physical properties of the catchment.

As a result of the large stochastic component in most hydrological variables, deterministic models require a great deal of data about detailed space-time variation of parameters. When adequate data are not available it is often necessary to use lumped parameters especially where no check can be made on the spatial variation of the parameters involved (such as soil moisture and overland flow parameters). An alternative approach, which is feasible in small catchment areas, is to treat the catchment as a distributed system by subdividing the catchment into a large number of elements and calculating the runoff for each element by reference to individual characteristics (such as the method adopted by Huggins and Monke, 1968 and Solomon and Gupta, 1977). Whether the lumped or distributed system has been adopted it should be remembered that even if the streamflow has been correctly simulated by the model, there is no assurance that the physical processes have been correctly simulated. However, the broader the range of conditions for which streamflow can be adequately simulated with any one particular deterministic model, the greater is the confidence that the parameter values used and processes simulated have realistic physical meaning (Moore and Claborn, 1971). "Numerical values of the parameters would tend to fluctuate randomly from data set to data set if they expressed such random components of data. Therefore, consistent results of optimization, with rational interpretation, would imply that the parameters express real, not random, information contained in the data." (Snyder, Mills and Stephens, 1971, 443). The deterministic model provides a powerful tool in the field of water resource analysis but it must be accepted that in all cases both the data and the knowledge will be incomplete and that simplifications will have to be made in order to obtain workable simulation (Moore, 1971).

It is evident from the above discussion that the choice between deterministic, quasi-deterministic and stochastic models for the simulation of the rainfall-runoff process depends primarily on the nature and time-scale of the problem, the quantity and quality of available input data, the input and output requirements and the signal to noise ratio in the data. Both types of models should be considered in the selection process but for the purpose of this research project it was decided to concentrate on the deterministic models because of their dependence on known physical relationships, their adaptability to changing catchment conditions, their suitability for use in ungauged catchments and their suitability as educational tools in hydrology. The majority of the deterministic models used for digital simulation of the rainfall-runoff process can be described as conceptual mathematical catchment models based on moisture accounting principles where all or most of the model parameters can be related to the physical environment. Eight such models will be discussed in Chapter 3.

1.3 The Structures and Uses of Conceptual Models

The definition of a conceptual model given by Manley (1977) illustrates that the moisture storage concept constitutes the basis of conceptual model structure. Moisture storages are used to represent component parts of the land phase of the hydrological cycle and conceptualizations of the various processes taking place are represented in the models in the form of mathematical functions that control the distribution of moisture input.

The moisture storage concept is used in various forms where the most simple is the linear storage of finite capacity that may be represented in diagramatic form by a two dimensional rectangular container. The additions and subtractions of moisture from the storage are uni-dimensional with the finite capacity (an input parameter) representing the maximum moisture deficit. The current moisture deficit is represented by the difference between the current moisture level and the maximum capacity. The finite linear storage is operated by diverting moisture to the storage until the current moisture level reaches the maximum value and then any additional moisture bypasses the storage. In each time-interval, the additions and subtractions of moisture are governed by functions that may be dependent on the current level of moisture in the storage or on the dimensionless storage ratio which is the ratio of the current level to the preset capacity. The storage ratio is a most useful index of antecedent conditions and the inclusion of the storage ratio in moisture distribution functions reduces the dependence on the absolute value of the current moisture level in storage. However, the use of a finite capacity in storage concepts limits the effective control of incomimg moisture (by functions governing the redistribution of moisture from the storage) to that part of the incoming moisture that can be accomodated by the remaining storage deficit. Consequently many model storages do not have a finite capacity and extractions of moisture are dependent on the current storage level rather than the storage ratio. Crawford and Linsley (1966) reached a compromise between the two approaches by introducing the use of a 'nominal' or median value of storage as an input parameter that allows the use of a storage of infinite capacity and also provides a dimensionless storage ratio in the form of the ratio of the current level to the nominal level.

Moisture storages of finite or infinite capacity have been used in conceptual models to simulate processes such as interception storage, surface depression storage, various forms of soil moisture storage as well as storages to route flow components (overland flow, interflow and base flow)to channel storage. The number of storages incorporated in the structure of any one conceptual model, the manner in which they are operated and the sophistication of the functions used to distribute moisture between storages are all dependent primarily on the use for which the model has been devised and, to a lesser extent, on the characteristics of the catchment area in which the model was first operated.

Conceptual models that have been developed for specific purposes have structures that provide the highest level of simulation for those processes that are regarded as being important for the specific purpose and other processes are often poorly represented in the structure or omitted altogether. A good example is the model of Shih, Hawkins and Chambers (1972) which was developed for use in forested catchments and has no overland flow component as one of the assumptions of model development was that all rain reaching the ground would infiltrate. The model also neglects the processes of channel routing because the process was regarded as unimportant in the small catchment used for model development. The resulting structure of the model is adequate for the specific purpose but would not be adequate for general use. Other specific purposes for which conceptual models have been developed include;

simulation of surface runoff hydrographs (Huggins and Monke, 1968;
  Kozak, 1968; Dawdy, Lichty and Bergmann, 1972; Krzysztofowicz and
  Diskin, 1978);
drought analysis (Burnash and Ferral, 1973);
streamflow forecasting (Nash and Sutcliffe, 1970);
runoff in urban or paved areas (Watkins, 1962; Maniak, 1973; Wood, 1975);
flood routing (Onstad, 1973);
reservoir regulation (Rockwood, 1964) and
snow accumulation and melt processes (Leaf and Brink, 1973).

Many conceptual models have been developed for general use and incorporate simulation of a large number of hydrological processes. The general purpose models often incorporate all the flow components and are necessarily complex in structure. Some of the better known general purpose models are those of Dawdy and O'Donnell (1965), Boughton (1966), Crawford and Linsley (1966), Hydrocomp (1969), Claborn and Moore (1970), Porter and McMahon (1971), Holtan and Lopez (1975) and Bowles and Riley (1976).

The principle uses of conceptual models (whether specific or general purpose) in water resource analysis can be summarised as being:

1) The prediction of runoff from recorded or generated rainfall where no records of runoff exist. In this case parameter values are estimated from the physical properties of the catchment and it is therefore necessary that all the parameters in the model should either have physical interpretation or be related in some way to easily measured physical properties in the catchment. Another approach is to calibrate the model in a nearby gauged catchment that is 'hydrologically similar' and to change only those parameter values that can be estimated reliably from physical features to generate a runoff record for the ungauged catchment. An investigation of the feasibility of the parameter transfer process under suitable conditions is described in Chapter 5.

2) The extension of runoff data for periods of measured or generated rainfall beyond that for which runoff records are available. In this case parameter values may be estimated by calibration of the model against existing data.

3) The estimation of changes of runoff due to anticipated changes in catchment conditions. Parameter values with physical interpretation, that have been optimized by calibration, may be changed to simulate the response of the catchment under different conditions.

1.4 The Requirements of a Conceptual Model

If a simulation model is to be used for the above purposes the model should, as far as possible, conform to the following requirements:

1) The input data required by the model should be available for most catchment areas. The number of input variables should be limited and

the requirements for each variable should be as flexible as possible.

2) The model should be general, that is, it should be applicable to all hydrological regimes and to both large and small catchment areas. Experimental catchment areas are usually small in order to reduce the errors in the input and calibration data as well as the variation in physical characteristics, but water resource problems are more often associated with large catchments.

3) The model should be simple enough for the user to operate and understand. As the complexity of models increases, so do the requirements of input data and computer facilities, the number of calibration runs necessary and the cost of each run of the model. The simplicity of the model structure is one of the most important criteria in the choice of a model for a problem especially when the sophistication of available computer facilities is limited and when the user does not have unlimited access to a computer and has to pay commercial rates for computer time.

4) The model should provide output at a level of accuracy that is acceptable in relation to the problem being studied.

The complexity of hydrological systems and the variation in data collection processes from area to area and country to country, make it extremely difficult to produce a conceptual model that operates satisfactorily under the entire spectrum of hydrological environments for any chosen level of output. As a result, a model is usually built for a specific problem in a specific area and is designed to be compatible with the particular hydrological regime, the input available and the output required. It is therefore not surprising that there has been a proliferation of models in the literature and that very few have satisfactory application outside the area in which they were first operated. When the need arises for the use of a conceptual simulation model the user has a wide range of models in the literature from which to choose but it is usually necessary to make some alteration to the input or structure of the model that has been selected as being most suitable for the particular problem.

The general requirements of a model as set out above should be viewed in the light of the changing objectives of deterministic model formulation. It was stated in the discussion on white box models that the goal of deterministic model development was the complete explanation of hydrological processes by cause-effect relationships. However, in view of the complexity of hydrological systems, the goal is not compatible with the objective of providing a model that is sufficiently simple to be of general use. A review of the literature on digital hydrological simulation indicates that those involved in model development have long been aware of the need to restrict model complexity for practical purposes but there is also an apparent trend away from the goal of simulating of as many processes as possible towards the development of simple models based on fewer, selected processes.

In 1965 Dawdy and O'Donnell (1965, 123) wrote that "Quantitative models of catchment behaviour to be useful (i.e., acceptably accurate) must inevitably be complex, yet must be feasible to operate... The ideal model would specify completely the properties of and the processes that occur in all the relevant components of a catchment. The specification would be given in terms of physical parameters and would involve all behavioural relationships within the catchment. Given such a full specification, the hydrologic effects of a rainfall event over a catchment could be determined objectively." The trend away from the ideal of simulation of all processes towards selective simulation of the most important processes is indicated in the statement of Crawford and Linsley (1966, 8); "A practical hydrologic model that is a skeleton of the hypothetical "absolute knowledge" model is the goal of digital hydrologic simulation.", as well as the statement by Smith (1970, 126); "No theoretical model of a natural watershed could account for all the variables and their interrelationships that affect the runoff process. On the other hand, no model which is sufficiently simple to be a general engineering tool can hope to model well the results of all these complexities. The objective of model formulation is to make simplifying assumptions so the model is not unwieldly and yet retains the most important characteristics of the physical system."

One of the factors that could account for the trend away from simulation of the maximum number of physical processes is the growing realization that model complexity is not necessarily a prerequisite for adequate simulation with respect to a large number of engineering applications. As Garrick, Cunnane and Nash (1978, 375) have pointed out; "Experience in the current decade has indicated that is is (sic) surprisingly easy to develop simple conceptual models which, when suitable values of the parameters are chosen, can reasonably well simulate the rainfall-discharge relationship in a given catchment. One consequence of this experience is to bring in question the utility of the more elaborate models which seek to represent explicitly each of the several parts and paths of the earthbound portion of the hydrological cycle." Another factor that has influenced the trend towards simplicity of model structure is that users of hydrological models tend to regard simplicity of structure as a most attractive benefit; so much so that they are often prepared to sacrifice accuracy by using a simple method when other available methods, which are more complex, would provide better simulation. The popular Rational Method for example, is based on assumptions which cannot be readily satisfied under actual circumstances (Chow, 1964) but "Despite much criticism, the Rational Method of computing peak discharges will continue to be used by most organisations because of its simplicity." (Chien and Simsek, 1976, 307).

A third factor which is likely to have influenced the trend away from detailed simulation of a very large number of processes is that the expected benefits of this approach have not fully materialized giving rise to a degree of disillusionment. One of the important expected benefits of a high level of correspondence between model components and the physical catchment processes is that model parameter values could be obtained with a high level of confidence from field observation and that model sub-components would provide reliable measures of their relevant catchment processes. That is, the observed streamflow would be accurately reproduced by the model by accurate simulation of each of the individual component processes concerned. However the observation that the model parameter set obtained by calibration is dependent on the objective function used (Diskin and Simon, 1977), tends to undermine the confidence that can be placed in the physical interpretation of parameter values. Lack of confidence in the degree to which parameter values reflect reality does not necessarily imply a lack of confidence in the ability of the model to produce adequate simulation. A recent investigation of parameter values for a model, conducted by Mein and Brown (1978, 303), gave rise to the following conclusion; "On the basis of several tests with the Boughton model it is concluded that for this model at least, relationships derived between any given parameter value and measurable watershed characteristics would be imprecise, i.e., they would have wide confidence limits. One could not be confident therefore in changing a particular parameter value of this model and then claiming that this alteration represented the effect of some proposed land use change. On the other hand, the model performed quite well in predicting flows with these insensitive parameters, showing that individual parameter precision is not a prerequisite to satisfactory output performance." It would appear that once the dominant processes (with respect to the use for which the model is being developed) have been included in the model structure, the addition of further components provides increasingly less benefit since "...as each refinement adds more parameters with diminishing net gain in accuracy, the added parameters are less sensitive. Therefore, although a model may appear more realistic, the fitted parameters may reflect reality less and less in their numerical values. Small errors in data may generate large errors in some of the less sensitive parameters." (Dawdy and O'Donnell, 1965, 135). The increasing sophistication of high speed digital computers is increasing the hydrologist's ability to represent more processes in model structure without marked increases in computation time but the additional benefits derived do not appear to justify the increased complexity. The most rewarding approach at the present level of knowledge of hydrological processes is firstly to identify the dominant processes effecting those aspects of the output that require the most accuracy and to improve the level of simulation of the chosen processes.

1.5 The Choice of a Model

When making the choice of a model there are a number of interrelated factors that should be considered:

1) An important factor is the choice of objective function that the user wishes to minimize during calibration of the model. The particular problem for which the model is to be applied dictates the requirements of the model output and these requirements should be expressed in the form of an objective function to ensure that calibration processes are executed objectively rather than subjectively. The calibration of the

model involves the optimization of the model parameters to give the best value of the objective function, that is, the best correspondence between simulated and observed runoff in relation to the problem. Recent research on objective functions by Diskin and Simon (1977) has illustrated that no single objective function can serve as a universal tool for the optimization of hydrological models. The calibration of a single model in a single catchment with different objective functions will give rise to different sets of model parameter values; "Thus the optimal set of parameters is optimal only in the context of the objective function selected." (Diskin and Simon, 1977, 130). There is also the consideration that even when the optimal set of parameter values has been obtained by calibration for a selected objective function, the parameters are optimal in the sense that the user has subjectively decided that further calibration is unlikely to improve the value of the objective function or that the resulting value of the objective function represents an adequate level of accuracy with respect to the application in mind. Another important outcome of the study by Diskin and Simon (1977) was the illustration of the need to consider more than one objective function in the calibration process for a given model and a given engineering application. The need arises firstly from the fact that the best form of the objective function is usually not known in advance and secondly, the use of a number of suitable objective functions in parallel is less likely to lead to a local minimum for the one objective function adopted. As the objective function or functions define which aspects of the hydrograph require the most accuracy in simulation as well as the form and time-interval of the output, the chosen model must be compatible with the objective function.

2) The choice of the model and the choice of the objective function are limited by the quantity and form of input data that are available

or that could be satisfactorily generated, as well as the length and form of the existing runoff record that can be used for calibration.
3) The complexity of the model structure and the form in which the model is available should be taken into account. A complex model that simulates all the processes which take place in the catchment at small time-intervals is not necessarily the best model to choose for any one particular engineering application (O'Connell, Nash and Farrell, 1970; Pitman, 1977; Diskin and Simon, 1977; Garrick, Cunnane and Nash, 1978). Whereas the models that are complex in terms of structure and input requirements could be expected to provide adequate results for a wide range of objective functions, the more simple models which have a smaller range of applications can give adequate results at greatly reduced cost, provided that the objective function is suitable. As Diskin and Simon (1977, 131-132) have pointed out "...if the annual yield of a watershed is all the information needed, the value obtained by summing up 35 040 values of runoff values for 0,25-h intervals is not necessarily better than that obtained by adding twelve monthly values or even a value of yearly runoff generated directly by a suitable model." Thus the choice of a model that is just sufficiently complex in terms of input and structure to meet the requirements of the objective function may well minimize the cost involved. In addition, the choice of a model that is available in the form of a computer program reduces the substantial time and cost of developing a program to run a model described in the literature.

1.6 The Aims of the Research Project

The first aim of the research project (discussed further in Chapters 3 and 4) is to examine a variety of models, drawn from the literature, under semi-arid small catchment conditions and thereby to identify inadequacies in the models under these conditions and to modify the models accordingly to increase their general applicability. It should be stressed that the majority of models described in the literature are not generally available in the form of computer programs with the result that programs will have to be written to operate most of the models selected for study. It is frequently the case that the description of a model in the literature is confined to the general principles adopted by the author and lacks sufficient detail to ensure that a program written to operate the model incorporates all of the subcomponents used or that they are identical in structure. The resultant model represented by the program can therefore not be regarded as the same model used by an author and caution should be exercised when comparing output or parameter values obtained.

The second aim of the research (discussed in Chapter 4) is to compare the performance of the selected and modified models within various rainfall input categories for selected objective functions to determine whether the models with the more complex structure provide better results than the simple models. If a simple model could be made to provide results that are at least comparable with those of the more complex models, it would prove to be far more useful to the practising engineer or hydrologist.

The third aim is to compare the performance of models that require fine time-intervals for input data with those that require coarser time-intervals to ascertain whether the use of fine time-intervals for input data is justified for selected objective functions. During the development and modification of the models the goal will be to provide the practising engineer and hydrologist with models, in the form of computer programs, that can be calibrated to provide output at an acceptable level at the minimum cost and with the minimum amount of preparation. Thus a model that is simple in terms of structure and input requirements will be regarded as more useful than a complex model that provides an equivalent level of output but it should be stressed that a simple model, by nature of its structure, may be less useful for the understanding and explanation of the complex processes that occur in the natural catchment. The resultant models should therefore be regarded primarily as tools for providing design information rather than tools for aiding the understanding of natural processes.

The fourth aim, related to the above aims, is to identify the major deficiencies of a very simple model (Dalton Model of Diskin et al, 1973) with respect to commonly used objective functions and to modify the model just sufficiently to give output at a level of accuracy that is competitive with that of the more complex models. The process of selective modification would result in a model that gives acceptable output with a minimum of structural complexity. The development of the required simple model (called DALT) is described in Chapter 3.

The fifth aim (discussed in Chapter 5) is to examine the feasibility of transferring parameter values for a model from the gauged to the ungauged catchment, that is, to test the premise that parameter values obtained by calibration may be transferred to a nearby ungauged catchment with similar vegetation, climate and lithology (and where suitable rainfall records are available) to provide a record of runoff where no measurement has been made. The comparison of model performance with respect to complexity of both structure and input requirements, as expressed in the second and third aims, will be extended to the 'ungauged' catchment situation in Chapter 5.

1.7 The Models Tested in the Study Catchment

In order to pursue the above aims it is necessary to select models from the literature that contain:

1) A variety of uses. The selection should cover models designed for flood peak simulation, discharge volume simulation and those designed to simulate the entire hydrograph.

2) A variety of time-intervals for input data. The models will be subdivided into those that require hourly or daily rainfall input data.

3) A variety of complexity of model structure within each time-interval group for input. The number of parameters and the number of storages gives an indication of model complexity.

4) A variety of infiltration functions. While many measurements have been made of point infiltration relatively little is known about the areal assessment of infiltration and it is the infiltration component of a model that plays a leading role in the calibration process.

With the above requirements in mind the following models were chosen for examination, and are discussed in Chapter 3:

1) The models requiring rainfall data on an hourly basis (in descending order of complexity).

a) The Stanford Watershed Model IV by Crawford and Linsley (1966). The model was chosen because it is one of the most complex and most generally applicable models that has been developed. The version of the model used in this research project will be referred to as FORD. It should be noted that all of the models selected operate on iterations of the same time-interval as the rainfall input data with the exception of model FORD which operates on iterations of a quarter hour irrespective of the time-interval chosen for rainfall data.

b) A model by Porter and McMahon (1971) which will be referred to as PORT. This model was chosen primarily for its sophisticated approach to the infiltration problem.

c) A model by Dawdy, Lichty and Bergmann (1972) referred to as BERG. The model was chosen because it is designed for flood peak simulation and will provide a contrast with FORD and PORT which are designed to simulate the entire hydrograph.

d) An hourly version of the model DALT (see daily models) which will be referred to as DALH. The model DALH is relatively simple in structure and was developed by the author to extend the range of complexity of the hourly models and to increase the flexibility of input requirements and uses of the daily model DALT.

2) The models that require daily rainfall as input.

a) A daily version of the Stanford Model (FORD) referred to as SMDV. Model SMDV was developed by the author to provide a range of complexity for the daily models and to provide a version of the Stanford Model that is compatible with the type of rainfall data that is generally available in South Africa.

b) A daily version of the hourly model PORT referred to as PDAY. This model was developed by the author to increase the flexibility of input requirements for model PORT.

c) A model developed by Nielsen and Hansen (1973) referred to as HANS which was chosen as an intermediate model in terms of complexity and because of its unusual approach to the infiltration problem.

d) A model developed by Diskin, Buras and Zamir (1973). The model is very simple in structure and was chosen to highlight the major deficiencies of the simple models and to serve as a starting point for the development of model DALT that is just sufficiently complex to compete (in terms of accuracy of output) with the complex models.

1.8 The Choice of Catchment Areas

In order to meet the aims of the research project, it was desirable for the selected models to be tested with data from at least two catchment areas and with data comprising rainfall and runoff measurements on an hourly basis and evaporation measurements on at least a monthly basis. In choosing suitable catchment areas three major requirements were taken into consideration:

1) In terms of the aim of increasing the applicability of the models to South African conditions it was felt that the catchments to be chosen should have a semi-arid climate as the major part of South Africa falls into this category.

2) The size of the catchments should be restricted to relatively small catchments. There are two main reasons for the choice of small catchments, the first being that in testing the models it is not known how much of the error in the simulated output is due to error in the input (rainfall) and observed output (streamflow) data and how much is inherent in the model itself. There is therefore a need to reduce the errors in the rainfall and runoff measurements as far as possible and this is achieved by using a high density of instrumentation. Relatively high densities of gauging networks become economically feasible only on a relatively small scale. The second reason is that the catchments must be as similar as possible in terms of climate, vegetation and lithology in order to test the feasibility of parameter transfer from one catchment to another. As a general rule, the variation of physical characteristics of a catchment tends to increase with catchment size.

3) It is desirable for the comparison and development of the models that each catchment should be as homogeneous and as stable as possible to minimize spatial and temporal variations in the values of the hydrological parameters. Under these conditions there is a better chance of obtaining representative values of the model parameters.

Unfortunately, rainfall and runoff data measured at a time-interval of one hour were not available for suitable semi-arid catchments at the outset of the research project and it was necessary to gauge catchments that met the specified requirements. Five small catchments in the Ecca Pass area near Grahamstown were found to be suitable as there is a minimum of farming activity, the vegetation is of a type that is not very sensitive to grazing and the climate, vegetation and lithology appear to be as uniform as the model user could hope to find in practice. It should be stressed however that the decision of whether one catchment is hydrologically similar to another is subjective, and that variations of many important hydrological variables such as soil depth and the texture are not readily apparent to the observer.

The five catchment areas that have been chosen as a source of rainfall and runoff information have been monitored since February 1976. During the period March 1976 to June 1977 a number of flow events were recorded to give a record of runoff containing two 'wet' periods separated by a 'dry' period of ten months. The flow events occured under a variety of conditions with runoff resulting in some cases from high intensity short duration rainfall and in other cases from low intensity long duration rainfall. Whereas the available data are suitable to form the basis of a relative comparison of model performance, there is some doubt as to whether the data record is sufficiently long to incorporate the full range of soil moisture conditions. Consequently the degree to which an individual model may be tested for a semi-arid regime may be limited but the refinement of simulation models should be regarded as a continuous process with each research effort contributing to a long term objective.

The selected models will be calibrated with the data available and during the calibration process, an attempt will be made to overcome any obvious deficiencies in model structure. When the models have been calibrated their relative performance will be compared with respect to the values obtained for the objective functions described in Chapter 4.

1.9 The Hypotheses

The aims of the research programme are orientated essentially to increasing existing knowledge about the relationship between model complexity and the accuracy of simulated discharge with respect to various applications. As complex models simulate a greater number of hydrological processes taking place in the catchment than simple models, the hydrologist might intuitively expect the accuracy of simulation to increase with increasing model complexity. However, research reported in recent literature indicates that there is a certain level of complexity above which additional model complexity becomes superfluous for a large number of applications (Garrick, Cunnane and Nash, 1978). In view of the growing uncertainty as to the validity of choosing complex models in order to ensure the highest accuracy of simulation, the premise that the accuracy of simulation increases with model complexity will be tested in the study catchments. Model complexity may take the form of structural complexity or complexity of input requirements and to accomodate the two forms of complexity, the following two hypotheses are put forward:

1) Within any group of models requiring the same time-interval for rainfall input, the models of complex structure provide more accurate output than the models with more simple structure.

2) The models that require hourly rainfall input generally provide more accurate simulation than the models that require daily rainfall input.

The comparison of model performance will also form an integral part of the research into the feasibility of parameter transfer as expressed in the fifth aim of the research programme. As parameter transfer is a form of model application, the same relationships between model complexity and simulation accuracy expressed in Hypotheses 1 and 2 will apply. Consequently Hypotheses 3 and 4 take the following form:

3) Within any group of models requiring the same time-interval for rainfall input, the models of complex structure are more suitable for parameter transfer applications than the models of more simple structure.

4) The models that require hourly rainfall input are generally more suitable for parameter transfer applications than the models that require daily rainfall input. The suitability of models for parameter transfer applications will be determined by the degree of deterioration in the values of the statistics used as criteria of goodness of fit.

Hypotheses 3 and 4 are concerned with the spatial aspects of parameter transfer, that is, the transfer from one catchment to another. However, the proposed research framework is suitable for investigation of temporal as well as spatial aspects of parameter transfer. The temporal aspects involve investigation of the relationship between model complexity and the length of calibration record necessary to obtain parameter values that are representative of the hydrological regime. The relationship may be investigated by comparing parameter values obtained from a very short calibration record with those obtained by using the full length of calibration record available. The contribution that can be made to this important field of research is somewhat limited by the relatively short record of calibration data available for the study catchments. However, the following hypothesis is put forward for testing within the limits of the data available.

5) Within the group of models that require hourly rainfall input, the use of a very short calibration record (1 month) results in less representative parameter values for the models of simple structure than for the more complex models.

The catchment areas that have been chosen as a source of rainfall and runoff information will be more fully described in Chapter 2. The development of a hydrological gauging network is a costly and time consuming process, even in small catchment areas, and it was necessary to devise a comprehensive data control system to manage the large volume of data being collected. As a description of the data control system is of relevance to the use of the models listed in Appendix A (and may be of benefit to investigators planning new data control systems) the elements of the data control system and some of the problems encountered in the development phase have been included in the following chapter.

CHAPTER 2

THE DATA COLLECTION NETWORK AND DATA CONTROL METHODS

2.1 Introduction

In view of the aims of the research project set out in Chapter 1 the requirements of the selected catchment areas are that they should be small, semi-arid catchments that are as similar as possible in terms of climate, vegetation and lithology and that the catchment areas should be reasonably stable with respect to land use.

The decision as to what constitutes a small catchment is somewhat subjective and in terms of the prerequisite of homogeneity, the smaller the catchment area chosen, the better. However, one of the objectives in the formulation and modification of the simulation models was to provide models that could be used in large catchments as well as small catchments since water resource analysis is usually done on a large catchment basis. Such models do not require, as input, the type of detailed information that can be obtained from very small 'experimental plot' situations and the smaller the catchment area chosen for development of the model the less suitable the model is likely to become for use in the less homogeneous larger catchments. As a range of catchment sizes was to be selected within the 'small catchment' category, the lower limit was chosen arbitrarily as 1 square kilometre so as to exclude the very small catchments. At the other end of the scale the chosen catchment should not only meet the requirement of reasonable homogeneity but should also be small enough to make a fairly dense raingauge network economically and operationally feasible. A third consideration was that the catchments should be small enough to display small catchment characteristics from a modelling point of view, that is, the time of concentration should be substantially less than one day. The use of data for relatively small catchments allows rigorous testing of the suitability of model structure for simulating hydrological processes associated with the land surface. The Committee on Runoff of the American Geographical Union have defined a small watershed "...as one that is so small that its sensitivities to high intensity rainfalls of short duration and to land use are not suppressed by the channel storage characteristics." (American Geophysical Union, 1957, 379). With this definition in mind, Chaudhry (1975) is of the opinion that a small catchment may be as large as 50 square miles (129 square kilometres), depending on the relative predominance of channel storage effects. An upper limit of 100 square kilometres was chosen for the study area primarily in view of the economic considerations of establishing and maintaining a gauging network of 'above average' density in order to reduce the errors in model input information as far as is feasible.

A catchment area of approximately 73 square kilometres, drained by the Ecca River (previously named the Brak River, a tributary of the Fish River) in the Eastern Cape was selected as it met all the requirements, particularly as it is situated only 20 kilometres by road from Grahamstown which was an important consideration in terms of transport costs. To ensure a high level of conformity between catchment areas, four additional catchments were selected within the Ecca catchment constituting sub-catchments of the system, (Figure 1) to give a range of catchment areas from approximately 1 square kilometre to 73 square kilometres. Although the climate, vegetation and lithology appear to be uniform over the Ecca catchment, spatial variations obviously do exist and it is necessary to describe these variations, and the variations in other physical features, to aid the explanation (in Chapters 4 and 5) of differences in hydrological response between the catchment

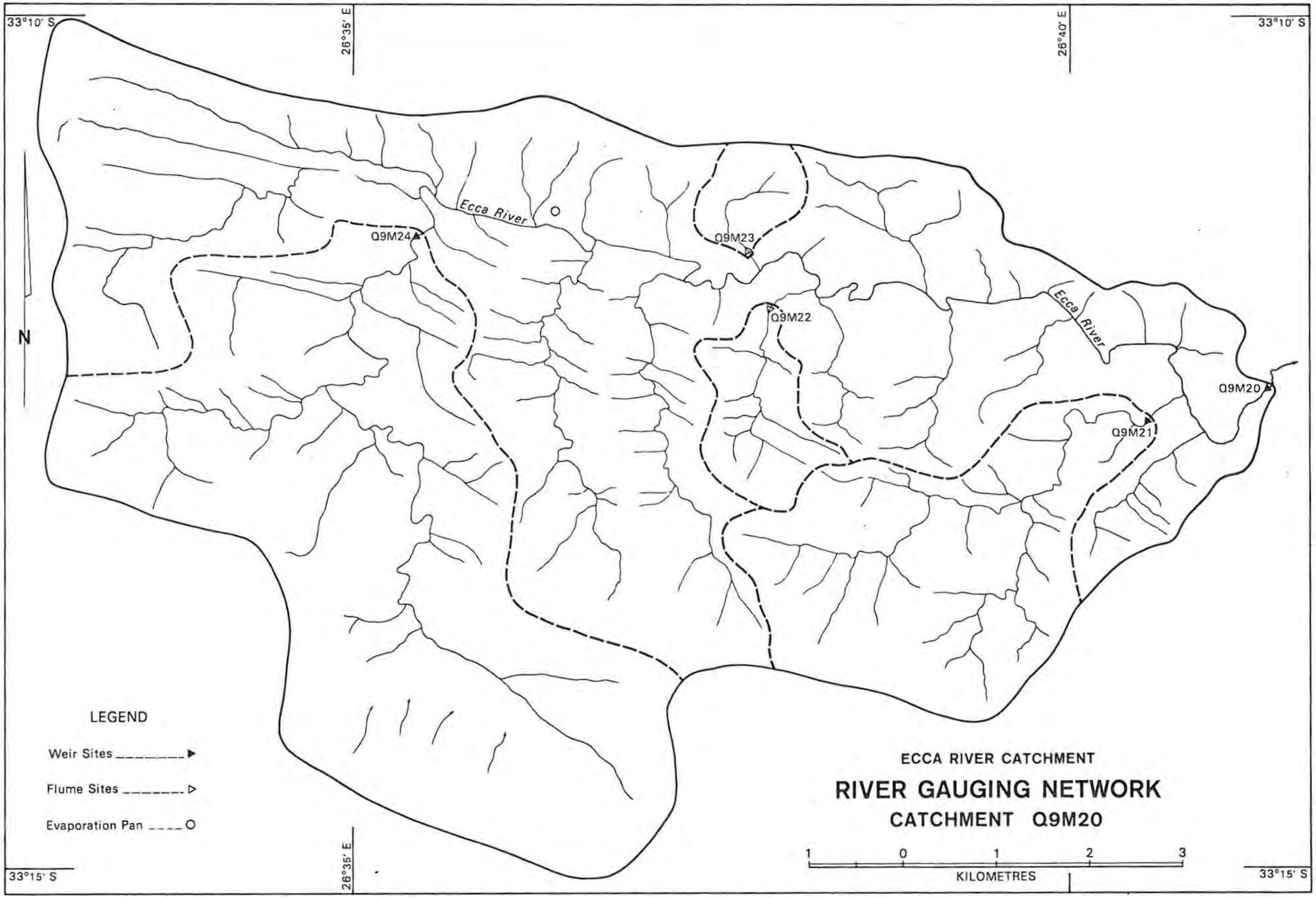

33°10' S
26°35' E
26°40' E
33°10' S
N
Ecca River
Q9M24
Q9M23
Q9M22
Ecca River
Q9M20
Q9M21
LEGEND
Weir Sites ▶
Flume Sites ▷
Evaporation Pan ○
ECCA RIVER CATCHMENT
RIVER GAUGING NETWORK
CATCHMENT Q9M20
1 0 1 2 3
KILOMETRES
33°15' S
26°35' E
33°15' S

FIGURE 1

areas.

2.2 Climate

The Ecca catchment has a mean annual rainfall of approximately 420 millimetres per annum (Midgley and Pitman, 1969) with the wettest months being November and March, and 40 percent of the annual rainfall occurs in the 'winter' months April to September (Table 1). The average monthly rainfalls reflected in Table 1 were obtained from a rainfall record of monthly values for the Ecca catchment for the period 1881 to 1972 which was generated from records of nearby rainfall stations. The procedure adopted for the creation of the rainfall record was that of Pitman (1973) in which the monthly rainfalls in each record were expressed as a percentage of the mean annual precipitation (MAP) at that station and the percentage values for each month were averaged for all overlapping records. The estimated MAP for the Ecca catchment was then used to derive a rainfall record from the averaged percentages for each month.

The actual recorded daily rainfalls in the Ecca catchment for the period February 1975 to December 1977 were analysed by using program STAT (Appendix A) to determine the average length of dry periods. It was found that the average number of consecutive days on which no rainfall was recorded was only 4 days with a standard deviation of 4 days (Table 2). A rainfall record for Grahamstown, covering the same period, was analysed using program STAT and the same average and standard deviation (4 days) of the number of consecutive dry days was observed. The observed similarity in the rainfall pattern between the Ecca catchment and Grahamstown lends support to the creation of an artificial record from data at nearby stations. The values of Table 2 have been plotted in Figure 2 to demonstrate that although the frequency of rain days is similar for the Ecca catchment and Grahamstown, the Ecca catch-

TABLE 1

CLIMATE STATISTICS FOR ECCA CATCHMENT

MONTH	MEAN RAINFALL(MM)	MEAN PAN EVAPORATION(MM)	CONVERSION FACTOR*	FREE SURFACE EVAPORATION(MM)
1	37	180	0,96	173
2	40	140	0,96	134
3	49	130	0,91	118
4	35	95	0,95	90
5	33	80	0,96	77
6	20	70	0,92	64
7	20	80	0,96	77
8	25	95	0,96	91
9	36	100	0,96	96
10	43	130	0,96	125
11	45	150	0,96	144
12	37	180	0,90	173
TOTAL	420	1430		1362

* Conversion factor used in the estimation of free water surface evaporation

TABLE 2

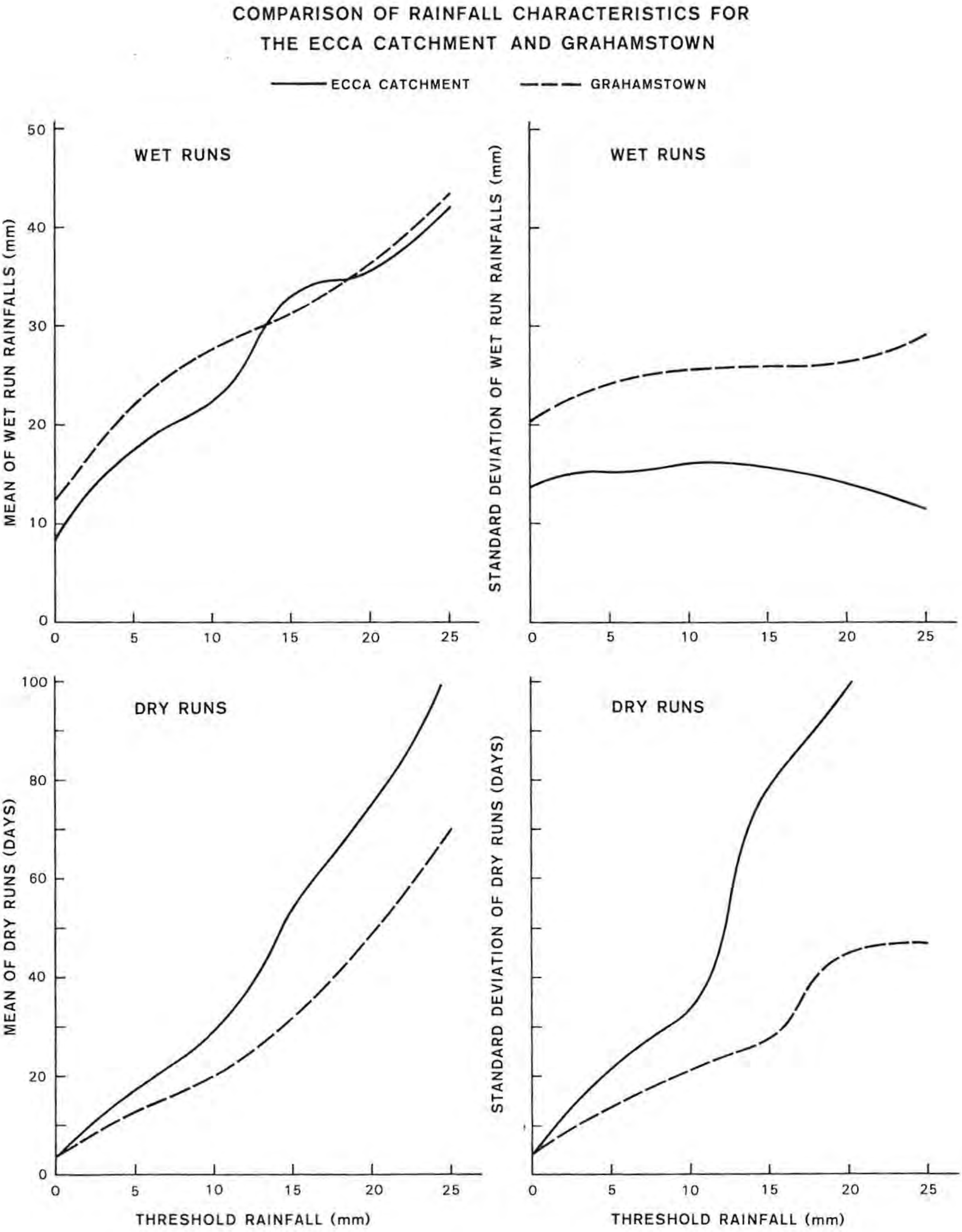
COMPARISON OF RAINFALL CHARACTERISTICS FOR THE ECCA CATCHMENT AND GRAHAMSTOWN

GRAHAMSTOWN RAINFALL

THRESHOLD DAILY RAINFALL(MM)	DRY RUNS(DAYS)		WET RUNS(DAYS)		WET RUN DEPTHS(MM)		
	MEAN	S.DEV	MEAN	S.DEV	MEAN	S.DEV	CofV
0	4	4	2	1	12,34	20,08	1,63
1	6	6	2	1	14,87	21,20	1,43
5	13	14	2	1	22,43	24,25	1,08
10	20	21	1	1	27,68	25,57	0,92
15	32	27	1	1	31,11	26,00	0,84
20	50	46	1	1	36,83	26,42	0,72
25	70	47	1	1	43,21	29,05	0,67

ECCA RAINFALL

THRESHOLD DAILY RAINFALL(MM)	DRY RUNS(DAYS)		WET RUNS(DAYS)		WET RUN DEPTHS(MM)		
	MEAN	S.DEV	MEAN	S.DEV	MEAN	S.DEV	CofV
0	4	4	2	1	8,06	13,85	1,72
1	8	8	2	1	11,21	14,66	1,31
5	18	22	1	1	17,75	15,05	0,85
10	29	33	1	1	22,24	16,03	0,72
15	55	80	1	1	33,38	15,95	0,48
20	75	98	1	1	35,85	13,89	0,39
25	106	125	1	1	42,30	11,70	0,28



COMPARISON OF RAINFALL CHARACTERISTICS FOR THE ECCA CATCHMENT AND GRAHAMSTOWN

FIGURE 2

ment generally receives less rainfall in each rainfall event and consequently the mean and variance in the rainfall depths for the wet runs tend to be lower for increasing threshold rainfall and the mean and variance in the length of dry runs tend to be higher.

Rainfall records obtained from the raingauge network (discussed later in this chapter) in the Ecca catchment illustrate that there is a consistent pattern of spatial variation in the rainfall. During wet periods associated with cold fronts the raingauge catch tends to be highest in the South (Botha's Ridge) and decreases progressively in a Northerly direction. There is also a less obvious decrease from West to East across the catchment and the overall pattern has been illustrated in Figure 3 by plotting isolines representing point precipitation expressed as a percentage of the estimate of the average rainfall over the area. The values used for the interpolation process in Figure 3 were obtained by expressing the total monthly catch at each raingauge as a percentage of the average rainfall for that month and averaging the percentages over all the months of the record. It was noted that some rainfall events deviated from the pattern shown in Figure 3. The majority of these events were associated with convectional thunderstorms which, when isolated, did not show any consistent pattern.

2.3 Vegetation

The vegetation of the region can be described as Valley Bushveld (Karoo and Karroid Bushveld Types iv, Acocks, 1953) consisting of tall sub-succulent woodland which thins to a low succulent scrub on the flatter areas. The vegetation appears to be reasonably uniform in type and density over the catchment but in order to assess the relative spatial changes that occur, the vegetation has been mapped from a hydrological point of view, that is, relative changes of density in canopy cover and in ground cover have been plotted in Figures 4 and 5

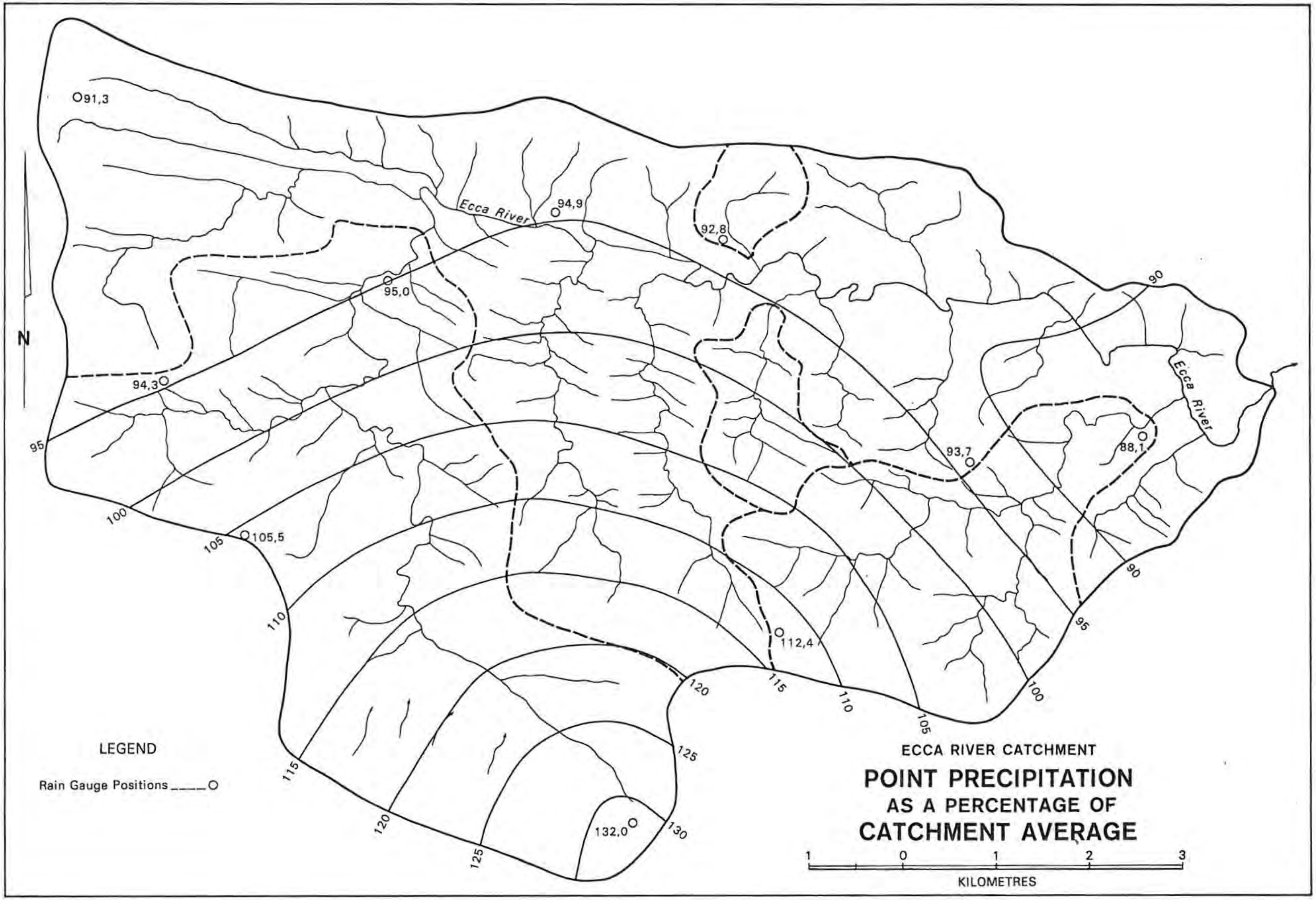
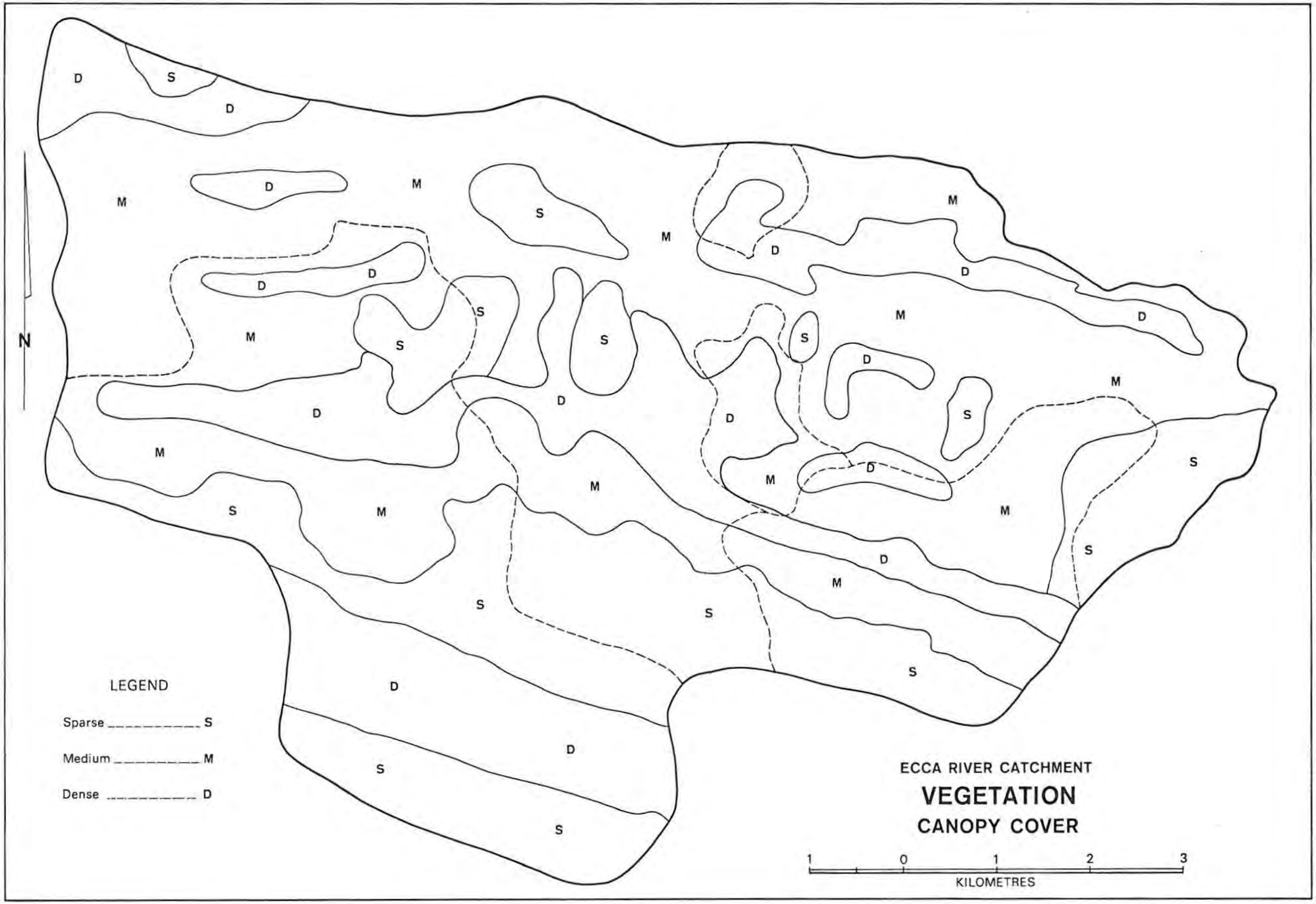

ECCA RIVER CATCHMENT
POINT PRECIPITATION
AS A PERCENTAGE OF
CATCHMENT AVERAGE
LEGEND
Rain Gauge Positions ____ O
N
Ecca River
Ecca River
91,3
94,9
92,8
95,0
94,3
93,7
88,1
105,5
112,4
132,0
90
90
95
95
95
100
100
105
105
110
110
115
115
120
120
125
125
130
1
0
1
2
3
KILOMETRES

FIGURE 3


N
LEGEND
Sparse ____________ S
Medium ____________ M
Dense ____________ D
ECCA RIVER CATCHMENT
VEGETATION
CANOPY COVER
1 0 1 2 3
KILOMETRES
D S D
M D M S M M D D
D D S S S D M
S S D D S D M D
S D M
M D D S
S M M M D M S
M M S
D M
S S S
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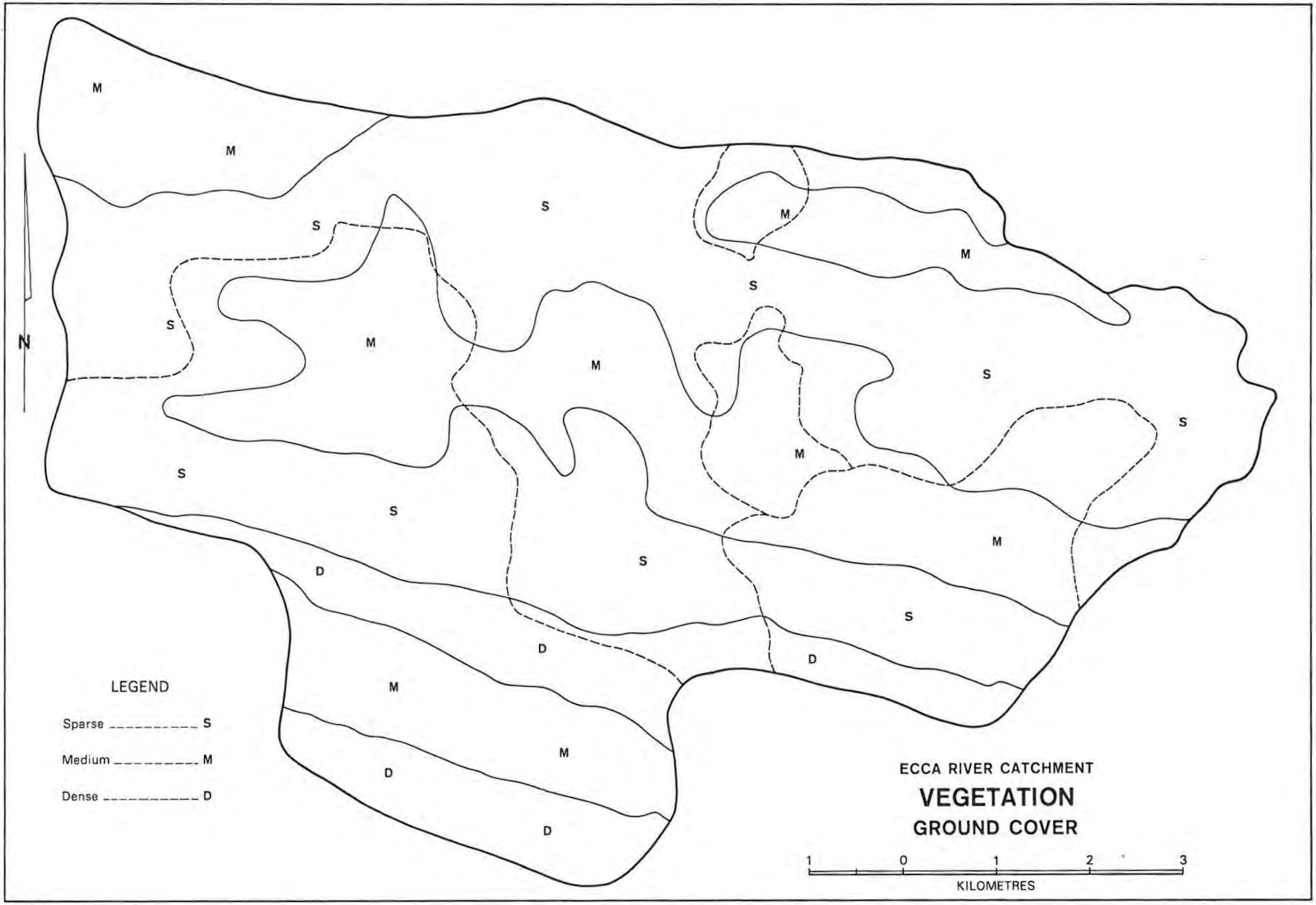
D
S
S

FIGURE 4


N
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S
D
M
M
D
D
LEGEND
Sparse S
Medium M
Dense D
ECCA RIVER CATCHMENT
VEGETATION
GROUND COVER
1
0
1
2
3
KILOMETRES

FIGURE 5

to denote possible spatial variations in interception (canopy cover) and resistance to overland flow (ground cover). The relative categories of vegetation density, dense, medium and sparse were delimited from aerial photographs and over 100 photographs were taken in the field at representative sample points chosen by observation of the aerial photographs. A composite map showing relative density variation in vegetation cover (Figure 6) was then compiled by superimposing Figure 4 on Figure 5 to give 9 categories of relative density. The percentage areas covered by each category in each catchment for canopy cover and ground cover are reflected in Table 3 and it would appear that catchments Q9M22 and Q9M23 show the most deviation from the pattern for the catchment as a whole (Q9M20) with less ground cover and more canopy cover.

2.4 Geology

Three major rock units are found in the region, namely the Witteberg Group representing the Cape Supergroup and the Dwyka and Ecca Groups of the Karoo Supergroup (Figure 7). The geological structure of the area is relatively simple with the rocks dipping at approximately 40°N in the Southern part of the catchment and the dip progressively decreases Northwards until the Ecca shales are almost horizontal. The general strike is 315/135° mag. and the cross sections of Figure 8, showing the general pattern of dip and lithology sequence, are approximately at right angles to strike.

2.4.1 The Witteberg Group

The group is represented by the Witteberg quartzite and shale with the quartzite forming a well defined ridge (Botha's Ridge) along the Southern boundary of the catchment. The Witteberg shales occur North of the quartzite and vary markedly in colour throughout the region being grey-green in the East and almost black in the West.

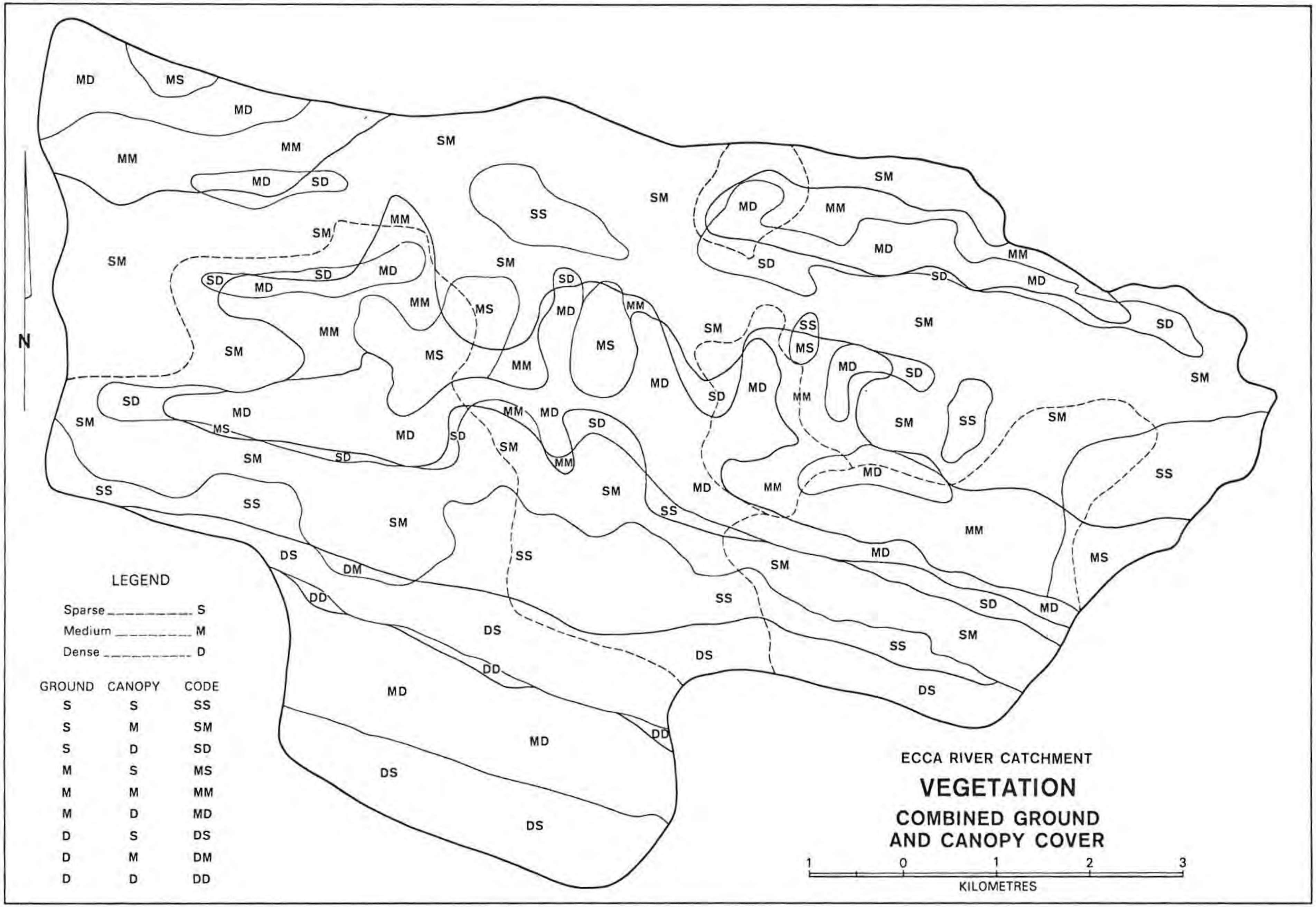

N
LEGEND
Sparse S
Medium M
Dense D
GROUND CANOPY CODE
S S SS
S M SM
S D SD
M S MS
M M MM
M D MD
D S DS
D M DM
D D DD
ECCA RIVER CATCHMENT
VEGETATION
COMBINED GROUND AND CANOPY COVER
1 0 1 2 3
KILOMETRES

FIGURE 6

TABLE 3

RELATIVE VEGETATION DENSITY (% AREA)

CATEGORY	CATCHMENT				
GROUND COVER	Q9M20	Q9M21	Q9M22	Q9M23	Q9M24
DENSE	11	13	0	0	28
MEDIUM	36	37	82	53	39
SPARSE	53	50	18	47	33
CANOPY COVER					
DENSE	26	17	48	38	34
MEDIUM	48	54	52	62	29
SPARSE	26	29	0	0	37

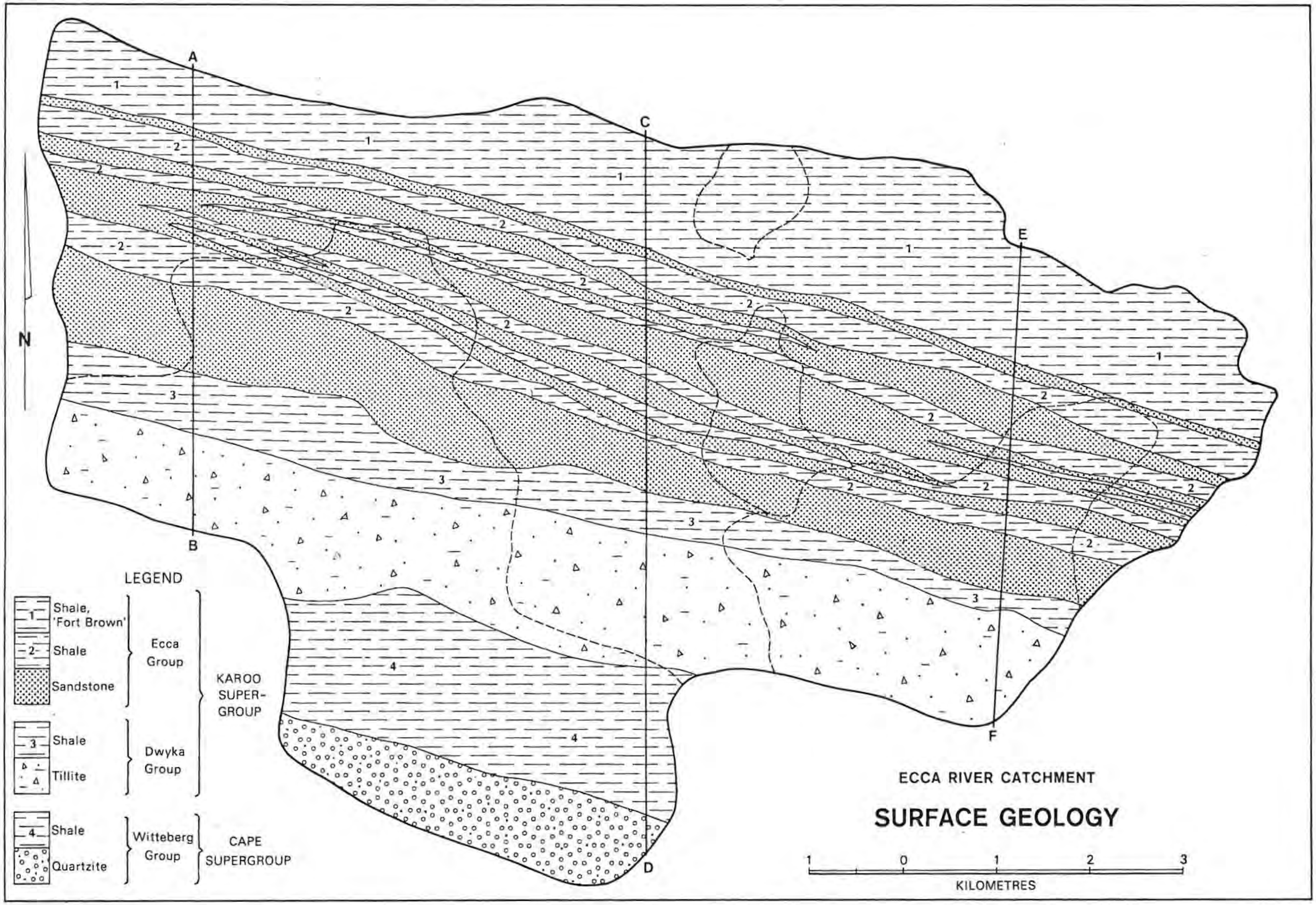
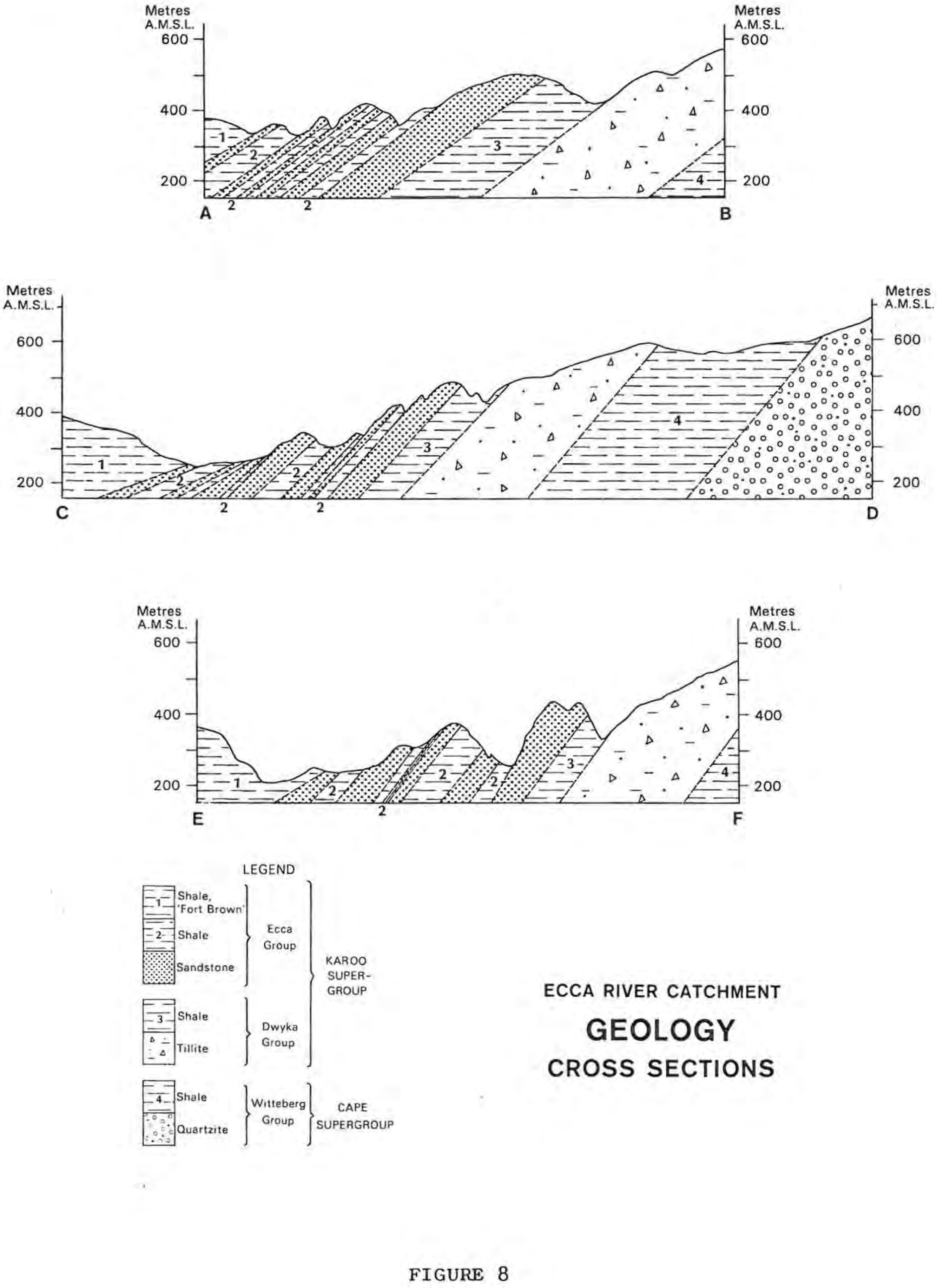

A
B
C
D
E
F
N
1
2
3
4
LEGEND
1 Shale, 'Fort Brown'
2 Shale
Sandstone
Ecca Group
3 Shale
Tillite
Dwyka Group
KAROO SUPER-GROUP
4 Shale
Quartzite
Witteberg Group
CAPE SUPERGROUP
ECCA RIVER CATCHMENT
SURFACE GEOLOGY
1
0
1
2
3
KILOMETRES

FIGURE 7



ECCA RIVER CATCHMENT

GEOLOGY

CROSS SECTIONS

FIGURE 8

2.4.2 The Dwyka Group

The Lower Dwyka is represented by hard, black tillite showing numerous angular rock fragments in a fine matrix. Above the tillite is the Dwyka shale represented by the 'White band' or Whitehill shales (Johnson, 1976) being about 15 metres thick. The shale is black (carbonaceous) but turns white on weathering and has inclusions of chert. There is some controversy as to whether the Whitehill shales are part of the Dwyka Group or the lower Ecca Group.

2.4.3 The Ecca Group

The Ecca Group has been subdivided into three formations, namely the Collingham formation, the Rippon formation and the Fort Brown shales (Johnson, 1976). The Collingham formation is about 30 metres thick consisting mainly of hard grey siliceous shale and is found immediately above the Whitehill shale. The Rippon formation is about 1000 metres thick at the Ecca Pass (Johnson, 1976) and consists of dark grey fine to very fine grained lithofeldspathic sandstones interbedded with verved rhythmitites and mudrock. The highest formation of the Ecca Group is the Fort Brown shale which forms the range of hills along the Northern watershed. These shales are about 1000 metres thick (Johnson, 1976) and are very hard with extreme regularity of bedding and dipping at approximately 20°N.

The percentage surface area covered by each rock type in each catchment is reflected in Table 4 and it would appear that, as in the case of the vegetation density, the greatest deviation from the pattern for the main catchment is for catchments Q9M22 and Q9M23.

2.5 Physical Features

As a result of the East West strike of the rock formations and the alternating shale and sandstone bands, the area is highly dissected with the main stream flowing parallel to strike and the main

TABLE 4

GEOLOGY: SURFACE AREA (%) COVERED BY EACH ROCK TYPE

CATEGORY	CATCHMENT				
	Q9M20	Q9M21	Q9M22	Q9M23	Q9M24
W. QUARTZITE	4	-	-	-	14
W. SHALES	8	-	-	-	26
D TILLITE	18	40	-	-	25
D SHALES	7	12	-	-	12
E SANDSTONE	27	30	69	-	16
E SHALE	16	18	31	-	7
FORT BROWN SHALE	20	-	-	100	-
SUMMARY					
SHALES	49	70	69	0	55
OTHER	51	30	31	100	45

tributaries forming deeply incised valleys at right angles to strike. The highest ground is formed by Botha's Ridge in the South reaching 738 metres to give a maximum basin relief of 570 metres. The whole area is characterised by extensive outcrops with little soil on the hill tops and valley side slopes. All the stream channels are ephemeral with approximately 2 flow events occuring per annum (opinion of local farmers) to give a mean annual runoff estimated at 0,48 million cubic metres (Midgley and Pitman, 1966). A morphometric analysis of the drainage network was conducted by ordering the stream channels according to the method described by Horton (1945). The ordered channel system was used to calculate the bifurcation and length ratios to derive a value for Horton's P ratio (Horton, 1945) which was then used to estimate the mean annual sediment yield for the Ecca catchment by using the empirical method described by Roberts (1976). The estimate derived was 174 cubic metres per square kilometre of catchment area per annum which can be regarded as moderate in terms of sediment yields measured in other semi-arid catchments in South Africa (Roberts, 1976).

Among the morphological variables having hydrological interpretation that were measured in the Ecca system was an index of catchment shape. The index chosen was the lemniscate ratio (Chorley, Malm and Pogorzelski, 1957) which is derived by calculating the ratio of the length of the perimeter of the best fit lemniscate loop for each catchment to the length of the perimeter of the catchment itself. The lemniscate ratio is a most useful index of catchment shape for if it is accepted that the 'normal' shape of a drainage basin in the absence of strong geological control is lemniscate in form, then the lemniscate ratio provides a meaningful measure of the extent of geological control. In addition, it provides an index of catchment shape that is not based on the usual and somewhat meaningless comparison with the shape of a circle. The lemniscate ratios that were calculated for selected sub-catchments are shown in Figure 9 and it can be seen that the Southern catchments, and in particular the South Western catchments, have the strongest geological control whereas the Northern catchments, which have developed in the uniform Fort Brown shale, approximate the ideal lemniscate form.

In order to determine further morphological differences between the Ecca catchment and the gauged sub-catchments, hypsometric analyses were done. A hypsometric analysis illustrates the relation of horizontal cross-sectional drainage basin area to elevation of the cross-section relative to the basin outlet, and is dependent on two dimensionless variables, namely, relative height which is the ratio of the height of a given contour (above the catchment outlet) to maximum basin relief (the height difference between the catchment outlet and the highest point on the basin perimeter) and the relative area which is the ratio of horizontal cross-sectional area to total basin area. The hypsometric curve which is a plot of the continuous function relating relative height to relative area, gives an indication of maturity as it has been found that "...the shape of the hypsometric curve varies in early geologic stages of development of the drainage basin, but once a steady state is attained (mature stage), tends to vary little thereafter, despite lowering relief." (Strahler, 1964, 4-69). The hypsometric curves for the Ecca catchment and the 4 sub-catchments have been plotted in Figure 10 and it can be seen that whereas catchments Q9M20, Q9M22 and Q9M24 have curves characteristic of the mature stage (equilibrium) catchment Q9M21 and especially catchment Q9M23 indicate inequilibrium conditions.

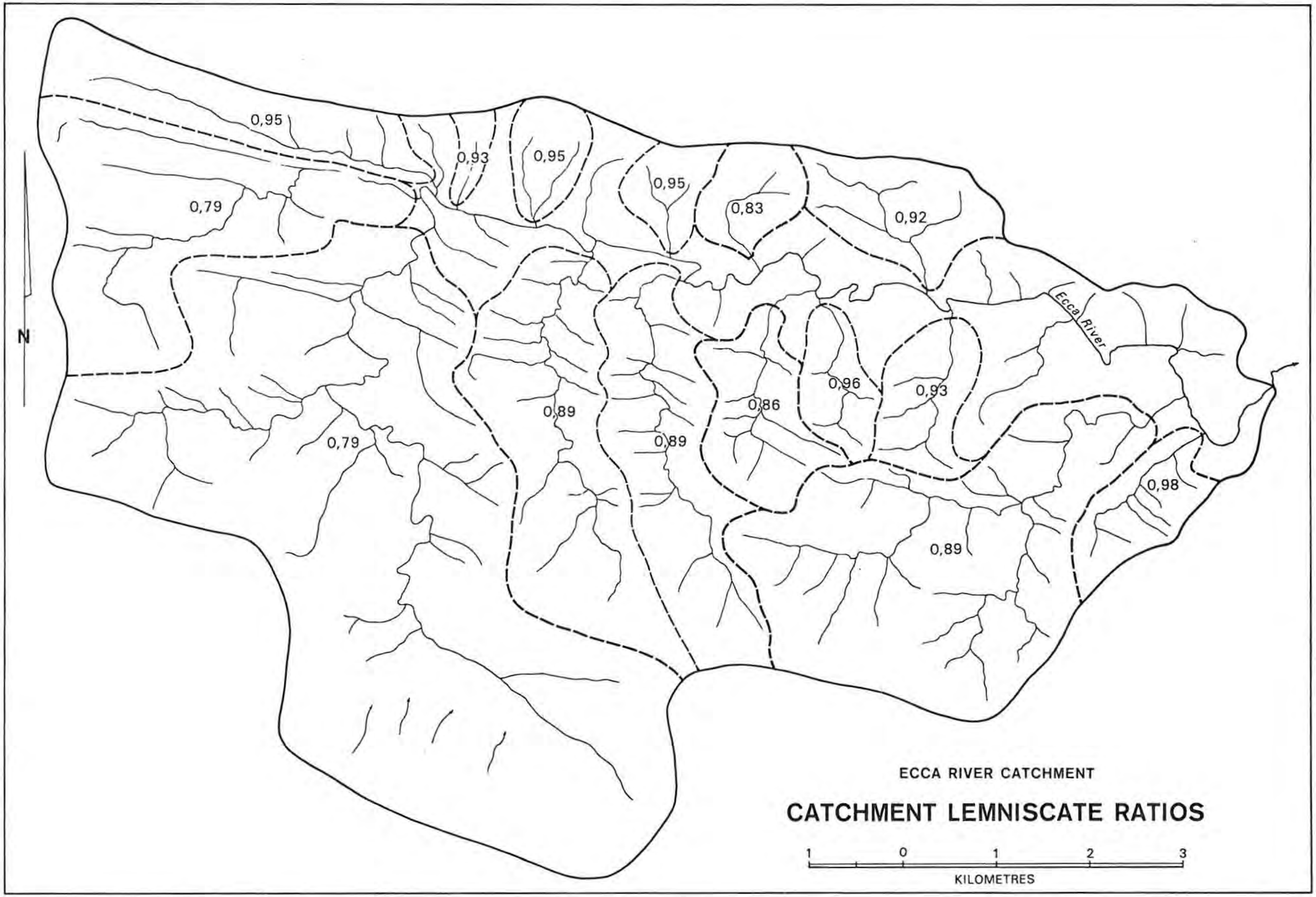
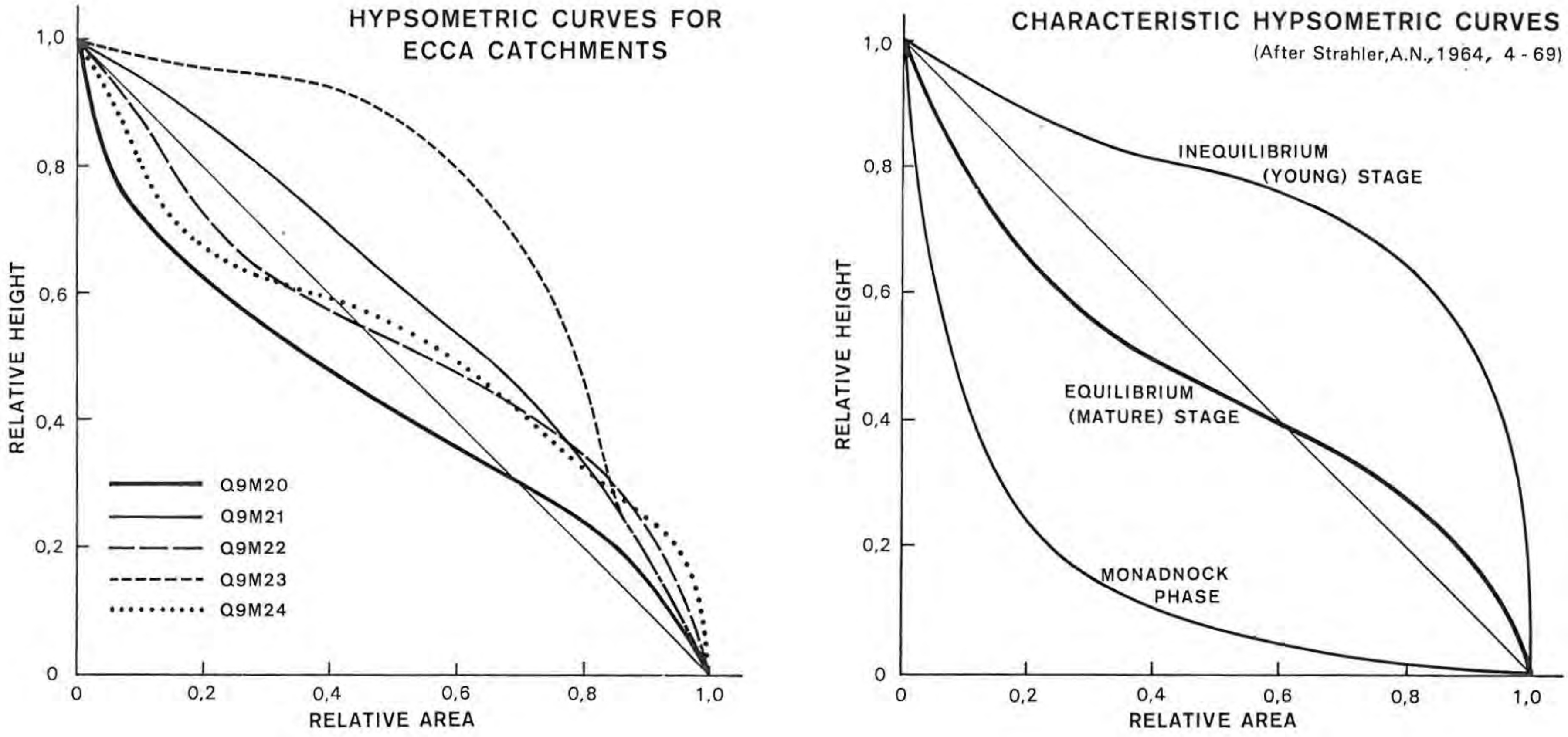

0,95
0,93
0,95
0,95
0,83
0,92
0,79
N
Ecca River
0,96
0,93
0,86
0,89
0,89
0,79
0,98
0,89
ECCA RIVER CATCHMENT
CATCHMENT LEMNISCATE RATIOS
1 0 1 2 3
KILOMETRES

FIGURE 9



HYPSOMETRIC CURVES FOR ECCA CATCHMENTS

CHARACTERISTIC HYPSOMETRIC CURVES (After Strahler,A.N.,1964, 4 - 69)

FIGURE 10

To give an indication of the degree of dissection in the catchment areas a slope map of the catchment area as a whole was compiled by delimiting areas falling into five slope categories (for the sake of clarity of presentation, three categories are depicted in Figure 11). The areas covered by each slope category for each catchment were measured (Table 5) and plotted in histogram form in Figure 12 which shows that catchments Q9M23 and Q9M24 have a similar slope category distribution to the main catchment but catchments Q9M21 and Q9M22 have a greater percentage in the higher slope categories. The difference between the catchments can be shown more clearly if the relationship between percentage slope and cumulative percentage area is assumed to be a continuous function as shown in Figure 13.

2.6 The Gauging Network

In order to test the chosen models (described in Chapter 3) it was necessary to provide areal assessments of the rainfall over each catchment on an hourly basis with a reasonably dense raingauge network to minimize the errors in rainfall as much as possible. There is no reliable method of determining the required density of the raingauge network in advance. Any method would have to be based on detailed information of the spatial variation in rainfall characteristics and if such data already existed, it is doubtful whether there would be a need to take further measurements. However, once the network had been established for some time it would be feasible to assess the adequacy of the network density by applying some criteria such as the 0,9 inter-gauge correlation as suggested by Zawadski (1973). In estimating the required density of raingauges, the time-interval used for data collection should be considered. The variability of hourly rainfall values is higher than that for daily or monthly totals at each raingauge and therefore for hourly values the density

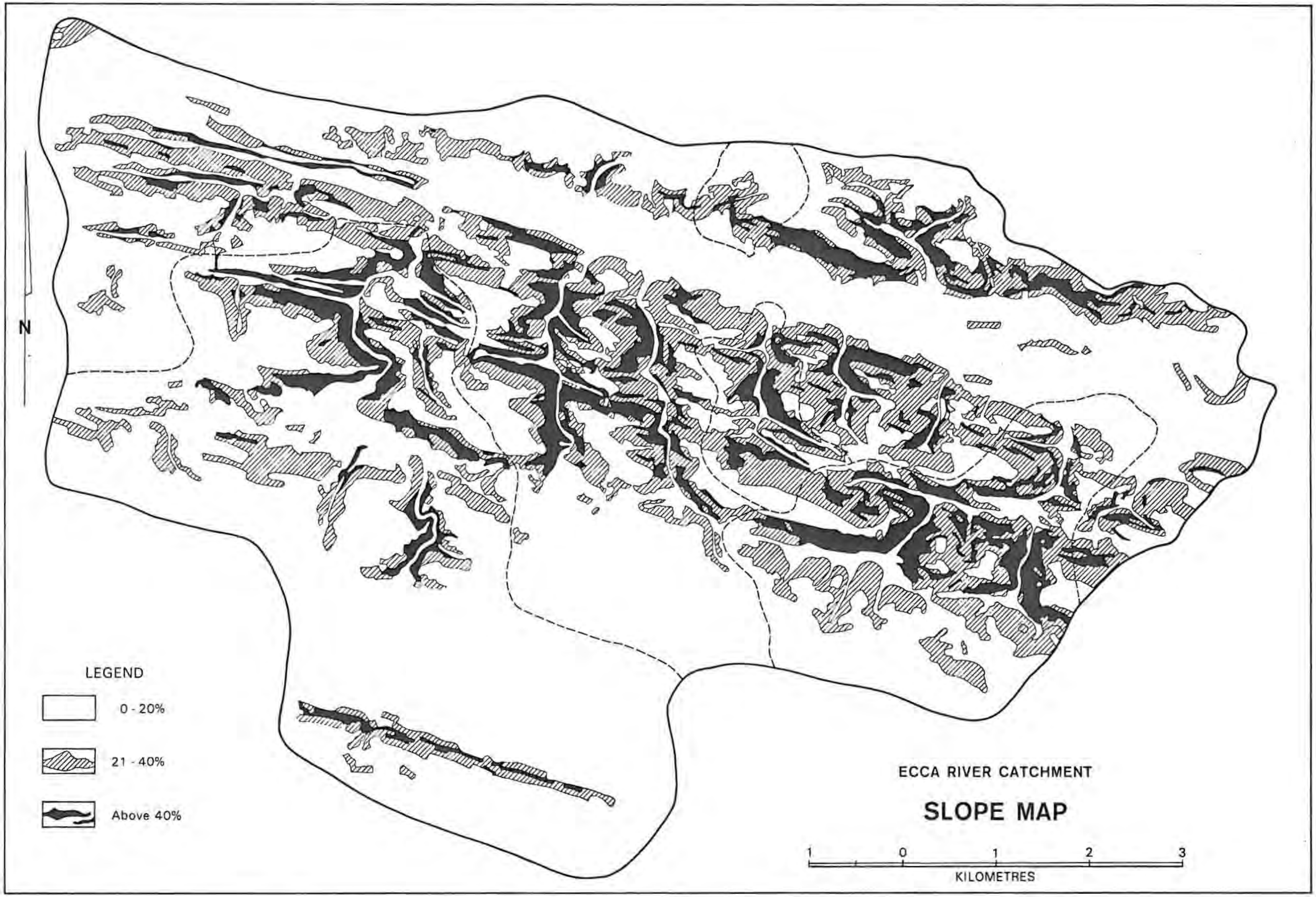

N
LEGEND
0 - 20%
21 - 40%
Above 40%
ECCA RIVER CATCHMENT
SLOPE MAP
1
0
1
2
3
KILOMETRES

FIGURE 11

TABLE 5

SLOPE CATEGORY AREAS(%)

	CATCHMENT				
SLOPE CATEGORY	Q9M20	Q9M21	Q9M22	Q9M23	Q9M24
Less than 10%	39	23	13	47	44
10% to 20%	30	29	20	27	35
20% to 30%	13	19	30	13	9
30% to 40%	6	10	10	6	4
More than 40%	12	19	27	7	8

SLOPE CATAGORIES FOR ECCA CATCHMENTS

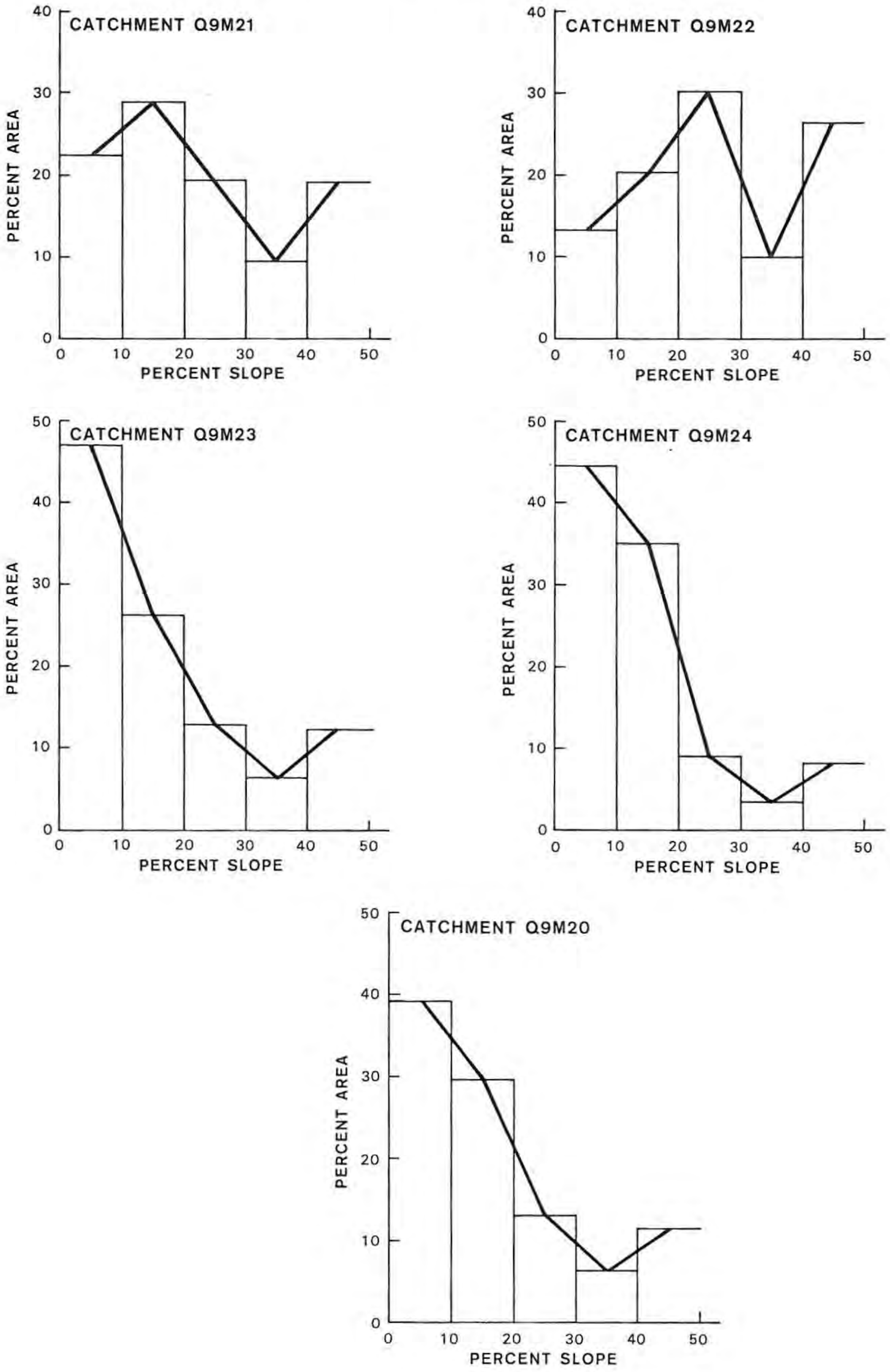


FIGURE 12

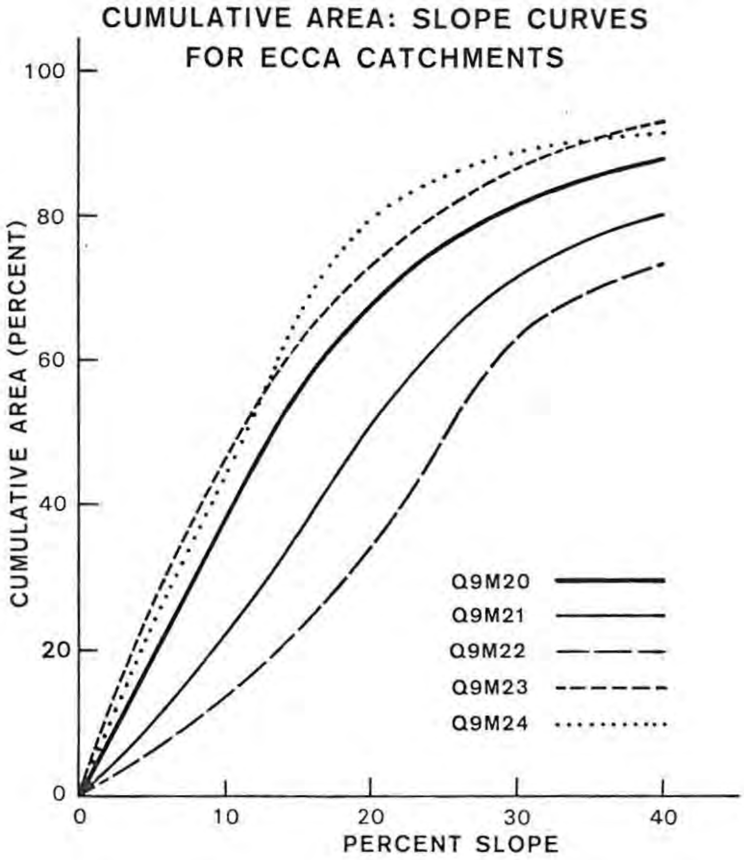

CUMULATIVE AREA: SLOPE CURVES
FOR ECCA CATCHMENTS
CUMULATIVE AREA (PERCENT)
100
80
60
40
20
0
0
10
20
30
40
PERCENT SLOPE
Q9M20
Q9M21
Q9M22
Q9M23
Q9M24

FIGURE 13

should be greater. Perhaps the most appropriate approach to the assessment of raingauge density would be to investigate the loss of accuracy of model simulation that arises from the use of progressively fewer gauges for input data. This approach was adopted in a catchment area of approximately 1000 square kilometres with 49 gauges by Johanson (1971) who found that the number of raingauges that are required to achieve adequate simulation in a catchment area is relatively independent of the area of the catchment. The density of raingauge networks that have been used for hydrological modelling tend to vary widely. For example, Manley (1977) used a network of 4 daily gauges (of which one was autographic for obtaining hourly values) in a catchment of 414 square kilometres whereas Egbuniwe and Todd (1976) applied the Stanford model in a 9 000 square kilometre catchment using a single gauge that was not situated in the catchment itself.

It was estimated that a raingauge network of approximately one autographic gauge per ten square kilometres would be adequate for the Ecca catchments in terms of accuracy and feasible in terms of network maintenance and data control since each additional gauge would increase markedly the volume of hourly data to be processed. The distribution of these gauges (Figure 14) was determined by trial and error location on a map to provide a network that gave (1) a reasonably uniform distribution, that is, nearly equivalent Thiessen polygonal areas (Thiessen, 1911), (2) locations on hillslopes, hilltops and valley floors, (3) ready access by road to within easy walking distance of each gauge and (4) suitable vegetation cover and topography in the immediate locality. It was found that the largest limiting factor was accessibility since few farm roads existed in such a highly dissected area and the chosen distribution was considered to be the most suitable under the circumstances.

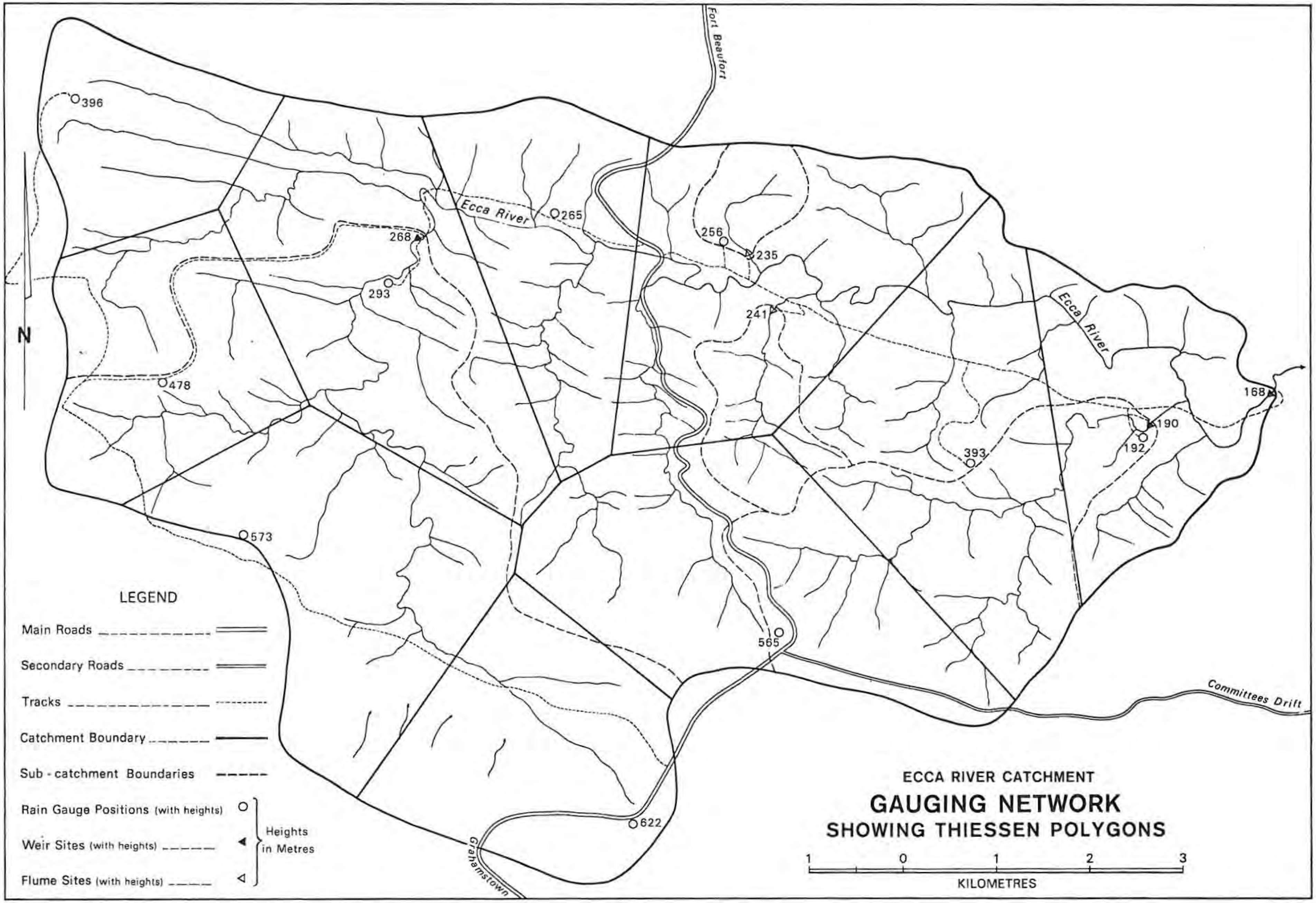

Fort Beaufort
396
Ecca River
265
268
293
256
235
241
N
478
573
Ecca River
168
190
192
393
565
622
Committees Drift
Grahamstown
LEGEND
Main Roads
Secondary Roads
Tracks
Catchment Boundary
Sub - catchment Boundaries
Rain Gauge Positions (with heights)
Weir Sites (with heights)
Flume Sites (with heights)
Heights in Metres
ECCA RIVER CATCHMENT
GAUGING NETWORK
SHOWING THIESSEN POLYGONS
1
0
1
2
3
KILOMETRES

FIGURE 14

The raingauges installed were the Casella autographic gauges with an intake diameter of 203 millimetres (8 inches) giving a chart range of 10 millimetres of rainfall. The gauges were initially installed with the rim of each gauge 30 centimetres above ground level to obtain the best compromise between loss of catch due to air turbulence over the mouth of the gauge, and excess catch due to insplash from the ground. In order to obtain a rim height of 30 centimetres the manufacturers recommend that the lower portion of the gauge should be inserted into the ground with some provision made for the water to run away. However, adequate drainage could not be provided because of the very thin soil layer and it was found that the rising water level in the hole impeded the syphon action of the gauge and all gauges had to be raised so that the base of the gauge was at ground level and the rim at 60 centimetres. It was felt that the additional height would not result in a substantial increase in turbulence because the surrounding vegetation was generally of the order of 15 to 20 centimetres above ground level.

The second form of input data necessary for the operation of the models comprises estimates of potential evaporation in the form of free water surface evaporation. To meet this need an American A Class evaporation pan was installed in the Ecca Valley (Figure 1). Ideally, hourly values of pan evaporation would be preferred but as no autographic recording device has been developed for evaporation pans, such fine time-intervals of measurement could not be made. It is common practice to use monthly or even mean monthly values of pan evaporation as input to models including those models that require fine time-intervals for rainfall input data. However, it was felt that at least daily values of pan evaporation should be derived and as it was not feasible in terms of travelling costs to visit the evaporation pan every day, the pan was read once per week. Daily values were derived by simple proportion with weekly values obtained from a second pan, installed in Grahamstown, of the same type that was read every day.

In order to calibrate the models it was necessary to measure the runoff at the outlets of the chosen catchments on an hourly basis. In catchments Q9M20, Q9M21 and Q9M24 suitable gauging sites were found with suitable foundations and with sufficient fall on the downstream side to prevent submergence of the measuring structure during flow events that approached the planned capacity of the structure. Taking into account the design flood (Table 6), the likely rate of sediment discharge and the nature of the chosen sites and bearing in mind that the requirement of flow measurement was reasonably accurate measurement of the full range of flow values (that is, accuracy of peak flow and low flow was required) it was decided that sharp crested rectangular weirs with a V-notch section for low flows would be the most suitable type of structure. In the two smallest catchments (Q9M22 and Q9M23) however, it was estimated that the size of the resulting weir pool would be too small in relation to the sediment load for this type of structure as it was evident that the weir pool could silt up in a single flow event. This was particularly true of catchment Q9M23 where a very high rate of sediment discharge in relation to the other catchments was observed. The high sediment yield lends support to the premise that catchment Q9M23 is in a state of inequilibrium as suggested by the shape of the hypsometric curve in Figure 10. To overcome the problem of having a very small weir pool in relation to the estimated rate of sediment deposition, structures of the flume type were chosen for these catchments so as to allow the sediment load to pass through the measuring device but as a result, some accuracy in the low flow range had to be sacrificed. The type of structure chosen was the Robinson Trapezoidal

TABLE 6

ESTIMATED RATED FLOODS FOR ECCA CATCHMENTS

CATCHMENT	AREA km^2	RATED FLOOD (CUMECS)	CATASTROPHIC FLOOD (CUMECS)	GAUGING STRUCTURE
Q9M20	72	180	1100	WEIR
Q9M21	8	60	350	WEIR
Q9M22	2	28	180	FLUME
Q9M23	1	16	100	FLUME
Q9M24	24	100	600	WEIR

(After Johanson, 1974, 3)

Note: The rated flood is taken as being that which has a recurrence interval of 20 years and the catastrophic flood as a flood with a recurrence interval of 1000 years.

flume with a 0,91 metre (3 feet) width in the throat to give the desired design capacity. Continuous recording of the water level at all gauging sites was accomplished by the installation of OTT type X autographic water level recorders with a 1:5 ratio for catchments Q9M20, Q9M21 and Q9M24 and a 1:2,5 ratio for the smaller catchments Q9M22 and Q9M23.

2.7 Data Control

The efficient manipulation, storage and selective recall of some 176 000 data values per annum necessitated the development of an adequate data control system. As is the case in most computer systems, the available computer facilities at Rhodes University have not been static but have progressively increased in sophistication with changing hardware. As a result, the data control system developed for the handling of rainfall, runoff and evaporation data has developed to the present state since the beginning of the research programme in response to the ever changing level of sophistication of the available computer facilities. It is clear that further changes will occur which will permit additional refinement of the data control system as described at the time of writing.

2.7.1 The rainfall data control system

The raingauges could be visited only once per week because of the cost of transport and as it is not feasible to obtain accurate hourly values of rainfall from a chart that has a time-span of one week (weekly rotation of the drum), modifications had to be made. The cog sets on the gauges were replaced with new cog sets that gave daily revolution and daily charts were used to obtain accurate hourly values. In view of the fact that the drum would revolve seven times before replacing the chart, the metal chart retaining clips were removed to avoid loss of record and the charts were held in position with a strip of cellotape of a type that would retain the lines drawn by the recording pen. When removed, each chart has seven traces but as the daily charts have a time-span slightly in excess of one day to allow for some flexibility in chart changing times under normal conditions, the time-scale after the first trace no longer corresponds to the correct time of day and the discrepancy increases with each trace. It is therefore necessary to process the charts with a digital converter (or digitizer system) to obtain the correct starting time and day for each rainfall event. An eleventh raingauge was installed in the catchment and set to weekly revolution to act as a timing control should the situation arise where there is some doubt as to the identification of the separate traces. This gauge has a 127 millimetre intake and a 25 millimetre chart range and is used for timing control only and does not form part of the network.

The digitizer system used was the GP-2-BCD graphical digitizer interfaced with a Facit 4070 paper tape punch. The major problem encountered with this type of assembly was that the digitizer sometimes gave an incorrect set of co-ordinate values and as the co-ordinate values were punched onto paper tape, the erroneous values were not discovered until the paper tape was run through the computer and the data were processed by the computer program. To overcome this problem, the graphical digitizer has been interfaced directly to a NOVA computer which is compatible in terms of hardware and the system has been modified so that 5 sets of co-ordinates (instead of one) are automatically taken at each point digitized. The mean of the X co-ordinates and the mean of the Y co-ordinates are then immediately processed by program Multitrace (written in Multi-task Extended Basic), provided that the standard deviation of the X or Y values does not exceed a preset tolerance level. The output from program Multitrace appears on a V.D.U.

(visual display unit) screen in front of the operator as each point is digitized so that the operator can keep a constant check on the results. Should the tolerance level of accuracy be exceeded, a warning bell sounds and the operator receives a request to re-digitize the last point. Program Multitrace gives the time at each point digitized (corrected for errors such as clock error and expansion of the chart), the rainfall since the previous point and the intensity of the rainfall.

The hourly rainfall values for each raingauge are then extracted manually from the charts and are keyed into a Maximop file (HRPRMAXIMOP) under the ICL 1900T computer system via a V.D.U. terminal (Figure 15). The ICL 1900T system at Rhodes University is entirely a terminal system with no card punch or reader devices and the Maximop sub-system provides each user with a file in which programs and data sets may be stored and edited in card format and programs may be compiled and run via the terminal. The manual link between the NOVA and the ICL 1900T system will be eliminated when the planned link between the two computers comes into being but the present manual link can be regarded as an advantage in that it provides an extra check point in the system. Once the hourly data have been keyed into the Maximop file, a single command via the terminal executes the rest of the data control processes shown in Figure 15.

The data file containing the hourly rainfall values for each raingauge, referred to as the raw data, together with programs in compiled form and executive files are then selected by the 'George' system where program HOUR calculates the average rainfall over each catchment for each hour, referred to as the refined data, by using the Thiessen polygon weighting factors for each catchment and then writes the raw and refined data to disc file WORK 1. Program HOUR also provides a printed daily and monthly summary of raw and refined data. Program

DATA CONTROL SYSTEM FOR RAINFALL DATA

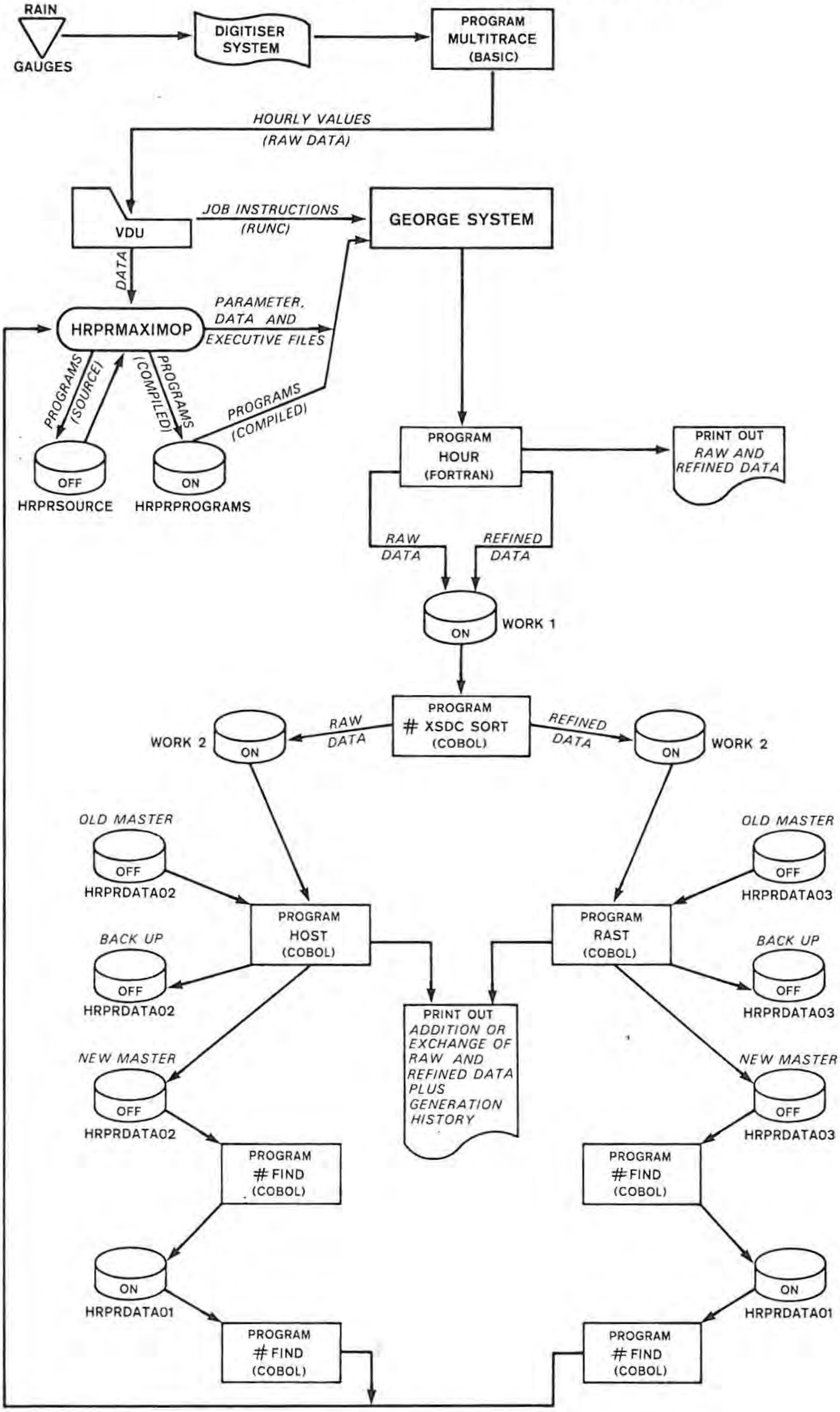


FIGURE 15

XSDC SORT then separates the raw data from the refined data, checking that the year, month and day codes are compatible and sends the two sets of data into separate streams for further processing. The refined data are picked up by program RAST which scans the data to determine whether the incoming data represent a new addition to the master file or an overwrite of an existing section of record that contains errors. The program then slots the data into the master file (HRPRDATA03) in their correct chronological position and creates a new master file with a security back-up copy of the file in the process. The raw data are handled in the same way as the refined data but by program HOST (corresponding to program RAST) using a separate master file (HRPRDATA02).

Selected portions of either the raw or refined master data files can be recalled to HRPRMAXIMOP for running with programs (that is, with the models) by initiating program FIND. For example, if the refined data are required in separate files for each catchment for the period of March 1976, program FIND selects all the data for March 1976 from the master refined data file HRPRDATA03 and dumps them on an on-line data file HRPRDATA01 where they are picked up by program FIND again and separated into separate files in HRPRMAXIMOP for each catchment. The parameters used by program FIND are the codes on each card for record identification number, type of record, year, month, day and card code where the card code indicates whether the card contains the first twelve hourly values for the day or the last twelve (Appendix A). Any single parameter or any combination of the parameters may be used for a FIND run.

2.7.2 The data control system for runoff data

The runoff data are handled in the same way as the rainfall data with the exception that the hourly values of runoff obtained after digitizing are equivalent to refined data and no raw data section exists (Figure 16). The hourly values of runoff for each catchment are produced by program FLOWTRACE and after being keyed into a Maximop subfile are processed by program PSTP which provides a daily and monthly summary before the data are processed by program XSDC SORT and RUST to provide the master file HRPRDATA04.

2.7.3 The evaporation data

The evaporation records for the Grahamstown and the Ecca catchment pans do not involve a digitizing process and because they consist of daily values the records are far more manageable in terms of bulk. These records are keyed directly into holding files under the Maximop system where they are readily accessible at all times, and can be updated simply by editing.

The data control system as described was developed for the provision of data in the format required by the simulation models discussed in the following chapter.

DATA CONTROL SYSTEM FOR RUNOFF DATA

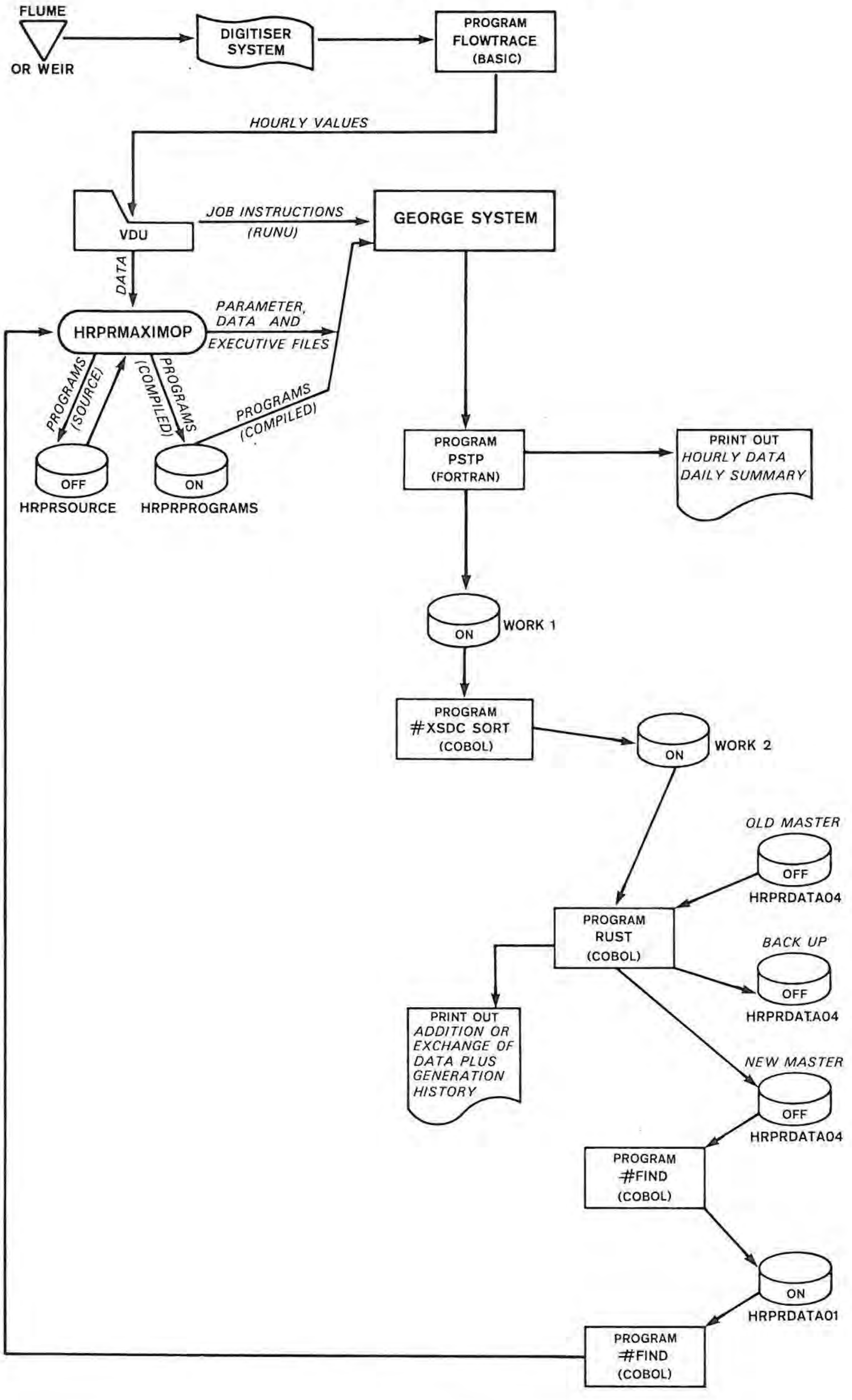


FIGURE 16

CHAPTER 3

THE DESCRIPTION AND DEVELOPMENT OF THE SIMULATION MODELS

3.1 Introduction

The digital simulation models that have been calibrated using data from the Ecca catchments take the form of digital computer programs written in standard Fortran IV and these programs have been listed in Appendix A. The basic principles used in the models have, in general, been drawn from recent literature but many modifications have been introduced because it was felt that the modifications would make the models more applicable to South African conditions; or because the results obtained indicated that modification was necessary or simply for the purpose of reducing duplication in some modelling techniques. It is necessary to describe the models in some detail despite the fact that large portions of some of the models have been described in the literature. It is felt that a description of the models and the presentation of some of the important functions in graphical form would greatly facilitate the clear understanding of the model structure which is so important to a reader who might wish to make use of the computer programs in Appendix A.

As the models take the form of digital computer programs, the description of a model is, in essence, a description of the consecutive steps executed by a computer program and it is therefore desirable that the text should be closely integrated with the program. For this reason the parameter and variable identifiers used in the program will be used in the text and the mathematical functions constituting the model components will be expressed in the form of the Fortran IV statements used in the program. The use of Fortran statements in the text should not present a problem for readers who are not familiar with the notation if it is realized that the execution of steps in an arithmetic statement takes the order;

(1) the contents of brackets starting with the innermost pair,

(2) exponents (**),

(3) multiplication (*) and division (/),

(4) addition (+) and subtraction (-).

Consequently the equation

$$A = \frac{(B - 1,0)^D}{C} + 3,0 \qquad \text{(Eqn. 1)}$$

written in Fortran would appear as

```
     A = ((B - 1.0)**D)/C + 3.0   .
```

The fact that Fortran statements require decimal points rather than commas may lead to confusion when text punctuation follows a Fortran statement. Consequently text punctuation following a Fortran statement will be displaced by three spaces as in the case of the full stop at the end of the Fortran statement given as an example above. The description of each model includes reference to a large number of model parameters and variables. In order to assist the reader, the parameters and variables have been listed at the end of each section (for each model) in the order in which they are mentioned in the text.

Each of the models described may be regarded as consisting of two main sections where the first section incorporates the moisture accounting techniques while the second section involves the storage delay components that determine the time-distribution of runoff. It is in the latter section of the models that most of the modifications have been made. Similar time-delay, channel routing and evaporation components have been incorporated into most of the models and to avoid repetition, these common aspects will be discussed briefly before giving a more detailed account of the structure of the individual models.

In all the models, the estimate of potential daily evapotranspiration was taken as being equivalent to the estimate of free water surface evaporation for the day and in the case of the hourly models, the estimated daily potential evapotranspiration was distributed over the average daylight hours 07h00 to 19h00 by means of the triangular distribution employed in model FORD. This approach was adopted in the hourly models because it is more meaningful than the even distribution of the daily estimate over 24 hours.

The routing of the inflow hydrographs in the hourly models PORT, BERG and DALH is accomplished by use of the Nash-Muskingum routing equation (Nash, 1959). This approach was adopted for the convenience of the model user since values for the constants in the equation may be estimated for any catchment in South Africa by reference to the publication by Bauer and Midgley (1974). The translation of the channel inflow hydrograph to account for travel time to the gauging point is accomplished by a direct lag procedure in all the models except for model FORD in which use is made of a time-delay histogram. Preference was given to the direct lag procedure because it was found to be more flexible and involved less computational effort.

3.2 Description of Models FORD and SMDV

Model FORD constitutes a version of the Stanford Watershed Model IV (Crawford and Linsley, 1966) programed by Anderson of the United States Weather Bureau and obtained from the Hydrological Research Unit of the University of the Witwatersrand. Whereas the Stanford Watershed Model IV was set up to handle an unlimited number of either segments or flowpoints the Anderson version used is set up for simulation at a single flowpoint. A second Anderson version that is set up for simulation at six flowpoints was obtained but the computer core requirements for this version exceeded the facilities available. The single flowpoint version used treats the entire catchment area as a single segment and the operations carried out on the input data are the same as for any flowpoint in the Stanford Watershed Model IV with the exception of a modification to the infiltration equation which will be discussed in this section. The advantage of using the Anderson version rather than the original model lies in the fact that the Stanford Model was programmed in SUBALGOL (an extinct version of Burrough's early compiler) whereas the Anderson version is available in standard Fortran IV which can be used at most computer centres. The Fortran program has been adapted by the author to incorporate further modifications which will be discussed in this section.

The Stanford Watershed Model IV incorporates mathematical simulation of a large number of the processes taking place in the catchment and the nature of the functions is such that the model is sufficiently flexible to give adequate results in almost any catchment. Claborn and Moore (1970, ii) have described the Stanford Watershed Model IV as "a tremendous breakthrough in hydrological research", and it can be regarded as the first generalized model that is generally available. Perhaps the biggest disadvantage of the model for the average user is its complexity for as Claborn and Moore (1970, ii) found, "...it was difficult to obtain a clear understanding of the inner workings of the model." A great deal of time and effort in studying the model is required before the user is in a position to operate the model efficiently and unfortunately the input data required for the model are not generally available in South Africa. Provided suitable input data are available, the model has a very wide range of applications and it will provide a good standard for comparison with other models.

3.2.1 The general structure of model FORD

The general input requirements for the model are quarter hourly, hourly or 6 hourly rainfall data, daily or average monthly pan evaporation and hourly or 6 hourly flow data where the flow data are required for statistical comparison of simulated and observed flows. Irrespective of the chosen time-interval for rainfall input data, the model operates on quarter hourly iterations for processing rainfall data (evaporation from storages is calculated on an hourly basis). It should be noted that although program FORD requires rainfall data in metric units of tenths of a millimetre, calculations are done in imperial units with the result that many of the input parameters are in inches and the output is in the form of cusecs (1 cubic foot per second) and cusec days. Figure 17 shows a flow diagram of the model where the first process to be simulated is that of interception. (The snowmelt function of the Stanford Model is omitted from the Anderson version and has little application in South Africa).

3.2.2 Interception storage function

Interception is simulated by use of a simple linear storage of finite size (EPXM) that is subjected to evaporation demands. The rainfall input PR is added to the interception storage level SCEP and the overflow from the storage constitutes the rain reaching the ground (P3).

3.2.3 The impervious area function

The rainfall P3 is then subjected to the impervious area function

$$\mathrm{SIMPV} = \mathrm{SIMPV}+\mathrm{P3}*\mathrm{AT} \qquad \text{(Eqn. 2)}$$

where AT is the impervious area of the catchment and the impervious area volume SIMPV attributes directly to channel storage and is not subjected to the infiltration function.

FLOW CHART FOR MODELS FORD AND SMDV

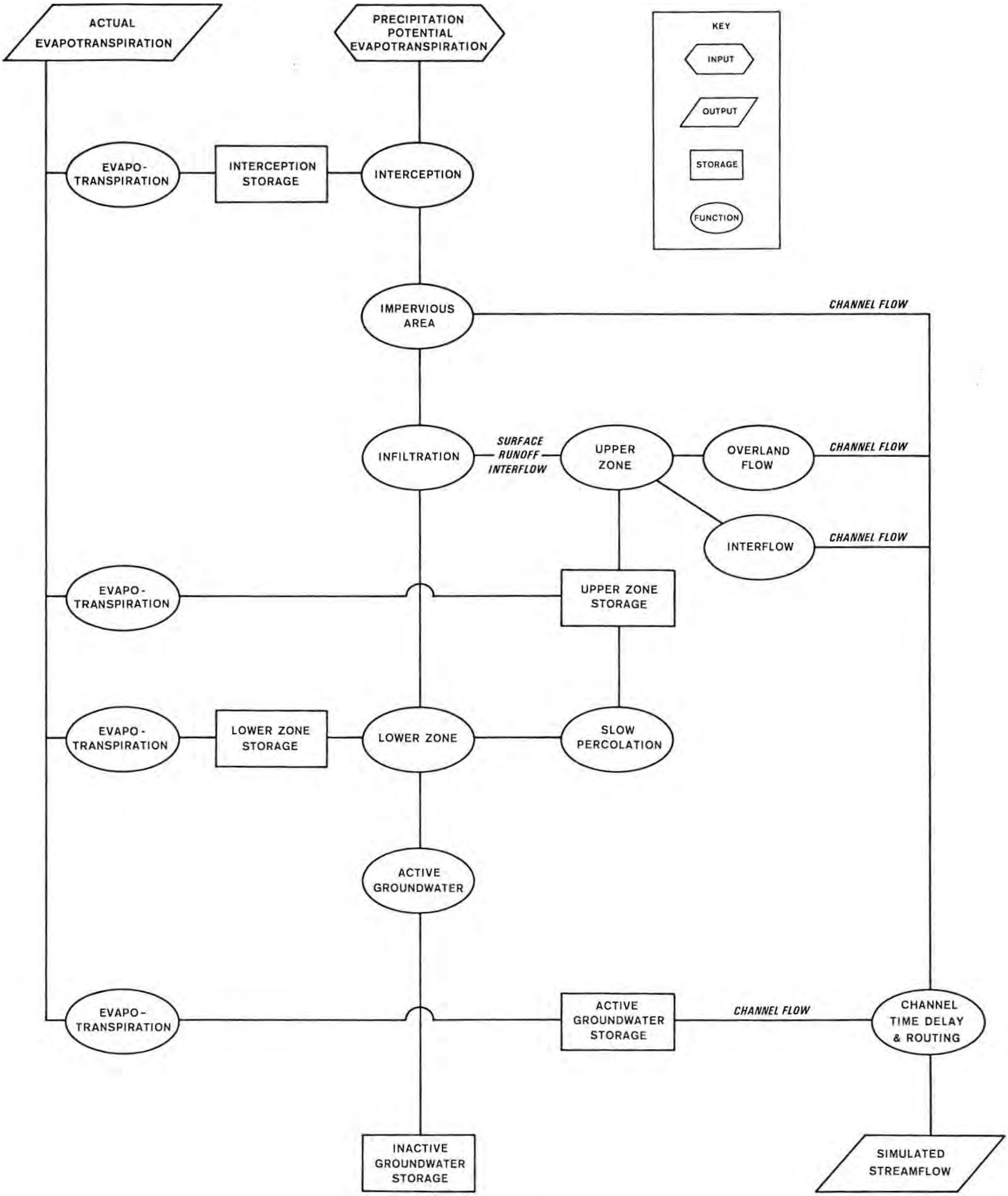


FIGURE 17

3.2.4 The infiltration function

The rainfall plus any moisture in surface detention storage P4 is then subjected to the infiltration function. Direct infiltration to the lower zone functions INFIL (representing areal variation in infiltration) occurs if the incident rainfall P4 exceeds the calculated excess precipitation SHRD as

$$\mathrm{INFIL} = \mathrm{P4} - \mathrm{SHRD} \qquad \text{(Eqn. 3)}$$

where for $\mathrm{P4} < \mathrm{D3FV}$, $\mathrm{SHRD} = \mathrm{P4*P4/(2*D3FV)}$ (Eqn. 4)

and $\mathrm{P4} \geqslant \mathrm{D3FV}$, $\mathrm{SHRD} = \mathrm{P4\text{-}0.5*D3FV}$ (Eqn. 5)

and where

$$\mathrm{D3FV} = \mathrm{CB/((LZS/LZSN)**POWER)} \quad . \qquad \text{(Eqn. 6)}$$

The parameter CB is the infiltration parameter, LZS/LZSN is the current lower zone storage ratio and POWER is a parameter that controls the range of infiltration values to give the estimate of mean infiltration rate for the current time-interval (D3FV). Equation 6 is perhaps the most important equation in the model since it contains the major 'coarse-tuning' parameters and unfortunately, Crawford and Linsley (1966) give very little guide to the estimation of these parameters as they have little physical interpretation. The infiltration from 25,4 millimetres of rainfall has been plotted against lower zone storage ratio (LNRAT = LZS/LZSN) for a range of values of POWER in Figure 18 to illustrate the nature of the infiltration function. It is clear from Figure 18 that the infiltration is highly sensitive to the value of CB in the lower range of the lower zone storage ratio. The implication is that for arid or semi-arid catchment areas where runoff is seldom due to storage limitations, an extremely delicate balance must be found between the value of CB and the nominal value of the lower zone storage ratio LZSN. Consequently, for the drier catchments, the user could expect greater calibration costs. At the other end of the

MODEL FORD

INFILTRATION FUNCTION

1 INCH = 25,4 mm

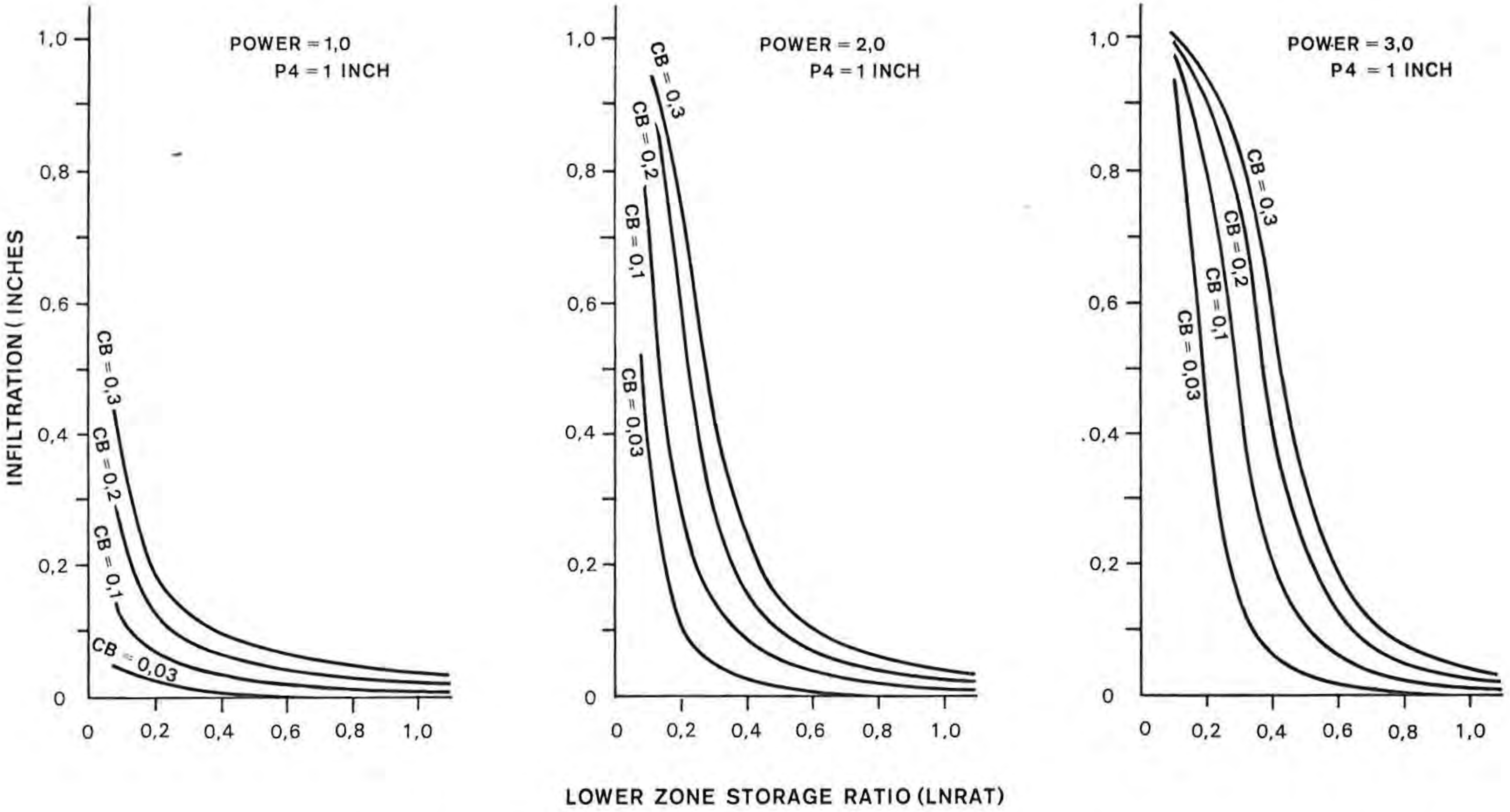


FIGURE 18

scale, that is, for the higher ranges of the lower zone storage ratio, the parameter CB becomes relatively insensitive for any value of POWER.

The infiltration function as given by Equation 6 is a modification of the original function used by Crawford and Linsley (1966) where for

LZS/LZSN < 1.0, b = CB/(2**(4*(LZS/LZSN))) (Eqn. 7)

and LZS/LZSN ⩾ 1.0, b = CB/(2**(4+2*((LZS/LZSN)-1.0))) (Eqn. 8)

and where b is the equivalent of D3FV in Equation 6. As shown by Figure 19 the new infiltration function represented by Equation 6 is less linear and more flexible than Equations 7 and 8 but the greater flexibility has been introduced at the expense of an additional parameter POWER which tends to complicate the calibration process.

3.2.5 The upper zone functions

The excess precipitation SHRD is then manipulated by the upper zone functions to determine how much of the excess (SHRD) represents a potential increase to overland flow surface detention (RXX). For

P4 < D3FV*RATIO RXX = P4*P4/(2*D3FV*RATIO) (Eqn. 9)

and for

P4 ⩾ D3FV*RATIO RXX = P4-0.5*D3FV*RATIO (Eqn. 10)

where

RATIO = CC*2**LNRAT .

The potential increase to overland flow surface detention (RXX) has been plotted against D3FV*RATIO in Figure 20 to show the decreasing reduction in RXX when the rainfall exceeds the controlling value of D3FV*RATIO. The parameter CC is an input parameter that allows the user to control the ratio between surface runoff and interflow as calculated by the model, but the value of the parameter must be obtained by trial and error. The value of RATIO has been plotted against lower zone storage ratio for various values of CC in Figure 21. The

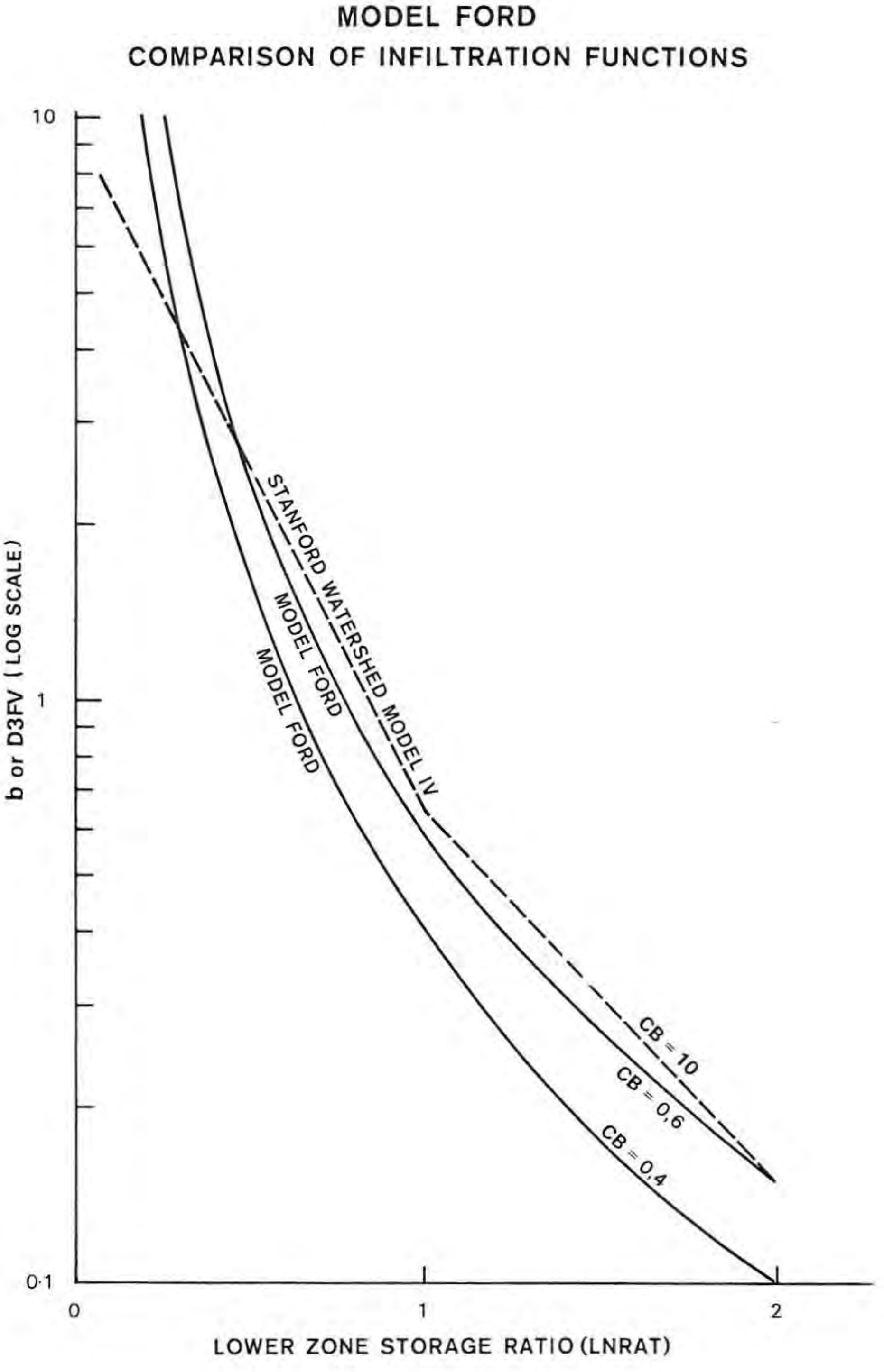

MODEL FORD
COMPARISON OF INFILTRATION FUNCTIONS
10
1
0·1
b or D3FV (LOG SCALE)
0
1
2
LOWER ZONE STORAGE RATIO (LNRAT)
STANFORD WATERSHED MODEL IV
MODEL FORD
MODEL FORD
CB = 10
CB = 0,6
CB = 0,4

FIGURE 19

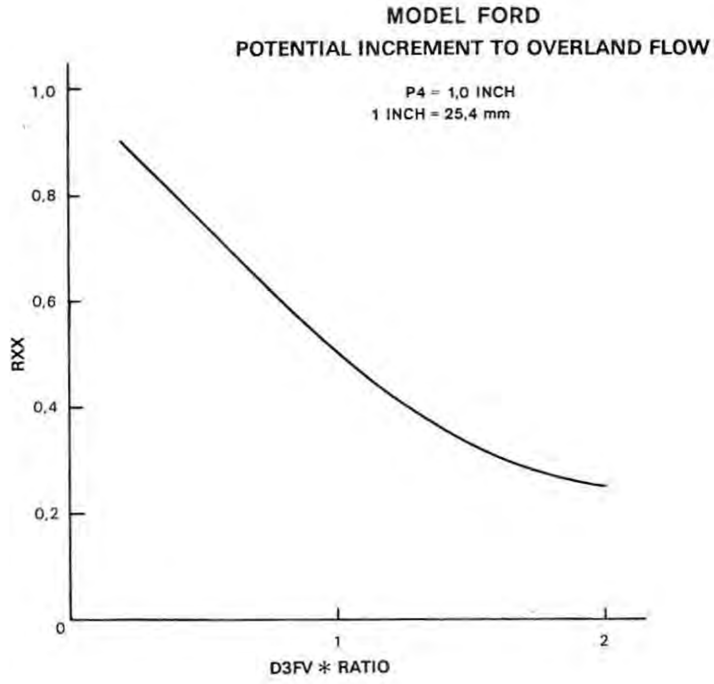


FIGURE 20

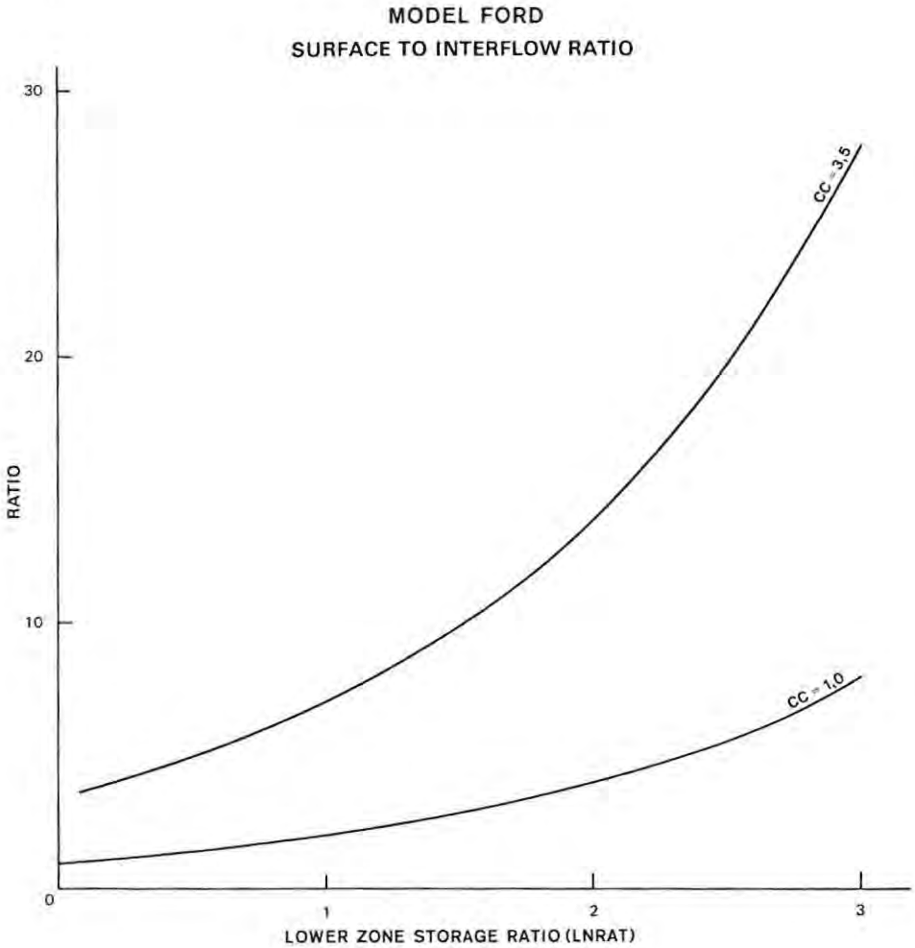


FIGURE 21

remainder of the excess precipitation (SHRD) that is not a potential increase to overland flow surface detention (RXX) is regarded as a potential increase to interflow detention (RGXX) so that

$$\mathrm{RGXX = SHRD{-}RXX} \quad . \tag{Eqn. 12}$$

The actual increment to overland flow surface detention (RX) and the actual increment to interflow detention (RGX) are taken as a percentage of the potential,

$$\mathrm{RX = RXX{*}PRE} \tag{Eqn. 13}$$

and $$\mathrm{RGX = RGX{*}PRE} \quad . \tag{Eqn. 14}$$

The percentage (PRE) is a function of the state of the upper zone storage and is calculated for

$$\mathrm{UZS < 2{*}UZSN}$$

as $$\mathrm{PRE = (0.5{*}(UZS/UZSN)){*}(1.0/(1.0+UZI)){*}{*}UZI} \tag{Eqn. 15}$$

where

$$\mathrm{UZI = 2.0{*}ABS(0.5{*}(UZS/UZSN)-1.0)+1.0} \tag{Eqn. 16}$$

and for

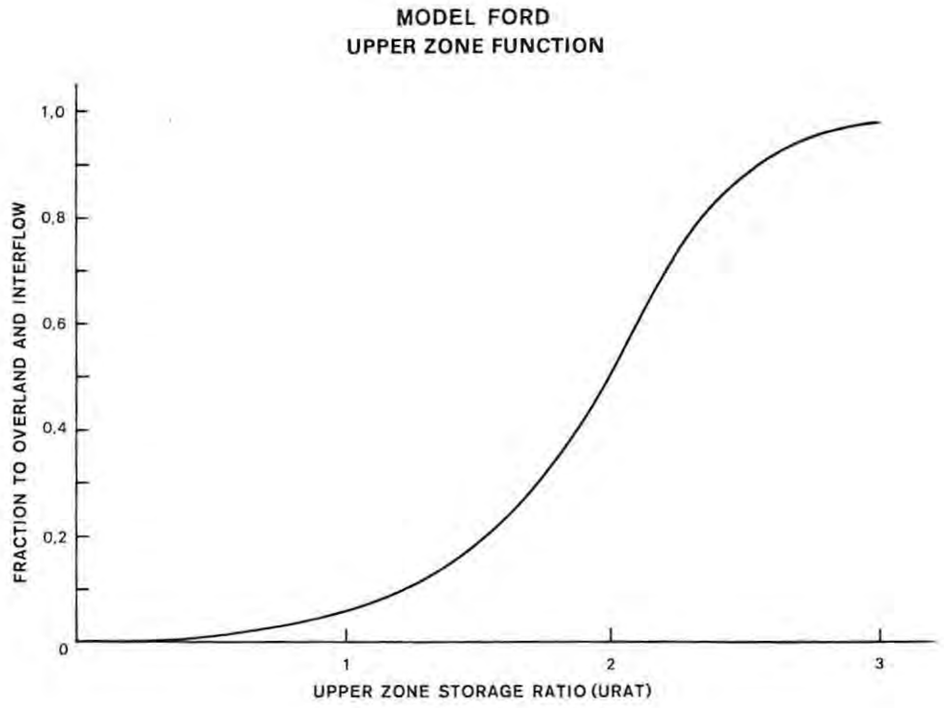
$$\mathrm{UZS \geqslant 2{*}UZSN}$$

as $$\mathrm{PRE = 1.0-(1.0/(1.0+UZI)){*}{*}UZI} \tag{Eqn. 17}$$

where

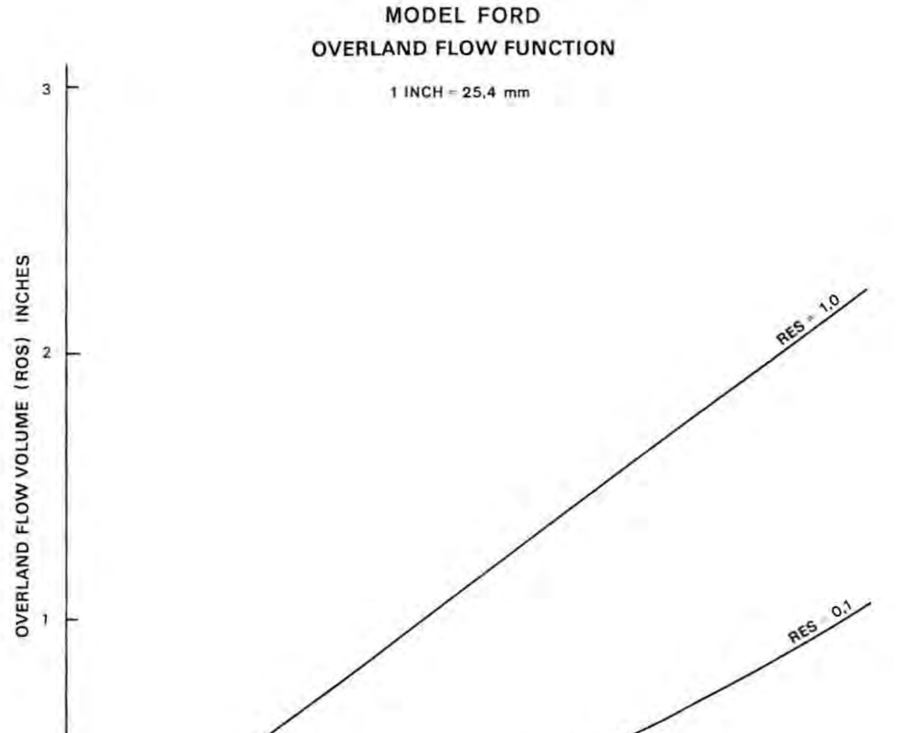
$$\mathrm{UZI = 2.0{*}ABS(((UZS/UZSN)-1.0)-1.0)+1.0} \quad . \tag{Eqn. 18}$$

The percentage of the potential increase to overland flow surface detention and interflow has been plotted against the upper zone storage ratio (UZS/UZSN) in Figure 22 and it can be seen that the inflection point in the curve occurs at 50 percent when the upper zone storage ratio is equal to 2 and is less than 10 percent when the storage level (UZS) is equal to the nominal level (UZSN). Figure 22 demonstrates that the nominal level of the upper zone storage (UZSN) should be relatively low so that the storage ratio exceeds unity when surface flow is required.



MODEL FORD
UPPER ZONE FUNCTION

FIGURE 22



MODEL FORD
OVERLAND FLOW FUNCTION

1 INCH = 25,4 mm

FIGURE 23

The upper zone storage level is increased by the excess rainfall that does not accrue to overland flow or interflow so that

UZS = UZS+SHRD-RGX-RX . (Eqn. 19)

3.2.6 The overland flow function

The actual increment to overland flow surface detention (RX) is processed by the overland flow function to determine the overland flow volume (ROS) for the present time-interval;

ROS = SRC*(D**1.67)*((1.0+0.6*((D/DE)**3))**1.67) (Eqn. 20)

with the proviso that the overland flow volume (ROS) may not exceed 75 percent of the actual increment to overland flow surface detention (RX). The parameter SRC in Equation 20 is a land surface parameter based on

SRC = 1020*SQRT(SS)/(NN*L) (Eqn. 21)

where SS is the overland flow slope, NN is Manning's n for overland flow and L is the length of overland flow. The overland flow volume (ROS) as calculated in Equation 20 for any time-interval is dependent on the current surface detention ratio expressed as the relationship between average surface detention (D) and the surface detention at equilibrium (DE) where

D = (RES+RX)/2.0 (Eqn. 22)

and for

RX ⩽ RES DE = (RES+RX)/2.0 (Eqn. 23)

but if

RX > RES DE = DEC*((RX-RES)**0.6) (Eqn. 24)

where the parameter DEC is based on the same variables as SRC and is given as

DEC = 0.00982*((NN*L/SQRT(SS))**0.6) . (Eqn. 25)

There is the additional constraint that the calculated surface detention at equilibrium (DE) may not become less than the average surface detention (D). The overland flow volume (ROS) accrues to channel storage and the remainder accrues to surface detention storage volume (RES) as

$$RES = RX-ROS \quad . \qquad \text{(Eqn. 26)}$$

The overland flow volume (ROS) as a function of the increment to surface detention (RX) and the volume in surface detention storage (RES) is shown in Figure 23 which illustrates that the relationship between ROS and RX becomes linear when RES is unity, that is, when ROS reaches its maximum value of 75 percent of RX.

The above overland flow function represents a major advance in the simulation of this phase of the hydrological cycle since the actual processes are simulated in some detail. Although the function is complex in structure the parameter values involved are easily obtainable from topographic maps and require little or no optimization. From the practical user point of view the function provides complexity at minimum cost.

3.2.7 The interflow function

The actual increment to interflow storage (RGX) increases the present storage level (SRGX)

$$SRGX = SRGX+RGX \qquad \text{(Eqn. 27)}$$

and the interflow volume (INTF) for the current interval is obtained by decay of the storage level (SRGX) as follows;

$$INTF = LIRC4*SRGX \qquad \text{(Eqn. 28)}$$

where

$$LIRC4 = 1.0-IRC**(1.0/96.0) \qquad \text{(Eqn. 29)}$$

and IRC is the interflow decay constant for a 24 hour period. The interflow storage level is then adjusted accordingly,

$$SRGX = SRGX-INTF \quad . \qquad \text{(Eqn. 30)}$$

3.2.8 The lower zone functions

The direct infiltration (INFIL) as calculated by Equation 3 is divided between lower zone, groundwater and inactive groundwater storages by a function that is similar to the function that allocates excess precipitation to the upper zone storages (Equations 15 and 17). The lower zone function is also based on a percentage (PRE) where for

$$\mathrm{LZS} \geqslant \mathrm{LZSN}, \qquad \mathrm{PRE} = (1.0/(1.0+\mathrm{LZI}))**\mathrm{LZI} \qquad \text{(Eqn. 31)}$$

but when

$$\mathrm{LZS} < \mathrm{LZSN}, \qquad \mathrm{PRE} = 1.0-\mathrm{PRE}*(\mathrm{LZS}/\mathrm{LZSN}) \qquad \text{(Eqn. 32)}$$

where

$$\mathrm{LZI} = 1.5*\mathrm{ABS}(((\mathrm{LZS}/\mathrm{LZSN})-1.0)+1.0) \quad . \qquad \text{(Eqn. 33)}$$

The percentage (PRE) is then used to calculate the addition to lower zone storage (F3) as

$$\mathrm{F3} = \mathrm{PRE}*\mathrm{INFIL} \qquad \text{(Eqn. 34)}$$

and $\mathrm{LZS} = \mathrm{LZS}+\mathrm{F3} \quad .$ (Eqn. 35)

The addition to active groundwater storage (F1) is calculated as

$$\mathrm{F1} = \mathrm{F1A}*(1.0-\mathrm{K24L})*\mathrm{PA} \qquad \text{(Eqn. 36)}$$

where

$$\mathrm{F1A} = \mathrm{INFIL}-\mathrm{F3} \quad . \qquad \text{(Eqn. 37)}$$

The parameter K24L controls increments to inactive groundwater storage and PA is the percentage pervious area in the catchment, that is

$$\mathrm{PA} = 1.0-\mathrm{AT} \quad . \qquad \text{(Eqn. 38)}$$

The addition to groundwater storage (F1) is added directly to the current level of groundwater storage (SGW)

$$\mathrm{SGW} = \mathrm{SGW}+\mathrm{F1} \qquad \text{(Eqn. 39)}$$

and the addition to inactive groundwater storage (RECH) is calculated as

$$\mathrm{RECH} = \mathrm{F1A}*\mathrm{K24L}*\mathrm{PA} \quad . \qquad \text{(Eqn. 40)}$$

The lower zone function as represented by Equations 31-33 has been plotted in Figure 24 and it can be seen that it has a similar form to its equivalent upper zone function (Figure 22) but the inflection point at 50 percent occurs when the lower zone ratio is unity. The difference between the two curves illustrates that the upper zone storage is designed to operate at much higher ratios and represents a very small proportion of the upper soil layers. In Figure 24 the curve gives contribution to base flow for even the lower ranges of lower zone storage ratio which means that in arid and semi-arid climates the model will give base flow from rainfall on a dry catchment. It may be necessary in such catchments to decrease the value of 1.5 in Equation 33 to reduce simulated base flow during dry periods.

3.2.9 The percolation function

Percolation of moisture from the upper zone storage (RECE) is based on the difference between the upper and lower storage ratios (which represents the moisture gradient) and is calculated as

$$RECE = 0.003*CB*UZSN*(DEEPL**3.0) \qquad \text{(Eqn. 41)}$$

where

$$DEEPL = (UZS/UZSN)-(LZS/LZSN) \qquad \text{(Eqn. 42)}$$

and the upper zone storage is adjusted accordingly

$$UZS = UZS-RECE \quad . \qquad \text{(Eqn. 43)}$$

The percolation (RECE) is divided between lower zone, groundwater and inactive groundwater storages in the same way as direct infiltration. The calculated percolation (RECE) has been plotted against DEEPL in Figure 25 to illustrate that the upper zone storage ratio must be approximately 5 times greater than the lower zone storage ratio before any appreciable (with respect to the nominal value of upper zone storage) percolation occurs.

3.2.10 The groundwater function

The base flow for each time-period (GWF) is calculated by decay

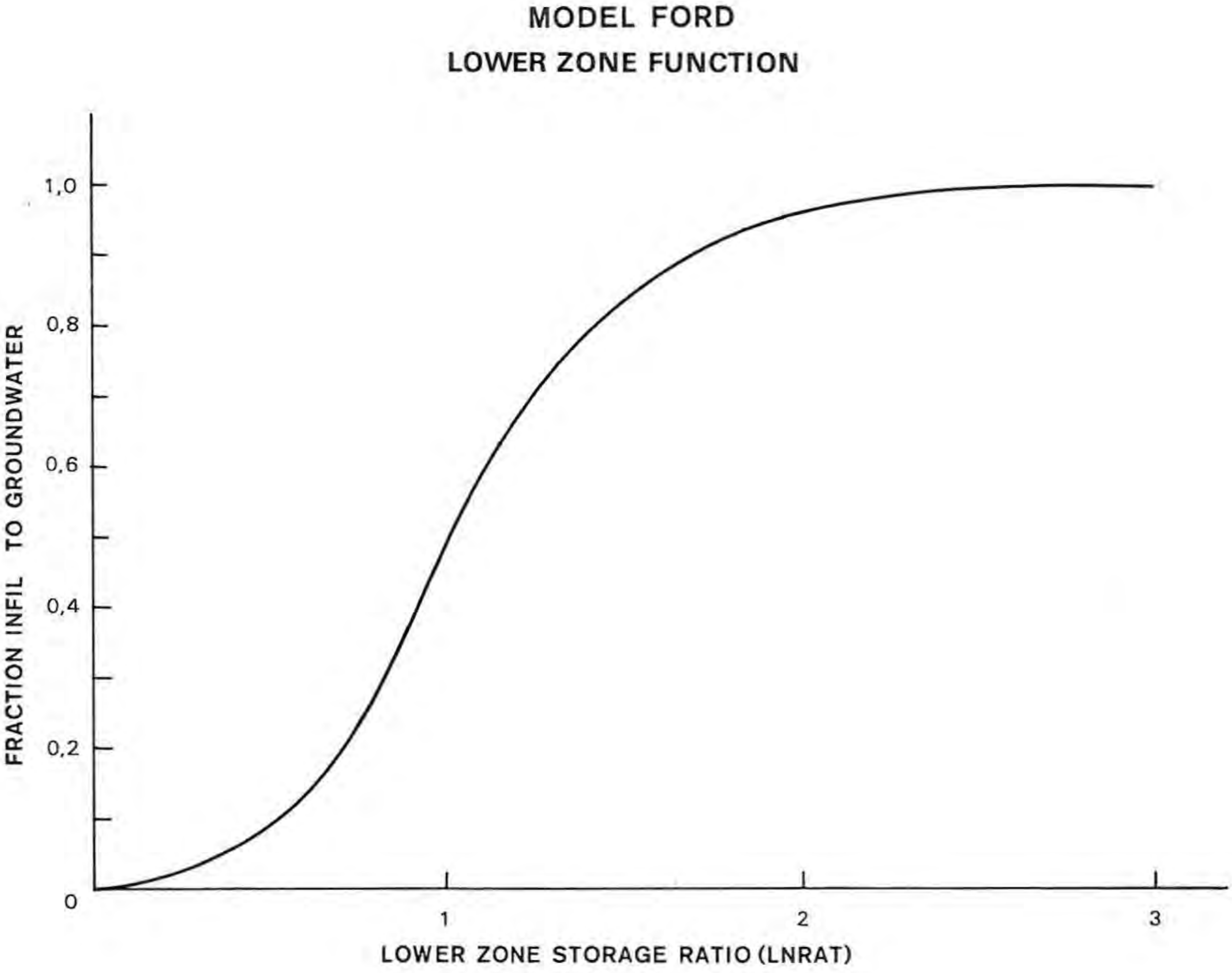

MODEL FORD
LOWER ZONE FUNCTION
FRACTION INFIL TO GROUNDWATER
1,0
0,8
0,6
0,4
0,2
0
1
2
3
LOWER ZONE STORAGE RATIO (LNRAT)

FIGURE 24

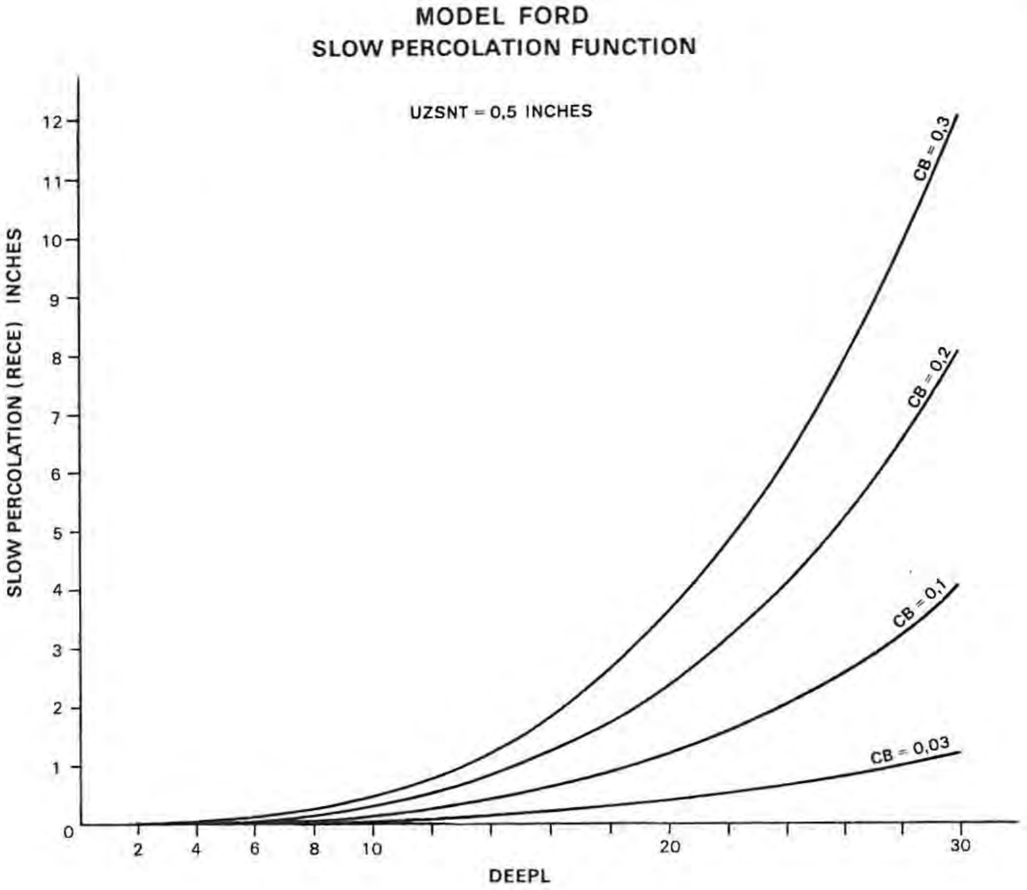


FIGURE 25

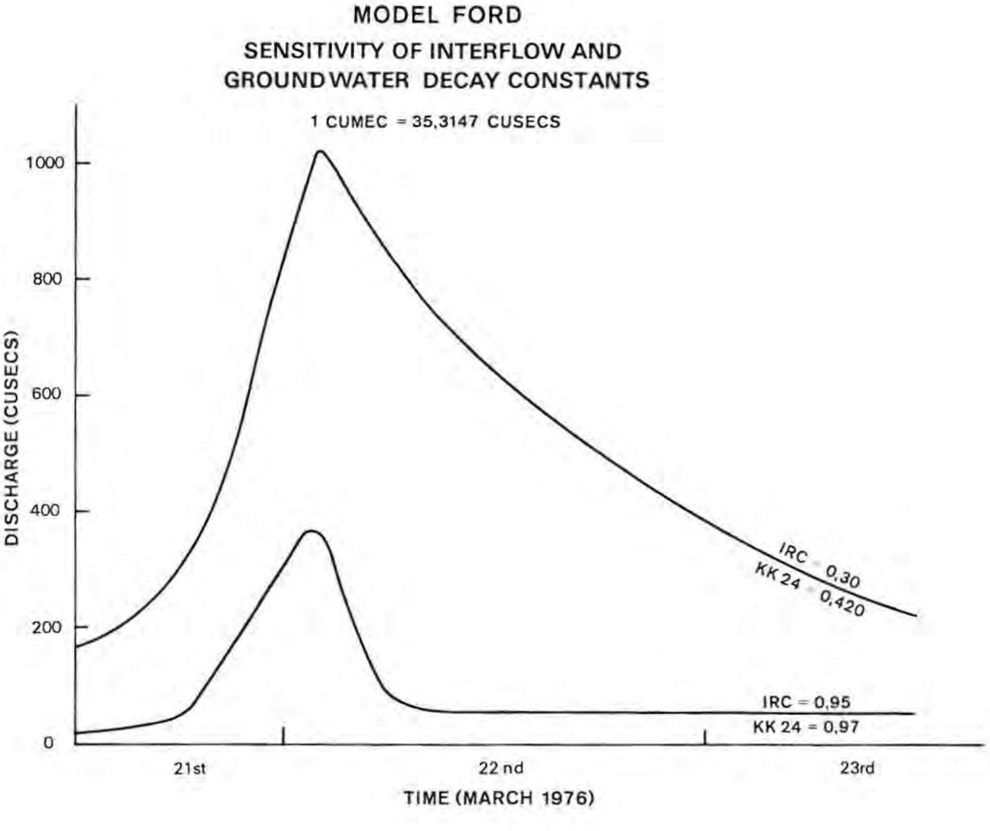


FIGURE 26

of the groundwater storage (SGW)

GWF = SGW*LKK4*(1.0+KV*GWS) (Eqn. 44)

where

LKK4 = 1.0-(KK24**(1.0/96.0)) . (Eqn. 45)

The parameter KK24 is the base flow decay constant for a 24 hour period and the variable GWS in Equation 44 is an antecedent index based on inflow to groundwater storage and is calculated as

GWS = GWS+F1 . (Eqn. 46)

The parameter KV in Equation 44 allows for variable groundwater recession rates. The nature of the groundwater and interflow recession functions can result in a large change of volume for changes in recession constants. Figure 26 shows simulated hydrographs for the Ecca catchment where the base flow and interflow recession constants were the only parameters changed but the result was a considerable change in peak. At the end of each 15 minute period the total contribution to channel storage (RU) is summarized as

RU = RU+(ROS+INTF)*PA+P3*AT+GWF . (Eqn. 47)

3.2.11 The evapotranspiration function

Evapotranspiration from the model storages is calculated on an hourly basis and to introduce more realism to the time-distribution of evapotranspiration demand, the estimated daily potential evapotranspiration is distributed by means of a triangular distribution between the average daylight hours of 07h00 to 19h00. It is assumed that evapotranspiration demand is met at the potential rate from the interception storage and then from the upper zone storage if the demand has not been met. Evapotranspiration takes place at a sub-potential rate from the lower zone and groundwater storages. The evapotranspiration from the lower zone storages (AETR) is dependent on the value of the lower zone storage ratio (LNRAT), the remaining potential evapotranspiration demand

(EP) and the evapotranspiration parameter K3 as follows;

if $EP < K3*LNRAT$

$$AETR = EP*(1.0-(EP/(2.0*K3*LNRAT))) \quad \text{(Eqn. 48)}$$

and if

$EP \geqslant K3*LNRAT$

$$AETR = 0.5*K3*LNRAT \quad . \quad \text{(Eqn. 49)}$$

The lower zone storage ratio LNRAT has been plotted against AETR in Figure 27 to illustrate the deviation from the more commonly used linear variation of evapotranspiration with lower zone storage ratio. The parameter K3 is an important parameter controlling base flow reaction during dry periods as it has a marked influence on the variance of the lower zone storage ratio under dry conditions. The evapotranspiration from the groundwater storage (LOS) is given as

$$LOS = SGW*K24EL*EP*PA \quad \text{(Eqn. 50)}$$

where K24EL is a parameter representing the fraction of the catchment area in which evapotranspiration is assumed to occur at the potential rate from groundwater storage.

3.2.12 The channel functions

Time-delay of the channel inflow is achieved by the use of a time-delay histogram obtained by planimetering contributing areas at successive points in the stream channel system where the distances between points represent equal flow times in the channels. The volume of channel inflow at any time-interval is multiplied by successive elements of the time-delay histogram to provide an outflow hydrograph that accomodates the effects of channel travel times but not channel storage attenuation. The major problem encountered during the use of time-delay histograms in the model for the Ecca catchments lay in the fact that the program allows for a minimum routing interval of one hour. In small catchment areas where the time of concentration is less

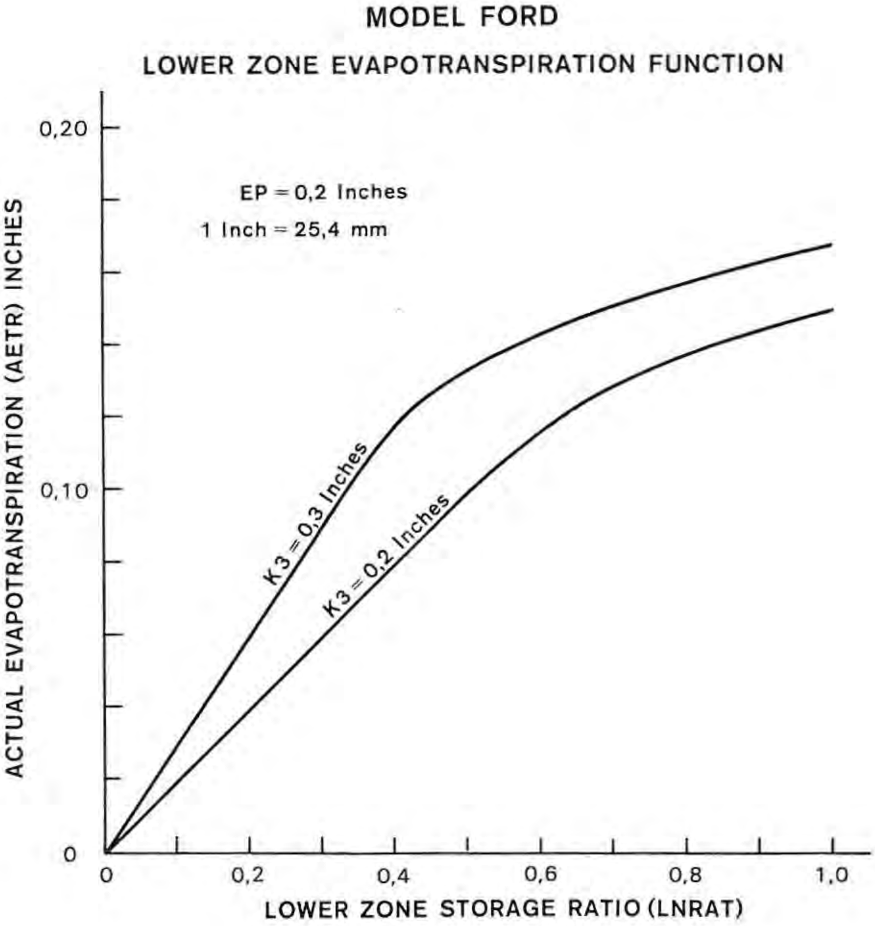
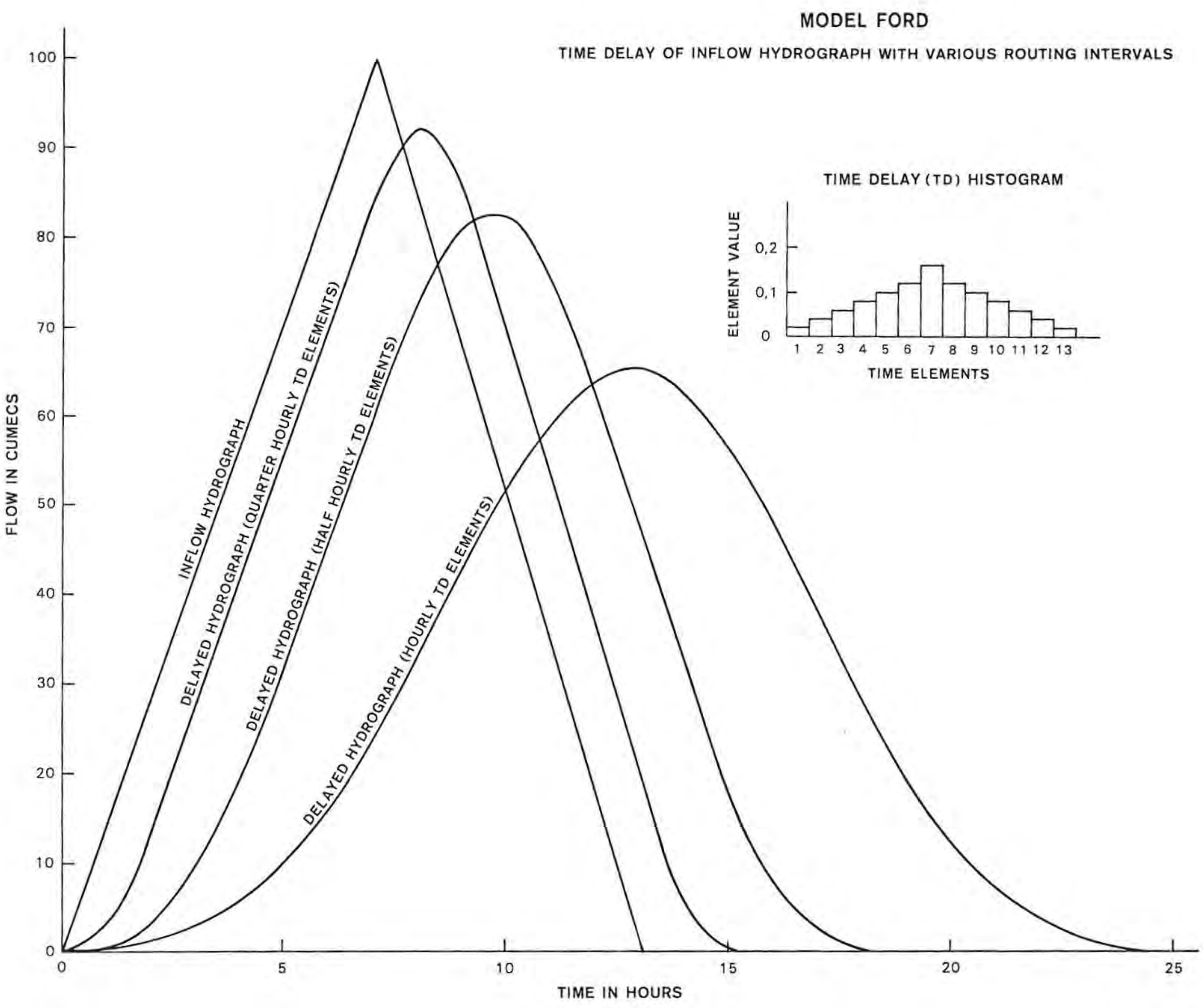

MODEL FORD
LOWER ZONE EVAPOTRANSPIRATION FUNCTION
ACTUAL EVAPOTRANSPIRATION (AETR) INCHES
0,20
0,10
0
EP = 0,2 Inches
1 Inch = 25,4 mm
K3 = 0,3 Inches
K3 = 0,2 Inches
0
0,2
0,4
0,6
0,8
1,0
LOWER ZONE STORAGE RATIO (LNRAT)

FIGURE 27

than 2 or 3 hours (as in the case of the Ecca catchments) the number of elements in the time-delay histogram becomes very limited and there was a clear need for the use of routing intervals of less than one hour to provide a more meaningful number and distribution of elements in the histogram. The program was consequently modified to accept any fraction of an hour or whole hours as routing interval without the addition of any further parameters. To illustrate the time-delay of an inflow hydrograph resulting from various routing intervals, the hypothetical triangular inflow hydrograph in Figure 28 has been translated with a hypothetical 13 element triangular time-delay histogram with quarter hourly, half hourly and hourly elements. The delayed hydrographs in Figure 28 also give an indication of the extent of hydograph attenuation that results from the use of a time-delay histogram as opposed to a direct lag procedure in which the hydrograph is delayed without attenuation. Although the histogram is based on the physical properties of the catchment, it was found that the resultant hydrograph from the model was relatively insensitive to the distribution of the elements. Two hypothetical and distinctly different histograms of 10 one hour elements were used with all other parameters held constant for Ecca data to produce the two hydrographs shown in Figure 29. Although the histograms represent theoretically different catchment shapes, the resultant hydrographs are similar. The model also has a variable lag option which can be utilized in addition to the time-delay histogram to provide different lag times for different flow intervals.

3.2.13 Channel attenuation

The hydrograph produced by channel translation is routed through a storage system to similate attenuation in the channel system. The attenuation is based on an attenuation constant KS1 where the flow for each time-interval (FLOWT) is given as



MODEL FORD

TIME DELAY OF INFLOW HYDROGRAPH WITH VARIOUS ROUTING INTERVALS

FIGURE 28

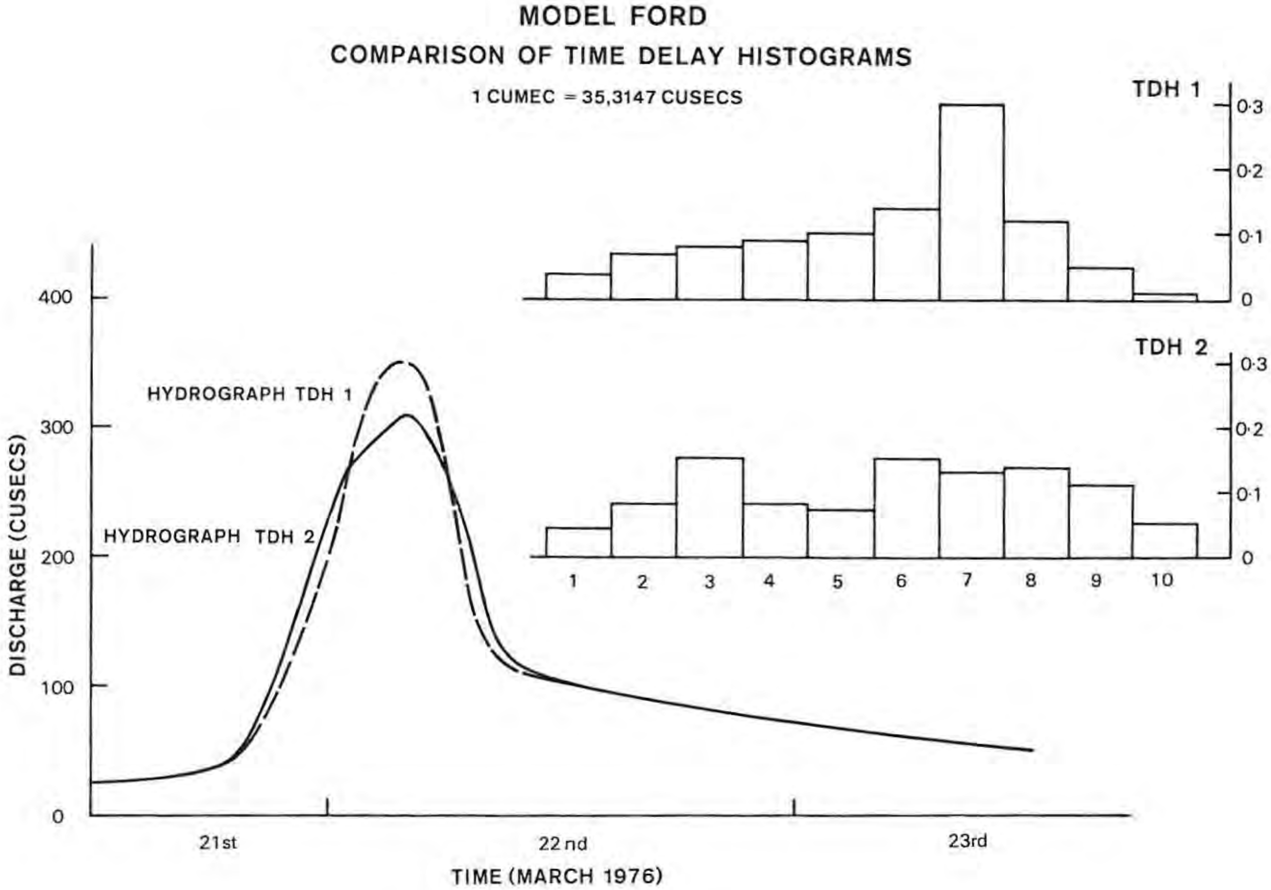

MODEL FORD
COMPARISON OF TIME DELAY HISTOGRAMS
1 CUMEC = 35,3147 CUSECS
TDH 1
0·3
0·2
0·1
0
TDH 2
0·3
0·2
0·1
0
1
2
3
4
5
6
7
8
9
10
HYDROGRAPH TDH 1
HYDROGRAPH TDH 2
DISCHARGE (CUSECS)
400
300
200
100
0
21st
22 nd
23rd
TIME (MARCH 1976)

FIGURE 29

FLOWT = TRS(I)-KS1*(TRS(I)-PREV) (Eqn. 51)

where the subscript I represents the current value of the translated hydrograph and PREV is the previous value of FLOWT. Variable channel attenuation may be obtained by specifying a different value of the channel attenuation constant for different flow intervals. To illustrate the nature of the channel attenuation function a hypothetical inflow hydrograph has been plotted in Figure 30 together with resultant hydrographs obtained by routing with two values of KS1. Figure 30 shows that KS1 becomes more sensitive for values above 0,5. To summarize the channel functions, the same hypothetical hydrograph has been plotted in Figure 31 with the resultant outflow hydrographs from time-delay and then attenuation.

3.3 Additional Modifications in Model SMDV

A version of the Stanford Model as described above was developed to operate on daily rainfall input. Since the Stanford is a powerful and generally applicable model, it was decided to produce a daily version to increase its applicability in South Africa. Hourly or quarter hourly rainfall is not generally available and if it is, it is for very short records only. The daily model SMDV is necessarily a simplification of FORD but the only major change in model structure is in the method of calculating overland flow. Otherwise the structure of the model and the functions governing movement of moisture between storages remain the same but iterations are on a daily basis.

The major problem encountered in creating a daily version of the Stanford Model was to provide an adequate overland flow function. The overland flow volume (ROS) as calculated by Equation 20 is not practical on a daily basis as it is based on the supply rate (intensity of rainfall) whereas daily rainfall contains very little measure of intensity. It was felt that a finite depression storage approach would be more

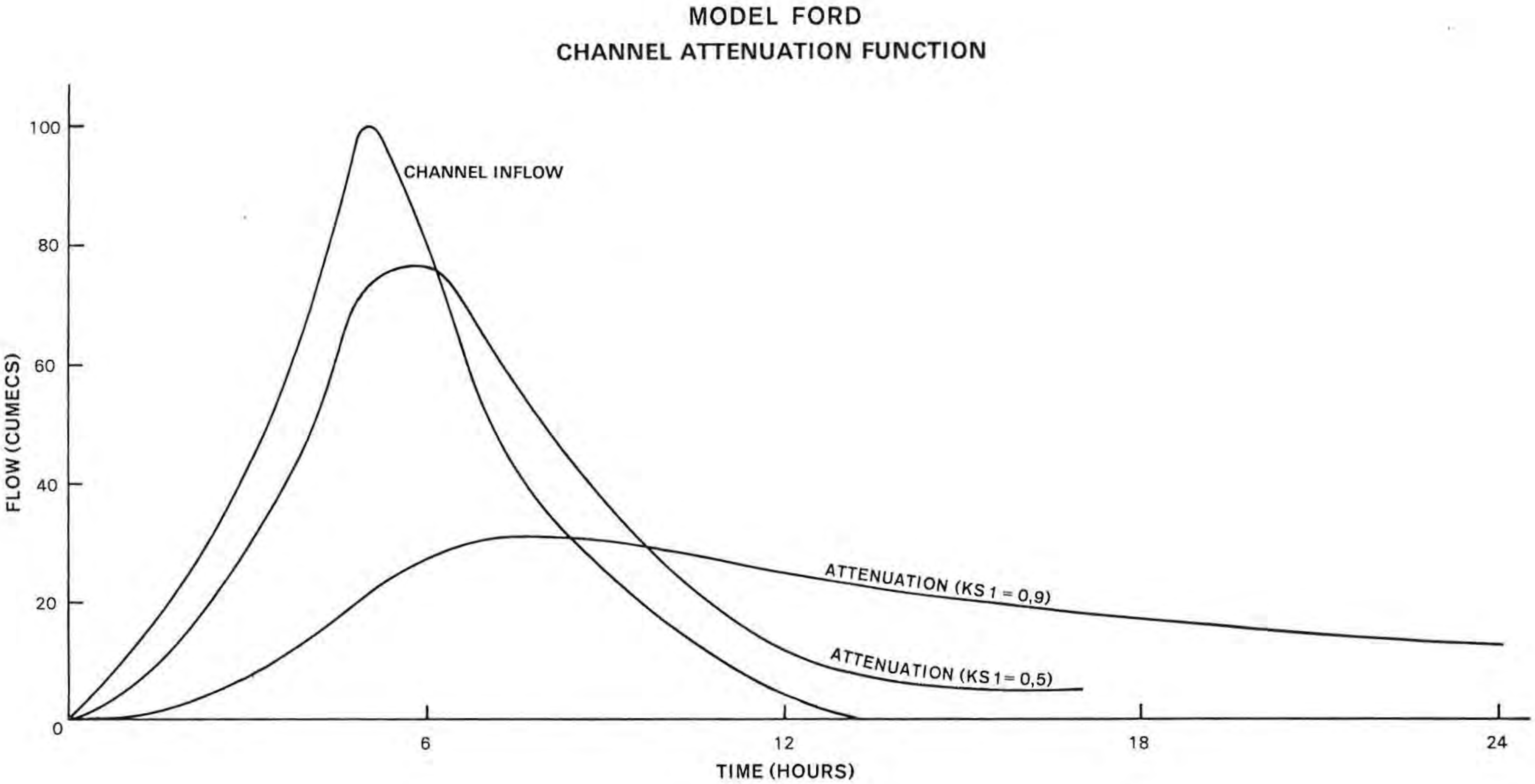

MODEL FORD
CHANNEL ATTENUATION FUNCTION
FLOW (CUMECS)
100
80
60
40
20
0
CHANNEL INFLOW
ATTENUATION (KS 1 = 0,9)
ATTENUATION (KS 1 = 0,5)
6
12
18
24
TIME (HOURS)

FIGURE 30

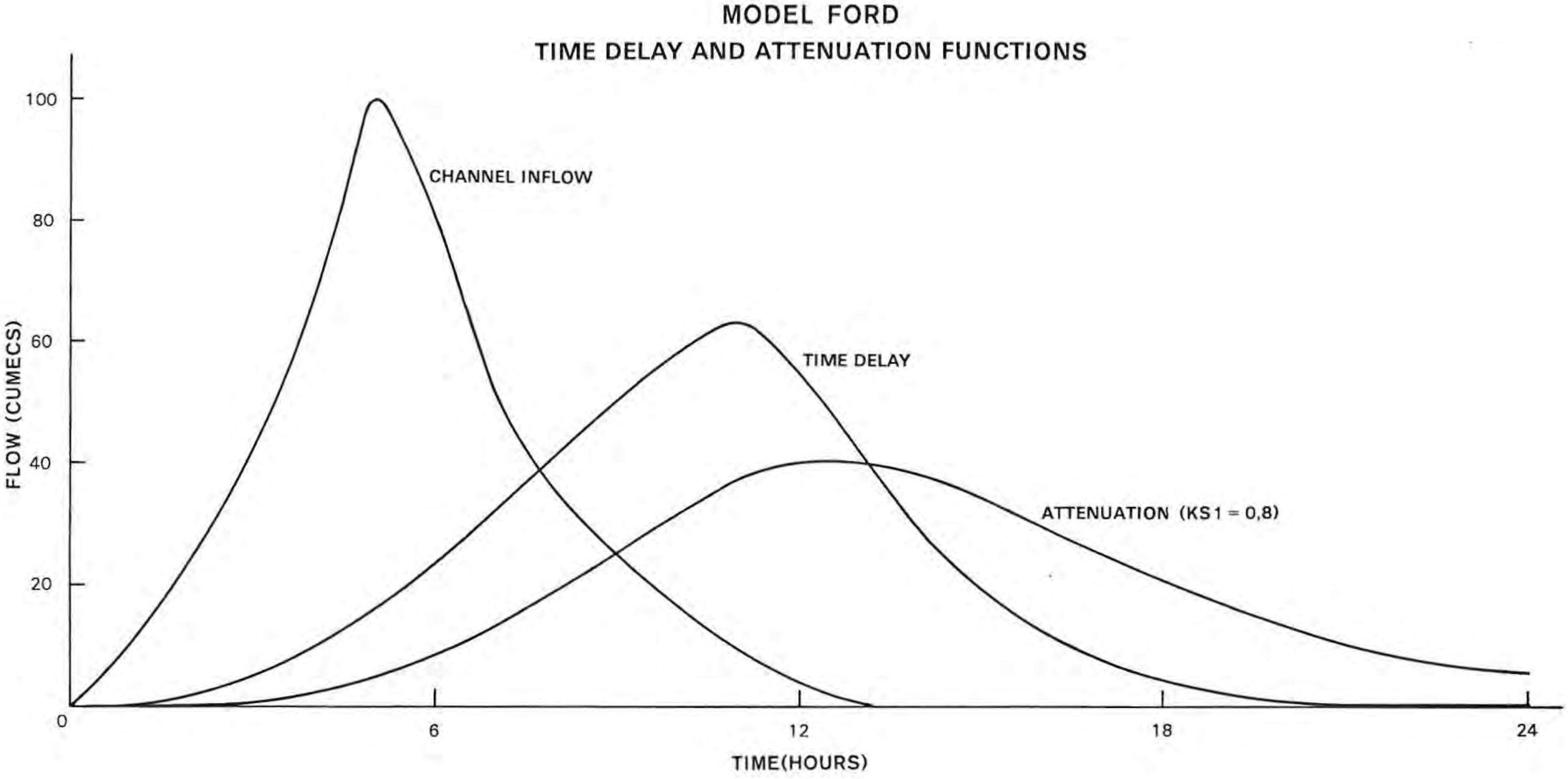

MODEL FORD
TIME DELAY AND ATTENUATION FUNCTIONS

FIGURE 31

meaningful. Giving a finite capacity to the depression storage (RESM) unfortunately involves the introduction of a further parameter that must be optimized but does provide the least deviation from the Stanford Model. Depression storage in model SMDV is operated by a linear storage of finite capacity (RESM) so that overland flow volume (ROS) is made up of two components of which the first may be spill from the storage (SPL) where

$$\mathrm{SPL} = \mathrm{RES}-\mathrm{RESM} \qquad \text{(Eqn. 52)}$$

where RES is set equal to RX, the actual increment to overland flow storage detention at the beginning of each time-period and after depletion by overland flow is subject to infiltration in the next time-period. The second source of overland flow is in the form of 'drainage' from the depression storage so that

$$\mathrm{ROS} = (\mathrm{RES}*\mathrm{URR})+\mathrm{SPL} \qquad \text{(Eqn. 53)}$$

where URR = RES/RESM with an upper limit of 0,75 (as in model FORD).

Time-delay in the daily models is done by a direct lag procedure where daily discharge volumes are lagged in days to account for time-delay in large catchment areas.

3.4 List of Parameters and Variables for Models FORD and SMDV

EPXM	Maximum capacity of interception storage.
PR	Quarter hourly rainfall.
SCEP	Interception storage level.
P3	Rainfall reaching the ground.
SIMPV	Impervious area volume.
AT	Fraction of catchment that is impervious.
P4	Moisture available for infiltration (incident rainfall).
INFIL	Direct infiltration (areal assessment).
SHRD	Excess rainfall.
D3FV	Mean infiltration rate for current time-interval.

CB	Infiltration parameter.
LZS	Lower soil zone storage level.
LZSN	Nominal value (median) of lower zone storage.
POWER	Exponent in mean infiltration rate equation.
LNRAT	Lower soil zone storage ratio.
RXX	Potential increase to overland flow surface detention.
RATIO	Variable in function that determines the ratio between overland flow and interflow.
CC	Parameter controlling overland flow/interflow ratio.
RGXX	Potential increase to interflow detention.
RX	Actual increment to overland flow surface detention.
RGX	Actual increment to interflow detention.
PRE	Variable controlling moisture distribution in both upper and lower zone functions.
UZS	Upper soil zone storage level.
UZSN	Nominal level of upper soil zone storage.
UZI	Exponent in the upper zone function (PRE).
ROS	Overland flow volume.
SRC	Land surface parameter in overland flow function.
D	Average surface detention.
DE	Surface detention at equilibrium.
SS	Overland flow slope.
NN	Manning's n for overland flow.
L	Length of overland flow.
RES	Surface detention storage volume.
DEC	Land surface parameter in surface detention function.
SRGX	Level of interflow storage.
INTF	Interflow volume.
LIRC4	Parameter in interflow function.

IRC	Interflow decay constant for 24 hour period.
LZI	Exponent in lower zone distribution function.
F3	Addition to lower zone storage.
F1	Addition to active groundwater storage.
F1A	Moisture available for active and inactive groundwater.
K24L	Parameter controlling increments to inactive groundwater.
PA	Percentage pervious area in catchment.
SGW	Groundwater storage level.
RECH	Increment to inactive groundwater.
RECE	The percolation volume.
DEEPL	Moisture gradient between upper and lower zone storages.
GWF	Base flow volume.
LKK4	Groundwater recession constant for quarter hour period.
KV	Variable groundwater recession parameter.
GWS	Antecedent groundwater storage index.
KK24	Base flow decay constant for 24 hour period.
RU	Total contribution to channel storage for current hour.
AETR	Actual evapotranspiration.
EP	Potential evapotranspiration.
K3	Lower zone evapotranspiration parameter.
LOS	Evapotranspiration from groundwater storage.
K24EL	Fraction of catchment where evapotranspiration occurs at the potential rate.
KS1	Channel attenuation constant.
FLOWT	Simulated flow for each time-interval.
TRS	Channel inflow for each time-interval.
PREV	Value of FLOWT in previous time-interval.
RESM	Capacity of depression storage in model SMDV.
SPL	Spill from depression storage (SMDV).

URR Depression storage ratio (SMDV).

3.5 Description of Models PORT and PDAY

The structure of the hourly model PORT and its equivalent daily model PDAY are based essentially on the model described by Porter and McMahon (1971). The model of Porter and McMahon was designed to operate on time-intervals of one day or one hour and like the Stanford Watershed Model IV it is a general model, complex in structure and with a high degree of physical correspondence to the catchment situation. The general structure of the hourly model PORT will be described and reference will be made to the modification of model PORT that was necessary for the development of the daily model PDAY. The relationship between model storages and moisture control functions is the same for both models and is illustrated by Figure 32.

3.5.1 Interception storage function

Incident rainfall is first separated into two parts, the first being the rainfall that falls on bare ground and the second being rainfall that falls on vegetation. The proportion is defined by an input parameter BARE which is the percentage bare ground in the catchment. The rainfall that falls on the vegetation is subjected to the operation of the interception storage which is a linear storage of finite capacity (VSC) that diverts all moisture until the storage is full. The storage is subjected to evaporation demands at the potential rate.

3.5.2 The infiltration function

Moisture bypassing the interception storage, together with moisture falling on bare ground is subjected to the infiltration function which is based on the Philip equation (Philip, 1964)

F = A+0.5*S*T**(-0.5) (Eqn. 54)

where F is the infiltration, A is the minimum value of F and S is the sorptivity. The sorptivity (S) is related to the moisture level of the

FLOW CHART FOR MODELS PORT AND PDAY

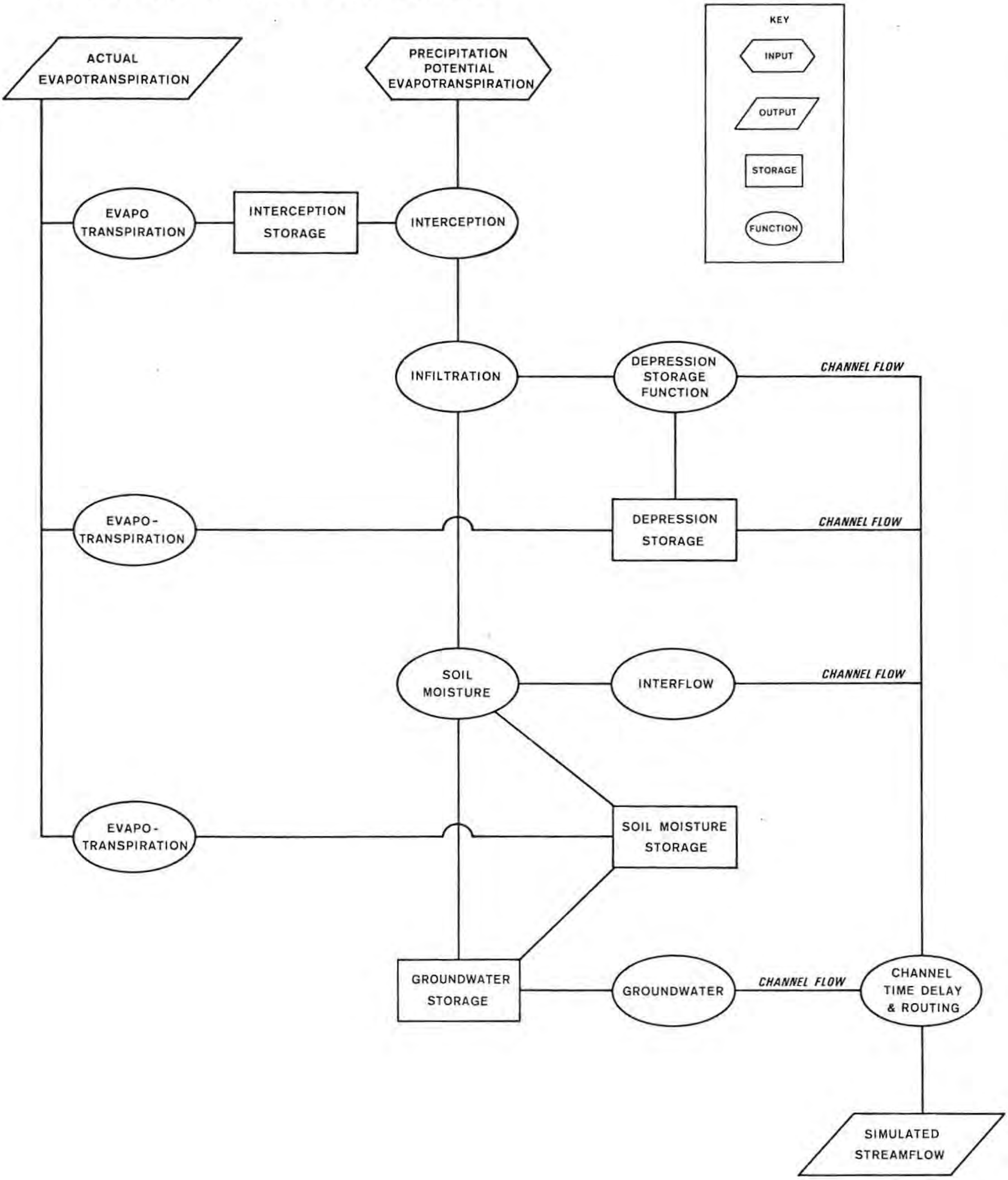


FIGURE 32

soil storage SSL by

$$S = X*EXP(-P*(SSL/SSC)) \quad \text{(Eqn. 55)}$$

where SSC is the soil storage capacity, and X and P are constants that must be obtained by trial and error. In order to provide a guide to the sensitivity of parameters P and X, the relationship between the calculated infiltration F and the soil storage ratio (RAT = SSL/SSC) has been plotted in Figures 33 and 34 for various values of the two parameters. The value of T in Equation 54 remains at unity unless the precipitation rate exceeds the infiltration capacity when the infiltration becomes time-dependent and drops more rapidly than it would due to decreasing sorptivity alone. However, in the case of an intermittent storm when rainfall ceases for a short time and then commences again, it is unrealistic to have the infiltration rate recover immediately to the level corresponding to T = 1 at the beginning of the second rainfall event. Porter and McMahon argue that the infiltration recovery will be time-dependent and the rate of recovery will depend on the speed of redistribution of the soil moisture profile as moisture is moved away from the saturated surface. In order to model the time-dependent recovery of infiltration after excess precipitation, Porter and McMahon put forward the following method. At the end of the period of excess precipitation, the calculated infiltration capacity is used in Equation 54 with T = 1 to calculate a value of S and the value of S is then used in Equation 55 to calculate a pseudo-value of SSL which is referred to as a pseudo-level of soil moisture storage (SSX). The pseudo-level (SSX) will be higher than the real level SSL and may be reduced to the real level over time to create the effect of time-dependent infiltration recovery. The reduction of the pseudo-level for each time-interval is taken as being proportional to the difference between open water evaporation and incident rainfall

MODEL PORT

THE INFILTRATION FUNCTION

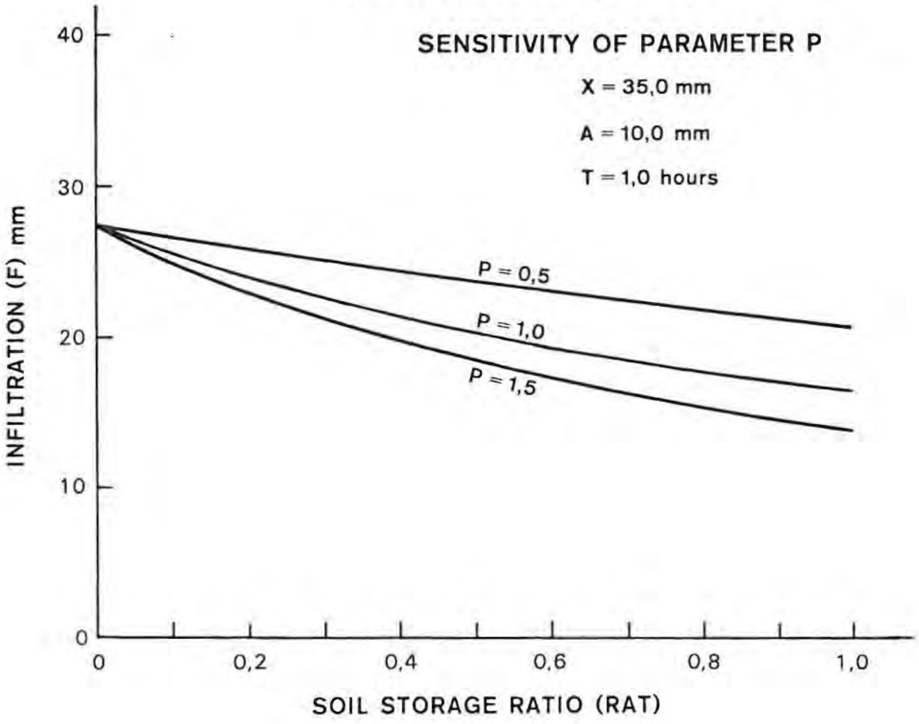


FIGURE 33

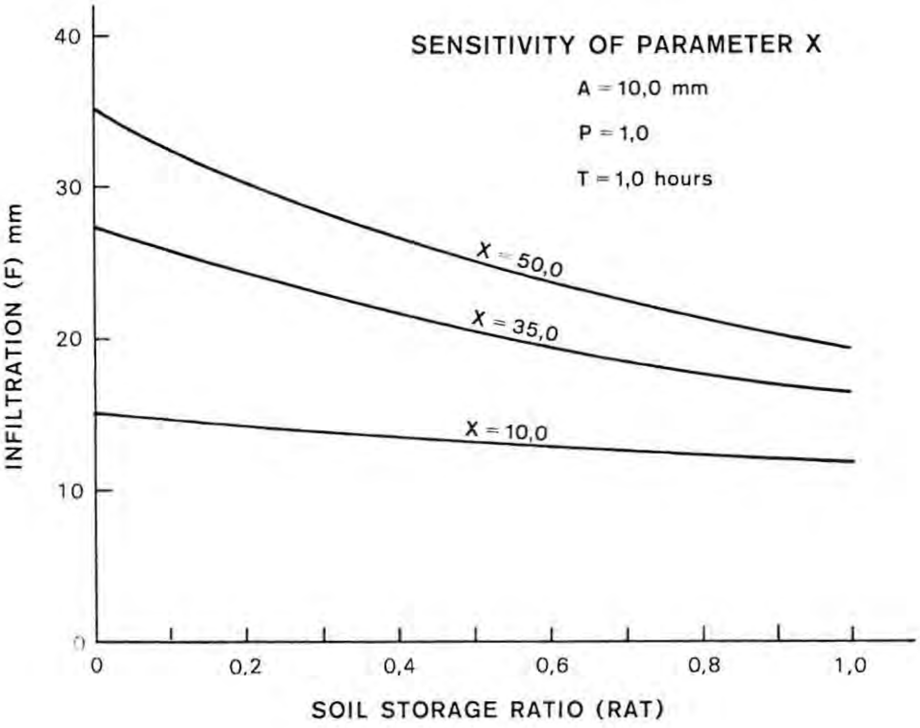


FIGURE 34

providing that the difference is positive. This method of time-dependent infiltration recovery was built into model PORT but when tested with Ecca data it was found that the rate of recovery of the pseudo-level was not realistic, and after some intermittent storms the difference between pseudo and real soil storage levels was so great that the time of recovery was of the order of months. As a result of the inadequate rate of recovery of the infiltration capacity the model often simulated large floods from relatively low rainfall when no flow was observed. The empirical method of infiltration recovery is based on the observation "that for many hours after cessation of an irrigation application, evaporation from the surface is the dominant factor in the recovery of infiltration capacity." (Porter and McMahon, 1971, 315). Consequently the first modification was to set the reduction in pseudo-level for each hour equal to the free water surface evaporation for that day. Despite the fact that such modification grossly exaggerates the volume of evaporation for the day, the rate of reduction of the pseudo-level was still inadequate. It was felt that the exaggerated volume of evaporation was permissible because the pseudo-level of soil moisture and subtractions from it are not included in the water balance calculations for the catchment. In order to increase the rate of reduction of the pseudo-level still further an attempt was made to include an empirical assessment of the second important factor in infiltration recovery, namely the drainage of soil moisture away from the saturated surface. Soil moisture drainage was empirically simulated by multiplying the difference between real and pseudo-levels by the ratio of the soil moisture deficit to the soil moisture capacity. In this way the reduction of pseudo-level would increase in a non-linear manner with increasing soil moisture deficit and with increasing exaggeration of the real soil moisture level. The two forms of reduction were combined to give the total reduction (RED) in pseudo-level for each hour as

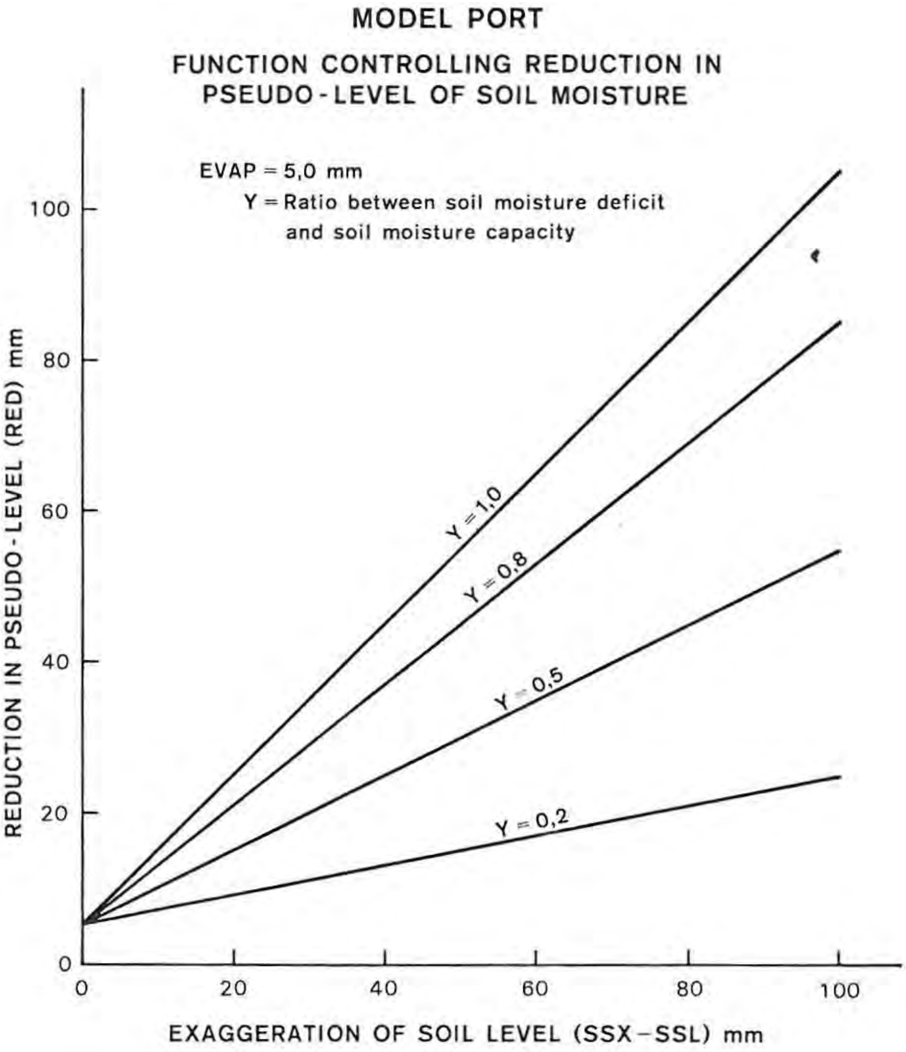
RED = EVAP+(SSX-SSL)*((SSC-SSL)/SSC) (Eqn. 56)

where EVAP is the free water surface evaporation for the day, SSX is the pseudo-level, SSL is the real level and SSC is the maximum soil moisture capacity. The calculated reduction in the pseudo-level has been plotted against the difference between real and pseudo-levels (SSX-SSL) for various values of the ratio between soil moisture deficit and soil moisture capacity ((SSC-SSL)/SSC) in Figure 35 to illustrate the proportion of the reduction under varying soil moisture conditions. The modification represented by Equation 56 gave a marked improvement in the performance of model PORT, but the results showed that further modification is necessary and there is a need to improve the degree of physical relevance of the modifications adopted. It is felt that the empirical method of infiltration recovery put forward by Porter and McMahon is an important contribution to the problem of simulating the infiltration process and further testing of this method is desirable. As Porter and McMahon (1971) have pointed out, the use of a single soil storage is one of the greatest simplifications of the model and further research into the empirical approach to time-dependent infiltration recovery may well benefit from the use of two soil storages.

For model PDAY the rainfall input is on a daily basis and contains very little measure of intensity and consequently it would not be realistic to have time-dependent infiltration assessment. The infiltration for PDAY is calculated from Equations 54 and 55 with the time-variable T set at unity, as recommended by Porter and McMahon.

3.5.3 The depression storage function

The excess precipitation TDSF is subjected to the depression storage function to determine overland flow. The depression storage



MODEL PORT

FUNCTION CONTROLLING REDUCTION IN PSEUDO-LEVEL OF SOIL MOISTURE

EVAP = 5,0 mm

Y = Ratio between soil moisture deficit and soil moisture capacity

FIGURE 35

is a linear storage of finite capacity (DSC) and there is an exponential decay of contribution to depression storage (D) as the depression storage level (DSL) increases;

D = B*EXP((-Y*DSL)/(DSC-DSL))*TDSF (Eqn. 57)

where Y is a parameter that can be used to govern the shape of the curve (it has no physical interpretation and is usually set to 1,0) and B represents the maximum fraction of catchment area that can contribute to depression storage when all depressions are empty and is usually set to 1,0. A guide to the sensitivity of the parameters Y and B can be obtained from the plot of contribution to depression storage against the depression storage deficit (DSC-DSL) for various values of the two parameters in Figures 36 and 37. The moisture in depression storage is subjected to evapotranspiration at the potential rate as well as infiltration to the soil to give a total infiltration volume FT for the time-period.

3.5.4 The soil moisture function

The infiltration (FT) is subjected to two types of diversion before accruing to the soil moisture storage. The first diversion is to accomodate upper zone runoff that may take place from lower intensity rainfall than is necessary to provide excess precipitation from the infiltration function. This type of diversion in model PORT is regarded as interflow (SC) and is calculated as

SC = UC*(SSL/SSC)*FT (Eqn. 58)

where UC is an input parameter that governs the contribution to interflow. The second type of diversion from infiltration volume is a contribution to groundwater (SG) that takes the same form as the interflow function

SG = UG*(SSL/SSC)*FT (Eqn. 59)

where UG is a parameter that governs the contributions to groundwater

MODEL PORT

DEPRESSION STORAGE FUNCTION

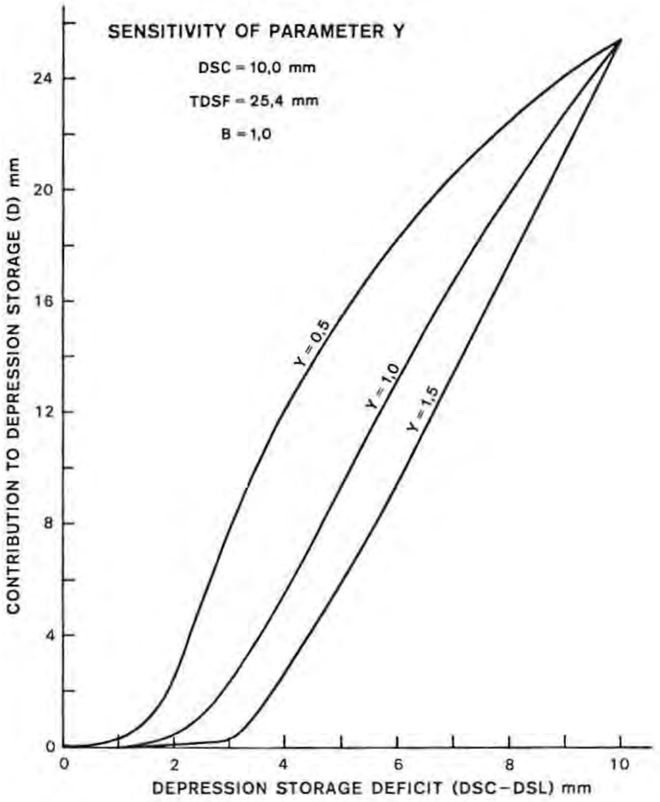


FIGURE 36

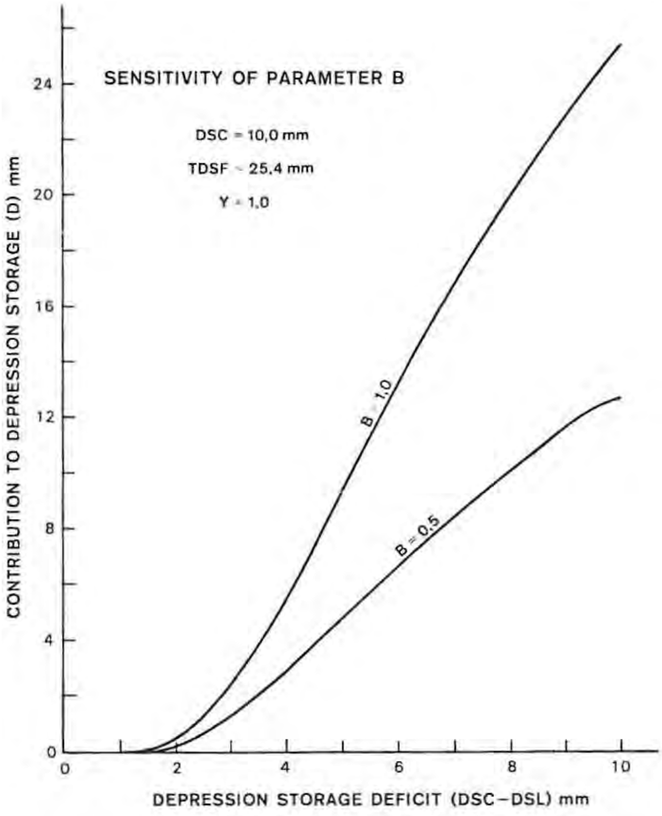


FIGURE 37

storage GS. As the soil moisture storage is a linear storage of finite capacity further contributions to groundwater storage occur when the soil moisture capacity is exceeded. The base flow for each time-period (CG) is taken as being proportional to the XN-th power of storage GS;

$$CG = C*GS**XN \quad . \qquad \text{(Eqn. 60)}$$

3.5.5 Channel functions

The routing technique used by Porter and McMahon is a modification of the technique used by Laurenson (1964) based on isochrones of time-delay to the measuring point. As Porter and McMahon do not give sufficient details of the method employed and since this method is similar to the method employed in the Stanford Model, it was decided to utilize a more simple direct lag procedure with an attenuation function so as to have a basis of comparison with the techniques used in the Stanford model.

Travel times in the channel system were accomodated by a direct lag procedure equivalent to the time of concentration (which can be estimated empirically or assessed from observed data) in hours. To accomodate attenuation of the channel inflow hydrograph by the channel system, the Nash-Muskingum routing equation (Nash, 1959) was used;

$$O_2 = C_0I_2 + C_1I_1 + C_2O_1 \qquad \text{(Eqn. 61)}$$

where O is the outflow from the channel reach and I is the inflow and where the subscripts 1 and 2 for variables O and I refer to the beginning and end of each time-period respectively. The Nash-Muskingum routing constants C_0 , C_1 and C_2 can be estimated readily for any catchment area in South Africa by reference to Bauer and Midgley (1974).

For the daily models, including PDAY, no attenuation was included for steps of one day because only daily discharge volumes are produced. However, should attenuation be required in very large catchments, Equation 51 may be incorporated easily in the model so as to route the discharge volumes through a hypothetical storage. A direct lag procedure was maintained for use of the model PDAY in large catchments where lag time exceeds one day.

3.6 List of Parameters and Variables for Models PORT and PDAY

BARE	Percentage bare ground in catchment.
VSC	Interception storage capacity (maximum).
F	Infiltration volume for time-interval.
A	Minimum infiltration volume permitted.
S	Sorptivity of the soil.
T	Time-counter in hours since beginning of excess rainfall.
SSL	Soil storage level.
X	Constant in equation relating sorptivity to soil moisture ratio.
P	Constant in equation relating sorptivity to soil moisture ratio.
SSC	Soil storage capacity (maximum).
RAT	Soil storage ratio.
SSX	Pseudo-level of soil moisture storage.
RED	Total reduction in SSX for each time-interval.
EVAP	Free water surface evaporation for the day.
TDSF	The excess precipitation.
DSC	Depression storage capacity (maximum).
DSL	Depression storage level.
B	Maximum fraction of catchment area contributing to depression storage.
Y	Constant in depression storage function.
FT	Total infiltration volume for time-period.
SC	Contribution to interflow for time-period.
UC	Parameter controlling contributions to interflow.
SG	Contribution to groundwater for time-period.
UG	Parameter controlling contributions to groundwater.

CG	Base flow volume.
GS	Groundwater storage level.
XN	Exponent in base flow equation.
O	Outflow from channel reach.
I	Inflow to channel reach.
C_0	Constant in Nash-Muskingum routing equation.
C_1	Constant in Nash-Muskingum routing equation.
C_2	Constant in Nash-Muskingum routing equation.

3.7 Description of Model BERG

The majority of the components of model BERG have been drawn from a model by Dawdy, Lichty and Bergmann (1972) which was developed to predict flood volumes and peak rates of runoff for small drainage areas. As it is a model designed to reproduce flood peaks only, it will provide a comparison with models FORD and PORT which are designed to reproduce the entire hydrograph. The structure of the model (shown in Figure 38) has two soil storages representing surface moisture storage and a lower zone moisture storage.

No daily version of the hourly model BERG has been developed in this study because the structure is orientated to the production of flood peaks and is therefore not compatible with the level of rainfall intensity information inherent in daily rainfall data.

3.7.1 Point infiltration function

The first operation of the model is to calculate point infiltration (FR) by using the estimated soil suction coefficient (PS) which is a function of soil moisture;

$$PS = SWF*(RGF-(RGF-1.0)*BMS/BMSM) \qquad \text{(Eqn. 62)}$$

where SWF represents the suction at the wetted front for soil moisture at field capacity, RGF is the ratio of the suction at the wetted front for soil moisture at wilting point to that at field capacity, BMS is

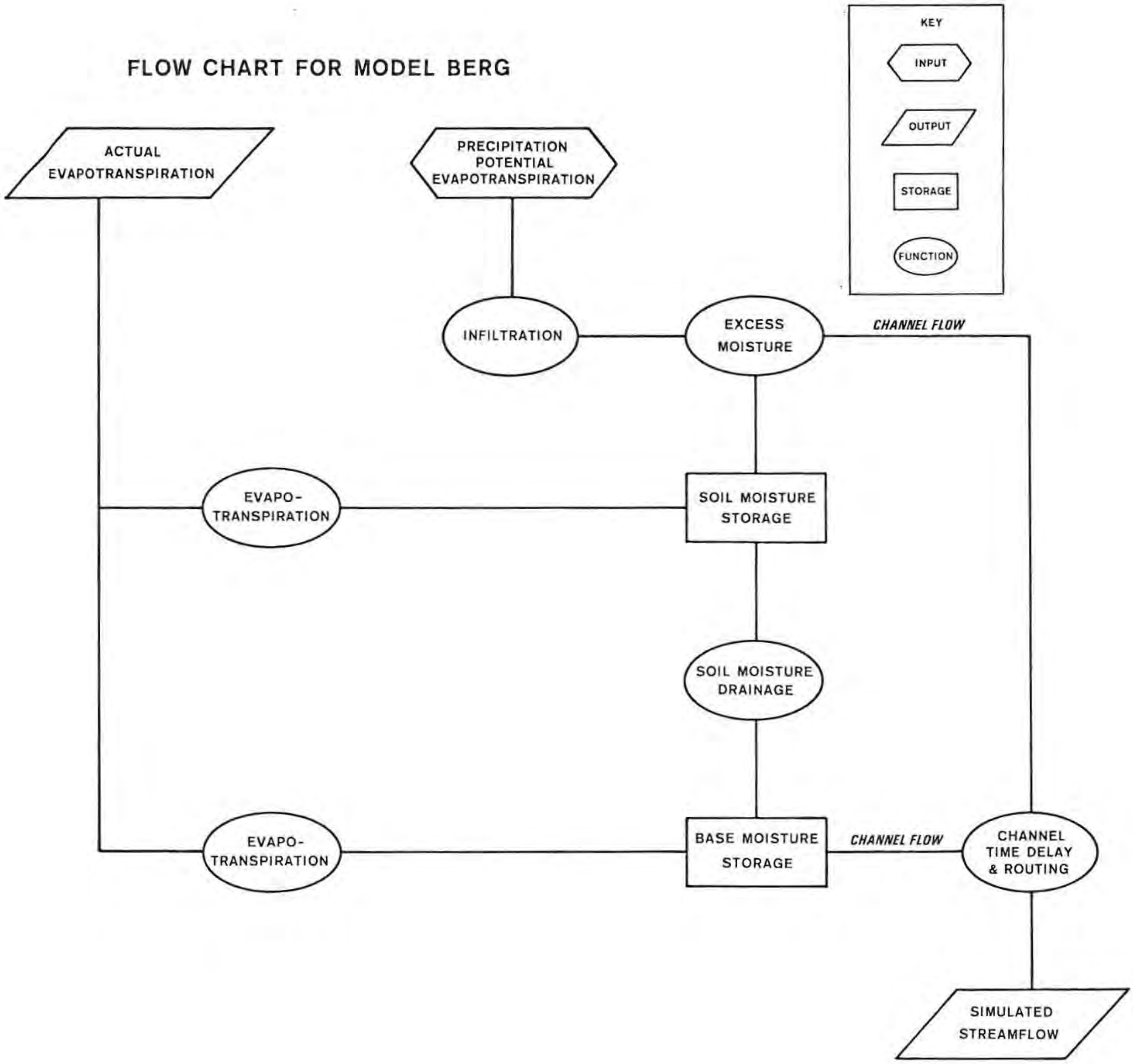

FLOW CHART FOR MODEL BERG
KEY
INPUT
OUTPUT
STORAGE
FUNCTION
ACTUAL EVAPOTRANSPIRATION
PRECIPITATION POTENTIAL EVAPOTRANSPIRATION
INFILTRATION
EXCESS MOISTURE
CHANNEL FLOW
EVAPO-TRANSPIRATION
SOIL MOISTURE STORAGE
SOIL MOISTURE DRAINAGE
EVAPO-TRANSPIRATION
BASE MOISTURE STORAGE
CHANNEL FLOW
CHANNEL TIME DELAY & ROUTING
SIMULATED STREAMFLOW

FIGURE 38

the moisture level of the base moisture storage that ranges between wilting point and field capacity and BMSM is the soil moisture storage volume at field capacity. The point infiltration (FR) is dependent on the content of the surface moisture layer that forms during rainfall (SMS) where for

$$\mathrm{SMS} = 0.0 \; , \qquad \mathrm{FR} = \mathrm{XSAT}*(1.0+\mathrm{PS}) \qquad \text{(Eqn. 63)}$$

and for

$$\mathrm{SMS} > 0 \; , \qquad \mathrm{FR} = \mathrm{XSAT}*(1.0+\mathrm{PS}/\mathrm{SMS}) \qquad \text{(Eqn. 64)}$$

where the parameter XSAT is the minimum (saturated) value of hydraulic conductivity used to determine soil infiltration rates. Figures 39, 40 and 41 show FR plotted against BMS/BMSM for values of SMS, SWF and RGF. The point infiltration (FR) is converted to an estimate of net infiltration over the catchment by reference to the supply rate of rainfall (RAIN) as follows;

$$\text{for} \quad \mathrm{RAIN} \leqslant \mathrm{FR} \; , \qquad \mathrm{QR} = (\mathrm{RAIN}**2.0)/(2.0*\mathrm{FR}) \qquad \text{(Eqn. 65)}$$

and for

$$\mathrm{RAIN} > \mathrm{FR} \; , \qquad \mathrm{QR} = \mathrm{RAIN}-\mathrm{FR}/2.0 \qquad \text{(Eqn. 66)}$$

where QR is the rate of generation of excess precipitation that does not infiltrate. The plot of QR against FR in Figure 42 illustrates the decreasing rate of reduction of QR for increasing point infiltration exceeding the incident rainfall. The difference between incident rainfall and excess precipitation (FRX = RAIN-QR) accrues to surface soil moisture (SMS). The two stage approach adopted for the areal assessment of the infiltration rate by Dawdy, Lichty and Bergmann (1972) is similar to that adopted by Crawford and Linsley (1966) for the Stanford Model, but should not be confused with the temporal (rather than spatial) two stage process for modelling infiltration adopted for steady rainfall conditions by Mein and Larson (1973) and later, for unsteady conditions, by Chu (1978).

MODEL BERG
POINT INFILTRATION FUNCTION

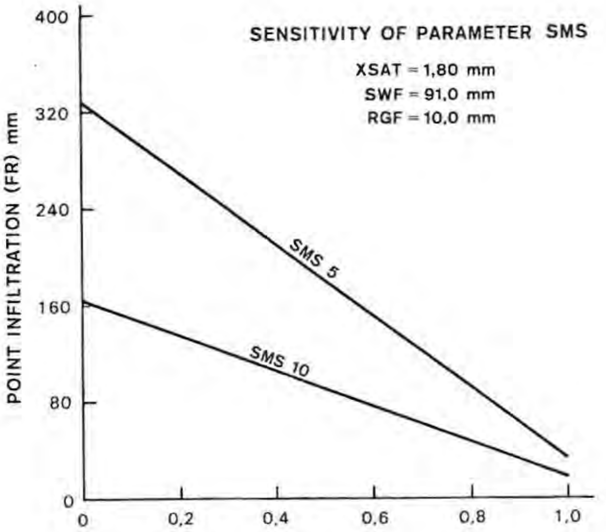


FIGURE 39

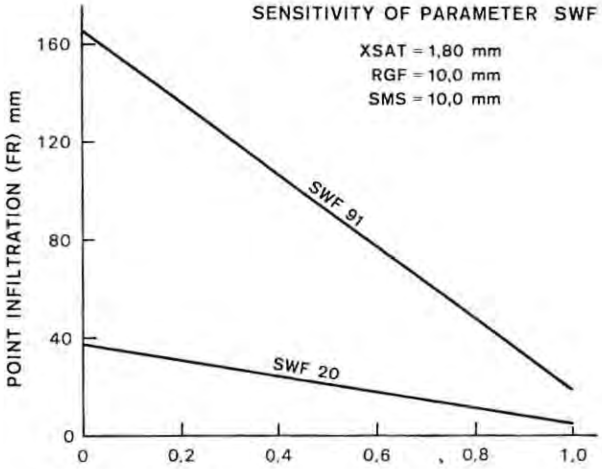


FIGURE 40

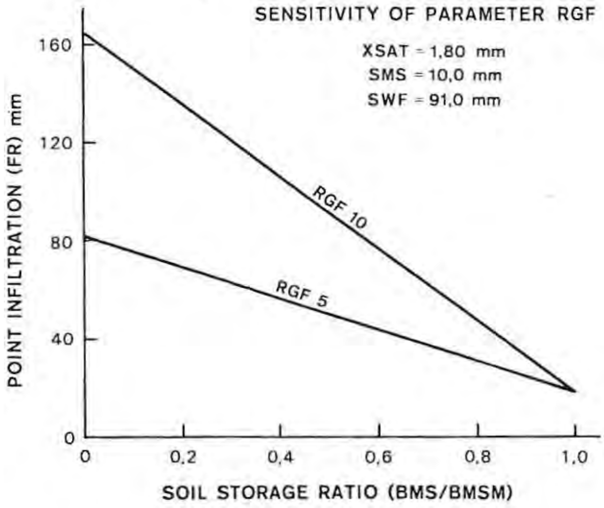


FIGURE 41

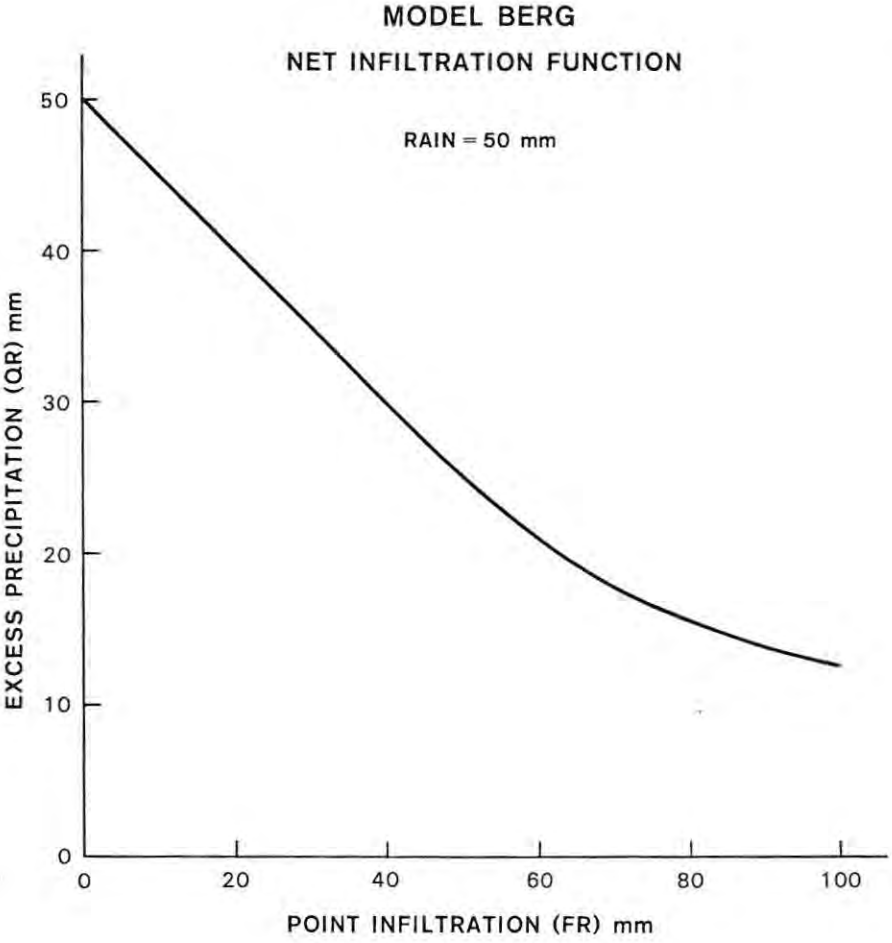

MODEL BERG
NET INFILTRATION FUNCTION
RAIN = 50 mm
EXCESS PRECIPITATION (QR) mm
50
40
30
20
10
0
0
20
40
60
80
100
POINT INFILTRATION (FR) mm

FIGURE 42

Moisture in the surface soil layer percolates at a constant rate (DRN) to the lower soil storage (BMS). Should the lower soil storage capacity (BMSM) be exceeded the spillage may be regarded as contribution to inactive groundwater storage, contribution to base flow or in the case of model BERG as a direct contribution to channel storage.

3.7.2 Evapotranspiration

Evapotranspiration demands are met at the potential rate from the surface soil layer (SMS) but if the demand is not satisfied by SMS the remainder is taken from the lower soil storage (BMS).

3.7.3 Routing procedure

The same method of direct time-lag in hours together with channel attenuation as used in model PORT is used in model BERG.

3.8 List of Parameters and Variables for Model BERG

FR	Point infiltration for time-period.
PS	Soil suction coefficient.
SWF	Suction at wetted front for soil moisture at field capacity.
RGF	Ratio of the suction at the wetted front for soil moisture at wilting point to that at field capacity.
BMS	Base moisture storage level.
BMSM	Base moisture storage capacity (maximum).
SMS	Moisture level of the surface soil layer.
XSAT	The minimum (saturated) value of hydraulic conductivity.
QR	Rate of generation of excess precipitation.
RAIN	Rainfall supply rate.

3.9 Description of Model HANS

The structure of model HANS has been drawn from a model described by Nielsen and Hansen (1973) and operates on daily rainfall and pan evaporation. The model structure (Figure 43) comprises three storages

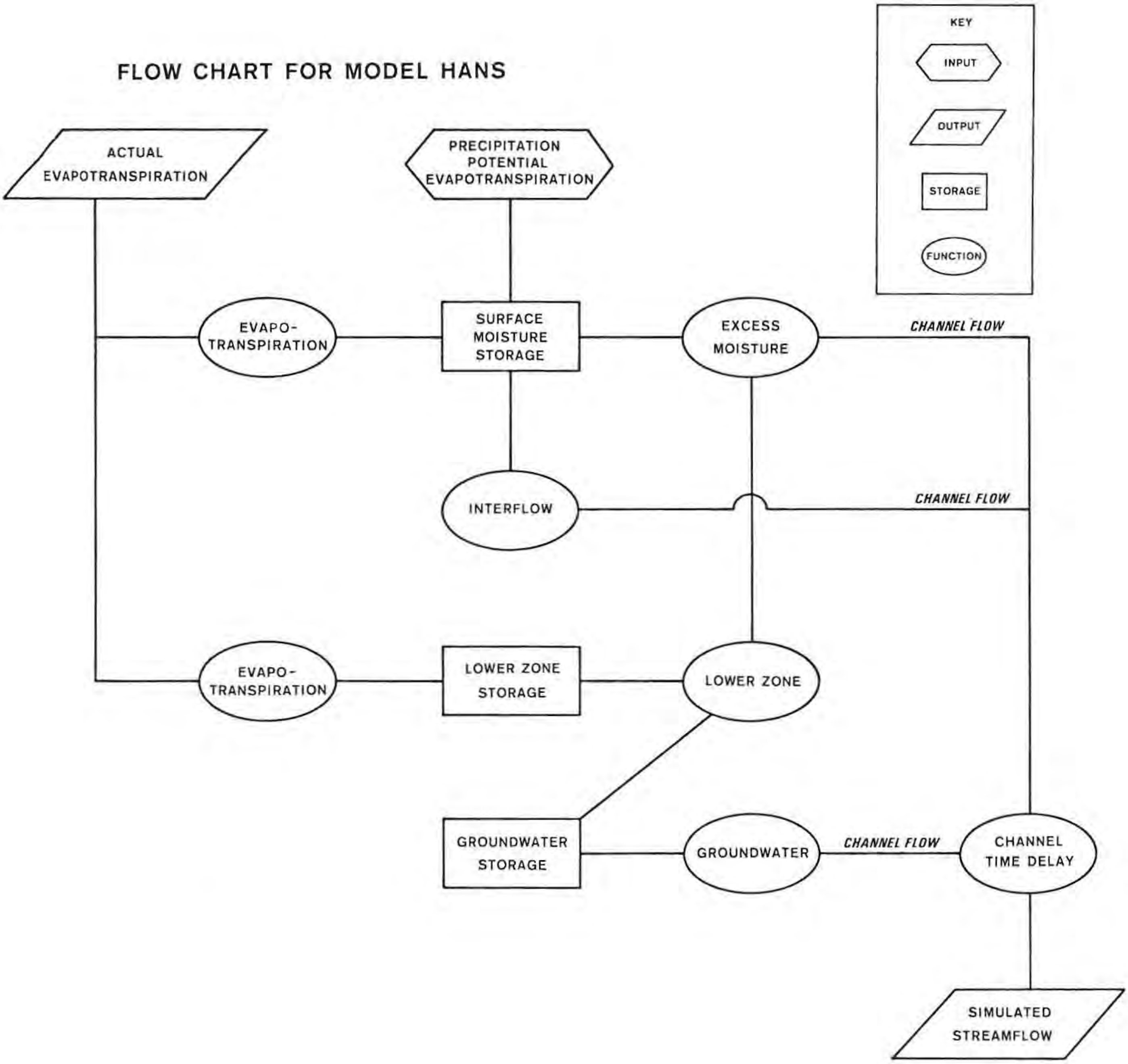

FLOW CHART FOR MODEL HANS
KEY
INPUT
OUTPUT
STORAGE
FUNCTION
ACTUAL EVAPOTRANSPIRATION
PRECIPITATION POTENTIAL EVAPOTRANSPIRATION
EVAPO-TRANSPIRATION
SURFACE MOISTURE STORAGE
EXCESS MOISTURE
CHANNEL FLOW
INTERFLOW
CHANNEL FLOW
EVAPO-TRANSPIRATION
LOWER ZONE STORAGE
LOWER ZONE
GROUNDWATER STORAGE
GROUNDWATER
CHANNEL FLOW
CHANNEL TIME DELAY
SIMULATED STREAMFLOW

FIGURE 43

(the snowmelt storage of the Nielsen and Hansen model has been excluded) to provide overland flow, interflow and base flow. The model of Nielsen and Hansen (1973) was chosen because it is intermediate in complexity between model PDAY and the very simple Dalton Watershed Model and because it is not based on a direct calculation of infiltration volume for each day.

3.9.1 The upper zone storage

Incident rainfall is added to the upper soil storage which is a linear storage of finite capacity (UZM). Any spillage (EXC) from this storage is subjected to the overland flow function which determines what proportion of any spillage is overland flow volume (OFL). The remainder of the spillage is divided between infiltration to the lower zone storage and contribution to base flow according to the value of the lower zone storage ratio (LZR/LZM) where LZR is the current moisture level and LZM is the storage capacity. In this respect the model deviates from the usual procedure adopted for calculating infiltration where infiltration is determined directly by means of a theoretical formula. The indirect method adopted in this model determines the infiltration as a residual of the net rainfall after subtraction of the empirically estimated surface runoff. As a result the necessity of optimizing the complex interrelationship between infiltration parameters is eliminated. Despite the fact that infiltration only occurs when the upper zone storage capacity is exceeded, increments to base flow may be obtained in the absence of surface runoff during relatively dry periods by manipulating the overland flow parameters.

The overland flow (OFL) is a function of spillage (EXC) from upper zone storage and the current value of the lower zone storage ratio as follows;

for LZR/LZM > CLO, OFL = COF*EXC*(((LZR/LZM)-CLO)/(1.0-CLO)) (Eqn. 67)

and for

LZR/LZM ≤ CLO, OFL = 0.0 . (Eqn. 68)

The parameters COF and CLO are both positive and dimensionless constants smaller than unity where COF is estimated as the ratio between overland flow volume and excess rainfall during periods when the soil is saturated, and CLO is estimated from periods when even heavy precipitation does not give rise to runoff. The overland flow from 25,4 millimetres of spillage has been plotted against lower zone storage ratio for values of CLO in Figure 44 to demonstrate the method of restricting overland flow during relatively dry periods. The overland flow (OFL) is routed to the stream during subsequent days according to an exponential weighting function;

SPS = OFL*(1.0/EKO)*EXP(-TO/EKO) (Eqn. 69)

where EKO is the time-constant in days and TO is the relevant time-interval since the initiation of overland flow.

3.9.2 The interflow function

The upper zone storage is depleted continuously by interflow where the contribution to interflow (AINF) is assumed to be proportional to the moisture level of upper zone storage (UZR) and to vary linearly with the lower zone storage ratio (LZR/LZM) as follows;

for LZR/LZM > CLI AINF = CIF*UZR*(((LZR/LZM)-CLI)/(1.0-CLI)) (Eqn. 70)

and for

LZR/LZM ≤ CLI AINF = 0.0 . (Eqn. 71)

The input parameters CIF and CLI are dimensionless constants smaller than unity and correspond to the overland flow parameters COF and CLO respectively. The value of AINF is routed to the stream channel as interflow during subsequent days according to the exponential weighting function

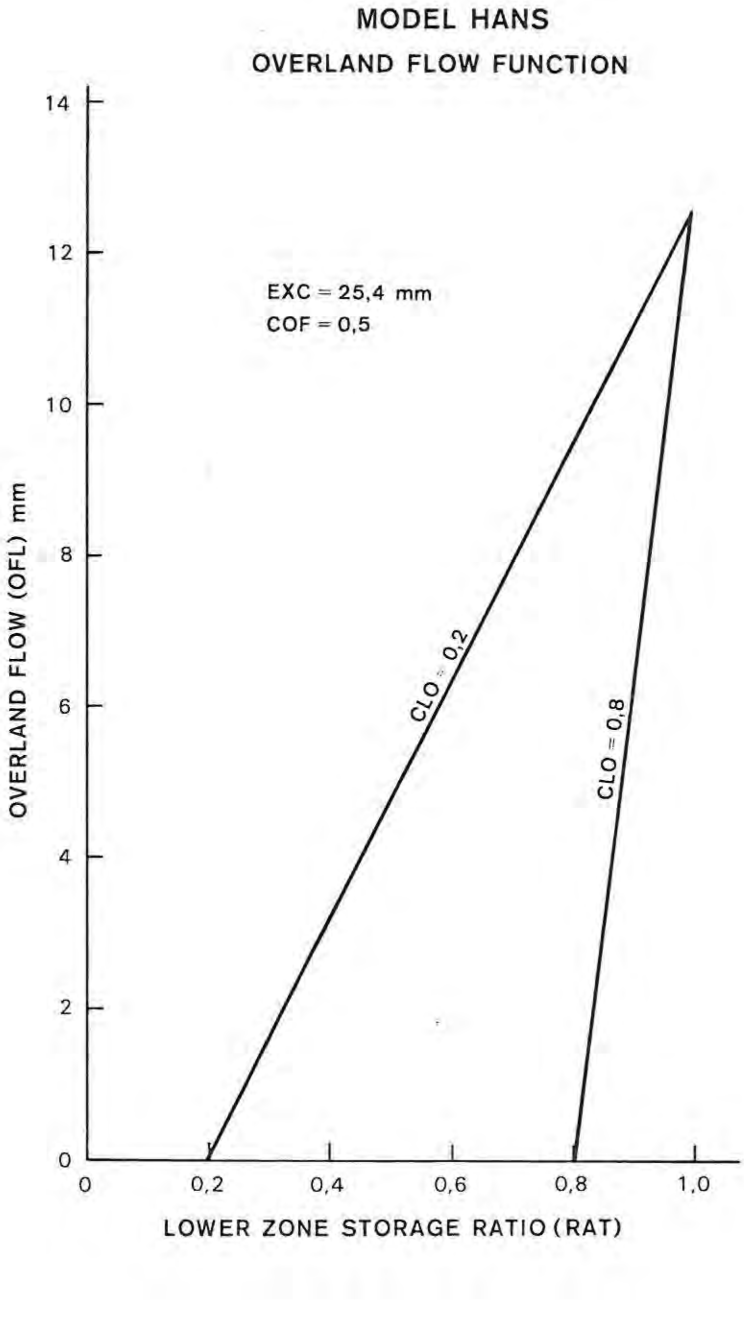

MODEL HANS
OVERLAND FLOW FUNCTION
EXC = 25,4 mm
COF = 0,5
CLO = 0,2
CLO = 0,8
OVERLAND FLOW (OFL) mm
14
12
10
8
6
4
2
0
0
0,2
0,4
0,6
0,8
1,0
LOWER ZONE STORAGE RATIO (RAT)

FIGURE 44

$$FIN = AINF*((1.0/EKI)*EXP(-TI/EKI)) \qquad \text{(Eqn. 72)}$$

where EKI is the time-constant in days and can be estimated from observed hydrographs.

3.9.3 Infiltration assessment

The excess precipitation (EXC) that does not accrue to overland flow (EXC-OFL) is taken to be infiltration and part (DL) is assumed to increase the moisture content of the lower zone storage,

$$DL = (EXC-OFL)*(1.0-(LZR/LZM)) \qquad \text{(Eqn. 73)}$$

whereas the remainder (G) percolates to groundwater storage,

$$G = (EXC-OFL)*(LZR/LZM) \quad . \qquad \text{(Eqn. 74)}$$

3.9.4 Base flow decay

Exponential recession of base flow is obtained by decay of the groundwater storage by using the following function;

$$BF = BFP*EXP(-1.0/EKB)+G*(1.0-EXP(-1.0/EKB)) \qquad \text{(Eqn. 75)}$$

where BFP is the value of BF in the preceeding time-interval and EKB is the time-constant in days.

3.9.5 The evapotranspiration function

Evapotranspiration demands are met first at the potential rate from the upper zone storage and a fraction of the remainder (EA) is met from the lower zone storage in proportion to the lower zone storage ratio,

$$EA = EP*(LZR/LZM) \qquad \text{(Eqn. 76)}$$

where EP represents the remainder of the evapotranspiration demand.

3.10 List of Parameters and Variables for Model HANS

UZM	Maximum capacity of the upper soil storage.
EXC	Moisture spillage from the upper soil storage.
OFL	Contribution to overland flow volume.
LZR	Moisture level of lower zone storage.
LZM	Maximum capacity of lower zone storage.

CLO	Dimensionless constant in overland flow function.
COF	Dimensionless constant in overland flow function.
SPS	Overland flow volume for current time-interval.
EKO	Time-constant for overland flow recession.
AINF	Contribution to interflow volume.
UZR	Moisture level in upper soil storage.
CIF	Dimensionless constant in interflow function.
CLI	Dimensionless constant in interflow function.
FIN	Interflow volume for current time-interval.
EKI	Time-constant for interflow recession.
DL	Contribution from infiltration to lower zone storage.
G	Contribution from infiltration to groundwater storage.
BF	Base flow volume for current time-interval.
BFP	Base flow volume for preceeding time-interval.
EKB	Time-constant for base flow recession.
EA	Evapotranspiration from lower zone storage.
EP	Potential evapotranspiration demand.

3.11 The Development of the DALT and DALH Models

The objective in the development of this range of models was to provide a model that could produce output at an acceptable level of accuracy with the least possible complexity of model structure. Such a model would produce the output at the cheapest cost and with the minimum amount of time expenditure by the user. In order to achieve this objective it was decided to choose the simplest of moisture accounting models and to identify the major deficiencies of the model with respect to chosen objective functions. The model could then be modified by increasing its structural complexity until the major deficiencies have been overcome and the model produces results that are at least comparable with the more complex models. The process of selective modification would ensure acceptable output with the minimum of structural complexity.

Perhaps the simplest moisture accounting model is that described by Diskin, Buras and Zamir (1973) which consists of a simple linear storage of finite capacity. This model will be referred to as the Dalton Watershed model and its very simple structure will form a basis for the development of the desired daily model DALT and its hourly counterpart DALH.

3.11.1 The description of model DALT

The operation of the Dalton Watershed Model described by Diskin et al (1973) is very simple as the model has a single linear storage with a finite capacity (SSM) which represents the maximum soil moisture deficiency averaged over the catchment. The soil moisture capacity at any time is given by the storage deficit (SSM-SSL) where SSL is the current soil moisture level. The soil moisture level is increased by the addition of daily rainfall and depleted by daily evaporation (estimates of free water surface evaporation) at the potential rate if there is sufficient moisture in storage. Runoff occurs if the current soil moisture level (SSL) exceeds the maximum level (SSM) and the excess is taken to be runoff for that time-period. This daily model was tested with data from the Ecca catchments using an objective function (described as objective function U7 in the following chapter) that minimizes errors in the mean daily discharge and the standard deviation of daily discharge since this type of objective function represents the most common requirements of a daily input model.

The test of the Dalton Model with Ecca data illustrated a number of deficiencies in the model structure but in making modifications to overcome the deficiencies it was decided that certain restraints should be imposed so as to avoid unnecessary increases in model complexity. The restraints decided upon were that the modifications should not involve the addition of any further storages and that the addition of parameters involved in the calibration process should be kept to a minimum. Within these restraints, any additional function should, as far as possible, have physical relevance. Restricting the model structure to a single storage may appear to be a severe limitation in view of the experience of Manley (1977) who experimented with single, double and triple storage structures and came to the conclusion that a single storage was not able to represent catchment response satisfactorily while the use of three storages gave rise to a degree of complexity which did not seem justified. Nevertheless, it was felt that the restriction of the structure of the DALT model to a single storage was the only effective way of keeping the number of parameters to a minimum and it was decided that the restriction would only be lifted if adequate simulation could not be achieved. The inclusion of each additional storage in model structure gives rise to a marked increase in the number of parameters which would be detrimental to the objective of model formulation since "Keeping the number of parameters as low as possible increases the information content per parameter and therefore allows both a more accurate determination of the parameter and a more reliable correlation of the values obtained with catchment characteristics." (Dooge, 1977, 91).

The first aspect of the Dalton Watershed Model that required modification was the evapotranspiration function. It was felt that the extraction of soil moisture to meet the evapotranspiration demand at the potential rate irrespective of the soil moisture level was not conceptually adequate and that an improvement in the model output could be achieved with the incorporation of a function to estimate actual evapotranspiration. As the model storage ratio is representative of the 'wetness' of the soil, it would be conceptually acceptable to extract moisture at the potential rate when the storage was full, that is at field capacity, and reduce the extraction to zero when the storage was empty (when the soil moisture deficit had reached its maximum). However, the nature of the function that estimates actual evapotranspiration for conditions between these limits is not known. In most moisture accounting models evapotranspiration demands are met at the potential rate from interception, depression and upper soil zone storages but at a fraction of the remaining potential rate from the lower zone storages when the content of the surface and upper zone storages is insufficient to meet the demand (as in models FORD, SMDV, HANS, BERG, PORT and PDAY). The extraction from lower zone storages is usually a function of the remaining potential demand and the state of the storage (often varying linearly with the storage ratio) but in the case of the Dalton Watershed Model, the surface, upper zone and lower zone storages are amalgamated into a single conceptual storage and the nature of a suitable evapotranspiration function must, of necessity, be obtained by experimentation. It was decided that the estimated actual evapotranspiration should be a function of the potential rate (free water surface evaporation) and vary with the state of the storage from the potential rate at a storage ratio of unity to zero when the storage ratio was zero. The assumption that the actual evapotranspiration is equivalent to the potential evapotranspiration (taken as estimated free water surface evaporation) when there is no limitation on the availability of water is the conventional approach adopted. However, Hellwig (1973) found that evaporation from an open water surface was 8 percent higher than that from a water saturated sand. He attributed the difference to higher energy storage in a body of water resulting in a greater temperature gradient between the evaporation surface of the water and the air during the night as compared to a water saturated sand. Morton (1978) has put forward the concept of a complimentary relationship between potential evapotranspiration and the actual evapotranspiration taking place from the catchment surface. The process of evapotranspiration consumes both energy and water thereby cooling and humidifying the air and as a result, reducing the potential evapotranspiration so that it is less than the estimate derived by using pan evaporation. Consequently "Potential evaporation responds negatively to changes in the availability of water for areal evaporation and is, contrary to much current opinion, more an effect than a cause of areal evaporation." (Morton, 1978, 31). However in the absence of any suitable empirical method of reducing the estimated potential evapotranspiration during periods of high moisture availability, the conventional approach has been adopted in model DALT. A number of functions operating between the limits of potential rate and zero were tried and have been plotted in Figure 45 to illustrate the wide range of curves that result. All the functions give the actual demand as a fraction (PRE) of the potential demand where;

(A) PRE = RAT**0.5 (Eqn. 77)

(B) PRE = (RAT**2.0)/((RAT**2.0)+(1.0-RAT)**2.0) (Eqn. 78)

(C) PRE = 2.0*(RAT**2.0)*(1.0/(1.0+RAT))**RAT (Eqn. 79)

(D) PRE = 2.0*RAT*(1.0/(1.0+RAT))**RAT (Eqn. 80)

(E) PRE = (RAT**0.5)+((RAT**0.5)-RAT) (Eqn. 81)

(F) PRE = 1.0/((1.0/RAT)**2.0) (Eqn. 82)

(G) PRE = RAT (Eqn. 83)

and where RAT is the storage ratio (SSL/SSM). The best results were obtained by using Equation 81 and this function was incorporated into the Dalton Watershed Model to produce model DALT1 (Figure 46).

Although the modification in model DALT1 provided an improvement

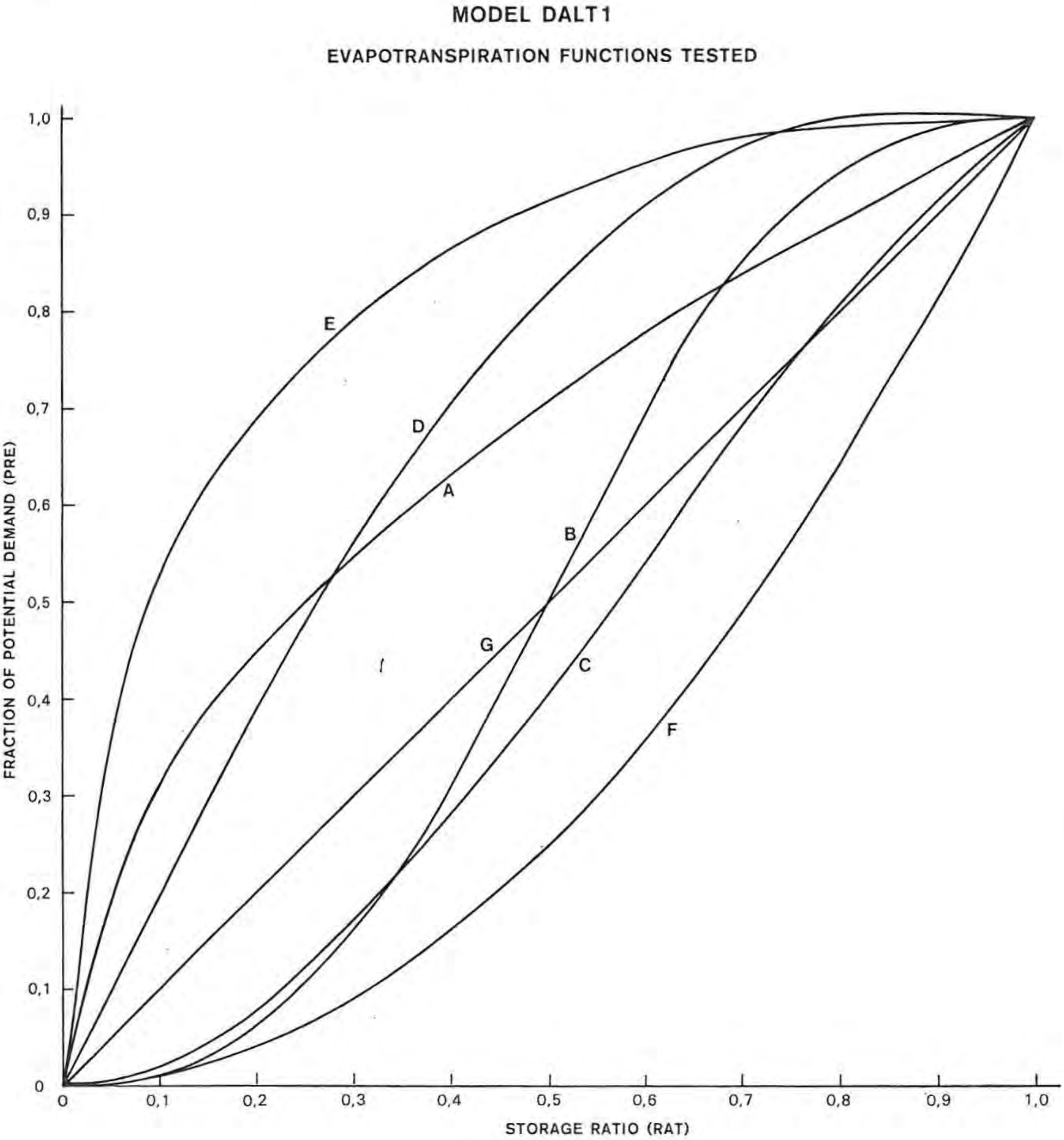
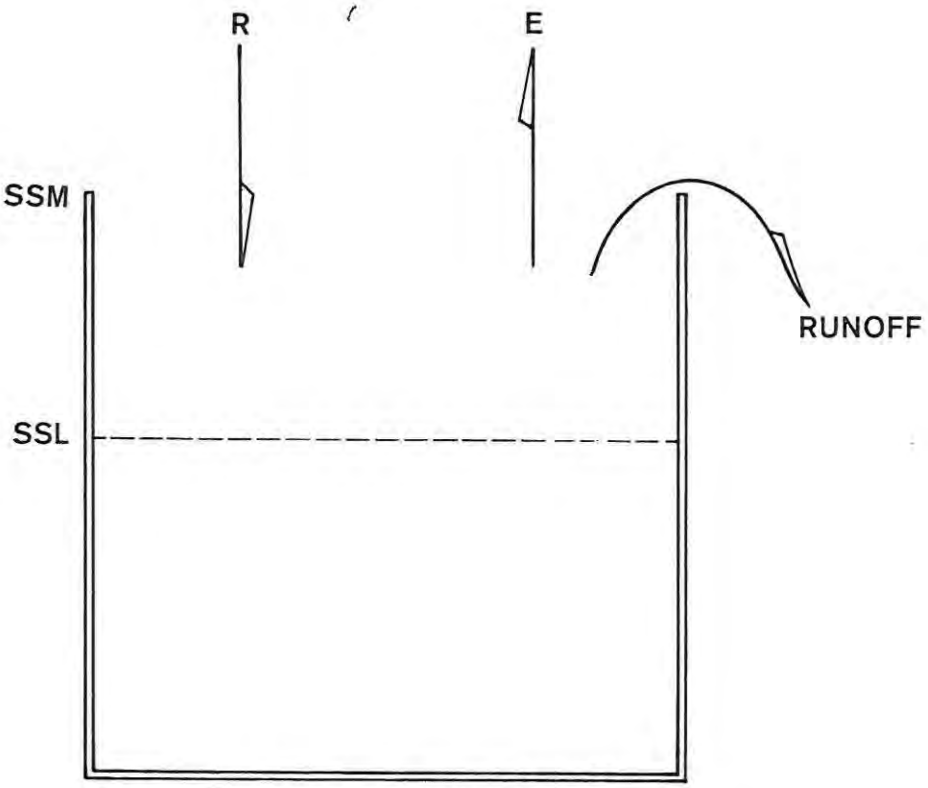

MODEL DALT1
EVAPOTRANSPIRATION FUNCTIONS TESTED
FRACTION OF POTENTIAL DEMAND (PRE)
STORAGE RATIO (RAT)
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
A
B
C
D
E
F
G

FIGURE 45

MODEL DALT1



$$\mathrm{RAT} = \mathrm{SSL} / \mathrm{SSM}$$

$$\mathrm{PRE} = (\mathrm{RAT} \ast\ast \; 0{\cdot}5) + ((\mathrm{RAT} \ast\ast \; 0{\cdot}5) - \mathrm{RAT})$$

$$\mathrm{EP} = \mathrm{EP} \ast \mathrm{PRE}$$

FIGURE 46

in the simulated discharge it was clear that the major deficiency still to be overcome was the lack of a base flow component in the model structure. The lack of base flow results in a marked exaggeration of the variance since the discharge during flood periods must be exaggerated to incorporate base flow volumes (that are not simulated) in the days following flood periods if the mean discharge is to be accurately simulated. It was evident that the incorporation of a base flow function would give the greatest improvement in the model performance with respect to the chosen objective function.

The chosen modification of model DALT1 to incorporate a base flow function is based on the observation that rainfall (of insufficient intensity to exceed infiltration capacity) on a 'dry' catchment does not always result in an increase in base flow despite the fact that the same rainfall event on a 'wet' catchment would produce a marked increase in discharge. The implication is that there is some level of soil moisture below which no percolation to groundwater takes place until such time as the moisture level has been exceeded. To simulate this effect an additional parameter was introduced (SSB) to represent the soil moisture level below which no increments to base flow are calculated, that is, base flow from the storage is only calculated when SSL exceeds SSB. Unfortunately no satisfactory guide can be given for the estimation of a value for parameter SSB and the value must be estimated during the optimization process. A suitable method of calculating the contribution to base flow in each time-interval would be to relate the contribution to the available moisture in storage (SSL-SSB) and to route the contribution to channel flow on succeeding days by exponential decay of a groundwater storage of infinite size. However the adoption of this approach would necessitate a departure from the single storage concept. An alternative is to direct the contribution for each time-interval directly to channel storage in a one-step rather than a two-step process and consequently the nature of the function must be of a form that will permit approximation of exponential decay in contributions so as to accomodate the characteristic exponential decay of base flow in the river channel. It was found by trial and error that the desired effect could be obtained with a single additional parameter by relating the contribution to the moisture 'head' above threshold (SSL-SSB) and the difference in the soil storage level to capacity and threshold to capacity ratios ((SSL/SSM)-(SSB/SSM)). The actual contribution to base flow (BF) when SSL exceeds SSB is taken as

BF = (SSL-SSB)*((SSL/SSM)-(SSB/SSM))**POWER (Eqn. 84)

where POWER is a positive dimensionless constant that controls the base flow recession rate. The base flow contribution (BF) as a function of the excess soil moisture above threshold (SSB) has been plotted in Figure 47 for various values of POWER to show the way in which recession may be controlled. The function does not involve the creation of a separate groundwater storage but as a result the parameter POWER cannot be obtained directly from observed hydrographs. However, it will be possible to relate POWER to the normally used 24 hour recession constant when the model is tested in a variety of catchments. The function was incorporated in model DALT1 to produce model DALT2 (Figure 48) and was found to produce a very marked improvement in model performance. A soil moisture threshold level that is conceptually similar to the parameter SSB has been incorporated into recent modifications (models 12 and 15) of the Dalton Model by Diskin and Simon (1977) with the objective of calculating percolation loss from the soil storage but in both models 12 and 15 the percolation is merely regarded as a loss from soil storage and does not

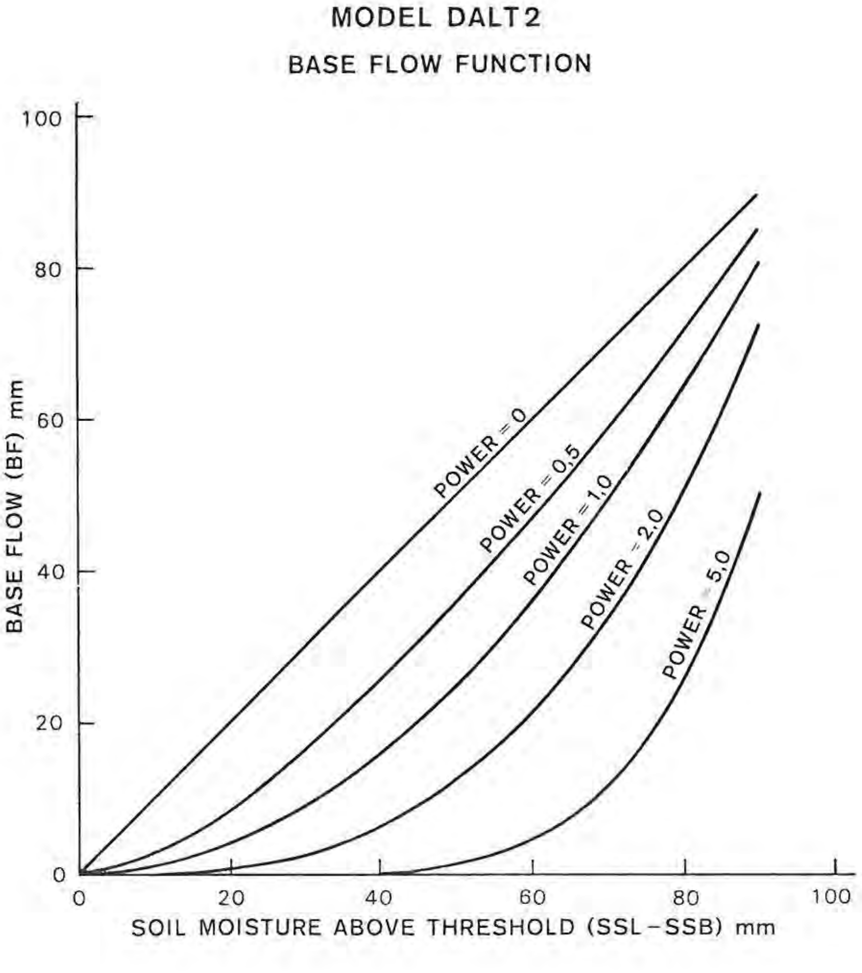

MODEL DALT2
BASE FLOW FUNCTION
BASE FLOW (BF) mm
0
20
40
60
80
100
SOIL MOISTURE ABOVE THRESHOLD (SSL-SSB) mm
0
20
40
60
80
100
POWER = 0
POWER = 0.5
POWER = 1.0
POWER = 2.0
POWER = 5.0

FIGURE 47

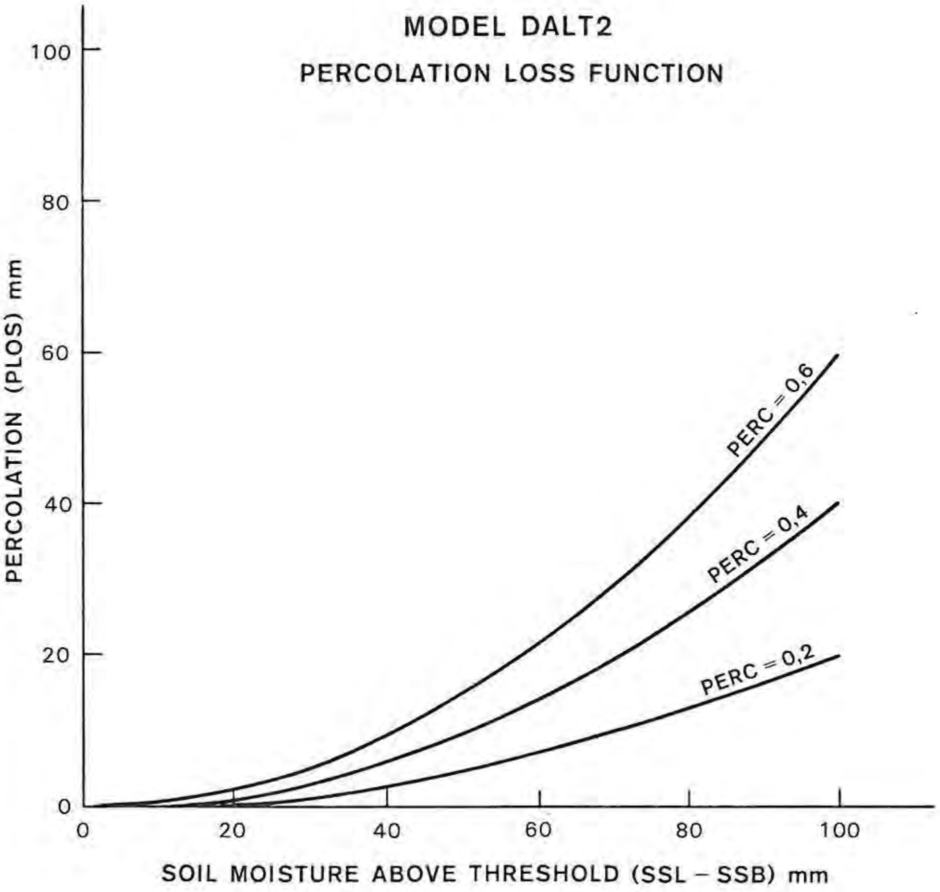

MODEL DALT2
PERCOLATION LOSS FUNCTION
PERCOLATION (PLOS) mm
0
20
40
60
80
100
SOIL MOISTURE ABOVE THRESHOLD (SSL – SSB) mm
0
20
40
60
80
100
PERC = 0,6
PERC = 0,4
PERC = 0,2

FIGURE 48

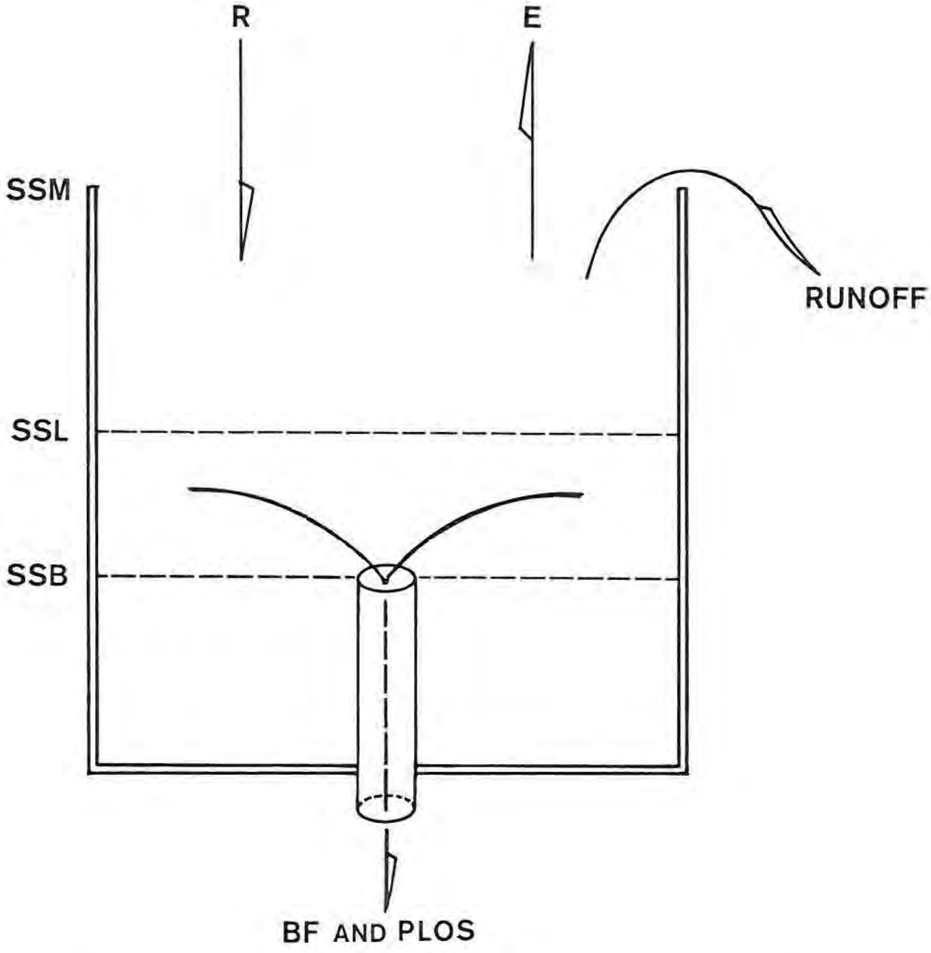
accrue to base flow.

In view of the fact that the single evapotranspiration function in model DALT2 is the only function that can account for moisture losses other than discharge, there is a need for a function that can account for the other forms of moisture loss such as deep percolation and subsurface drainage below the measuring structure. Deep percolation in this context refers to moisture that is 'lost' from the catchment by deep drainage that does not contribute to channel flow and is accomodated in many conceptual models as inactive groundwater or underflow (Crawford and Linsley, 1966; Claborn and Moore, 1970). However the term deep percolation in some models (such as those of Dawdy and O'Donnell, 1965; Bowles and Riley, 1976 and Krzysztofowicz and Diskin, 1978) refers to moisture contributing to active groundwater storage and reaches the stream channels as base flow. It was felt that in terms of deep percolation, the additional moisture loss (PLOS) would increase with increasing soil moisture content above threshold (SSB) until a maximum was reached where the maximum would be a relatively small percentage of the moisture available. The following function was developed for incorporation into model DALT2;

$$PLOS = (SSL-SSB)*((SSL-SSB)/(SSM-SSB))*PERC \qquad \text{(Eqn. 85)}$$

where the parameter PERC is a positive dimensionless constant less than or equal to unity and represents the maximum fraction of soil moisture above threshold (SSL-SSB) that can accrue to percolation under saturated conditions (when SSL = SSM). The percolation as calculated by Equation 85 has been plotted against soil moisture above threshold (SSL-SSB) for various values of PERC in Figure 49. The percolation loss (PLOS) is subtracted from the soil storage level before the contribution to base flow is calculated thus adding greater flexibility to the base flow and moisture loss components. As a deep percolation component is

MODEL DALT2



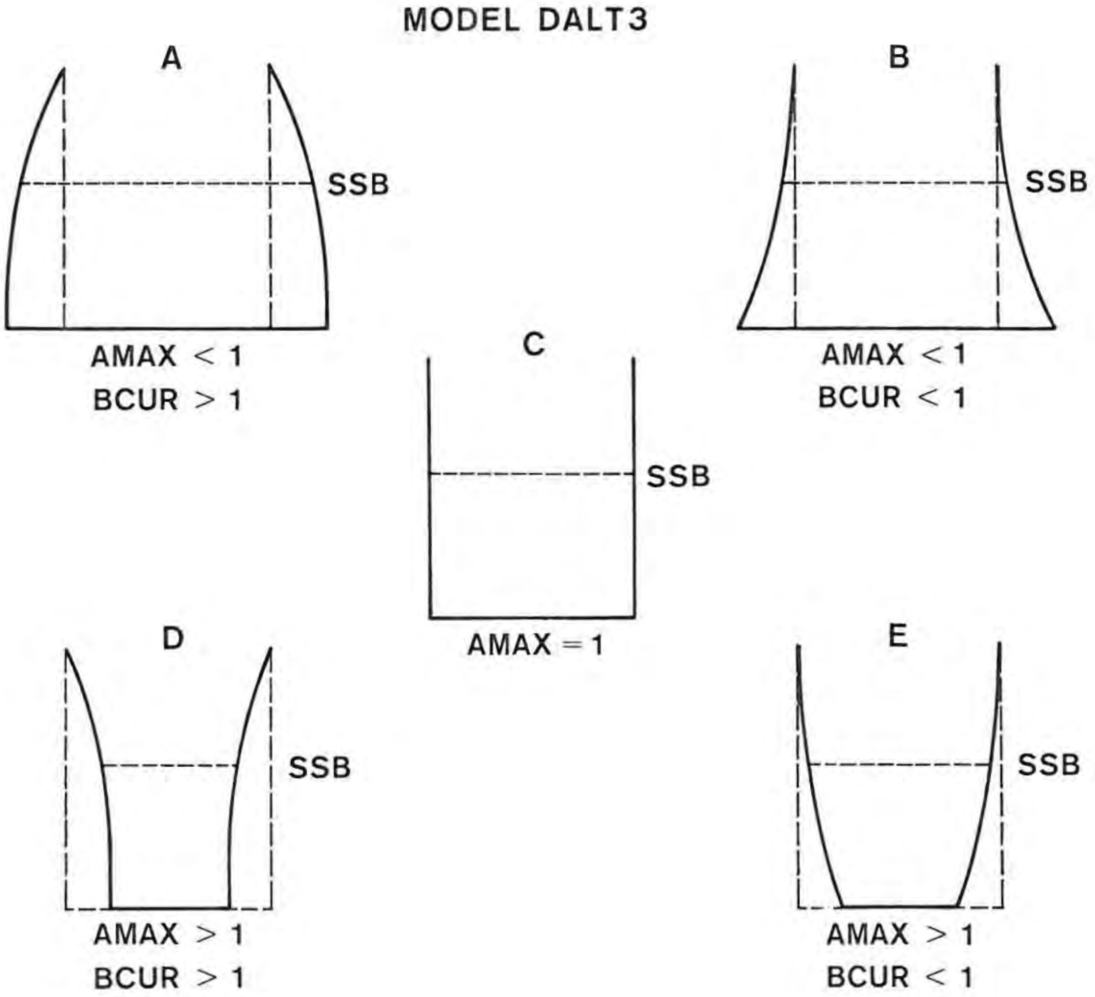
BF = (SSL − SSB) * (((SSL / SSM) − (SSB / SSM)) ** POWER)

FIGURE 49

not always essential for adequate representation of soil moisture levels, the parameter PERC may often be set to zero thus reducing the number of parameters involved in the calibration process. Parameter PERC was set to zero for all calibration runs in the Ecca catchments but the percolation function was incorporated into the structure of the model in anticipation of the loss rate function (evapotranspiration function) being inadequate for other hydrological regimes. An alternative approach that could have been adopted in the calculation of moisture loss is the amalgamation of evapotranspiration and deep percolation losses into a single lumped loss rate function. Krzysztofowicz and Diskin (1978) developed a highly flexible, single parameter, lumped loss rate function for calculating rainfall loss and a similar approach could have been adopted for the DALT model but the advantage of having a single parameter is offset by the fact that the parameter has little physical relevance.

A comparison of the performance of models DALT1 and DALT2 with other more complex models in Chapter 4 will show that model DALT2 provides results for the Ecca catchments that are competitive with those of the more complex models and as such the objective in the development of a simple model has been reached. However, it was felt that model DALT2 may not be sufficiently flexible to be competitive in a wide range of hydrological regimes and therefore a further modification (discussed below) would be necessary to overcome what is deemed to be the next most important deficiency in the model structure.

In moisture accounting models a large part of the non-linearity of the rainfall-runoff relationship is accounted for by the use of highly non-linear functions that govern the movement of moisture between storages. As model DALT2 consisits of a single linear storage it is limited in the degree of non-linearity of response that it can accomodate and this aspect is regarded as the next most serious deficiency of the model. As one of the constraints in the development of the model is that it should be restricted to a single storage model, the non-linearity of response provided by non-linear functions controlling movement of moisture between linear storages can only be compensated for by using a non-linear storage in DALT2, that is, to use a non-linear depth response function. It would be very difficult to give physical relevance to a non-linear depth function and consequently it would be difficult to provide a guide to parameter values but if the function can be kept relatively simple it would add tremendous flexibility to the model. An examination of the output from model DALT2 for the Ecca catchments showed that the desired value of base flow threshold (SSB) is higher during flood periods than the value required to initiate base flow in dry periods when rainfall has been insufficient to provide surface runoff. In order to obtain better results it would be necessary to exaggerate the soil moisture level response to rainfall during dry periods so that the soil moisture level exceeds the threshold more often. This effect can be achieved if the conceptual two dimensional rectangular representation of the linear storage is replaced by a 'bowl shaped container' as in Figure 50 (E) which would provide a greater increase in storage level for unitary input when empty than it would when nearly full. Such a 'container' would have a non-linear depth response function that would provide linear response when the storage is full and increasing exaggeration of response in moisture level as the storage ratio decreases. It should be noted that the chosen evapotranspiration function incorporated in model DALT2 does help to provide the desired control over the soil storage level by reducing the decrease in soil moisture during drier periods but the effect is limited. Although the function corresponding to the bowl shaped storage described above is the desired function



FAT = AMAX − ((AMAX − 1·0) * ((SSL / SSM) ** BCUR))

FIGURE 50

in the case of the Ecca catchments it may not be suitable for all catchments and consequently the non-linear depth function incorporated must be sufficiently flexible to provide a wide range of conceptual storage 'containers' but still be kept simple in form. After developing and experimenting with various forms of non-linear depth response functions the following function was adopted for incorporation in model DALT2 to produce model DALT3 (Figure 50);

$$\mathrm{FAT = AMAX-((AMAX-1.0)*((SSL/SSM)**BCUR))} \qquad \text{(Eqn. 86)}$$

where FAT is the factor by which the addition or subtraction to the storage is multiplied before adjusting the storage level. The input parameter AMAX sets the maximum exaggeration of storage level (when the storage is empty) and the input parameter BCUR controls the rate at which the exaggeration of soil moisture level decreases with increasing storage ratio. The parameters AMAX and BCUR are positive dimensionless constants and can be manipulated to give a wide range of values corresponding to an assortment of conceptual 'containers' as shown by the selection of 'containers' in Figure 50. The curves of FAT plotted against the storage ratio shown in Figure 51 correspond to the conceptual 'containers' in Figure 50.

The use of an exaggerated soil moisture level leads to the danger of violating the principles of moisture accounting and to prevent the model either creating or destroying moisture, the soil moisture level obtained by the use of a non-linear depth response function is referred to in the model as the pseudo-level of soil moisture (PSL). The pseudo-level (PSL) is operated in conjunction with the 'real' soil moisture level (SSL) so that SSL represents the state of the storage for moisture accounting at all times.

The improvement in model performance resulting from the incorporation of the non-linear function will be illustrated in Chapter 4.

It was found by experimentation that a further improvement of the results given by model DALT3 could be achieved if the non-linear depth response function was restricted to soil moisture levels below the base flow threshold SSB and the model in this form is referred to as DALT4. The non-linear depth response factor FAT in model DALT4 appears as

FAT = AMAX-((AMAX-1.0)*((SSL/SSB)**BCUR)) (Eqn. 87)

and the representation of the desired storage for the Ecca catchments is shown in Figure 52.

For any particular engineering application, it is unlikely that the model user would know in advance which of the models (DALT1, DALT2, DALT3 or DALT4) is the most suitable and consequently the four models have been incorporated into a single computer program called DALT (Appendix A) and the user is free to select any one of the models simply by setting the program control flags. If it is found that the simplest model (DALT1) does not provide output at an acceptable level of accuracy for the application in mind, the model complexity may be increased progressively by using the control flags. Hence the necessity of changing to another model, with a completely new set of parameters and the associated escalation of calibration costs, may be avoided.

In summary, the four models run by program DALT are referred to as;

(1) DALT1, a simple linear storage model as described by Diskin et al (1973) but with a modified evapotranspiration function,

(2) DALT2, is model DALT1 with a base flow function and an optional deep percolation function,

(3) DALT3 is a single non-linear storage model with the same evapotranspiration, base flow and deep percolation functions as DALT2, and a non-linear depth response function that is operative over the full range of storage values,

MODEL DALT3

NON-LINEAR DEPTH RESPONSE FUNCTION

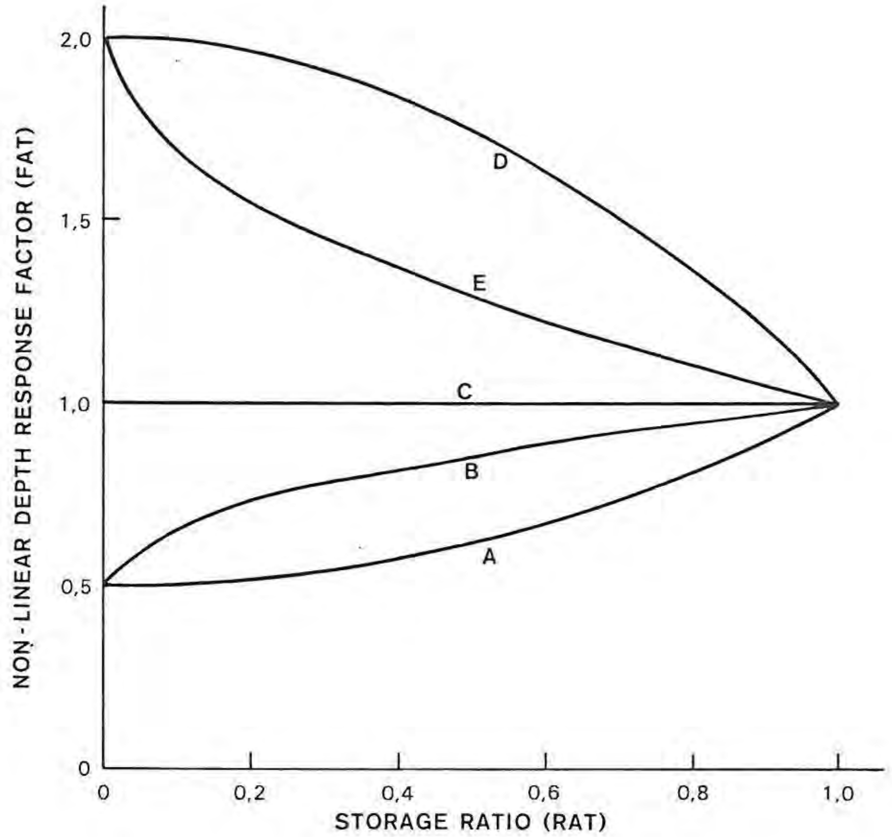
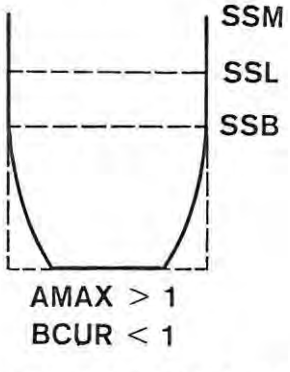


FIGURE 51

MODEL DALT4



$AMAX > 1$

$BCUR < 1$

$FAT = AMAX - ((AMAX = 1{\cdot}0) * ((SSL / SSB) ** BCUR))$

FIGURE 52

(4) DALT4 is model DALT3 with the non-linear depth response function being restricted to storage values below the base flow threshold.

3.11.2 The description of model DALH

The range of objective functions for which the DALT models are applicable was increased by creating a version of program DALT called DALH that will accept hourly rainfall (millimetres) and daily evaporation (millimetres) as input (Figure 53). The resultant hourly models DALH1, DALH2, DALH3 and DALH4 correspond to the daily models DALT1, DALT2, DALT3 and DALT4 respectively and the only changes involved were;

(1) iterations of the model are on an hourly basis,

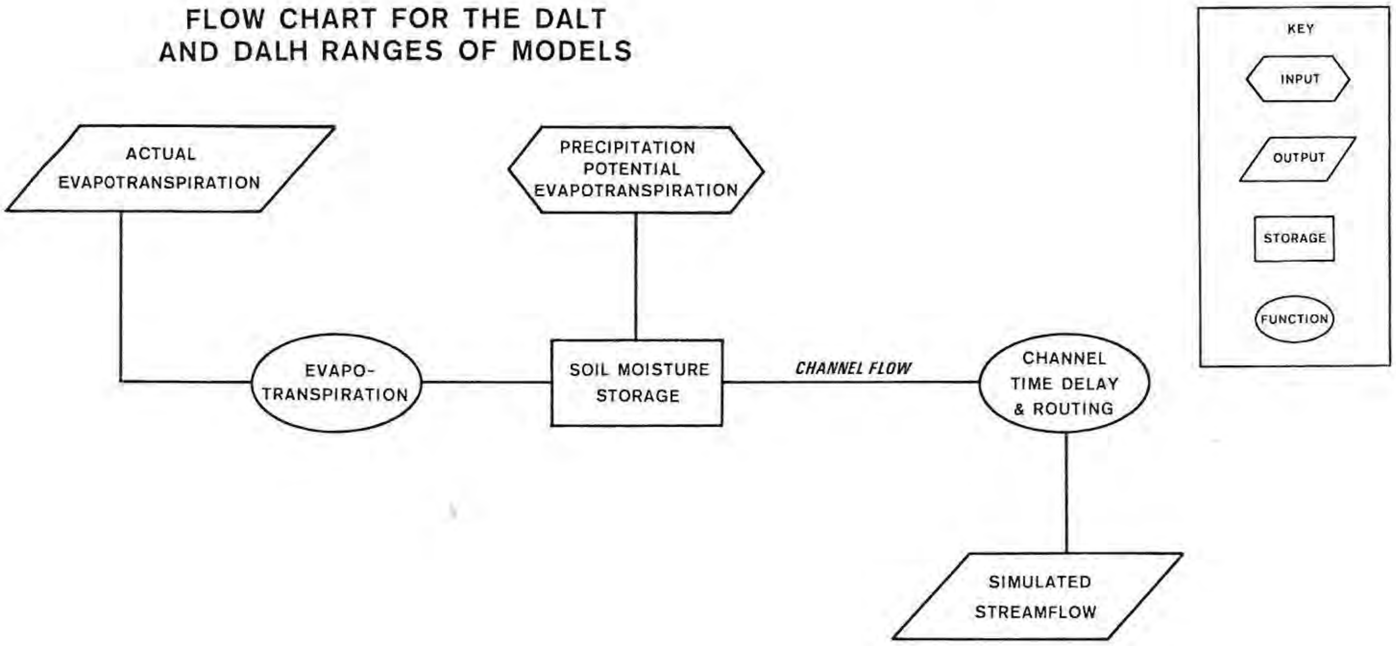
(2) the lag time was changed from days to hours and

(3) the channel inflow hydrograph is attenuated by using the Nash-Muskingum equation to conform with models PORT and BERG.

The output derived from the DALT and DALH models will be compared with that from the other models in the following chapter to illustrate the extent to which each level of modification (with the exception of the deep percolation function which was not used) is justified in terms of the increase in accuracy of the simulated discharge.

3.12 List of Parameters and Variables for Models DALT and DALH

SSM	Maximum capacity of the storage.
SSL	Level of moisture in storage.
PRE	Fraction used to estimate actual evapotranspiration from potential evapotranspiration.
RAT	Storage ratio.
SSB	Threshold level of storage below which no percolation to base flow takes place.
POWER	Exponent in the base flow function.
PLOS	Moisture lost from catchment due to deep percolation.
PERC	Deep percolation parameter.



FLOW CHART FOR THE DALT AND DALH RANGES OF MODELS

FIGURE 53

FAT	Non-linear storage depth response factor.
AMAX	Parameter controlling maximum exaggeration in non-linear response of storage level.
BCUR	Parameter relating exaggeration of response to storage ratio.
PSL	Pseudo-level of soil moisture.

CHAPTER 4

A COMPARISON OF MODEL PERFORMANCE

4.1 Introduction

The first three aims of the research project incorporate the selection of a number of models from the literature, the identification and correction of obvious deficiencies in the models and the comparison of their performance with respect to selected objective functions. The comparison of model performance would not only permit an assessment of each progressive step in the development of the DALT model (as embodied in the fourth aim) but would also determine whether or not models of complex structure provide superior output with respect to common engineering requirements of the output as compared with the simpler models. The cost of producing output at an acceptable level of accuracy and the time involved are major considerations for the practising engineer or hydrologist, especially when the sophistication of, and access to, computer facilities is limited and the user is paying commercial rates for computer time. In order to provide the user with some guide to model selection, the performance of the models will be compared with respect to the level of accuracy attained for selected objective functions in conjunction with the complexity of the model (in terms of both structure and input requirements) which to a large extent defines both the number of calibration runs required and the cost of each run.

There is some doubt as to whether the length of available input data record (one and a half years) is sufficient to conduct a thorough test of a model's performance with respect to any objective function but as the record covers a number of wet and dry periods it is felt that the record is adequate for relative comparison of model performance as each model will be calibrated with the same data set.

Whether or not the resulting parameter set for any one model would be truly representative of the hydrological regime is not known since the adequacy of record length for model calibration is likely to depend on the nature of the objective function used as well as the sensitivity of the model parameters. Haan (1972, 1387) has stated that; "The adequacy of record length for determining model parameters cannot be determined without knowing the purpose of the model and the consequence of various magnitudes of incorrect estimates." Although some doubt has been expressed about the adequacy of the record length for testing individual models in the Ecca catchment, it should be noted that Manley (1977) calibrated his hourly model with 3 months data and then with 12 months data. He found so little change in the second calibration that a third calibration with 2 years data was abandoned.

During March 1976 the first flood was recorded in the Ecca catchment area and whereas a single flood event is inadequate for extensive testing of even the hourly input models, much information could be obtained by calibrating the hourly models with the available data. The alternative was to wait for an unknown period of time (which could extend for several years) until at least one more flood event was recorded. It was appreciated at the time that the set of parameter values for a model obtained by calibration with a single month of hourly values would be unlikely to represent the optimum parameter set for the model that incorporates the long term variation of soil moisture conditions. It would be of interest, however, to note the extent to which the parameter set must be changed when more data become available as this process would provide the user with information as to the minimum length of record required for model calibration. The second objective would be to determine to what extent the hourly models are able to reproduce a single flood hydrograph with the starting conditions being optimized rather than generated by a long 'warm-up' period. The use of hourly input models to generate single flood events is probably the most common use of such models in flood warning and reservoir operation procedures. The use of hourly models to generate long records becomes very costly, for example a record of only 10 years would involve in excess of 87 000 iterations of the model.

4.2 The Choice of the Objective Function

As the aim is to assess the degree to which the hourly models are able to reproduce a flood hydrograph, the objective function to be minimized during the calibration process should be a measure of the one-to-one correspondence between simulated and observed hourly flows. It was decided to use the well known product moment correlation coefficient (r) as the measure of the one-to-one correspondence but the correlation coefficient would not reflect systematic errors in the model output. For example, if the simulated flows were always less than the observed flows by a constant amount, a correlation of unity would result but the simulated record would be of little practical use. To overcome this problem the regression equation was also calculated to indicate the presence of systematic errors where the presence of the errors could be judged from the deviation of the regression coefficient from unity and the deviation of the base constant (of the regression equation) from zero. In addition the logarithmic values of simulated and observed flows were used in the calculation of the correlation coefficient and regression equation so as to avoid giving too much weight to the flood peak. As the ability of the model to reproduce the entire hydrograph is being examined the base flow recession should be equally important as the peak. Since a correlation coefficient in the absence of systematic error reflects a higher level of accuracy of output than an equivalent correlation coefficient with systematic error present, the correlation coefficient, regression coefficient and base constant of the regression equation must be combined in some way to form the objective function. The three values were combined as follows;

$$U1 = r-(ABS(1,0-ABS(b))+ABS(a)) \qquad \text{(Eqn. 88)}$$

where U1 is the objective function to be optimized (to unity) during calibration, (r) is the product moment correlation coefficient, (b) is the regression coefficient and (a) is the base constant of the regression equation. The absolute values of the deviation of (b) and (a) from their desired values were used to prevent the objective function approaching the value of the correlation when the mean of the deviations approached zero. It is feasible to use the value of U1 in Equation 88 as a means of comparison of model performance in this case where the use of logarithmic values of observed and simulated flows and the magnitude of the flow values give the base constant (a) a value of the same order of magnitude as (b) and (r). In other cases the value of (b) may carry so much weight as to make U1 insensitive to the value of the correlation coefficient (r). A more sophisticated measure of one-to-one correspondence that is sensitive to systematic error, the coefficient of efficiency, has been used recently by other investigators for this purpose (Nash and Sutcliffe, 1970; Aitken, 1973; Manley, 1977 and Pitman, 1977) and both statistics will be used for the longer term data as a comparison later in this chapter.

4.3 Comparison of Performance of Hourly Models with Short Term Data

The hourly input models FORD, PORT, BERG and 3 versions of model DALH were calibrated in all five catchments with hourly rainfall and daily evaporation data for the month of March 1976. A flood event occured on the 20th March which gave approximately 480 iterations of the model as a 'warm-up' period before the flow event took place (recording began during late February), and flow was recorded in all the gauged catchments. Only the results for the Ecca catchment as a whole (measured at Q9M20) will be used for the comparison of model performance in this chapter and the results for the remaining catchments will be discussed in the parameter transfer section of Chapter 5.

During the calibration of the six chosen hourly models for the main catchment at Q9M20 with a single month of input data the calibration process was continued until it became evident that little further improvement in the objective function could be obtained. This process is, of necessity, subjective in nature and the final accepted value of the objective function depends to a certain degree on the skill and experience of the operator so that the accepted value of the objective function is not necessarily 'the best' output that the model could provide with respect to the objective function using the input data available. It was found, with model FORD for example, that similar levels of output could be obtained using different parameter sets. It is likely that the deviation of the accepted output from the 'best' output would increase with complexity of model structure (because the interaction between parameters is so complex) and with decreasing length of input data record because there is less confidence that the parameter values obtained are representative under the full range of antecedent conditions. However, in view of the fact that all the models were calibrated by the same operator after gaining an understanding of the internal workings of the models, there exists a good basis for comparison.

The accepted values of the objective function U1 for the models are set out in Table 7 which illustrates that if model DALH1 is to represent the simple models, then the performance of the models may

TABLE 7

COMPARISON OF HOURLY MODELS WITH SHORT TERM DATA FOR CATCHMENT Q9M20

MODEL	CORRELATION COEFFICIENT	REGRESSION COEFFICIENT	BASE CONSTANT	U1	RANK U1
FORD	0,93	1,00	0,14	0,79	2
PORT	0,92	1,00	0,16	0,76	3
BERG	0,40	0,20	0,03	-0,43	5
DALH3	0,98	0,93	0,03	0,88	1
DALH2	0,91	0,84	0,02	0,73	4
DALH1	0,35	0,14	0,05	-0,56	6

All correlation coefficients significant at the 0,95 level.

be ranked in descending order as FORD, PORT, BERG and DALH1 which coincides with the order of model complexity, that is, the models with the more complex structure give the best results. The values of the objective function U1 for models BERG and DALH1 are markedly inferior to those for FORD and PORT mainly because their structure is not suited to the requirements of the objective function. The two simple models produced the peak value accurately but the absence of a base flow function in both models gave rise to the introduction of strong systematic errors in the output as illustrated by the depressed values of the regression coefficient. The performance of model DALH1 was improved markedly by the inclusion of a base flow function in DALH2 and the value of U1 obtained is competitive with that of FORD and PORT. The addition of a non-linear depth response function as well as a base flow function in model DALH3 improved the value of U1 still further to give the best overall result of 0,88. In summary, the values of the objective function U1 show that all of the models, with the exception of models DALH1 and BERG, have the capacity to adequately reproduce a single flood hydrograph. The decision as to whether the values of U1 represent an adequate level of simulation is subjective and would depend on the nature of the problem being studied. One of the factors to be considered is that the objective function is sensitive to small errors in lag and the requirements of the output may allow a greater level of tolerance in the timing of the flood peak.

The advantage of using a simple model like DALH2 or DALH3 as opposed to a complex model like FORD is illustrated by Table 8 in which the models have been ranked in order of the cost involved in producing the accepted output. It is evident that the number of parameters that are involved in the calibration process (excluding parameters such as catchment area, evaporation constants and starting

TABLE 8

COST FACTORS FOR SHORT RECORD CALIBRATION (Q9M20)

MODEL	NO OF RUNS	MILL SECS PER RUN	TOTAL MILL TIME	CORE REQUIRED	NO OF PARAMETERS	RANDS (@ 9c PER MILL SEC)
FORD	35	309	10 815	33	20	973
PORT	28	112	3 136	11	15	282
BERG	18	70	1 260	10	7	113
DALH3	6	110	660	14	6	59
DALH2	5	110	550	14	4	49
DALH1	3	110	330	14	2	29
						1 505

values of model variables) is closely related to the number of calibration runs required as well as the number of mill seconds of central processor time used for each run. The number of mill seconds used for each run is somewhat higher than expected for the DALH models because the program gives, in addition to the hourly flows, the hourly values of the storage level as an aid to calibration. Nevertheless models DALH2 and DALH3 have provided output at a competitive level with model FORD but at a fraction of the price and with much less time spent on calibration. The mill seconds of central processor time in Table 8 may be converted to monetary terms to indicate the cost in terms of computer running time to an engineer or hydrologist who has to pay commercial rates. Approximately R0-09 is charged per mill second on the Rhodes University 1900T computer which gives a cost of approximately R1 000-00 for producing one month of hourly flow values for one catchment for model FORD. However the commercial rates charged and the running time vary markedly from one computer system to another so that the difference in cost between models may not be so great on other systems.

4.4 The Comparison of Model Performance with Longer Term Input Data

In February, March and May 1977 a number of flow events were recorded in the Ecca catchments which meant that a record of 15 months data was available for testing the models and the flow data contained two wet periods separated by a dry period of 10 months. The flow events that took place were preceded by a variety of antecedent conditions with flow initiated in some cases by high intensity rainfall on a relatively dry catchment and in other cases by relatively low intensity rainfall of long duration. It was felt that the record was sufficiently long to test the daily models as well as the hourly models.

4.4.1 The choice of objective functions

The objective function U1 used for the hourly models with the single month of input record was considered to be too stringent a test with longer term data. The major requirements of the output for longer records are considered to be the accurate reproduction of flood peaks as well as accurate monthly discharge. With longer records the exact timing of the peak is not very important so that the objective function should be tolerant with respect to small errors in lag. As objective function U1 (a measure of one-to-one correspondence between simulated and observed hourly flows) is highly sensitive to small errors in lag, a new objective function U4 was developed which is a composite objective function based on the combination of U2 and U3 where

$$U2 = \frac{\Sigma \left| VO_i - VS_i \right|}{\Sigma VO_i} \qquad \text{(eqn. 89)}$$

with V being the monthly discharge in thousands of cubic metres and O and S indicating observed and simulated data respectively. The second objective function U3 has been included to reflect errors in flood peaks;

$$U3 = \frac{\Sigma \left| PO_i - PS_i \right|}{\Sigma PO_i} \qquad \text{(Eqn. 90)}$$

where P is the peak flow in any one discreet flood event exceeding a threshold flow level of 0,1 cumecs. As it is the flood peak in each flood event that is of importance the objective function has been designed to eliminate minor secondary peaks in the flood hydrograph as well as minor fluctuations of base flow. Objective functions U2 and U3 have been combined to give objective function U4 so that

$$U4 = U2 + U3 \qquad \text{(Eqn. 91)}$$

and objective U4 was minimized during the calibration of the hourly models.

The production of peak flows with daily input data for daily models is not feasible in small catchment areas where the time of concentration is a fraction of one day and as a result the daily models have been programed to produce daily discharge values. With the output in this form the major requirements of the output for engineering purposes should be accurate reproduction of the mean and standard deviation of daily discharge values. The justification for reproducing the mean and standard deviation accurately lies in the fact that the design of reservoir capacities is dependent on these two statistics (Delleur, Tao and Kavvas, 1976). The fact that the daily models produce output in the form of daily discharge values does not preclude the derivation of instantaneous peak values for design purposes. Use may be made of "...the long known but little used relationship, i.e., the high correlation between flood peaks and the 24 hour flows in which the flood occurs. The daily mean flow, in cubic feet per second, i.e., the total flow volume in the day divided by 24 hr, is highly correlated with the instantaneous peak flow during the day for flood events." (Boughton, 1976, 241).In order to meet this requirement of accurate reproduction of the mean and standard deviation, an objective function U7 was developed for use with the daily models and is a composite of objective functions U5 and U6 where

$$U5 = \frac{MO - MS}{MO} \times 100 \qquad \text{(Eqn. 92)}$$

with M being the mean of the daily discharge values in thousands of cubic metres. The second part of U6 is based on the standard deviation of the daily discharge values (D) where

$$U6 = \frac{DO - DS}{DO} \times 100 \qquad \text{(Eqn. 93)}$$

to give

$$U7 = |U5| + |U6| \ . \qquad \text{(Eqn. 94)}$$

Two additional statistics U8 and U9 were calculated to provide a measure of one-to-one correspondence between observed and simulated daily runoff but they were not used as objective functions during the calibration. They are, however, useful aids to the comparison of model performance. The statistic U8 which incorporates the correlation coefficient and regression equation, has the same form as objective function U1 but daily runoff values in thousands of cubic metres were used instead of the logarithmic values of hourly flow. The statistic U9 is the coefficient of efficiency of model performance (Nash and Sutcliffe, 1970) calculated from daily runoff values and as it is also an index of one-to-one correspondence that is sensitive to systematic errors in the model output, it will provide a check statistic for U8. The calculation of U8 and U9 will determine whether or not it is feasible to use U8 in its present form as a measure of one-to-one correspondence that is sensitive to systematic error. Its advantage over U9 is that both the extent and nature of any systematic error are obtained readily from the regression coefficient and base constant. The statistic U9 has the form

$$U9 = \frac{\Sigma(RO_i - MO)^2 - \Sigma(RO_i - RS_i)^2}{\Sigma(RO_i - MO)^2} \qquad \text{(Eqn. 95)}$$

where R is the daily runoff in thousands of cubic metres, M is the mean daily runoff and O and S represent observed and simulated data respectively. Manley (1977) has recently used the statistic U9 in the form of the reduced error of the estimate ($\sqrt{1{,}0 - U9}$) as an objective function since it is more sensitive than U9 as the value approaches unity. However, the additional sensitivity with the use of daily discharge values was not required in this case.

A comparison of model performance with respect to the eight statistics (U2 - U9) was accomplished by calibrating the hourly and daily models with relevant input data for the period March 1976 to May 1977 inclusive in all five catchments, using U4 as the objective function for the hourly models and U7 as the objective function for the daily models. Each run involved approximately 11 000 iterations for the hourly models and 460 iterations for the daily models.

The comparison of model performance within each model group (hourly or daily) provides an indication of the extent to which increasing complexity of model structure is justified by increasing accuracy in the output. Similarly, a comparison of model performance between the two groups of models provides a valuable guide to the justification of using fine time-intervals for input data, that is, the justification of using an hourly model as opposed to a daily model to produce the required output. During the comparison of model performance using data from the Ecca catchment as a whole (Q9M20), particular attention is paid to the DALH and DALT models to ascertain whether each increase in structural complexity is justified by an improvement in the output and how the output at each level compares with that of the complex models such as FORD and its daily counterpart SMDV.

The values of the statistics obtained by calibrating all the models in catchment Q9M20 are reflected in Table 9(a), and the difference in accuracy provided by the various models may be assessed by reference to the values of each statistic. However, the comparison of model performance is complicated by the large number of models in Table 9(a) and by the fact that not all the statistics have the same optimum value. In order to facilitate the comparison of model performance the value for each statistic in Table 9(a) has been replaced by a rank number in Table 9(b) where the models have been ranked for each statistic in descending order of goodness of fit, that is, the model

TABLE 9(a)

BEST FIT STATISTICS FOR ALL MODELS CALIBRATED IN CATCHMENT Q9M20(LONG RECORD)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	0,31	0,42	0,73	-18,07	-4,44	22,51	0,51	0,88
PORT	0,47	1,58	2,05	-4,61	45,12	49,73	-0,16	0,38
BERG	0,90	0,99	1,89	75,83	77,29	153,12	-0,66	0,15
DALH4	0,32	0,49	0,81	-0,06	-12,37	12,43	0,67	0,93
DALH3	0,31	0,51	0,82	4,29	-11,51	15,80	0,61	0,93
DALH2	0,52	1,51	2,03	-0,98	-52,71	53,69	-0,51	0,62
DALH1	0,59	3,88	4,47	0,03	-80,37	80,40	-0,78	-0,23
Daily								
SMDV	0,21	-	-	-7,59	3,29	10,88	-1,16	0,09
PDAY	0,51	-	-	-0,98	6,24	7,22	-2,20	-0,42
HANS	0,33	-	-	2,84	-3,94	6,78	-1,04	-0,09
DALT4	0,34	-	-	-0,56	-5,51	6,07	-1,03	-0,08
DALT3	0,34	-	-	-0,70	-5,61	6,31	-1,07	-0,08
DALT2	0,46	-	-	-1,02	-26,36	27,38	-1,11	-0,55
DALT1	0,49	-	-	0,14	-148,63	148,77	-1,96	-5,51

TABLE 9(b)

RANKING OF BEST FIT STATISTICS FOR ALL MODELS (CATCHMENT Q9M20)(LONG RECORD)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	2(1)	(1)	(1)	13	3	8	3	3	32
PORT	9(4)	(6)	(6)	11	10	10	4	5	49
BERG	14(7)	(4)	(4)	14	12	14	6	6	66
DALH4	4(3)	(2)	(2)	2	8	6	1	1	22
DALH3	2(1)	(3)	(3)	10	7	7	2	2	30
DALH2	12(5)	(5)	(5)	6	11	11	5	4	49
DALH1	13(6)	(7)	(7)	1	13	12	7	11	57
TOTAL	56			57	64	68	28	32	305
Daily									
SMDV	1	-	-	12	1	5	12	7	38
PDAY	11	-	-	6	6	4	14	12	53
HANS	5	-	-	9	2	3	9	10	38
DALT4	6	-	-	4	4	1	8	8	31
DALT3	7	-	-	5	5	2	10	9	38
DALT2	8	-	-	8	9	9	11	13	58
DALT1	10	-	-	3	14	13	13	14	67
TOTAL	48	-	-	47	41	37	77	73	323

Note: Values in parenthesis are rankings for hourly models only.

that provides the best value for each statistic is given a rank number of one. The rankings clearly illustrate that there is a marked improvement in the output for the range of models DALH1 to DALH4 and for models DALT1 to DALT4 which justifies the increasing complexity of model structure. The only statistic that does not illustrate the improvement is U5 which represents the error in the mean of the daily runoff values. The reason for the lack of improvement in the mean lies in the fact that any model can be manipulated to produce the mean accurately, but with the more complex models a small amount of accuracy in the mean may be sacrificed for a marked improvement in the variance. The rankings in Table 9(b) show that models DALT1 and DALH1 are too simple in structure but DALT2 and DALH2 are more competitive with the more complex models. The models DALH3, DALH4, DALT3 and DALT4 give the best overall results despite the fact that they are far more simple in structure and cheaper to operate than the complex models such as FORD and PORT and their daily counterparts SMDV and PDAY. A visual comparison of the relative performance of the models may be obtained by reference to Figures 54 to 67 inclusive, in which the simulated discharge values have been plotted on a time-scale with the observed daily discharge values. However, the reader should be consciously aware during the visual comparison that the daily discharge values have been plotted on a logarithmic scale (to facilitate the presentation) with the result that the low values of discharge have been greatly exaggerated in comparison with the peak values.

For the purpose of comparing model performance in all five catchments, models DALT2 and DALH2 were chosen to represent the DALT and DALH range of models respectively. The reason for the choice of these two models is that they represent the minimum level of structural complexity to compete with the complex models. The values of the eight statistics

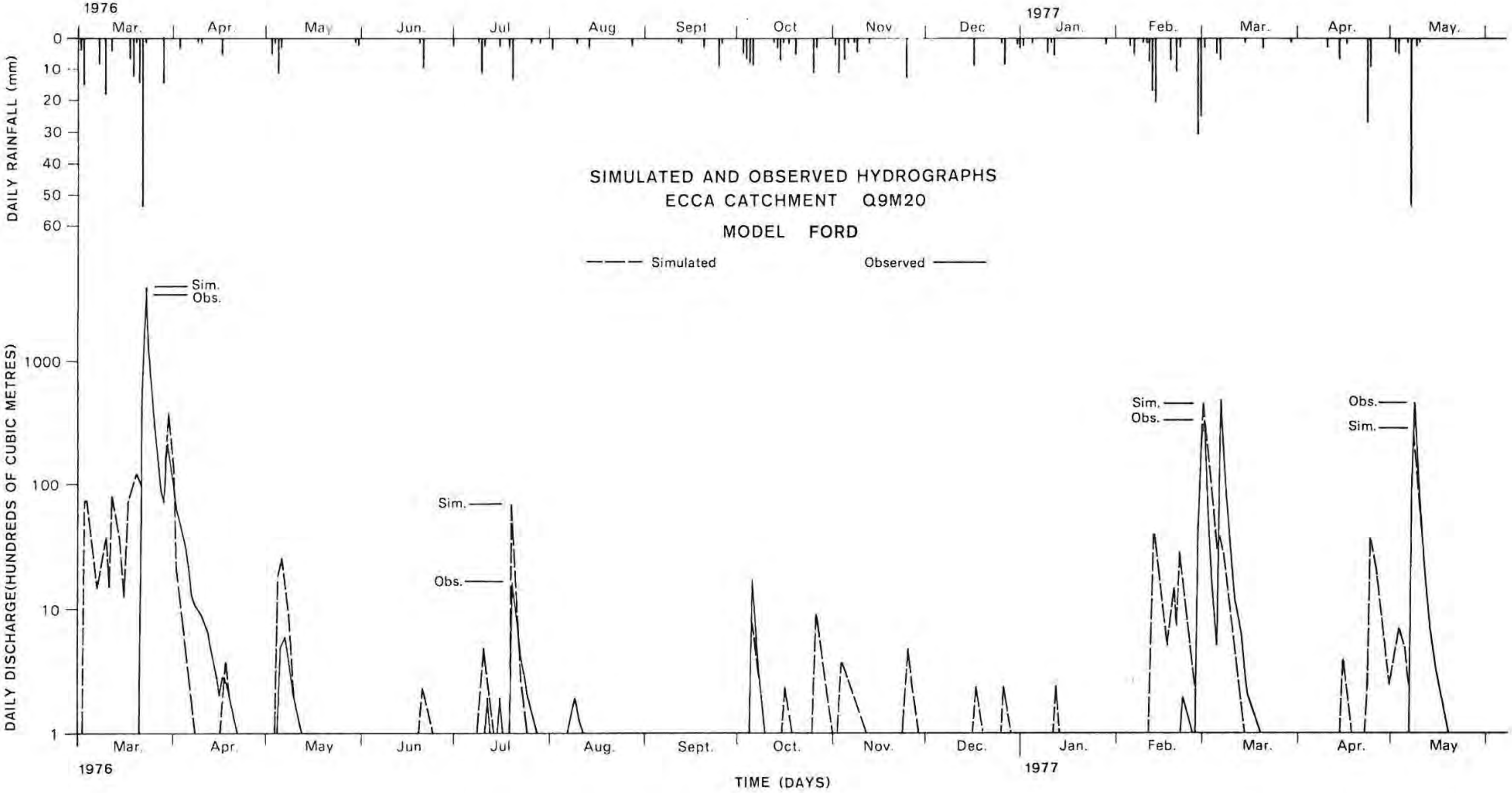

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL FORD
Simulated
Observed
1976
1977
Mar.
Apr.
May
Jun.
Jul
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
Sim.
Obs.
TIME (DAYS)

FIGURE 54

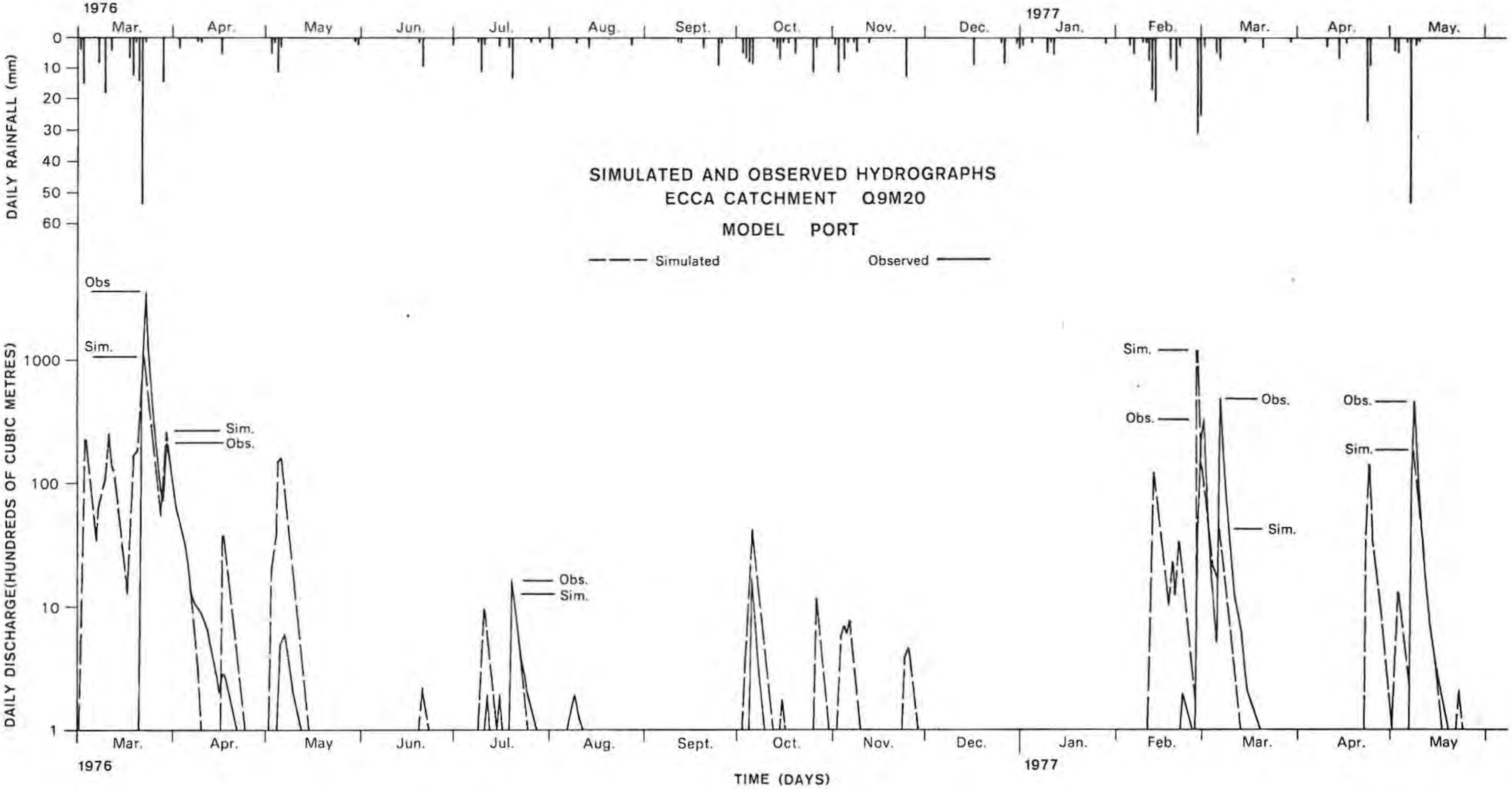

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL PORT
Simulated
Observed
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
Obs
Sim.
Sim.
Obs.
Obs.
Sim.
Sim.
Obs.
Obs.
Sim.
Obs.
Sim.
TIME (DAYS)

FIGURE 55

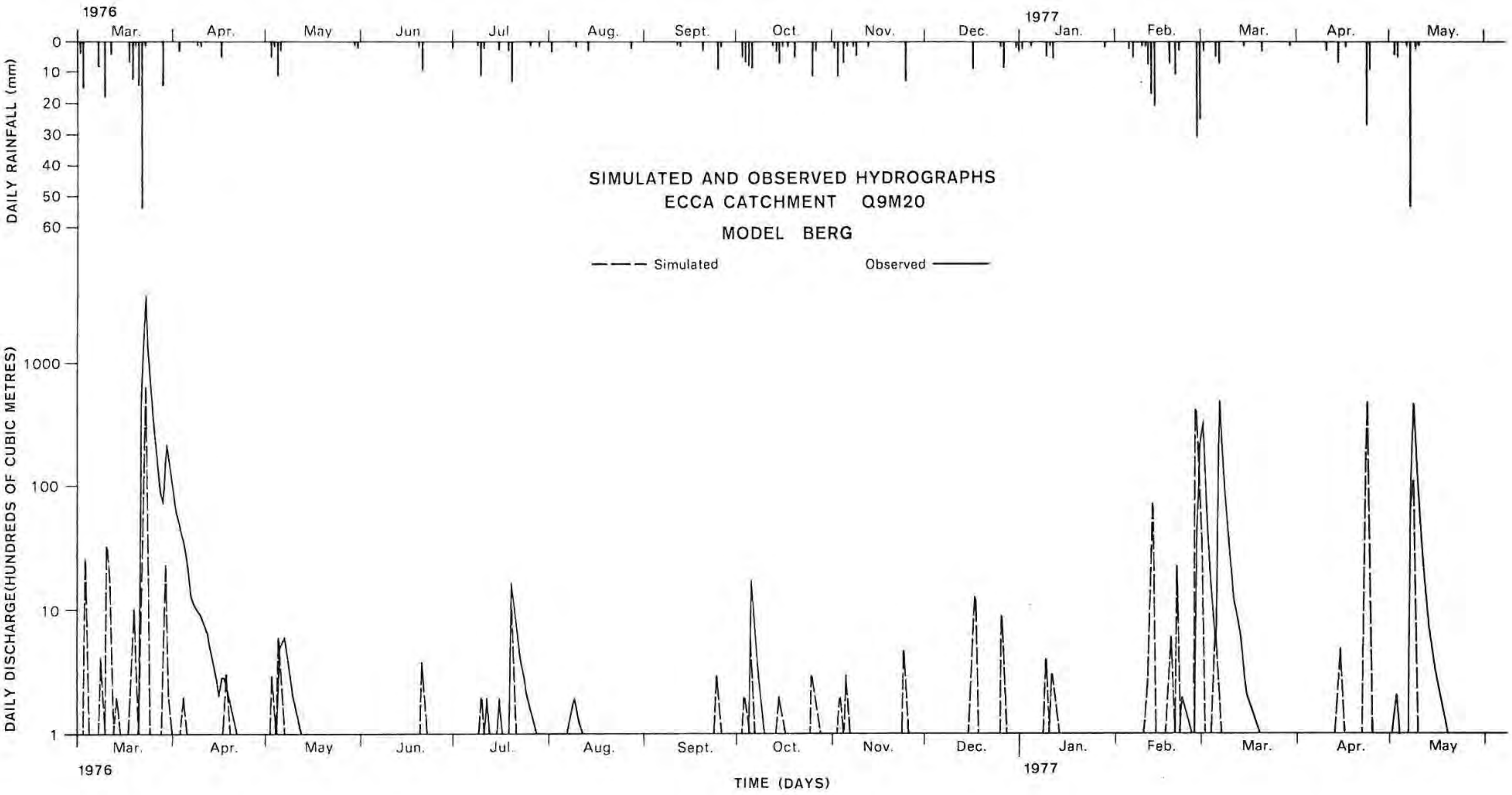

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL BERG
Simulated
Observed
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
1977
Jan.
Feb.
Mar.
Apr.
May
TIME (DAYS)

FIGURE 56

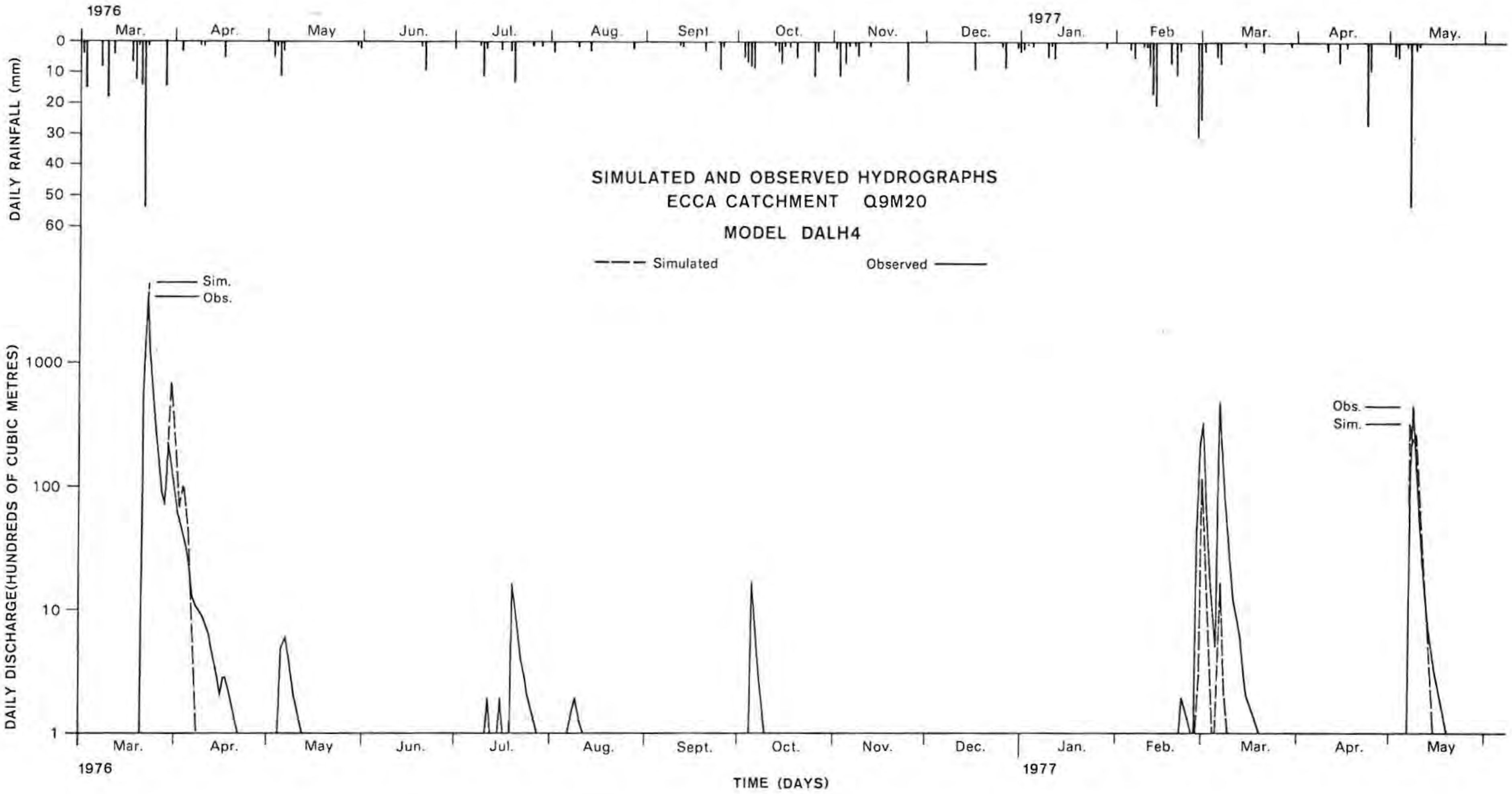

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALH4
Simulated
Observed
Sim.
Obs.
Obs.
Sim.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept
Oct.
Nov.
Dec.
Jan.
Feb
Mar.
Apr.
May.
TIME (DAYS)

FIGURE 57

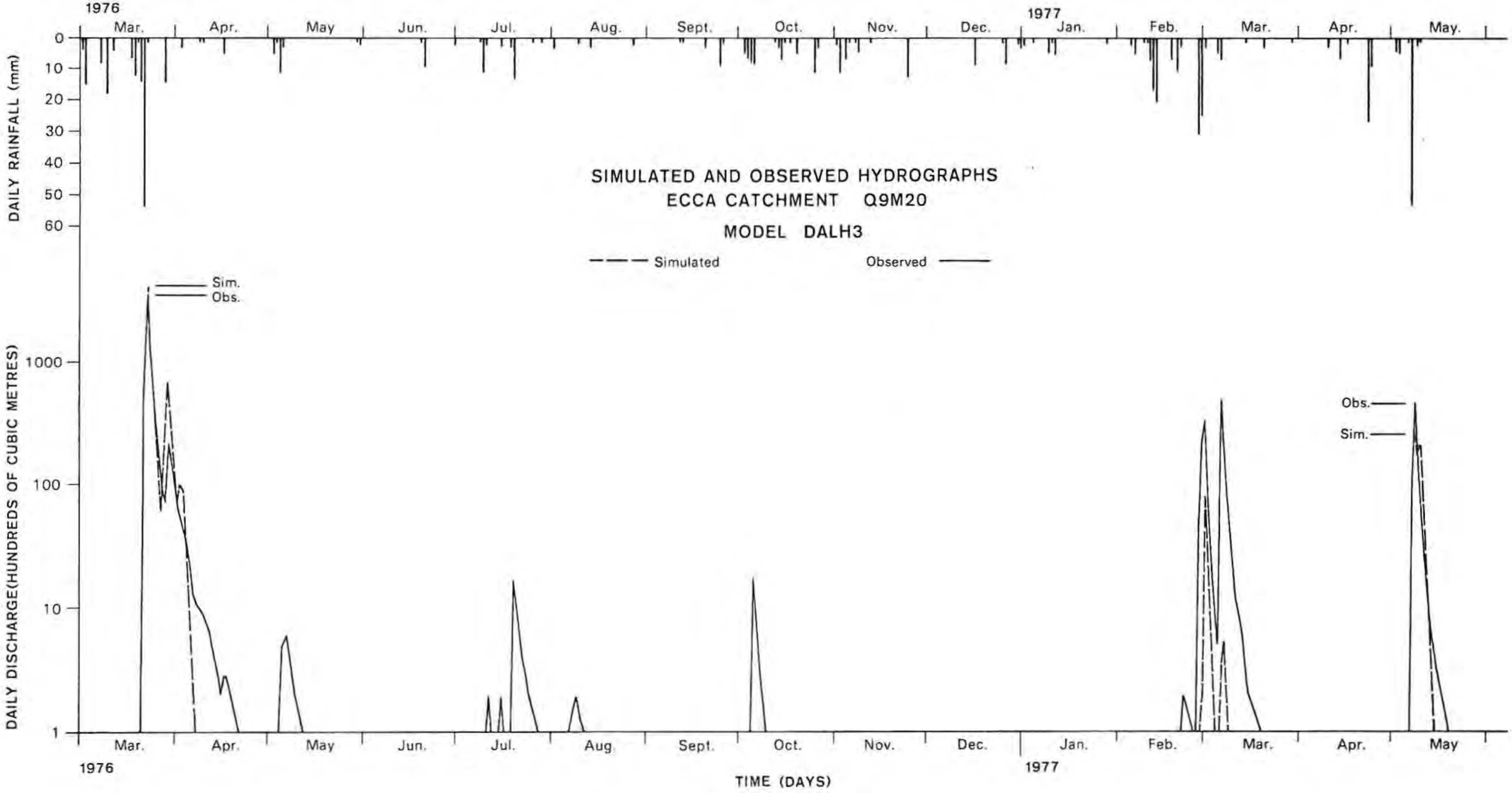

1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALH3
Simulated
Observed
Sim.
Obs.
Obs.
Sim.
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
1976
1977
TIME (DAYS)

FIGURE 58

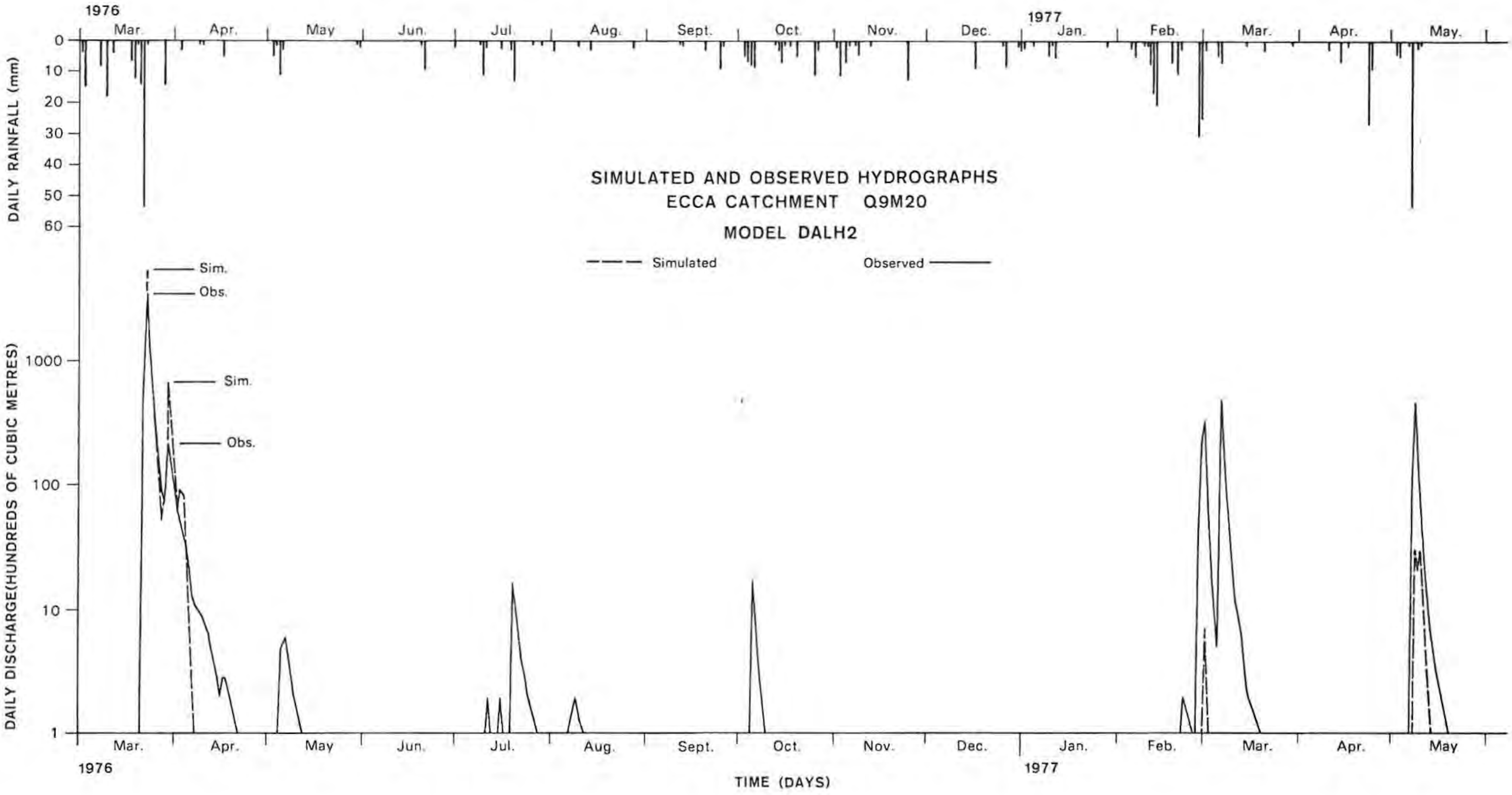

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALH2
Simulated
Observed
Sim.
Obs.
Sim.
Obs.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
TIME (DAYS)

FIGURE 59

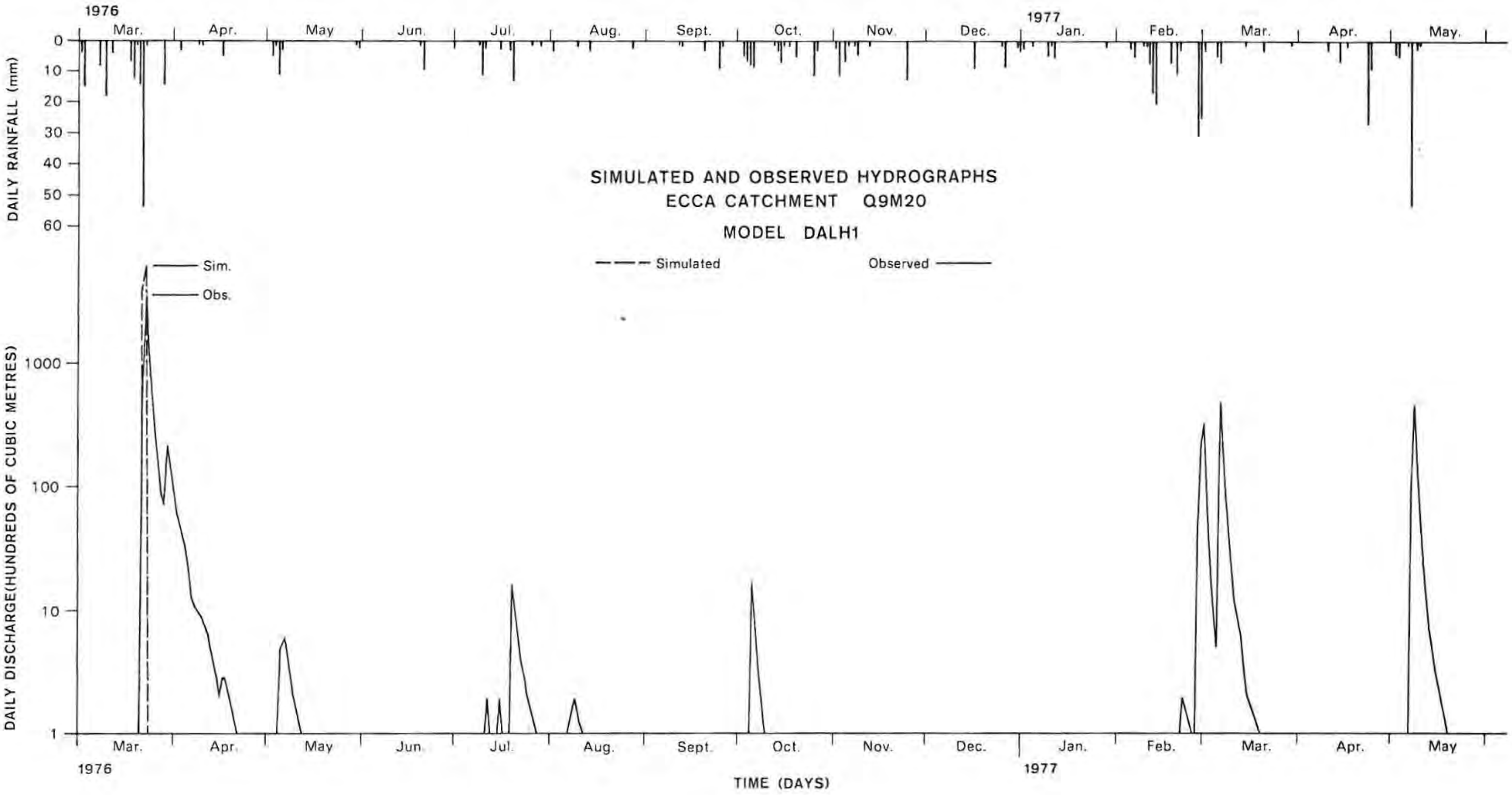

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALH1
Simulated
Observed
Sim.
Obs.
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
TIME (DAYS)

FIGURE 60

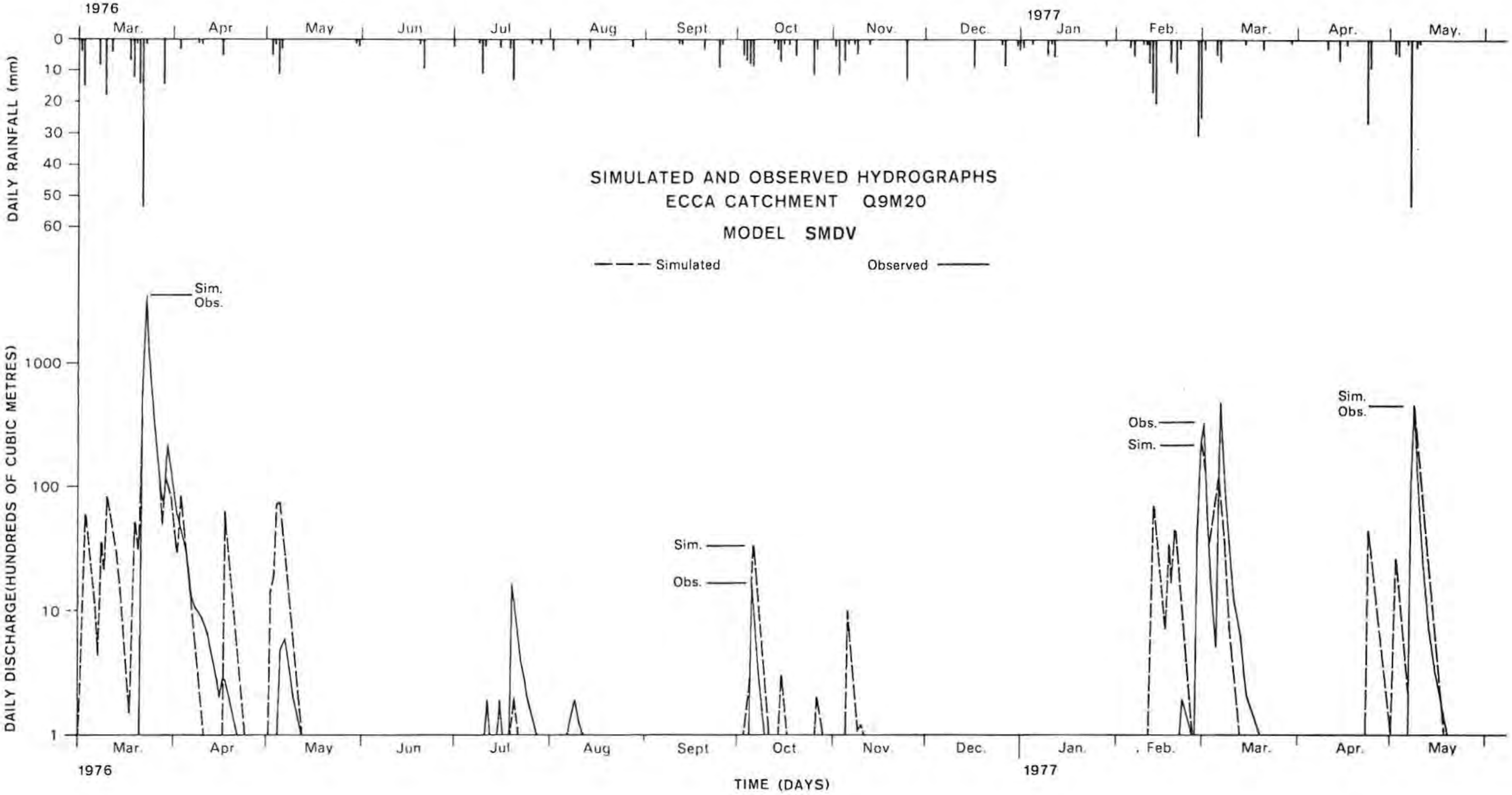

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL SMDV
Simulated
Observed
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
1977
Mar.
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov.
Dec.
Jan
Feb.
Mar.
Apr.
May.
Sim.
Obs.
TIME (DAYS)

FIGURE 61

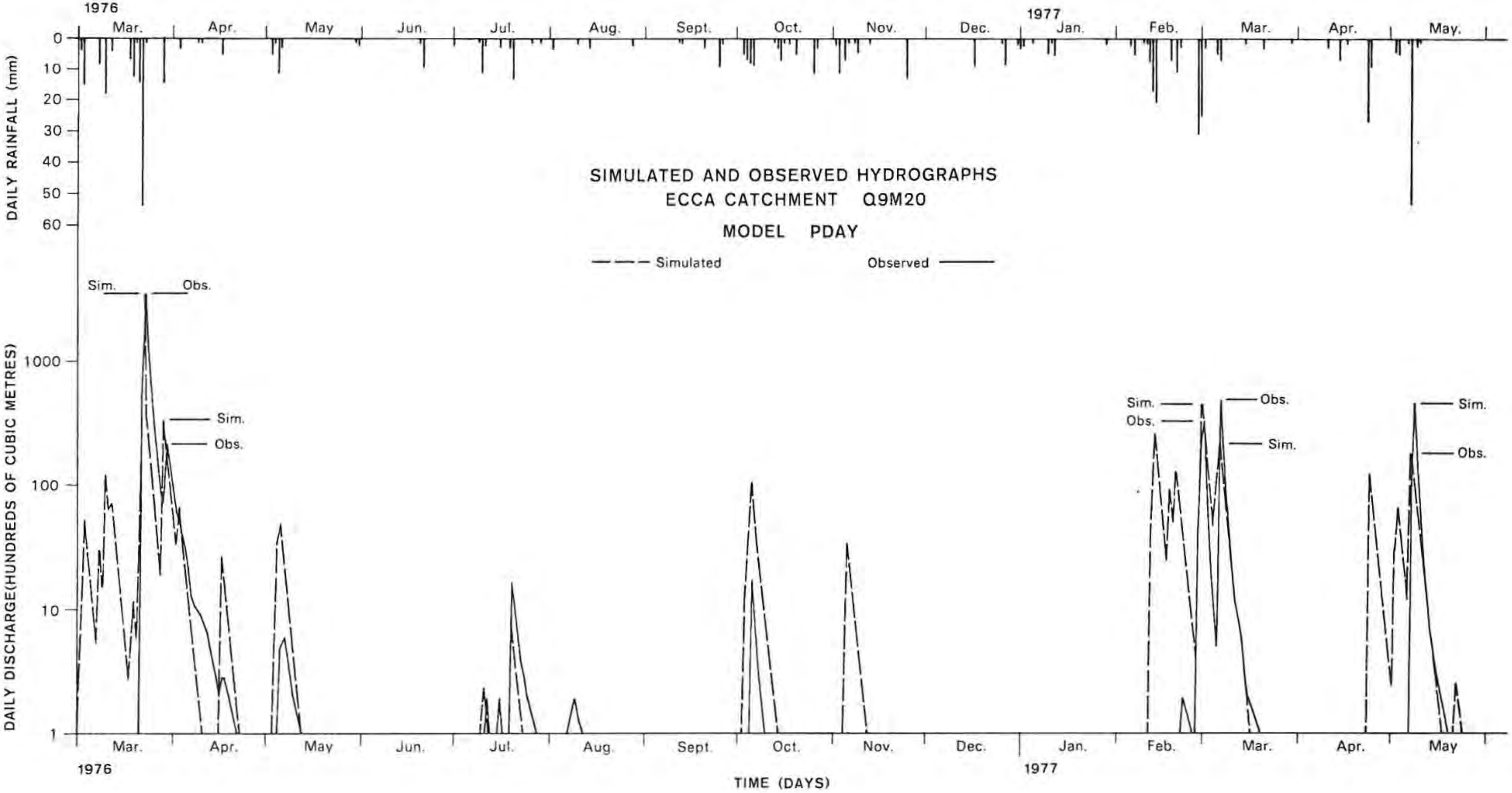

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL PDAY
Simulated
Observed
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
Sim.
Obs.
Sim.
Obs.
Sim.
Obs.
Obs.
Sim.
Sim.
Obs.
TIME (DAYS)

FIGURE 62

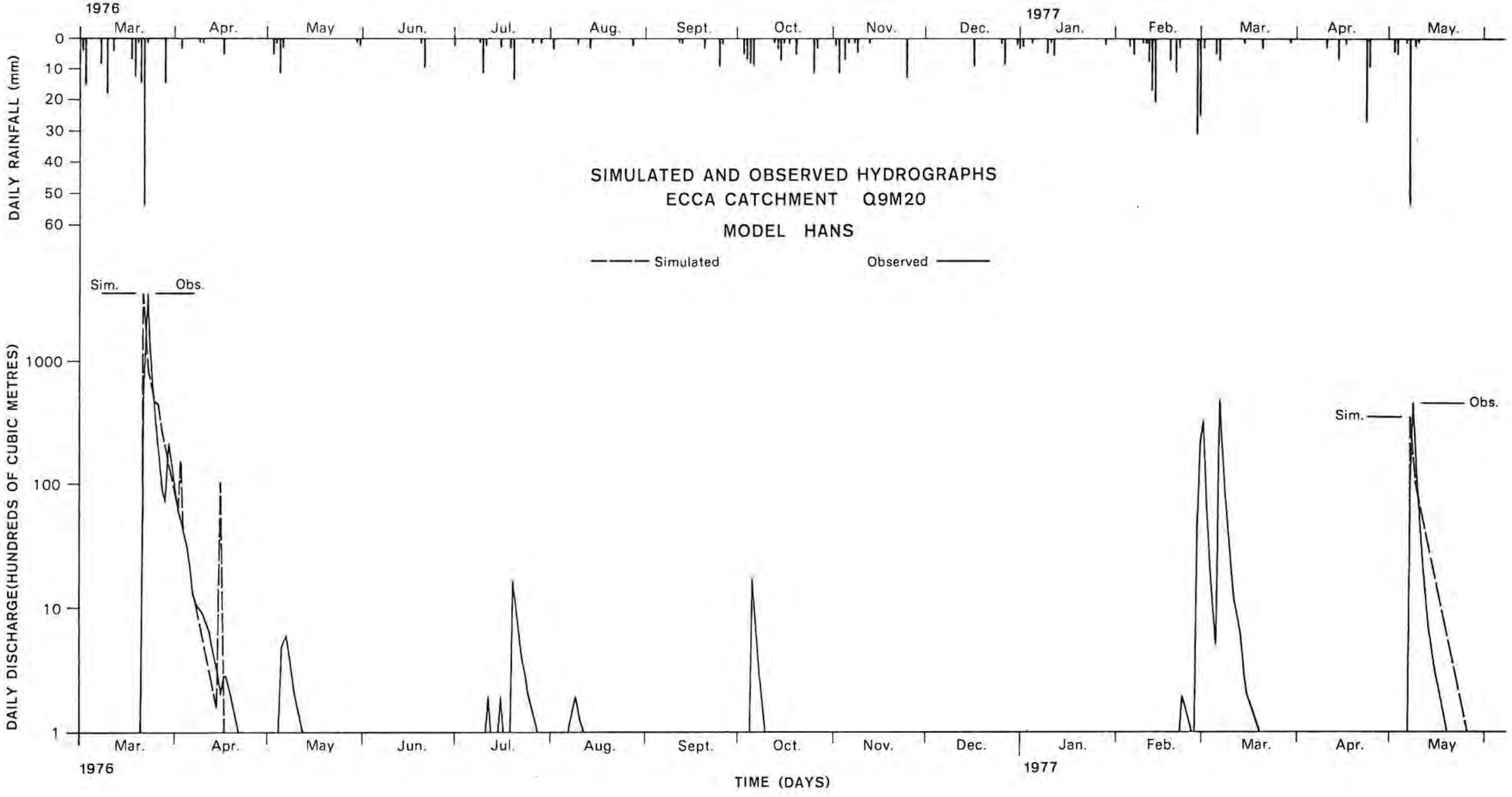

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL HANS
Simulated
Observed
Sim.
Obs.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
TIME (DAYS)

FIGURE 63

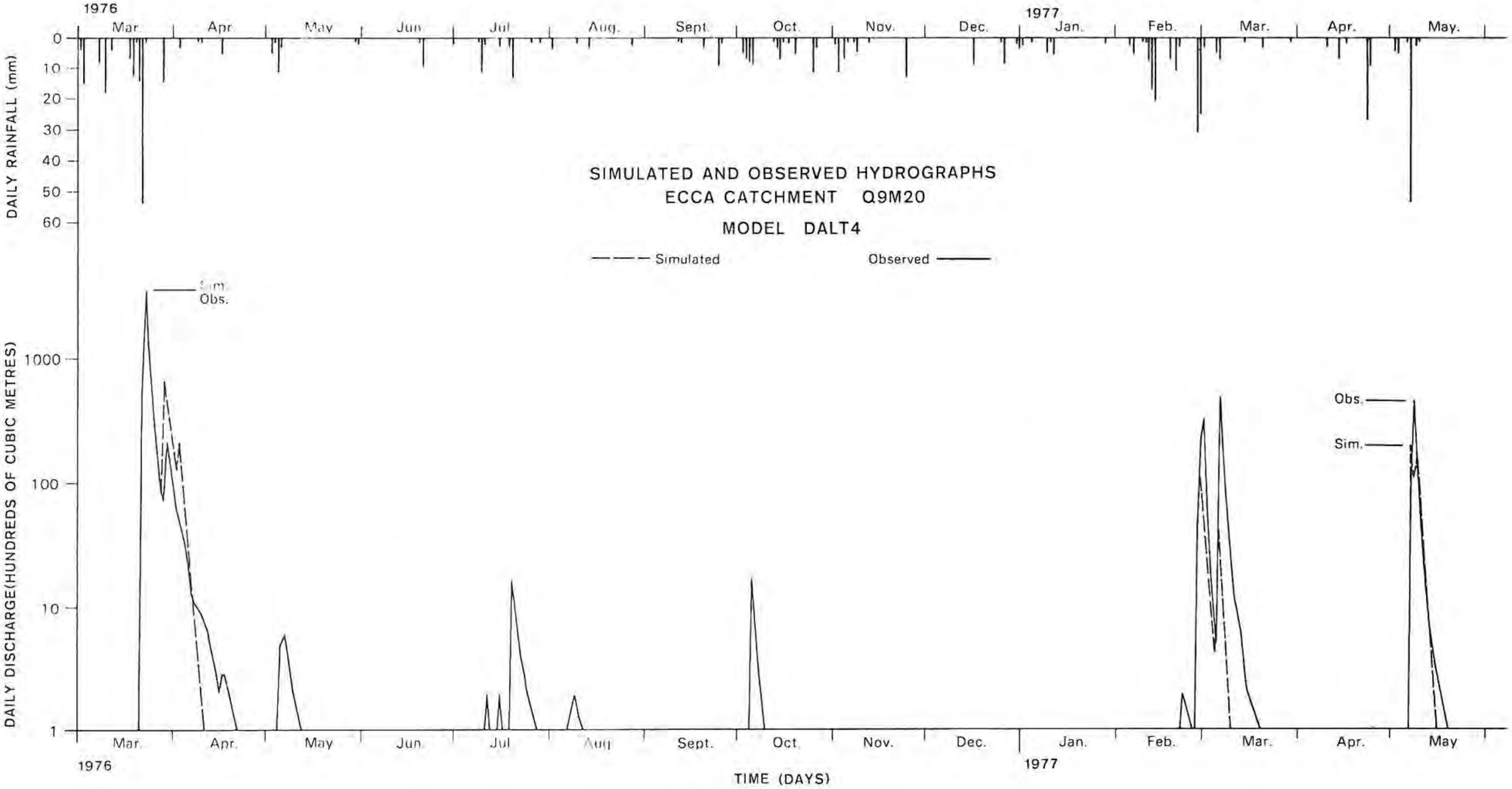

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALT4
Simulated
Observed
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
Sim.
Obs.
Obs.
Sim.
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
TIME (DAYS)

FIGURE 64

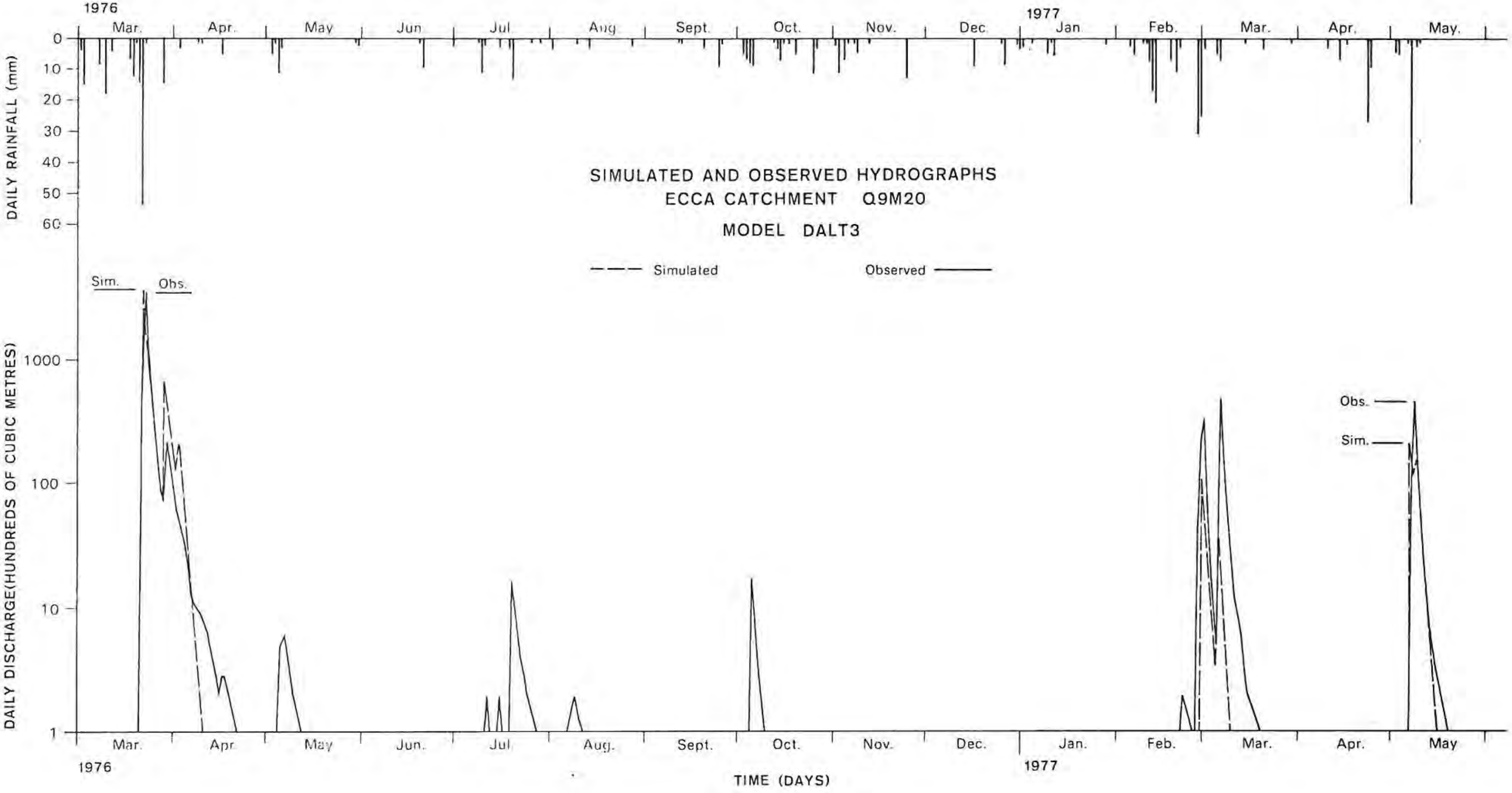

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALT3
Simulated
Observed
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
Sim.
Obs.
Obs.
Sim.
TIME (DAYS)

FIGURE 65

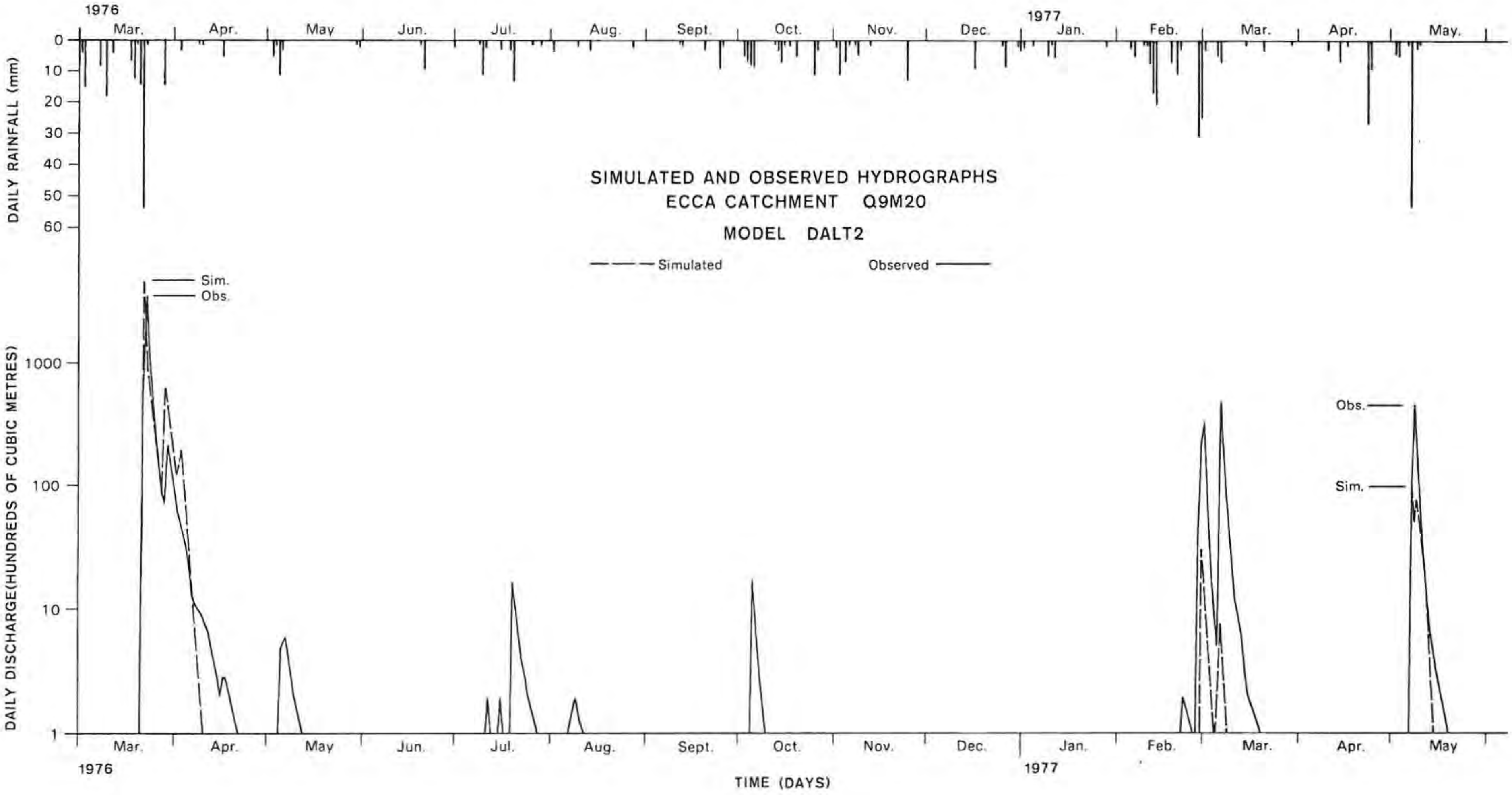

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALT2
Simulated
Observed
1976
1977
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
Sim.
Obs.
Obs.
Sim.
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
TIME (DAYS)

FIGURE 66

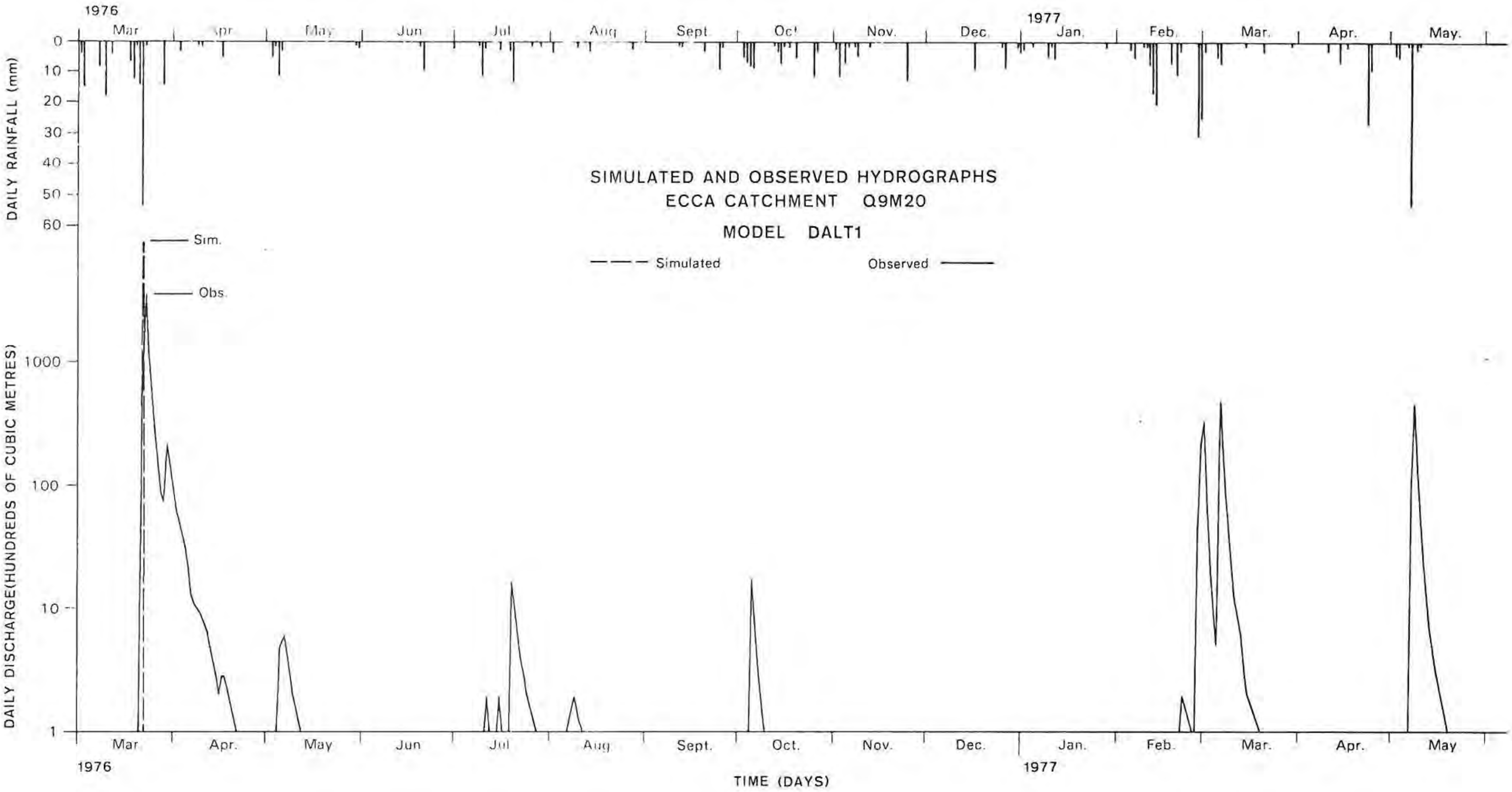

SIMULATED AND OBSERVED HYDROGRAPHS
ECCA CATCHMENT Q9M20
MODEL DALT1
Simulated
Observed
Sim.
Obs.
DAILY RAINFALL (mm)
0
10
20
30
40
50
60
DAILY DISCHARGE(HUNDREDS OF CUBIC METRES)
1000
100
10
1
1976
Mar
Apr.
May
Jun
Jul
Aug
Sept.
Oct.
Nov.
Dec.
1977
Jan.
Feb.
Mar.
Apr.
May
TIME (DAYS)

FIGURE 67

obtained by calibrating the eight selected models in the five catchments are reflected in Tables 10(a), 11(a), 12(a), 13(a) and 14(a) and to aid the comparison of model performance the values of the statistics have been ranked in the corresponding Tables 10(b), 11(b), 12(b), 13(b) and 14(b). The general pattern of model performance has been summarized for all five catchments in Table 15(a) by expressing the values of each statistic as a deviation from the optimum value for that statistic and summing the deviations over all five catchments. The total deviation in each statistic for each model was then ranked as before in Table 15(b). An examination of the pattern of model performance in each catchment shows that the general pattern illustrated by Table 15(a) is representative of each catchment so that Table 15(b) may be taken as the basis for the discussion of the results and reference will be made to marked deviations from the general pattern in the individual catchments.

4.4.2 The comparison of the hourly models

The statistic U4 was used as the objective function for the hourly models and the values obtained (Tables 15(a) and 15(b))show that model FORD, the most complex model, consistently gave the best results. There would appear to be little to choose between the more simple models DALH2 and BERG for statistic U4 but model BERG is clearly superior in the production of peak values (statistic U3) whereas model DALH2 is superior in the production of monthly values of discharge (statistic U2) since it has a base flow function which is lacking in model BERG. The most notable departure from the expected pattern of improved results with increasing complexity is reflected in the rankings for U2, U3 and U4 for model PORT which is the second most complex model. The poor results obtained for model PORT were due to the form of the infiltration function which resulted in unrealistic

TABLE 10(a)

BEST FIT STATISTICS FOR CATCHMENT Q9M20

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	0,31	0,42	0,73	-18,07	-4,44	22,51	0,51	0,88
PORT	0,47	1,58	2,05	-4,61	45,12	49,73	-0,16	0,38
BERG	0,90	0,99	1,89	75,83	77,29	153,12	-0,66	0,15
DALH2	0,52	1,51	2,03	-0,98	-52,71	53,69	-0,51	0,62
Daily								
SMDV	0,21	-	-	-7,59	3,29	10,88	-1,16	0,09
PDAY	0,51	-	-	-0,98	6,24	7,22	-2,20	-0,42
HANS	0,33	-	-	2,84	-3,94	6,78	-1,04	-0,09
DALT2	0,46	-	-	-1,02	-26,36	27,38	-1,11	-0,55

TABLE 10(b)

RANKING OF BEST FIT STATISTICS FOR CATCHMENT Q9M20

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	2(1)	(1)	(1)	7	3	4	1	1	18
PORT	5(2)	(4)	(4)	5	6	6	2	3	27
BERG	8(4)	(2)	(2)	8	8	8	4	4	40
DALH2	7(3)	(3)	(3)	1	7	7	3	2	27
TOTAL	22	-	-	21	24	25	10	10	112
Daily									
SMDV	1	-	-	6	1	3	7	5	23
PDAY	6	-	-	1	4	2	8	7	28
HANS	3	-	-	4	2	1	5	6	21
DALT2	4	-	-	3	5	5	6	8	31
TOTAL	14	-	-	14	12	11	26	26	103

TABLE 11(a)

BEST FIT STATISTICS FOR CATCHMENT Q9M21

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	0,51	0,56	1,07	-20,66	-21,52	42,18	0,78	0,81
PORT	1,88	4,58	6,46	-128,41	-176,15	304,56	-0,46	-6,24
BERG	0,81	0,79	1,60	58,67	58,22	116,89	-0,28	0,27
DALH2	0,59	0,81	1,40	12,18	-30,01	42,19	0,69	0,51
Daily								
SMDV	0,28	-	-	1,11	15,48	16,59	0,54	0,78
PDAY	0,42	-	-	5,17	11,16	16,33	-0,24	0,06
HANS	0,26	-	-	2,95	8,78	11,73	0,13	0,35
DALT2	0,54	-	-	2,21	2,69	4,90	0,31	0,42

TABLE 11(b)

RANKING OF BEST FIT STATISTICS FOR CATCHMENT Q9M21

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	4(1)	(1)	(1)	6	5	5	1	1	22
PORT	8(4)	(4)	(4)	8	8	8	8	8	48
BERG	7(3)	(2)	(3)	7	7	7	7	6	41
DALH2	6(2)	(3)	(2)	5	6	6	2	3	28
TOTAL	25	-	-	26	26	26	18	18	139
Daily									
SMDV	2	-	-	1	4	4	3	2	16
PDAY	3	-	-	4	3	3	6	7	26
HANS	1	-	-	3	2	2	5	5	18
DALT2	5	-	-	2	1	1	4	4	17
TOTAL	11	-	-	10	10	10	18	18	77

TABLE 12(a)

BEST FIT STATISTICS FOR CATCHMENT Q9M22

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	0,22	0,93	1,15	9,09	11,94	21,03	0,47	0,62
PORT	0,81	1,24	2,05	6,06	19,18	25,24	-0,11	0,19
BERG	0,70	0,51	1,21	38,38	46,15	84,53	0,14	0,52
DALH2	0,76	1,24	2,00	5,05	-56,92	61,97	0,21	-0,96
Daily								
SMDV	0,38	-	-	11,11	11,53	22,64	0,76	0,87
PDAY	0,25	-	-	9,09	8,55	17,64	0,63	0,73
HANS	0,36	-	-	10,10	-12,91	23,01	0,88	0,74
DALT2	0,60	-	-	5,05	2,38	7,43	0,75	0,78

TABLE 12(b)

RANKING OF BEST FIT STATISTICS FOR CATCHMENT Q9M22

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	1(1)	(2)	(1)	4	4	3	5	5	22
PORT	8(4)	(3)	(4)	3	6	6	8	7	38
BERG	6(2)	(1)	(2)	8	7	8	7	6	42
DALH2	7(3)	(4)	(3)	1	8	7	6	8	37
TOTAL	22	-	-	16	25	24	26	26	139
Daily									
SMDV	4	-	-	7	3	4	2	1	21
PDAY	2	-	-	4	2	2	4	4	18
HANS	3	-	-	6	5	5	1	3	23
DALT2	5	-	-	1	1	1	3	2	13
TOTAL	14	-	-	18	11	12	10	10	75

TABLE 13(a)

BEST FIT STATISTICS FOR CATCHMENT Q9M23

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	0,44	0,59	1,03	40,21	9,58	49,79	0,28	0,39
PORT	0,58	1,36	1,94	9,52	33,35	42,87	-0,03	0,41
BERG	0,78	0,62	1,40	71,96	67,93	139,89	-0,45	0,17
DALH2	0,28	1,19	1,47	5,82	-24,51	30,33	0,66	0,30
Daily								
SMDV	0,33	-	-	26,98	4,45	31,43	0,22	0,30
PDAY	0,47	-	-	25,40	-1,34	26,74	-0,24	-0,20
HANS	0,47	-	-	2,65	0,02	2,67	0,09	0,17
DALT2	0,38	-	-	23,28	-10,70	33,98	0,11	-0,02

TABLE 13(b)

RANKING OF BEST FIT STATISTICS FOR CATCHMENT Q9M23

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	4(2)	(1)	(1)	7	4	7	2	2	26
PORT	7(3)	(4)	(4)	3	7	6	6	1	30
BERG	8(4)	(2)	(2)	8	8	8	8	5	45
DALH2	1(1)	(3)	(3)	2	6	5	1	4	19
TOTAL	20	-	-	20	25	26	17	12	120
Daily									
SMDV	2	-	-	6	3	2	3	3	19
PDAY	5	-	-	5	2	4	7	8	31
HANS	5	-	-	1	1	1	5	6	19
DALT2	3	-	-	4	5	3	4	7	26
TOTAL	15	-	-	16	11	10	19	24	95

TABLE 14(a)

BEST FIT STATISTICS FOR CATCHMENT Q9M24

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	0,28	0,51	0,79	3,39	23,91	27,30	0,68	0,92
PORT	0,50	1,16	1,66	3,39	60,46	63,85	-0,25	0,37
BERG	0,86	0,71	1,57	66,95	74,83	141,78	-0,38	0,20
DALH2	0,12	0,64	0,76	-0,85	-17,30	18,15	0,81	0,85
Daily								
SMDV	0,27	-	-	-14,83	4,60	19,43	0,02	0,22
PDAY	0,48	-	-	-0,85	4,85	5,70	-0,62	-0,37
HANS	0,50	-	-	-5,09	-15,10	20,19	0,14	-0,01
DALT2	0,18	-	-	4,24	2,13	6,37	-0,18	-0,03

TABLE 14(b)

RANKING OF BEST FIT STATISTICS FOR CATCHMENT Q9M24

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	4(2)	(1)	(1)	3	6	6	2	1	22
PORT	7(3)	(4)	(4)	3	7	7	6	3	33
BERG	8(4)	(3)	(3)	8	8	8	7	5	44
DALH2	1(1)	(2)	(2)	1	5	3	1	2	13
TOTAL	20	-	-	15	26	24	16	11	112
Daily									
SMDV	3	-	-	7	2	4	4	4	24
PDAY	5	-	-	1	3	1	8	8	26
HANS	6	-	-	6	4	5	3	6	30
DALT2	2	-	-	5	1	2	5	7	22
TOTAL	16	-	-	19	10	12	20	25	102

TABLE 15(a)

TOTAL DEVIATION OF BEST FIT STATISTICS FROM OPTIMUM VALUES FOR ALL FIVE CATCHMENTS

MODEL	U2	U3	U4	U5	U6	U7	U8	U9
Hourly								
FORD	1,76	3,01	4,77	91,43	71,39	162,82	2,28	1,38
PORT	4,24	9,92	14,16	152,00	334,25	486,25	6,01	9,91
BERG	4,05	3,61	7,66	311,79	324,42	636,21	6,63	3,68
DALH2	2,27	5,39	7,66	24,87	181,45	206,32	3,14	3,69
Daily								
SMDV	1,46	-	-	61,62	39,34	100,96	4,61	2,74
PDAY	2,14	-	-	41,48	32,14	73,62	7,68	5,20
HANS	1,92	-	-	23,62	40,76	64,38	4,81	3,84
DALT2	2,17	-	-	35,81	44,26	80,07	5,13	4,41

TABLE 15(b)

RANKING OF TOTAL DEVIATION OF BEST FIT STATISTICS FOR ALL FIVE CATCHMENTS

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	2(1)	(1)	(1)	6	5	5	1	1	5
PORT	8(4)	(4)	(4)	7	8	7	6	8	7
BERG	7(3)	(2)	(3)	8	7	8	7	3	8
DALH2	6(2)	(3)	(2)	2	6	6	2	4	6
TOTAL	23	-	-	23	26	26	16	16	-
Daily									
SMDV	1	-	-	5	2	4	3	2	4
PDAY	4	-	-	4	1	2	8	7	2
HANS	3	-	-	1	3	1	4	5	1
DALT2	5	-	-	3	4	3	5	6	3
TOTAL	13	-	-	13	10	10	20	20	-

values for the pseudo-level of soil moisture and consequently the production of flood peaks during periods when no flow was observed. The results are an improvement on the original form of the function but clearly further development work is needed. The hourly models may be ranked in the order FORD, DALH2, PORT and BERG for the remaining statistics except for U5 where model DALH2 provided the best results. The lack of a clear pattern of improving results with increasing model complexity may be ascribed in this instance to a serious deficiency in the second most complex model (PORT) and to the fact that the structure of model BERG is not ideally suited to the majority of the statistics.

4.4.3 Comparison of the daily models

The statistic U7 was used as the objective function for the daily models and Tables 15(a) and 15(b) show that, as in the case of the hourly models, there is no clear relationship between complexity of model structure and accuracy of output. The daily models may be ranked in the order HANS, PDAY, DALT2 and SMDV for the statistic U7 but the pattern cannot be regarded as consistent in all the catchments. The same ranking of daily models applies to the summary of the performance of the models with all statistics but the values produced show that there is little difference between the models.

The first hypothesis put forward in Chapter 1 was that; "Within any group of models requiring the same time-interval for rainfall input, the models of complex structure provide more accurate output than the models with more simple structure." The test of the hourly models with the short record calibration (1 month) showed an improvement in the accuracy of output for increasing structural complexity for the models DALH1, BERG, PORT and FORD but it was also demonstrated that the simple models DALH2 and DALH3 could provide output that was competitive with the complex models FORD and PORT. The comparison of the performance of both the hourly and daily groups of models with the longer calibration record did not demonstrate the expected pattern of increasing accuracy with increasing structural complexity so that the hypothesis must be rejected for the combinations of models, data and objective functions tested.

4.4.4 Comparison of hourly models with daily models

The second hypothesis put forward stated that; "The models that require hourly rainfall input generally provide more accurate simulation than the models that require daily rainfall input." The expectation of a higher level of simulation with the use of hourly rainfall is based on the higher level of information contained in the input stream. However the results obtained illustrate (Totals of Table 15(b)) that the daily models have consistently provided superior output for statistics U2, U5, U6 and U7. It would appear that the use of fine time-intervals for input data may not be justified if the requirements of the output incorporate accurate monthly discharge or accurate reproduction of the mean and variance of daily discharge. In contrast, the results show that the hourly models have produced better values than the daily models for statistics U8 and U9 in three of the catchments (Q9M20, Q9M23 and Q9M24). The inference drawn is that the use of fine time-intervals may be justified if the requirement of the output incorporates a high level of one-to-one correspondence between daily values. Although the second hypothesis was found to be true under limited conditions (for statistics U8 and U9 only), the results show that the hypothesis must be rejected as a general statement.

4.5 Summary

The ranking of model performance for all statistics in all five catchments (last column, Table 15(b)) illustrates that increases in complexity of model structure and complexity of model input requirements do not necessarily provide an improvement in model output with respect to a number of objective functions. The model user may benefit by using, initially, a relatively simple model with the most convenient time-interval for input data (equivalent to the time-interval of the output required for the objective function). The savings in both operator and computer time that may be achieved by a judicious choice of model are clearly illustrated by Table 16 where the direct costs of obtaining the output for each model in the five catchments have been listed. If an objective function such as U7, for example, meets the requirements of a particular engineering application, then the use of a simple model like DALT2 may provide results that are competitive with those of a complex model such as FORD but with approximately one half of the number of calibration runs and at approximately one thirtieth of the computer costs.

The results obtained provide a valuable insight into the initial choice of model for various engineering applications in situations where calibration data are available. However, in a large number of South African catchments, no observed flow data are available for calibration which gives rise to the need for parameter transfer to the ungauged catchments. Very little is known about the feasibility of the parameter transfer process under various conditions or about factors influencing the choice of suitable models for such an application. It is hoped that the parameter transfer tests in the following chapter will contribute to this important, but little researched field of deterministic model application.

TABLE 16

CALIBRATION COST FACTORS.LONG RECORD ONLY (ALL CATCHMENTS)

MODEL	NO OF RUNS	MILL SECS PER RUN	TOTAL MILL TIME	CORE REQUIRED	NO OF PARAMETERS	RANDS (@ 9c PER MILL SEC)
Hourly						
FORD	60	1 800	108 000	33	20	9 720
PORT	93	1 255	116 715	14	15	10 504
BERG	49	746	36 554	14	7	3 289
DALH2	50	880	44 000	14	4	3 960
Daily						
SMDV	51	131	6 681	16	15	601
PDAY	50	113	5 650	16	13	508
HANS	55	114	6 270	16	10	564
DALT2	36	98	3 528	16	4	317
						25 503

CHAPTER 5

THE FEASIBILITY OF PARAMETER TRANSFER

5.1 Introduction

One of the main objectives in the development of a 'general purpose' deterministic model of the rainfall-runoff process is to provide a model that can be used in ungauged catchments to generate a record of runoff for design purposes where no such record exists. The parameter values for the model in the ungauged catchment could either be estimated entirely from physical features of the catchment or be obtained by calibration of the model in a nearby gauged catchment with similar climate, vegetation and lithology. In either event, the reliability of the generated data is not known and if the data are subsequently used for design calculation, the risk factor is uncertain.

As yet no model has been devised that will permit the estimation of all the model parameters from physical features of the catchment with sufficient reliability to provide output at a consistent level of accuracy that would normally be tolerable for most engineering applications. Some parameters either do not have sufficient physical interpretation or represent variables that are difficult to measure in the field or average over space. As a result, the guidelines that are usually given for the estimation of parameter values are, for most parameters, a guide to starting values in the calibration process. "Few hydrologists would confidently compute the discharge hydrograph from rainfall data and the physical description of the catchment. Nevertheless this is a practical problem which must often be faced by practising engineers." (Nash and Sutcliffe, 1970, 282). In view of the fact that some model parameters cannot be reliably estimated from physical features, the calibration of the model in a nearby gauged catchment and transfer of the parameters to the ungauged catchment tends to generate more confidence in the output than the estimation of parameters from physical features alone. The parameter transfer process usually involves transfer of those parameter values that cannot be reliably estimated from physical features while those that can be reliably estimated (such as catchment area) are obtained from the ungauged catchment.

A survey of the literature on hydrological model applications indicates that very little research has been done on the feasibility of parameter transfer with conceptual models. The results of parameter transfer tests that have been reported indicate that the transfer of parameters was successful in some cases but not in others. For example, Magette, Shanholtz and Carr (1976, 475) conducted tests for 'ungauged' catchments with the Kentucky Watershed Model and found that "reasonable estimates can often be obtained for ungauged areas...Hydrographs were predicted reasonably well for some areas and, conversely, were totally unacceptable for others." Similar results were obtained by Egbuniwe and Todd (1976) when applying the Stanford Watershed Model in Nigeria. On the basis of the fact that the derived hydrograph patterns appeared to be similar to the observed hydrographs, they concluded that, "It seems satisfactory to extrapolate watershed parameters to an adjacent watershed." (Egbuniwe and Todd, 1976, 456). In view of the doubt that exists there is a pressing need for further research into the feasibility of model parameter transfer from the gauged to the ungauged catchment.

At the outset of this research programme a number of interested parties put the question to the author in the general form; "Is it feasible to calibrate a model in a gauged catchment and then transfer the parameter values to an ungauged catchment with similar climate, vegetation and lithology, where suitable rainfall data are available, to generate a runoff record?" Objective thinking however, leads to the conclusion that there is no simple answer to the above question. The first consideration is whether or not 'similarity' in climate, vegetation and lithology is commensurate with similarity in response to moisture and energy input. A drainage basin can be considered as an open system because energy and matter both enter and leave the system. "In open systems the rates of import and export of material and energy will become balanced so that an equilibrium called the steady state is reached. The system is self regulating; any change in the controlling factors will cause a shift in the steady state that will tend to absorb the effects of the change." (Morisawa, 1968, 126). The concept of steady state in a catchment is based on the interrelationship of climate, vegetation and soil variables. The climate variables form the input to the system and interact with the vegetation and soil variables of the catchment surface under steady state conditions to define the output in the form of runoff and sediment load. Over a period of time the input and output of material and energy are balanced so that the output is a function of the long term interrelationship between vegetation, soil and climate variables with the climate variables being considered as essentially independent. The morphology of the landscape which influences the time-distribution of the output (runoff) is also dependent on the steady state conditions and in this respect Tricart and Cailleux (1972, 164) have referred to the steady state as a morphoclimatic equilibrium defined as a "morphoclimatic adjustment that is realised in a given region when the land forms are predominantly determined by a morphogenic system that is dependent on climatic factors." Tricart and Cailleux (1972, 160) explain their use of the word equilibrium with reference to steady state as follows, "The morphoclimatic system of any climate zone is dependent not only on climate but on vegetation and soil. It is on the interrelationship of these three factors that the concept of morphoclimatic equilibrium is based. The concept of morphoclimatic equilibrium, actually, is less a balance than a permanent state or steady state in the sense of the physicist. The fact that stream water always holds more foreign matter in suspension or solution than rainwater demonstrates that there is always erosion and that watercourses and slopes shift even if their profiles remain constant. The permanence of forms during a given period is, however, so frequent and so important that we conform to usage and refer to it in terms of an equilibrium." It is therefore reasonable to suppose that two catchment systems with equivalent climate, vegetation and soil distributions would have equivalent levels of steady state and equivalent system output for unitary input. However, the decision as to whether an ungauged catchment has a similar level of morphoclimatic equilibrium to a nearby gauged catchment is entirely subjective as the tolerance level of variation in any one of the groups of variables with respect to the effect of the variation on the system output is not known. It is not feasible to quantify accurately all aspects of the three groups of variables over space and the user must assess similarity by inspection. Large variations in many important variables (such as soil texture, depth and chemical composition) would not be apparent to the observer and the process of parameter transfer would entail a high level of risk even if all the parameters had a high level of physical relevance.

Knowledge about hydrological processes is far from complete and as a result the deterministic models contain many sub-components that lean heavily towards the 'black box' approach and the set of model parameter values obtained by calibration of the model against measured data is highly dependent on the form of the objective function used during calibration (Porter and McMahon, 1971; Diskin and Simon, 1977). Considering that a number of parameter sets for any one particular model may be obtained by calibration according to a range of objective functions, there is no reason to suppose that all the parameter sets would display the same level of transferability. Some objective functions are less exacting in terms of model performance than others so that a parameter set based on accurate reproduction of the mean and variance might be expected to display a higher level of transferability as compared with a parameter set based on one-to-one correspondence between observed and simulated values. There is also no reason to suppose that the parameter sets for two models of differing complexity would be equally transferable even if the parameter sets were obtained by calibration with the same objective function. In this respect, the models with the more complex structure may be expected to give better results with parameter transfer than simple models because there is a higher level of simulation of the processes taking place in the catchment. In the same way models that require finer time-intervals for input data may be expected to be superior in terms of parameter transfer than those requiring coarse time-intervals because the parameter values are based on a higher level of input information. Similarly, for any one model, the level of information contained in the input record in terms of the length of record might be expected to influence the level of transferability of the parameters. The relationships between parameter transferability and complexity of model structure, model input requirements and length of calibration record (as embodied in Hypotheses 3, 4 and 5) will be tested in this chapter with data from the five Ecca catchments.

The five Ecca catchments are probably as similar in terms of climate, vegetation and lithology as the user could hope to encounter in practice for parameter transfer applications and in addition, four of the catchments are sub-catchments of the main catchment, constituting subsets of the same system. If the main catchment is considered to be the gauged catchment and the four sub-catchments as the ungauged catchments then the feasibility of parameter transfer can be investigated under favourable conditions with the range of models selected. The parameter transfer tests were conducted in three stages making use of the same input records that were used for comparison of model performance in the previous chapter. In the first stage the feasibility of parameter transfer was tested with the four hourly models FORD, PORT, BERG and DALH2 using the short calibration record of one month, and particular attention was paid to the relationship between complexity of model structure and deterioration in output due to parameter transfer. In the second stage the feasibility of parameter transfer was tested with all the models using the longer calibration record of 15 months. The longer record provides information about the deterioration in the output with resect to various requirements of the output as embodied in statistics U2 to U9 with comparisons being drawn on the basis of the complexity of model structure as well as the time-interval used for input data. The objective of testing the feasibility of parameter transfer with both the short and long period of calibration was to obtain some indication of the degree to which the results obtained in stage one were influenced by the reduced level of input information in the shorter record. The third stage embodied the temporal rather than the spatial process of parameter transfer in which a single catchment was used to assess the degree to which the structural complexity of a model influences the length of calibration record necessary to obtain representative parameter values.

5.2 Parameter Transfer Tests with the Short Record

A simple test of parameter transfer with the short record was obtained by calibrating the hourly models in all five catchments and then using the parameter values for the main catchment in the other four catchments with their appropriate input records. Only those parameters actually involved in the calibration process were transferred and the 'correct' values were given to parameters that can be estimated from measurement such as area, lag time and routing constants. The output obtained from each model in each sub-catchment by using the parameters obtained from the main catchment (gauged) was compared with the output from the model in that catchment obtained by calibration. In this way, it was possible to ascertain the deterioration in output due to parameter transfer with respect to the 'best' output that the model could provide in that catchment and any deterioration can be ascribed to factors other than the ability of the model to simulate the observed flow.

As the input data consists of a single flood event, the deteriorations (due to parameter transfer) in the flood peak and total discharge were examined. The results obtained for the flood peak are shown in Table 17 and the results for the flood volume in Table 18. An examination of Tables 17 and 18 indicates that with the exception of the simple model DALH2, the deterioration in simulated output due to parameter transfer in catchments Q9M21 and Q9M22 is within reasonable limits (generally less than 20 percent error) but the results for catchments Q9M23 and Q9M24 indicate that parameter transfer under the given conditions is not feasible. The reaction of the catchment Q9M23 to the input rainfall has been underestimated by between 60 percent and 100 percent in all cases whereas the reaction for catchment Q9M24 has been overestimated by more than 100 percent. The marked difference

TABLE 17

PARAMETER TRANSFER EFFECT ON FLOOD PEAK (cumecs)
(SHORT RECORD)

	SUBCATCHMENT				
MODEL	Q9M21	Q9M22	Q9M23	Q9M24	TOTAL DIFF %
FORD(T)	1,3	0,3	0,1	5,1	
FORD(C)	1,1	0,2	0,6	1,0	
% D	+18	+50	-83	+410	561
PORT(T)	1,5	0,2	0,1	2,5	
PORT(C)	1,1	0,2	0,6	1,0	
% D	+36	0	-83	+150	269
BERG(T)	0,9	0,2	0,1	3,2	
BERG(C)	0,9	0,2	0,7	1,0	
% D	0	0	-86	+191	277
DALH2(T)	0,2	0,1	0,0	22,5	
DALH2(C)	1,2	0,3	0,8	1,1	
% D	-83	-66	-100	+1945	2194

Note: T = Transferred parameters used

C = Calibrated parameters used

D = Difference in output

TABLE 18

PARAMETER TRANSFER EFFECT ON FLOOD VOLUME (mm of rain)
(SHORT RECORD)

	SUBCATCHMENT				
MODEL	Q9M21	Q9M22	Q9M23	Q9M24	TOTAL DIFF %
FORD(T)	14,43	13,23	10,34	17,76	
FORD(C)	12,37	12,32	37,74	5,72	
% D	+17	+7	-73	+211	308
PORT(T)	14,46	14,16	13,31	17,14	
PORT(C)	13,45	14,16	36,16	6,54	
% D	+7,5	0	-63	+162	232
BERG(T)	2,45	2,36	2,06	3,81	
BERG(C)	2,45	2,36	14,35	1,25	
% D	0	0	-86	+205	291
DALH2(T)	3,82	4,57	1,87	19,72	
DALH2(C)	8,02	6,20	30,64	3,85	
% D	-52,36	-26,29	-93,89	+412,20	584

Note: T = Transferred parameters used

C = Calibrated parameters used

D = Difference in output

in hydrological response between these two catchments could be due to errors in flow measurement but as the capacity of the measuring devices was not exceeded, this possibility is discounted as the major cause. The second possibility is that the raingauge network was not sufficiently dense to reproduce accurately the spatial variations in the rainfall pattern. The large variations in catch from one gauge to another that have been observed during the data collection period would suggest that rainfall error is the largest contributing cause. Crawford and Linsley (1966, 154) have pointed out, "The accuracy of simulation output in semi-arid climates is strongly dependent on the rainfall inputs.... and the most serious source of error in simulation of streamflow in an ungauged arid watershed is likely to be a poorly defined rainfall regime." However, the third possibility, that of basic differences in hydrological characteristics, should not be overlooked. It may be that apparent similarity in climate, vegetation and lithology is not sufficient for the assumption of similarity in hydrological response. The most obvious difference between catchments Q9M23 and Q9M24 lies in the depth of the regional water table below the surface. Observations of depth to water table in 34 boreholes situated in the catchment area indicated that the water table is approximately 65 metres below the outlet of catchment Q9M24 whereas it is only approximately 30 metres below the outlet of catchment Q9M23 (Rumble, 1976). However the difference can be ascribed simply to surface topography with Q9M24 being a more headward catchment. It must be assumed that there are differences in hydrological parameters, such as average infiltration capacity, that are due to spatial variations in controlling variables (such as soil depth and jointing patterns) that are not readily apparent during inspection. It is evident from Tables 17 and 18 that the simplest of the four hourly models, DALH2, has the poorest results in terms of the transfer of parameter values but the pattern of increasing level of transferability with increasing model complexity is not otherwise apparent.

5.3 Parameter Transfer with the Longer Record

The hourly and daily models were calibrated in each catchment with the longer record using objective function U4 for the hourly models and U7 for the daily models and all the models were run in each sub-catchment with the relative rainfall records but using the parameter values obtained for the main catchment (as in the parameter transfer tests with the short record). Tables 19(a), 20(a), 21(a) and 22(a) show the deterioration in the value of the eight statistics (U2 - U9) that resulted from the use of parameter values obtained by calibration in the 'gauged' catchment Q9M20 with respect to the value of the statistics obtained by calibrating the models in each 'ungauged' sub-catchment. As before, the results of Tables 19(a), 20(a), 21(a) and 22(a) have been ranked in Tables 19(b), 20(b), 21(b) and 22(b) to facilitate the comparison of parameter transferability, and the total deterioration in each statistic for all four sub-catchments has been reflected in Table 23 and ranked in Table 24 to illustrate the general pattern.

5.3.1 The feasibility of parameter transfer

The feasibility of parameter transfer in each catchment could be gauged from Tables 19(a), 20(a), 21(a) and 22(a) but as the statistics are in different units, the assessment of feasibility can be facilitated by reference to Table 25 in which the average deterioration in the percentage error in each statistic for each group of models has been listed. The values in Table 25 for the hourly group of models display the same pattern for statistic U4 as that observed with the short record tests. The deterioration in statistics for catchment Q9M21

TABLE 19(a)

DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER
(CATCHMENT Q9M21)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	0	0	0	0	0	0	0	0	0
PORT	0	0	0	0	0	0	0	0	0
BERG	-0,04	-0,11	-0,15	-12,18	-10,00	-22,18	-0,14	-0,08	-44,62
DALH2	0,15	-0,09	0,06	-29,52	15,86	-13,66	-0,19	0,17	-27,19
TOTAL	0,11	-0,20	-0,09	-41,70	5,86	-35,84	-0,33	0,09	-71,81
Daily									
SMDV	-0,07	-	-	-20,66	-25,79	-46,45	-0,13	-0,02	-93,12
PDAY	-0,00	-	-	-3,69	-1,43	-5,12	-0,01	0,00	-10,25
HANS	-0,22	-	-	-10,70	-11,81	-22,51	0,22	-0,29	-45,31
DALT2	0,12	-	-	-33,58	-38,10	-71,68	-0,20	0,10	-143,34
TOTAL	-0,17	-	-	-68,63	-77,13	-145,76	-0,12	-0,21	-292,02

TABLE 19(b)

RANKING OF DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER(CATCHMENT Q9M21)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	3(2)	(1)	(2)	2	3	1	2	4	15
PORT	3(2)	(1)	(2)	2	3	1	2	4	15
BERG	6(4)	(4)	(4)	5	2	5	6	7	31
DALH2	1(1)	(3)	(1)	7	1	4	7	1	21
TOTAL	13	-	-	16	9	11	17	16	82
Daily									
SMDV	7	-	-	6	7	7	5	6	38
PDAY	5	-	-	1	5	3	4	3	21
HANS	8	-	-	4	6	6	1	8	33
DALT2	2	-	-	8	8	8	8	2	36
TOTAL	22	-	-	19	26	24	18	19	128

TABLE 20(a)

DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER
(CATCHMENT Q9M22)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	-0,09	0,07	-0,02	-19,19	-15,84	-35,03	-0,21	-0,07	-70,43
PORT	0,06	0,14	0,20	-21,21	-30,89	-52,10	-0,14	0,07	-104,21
BERG	-0,16	-0,27	-0,43	-47,48	-38,91	-86,39	-0,15	-0,30	-173,39
DALH2	0,07	0,30	0,37	-61,62	0,54	-61,08	-0,78	1,04	-121,83
TOTAL	-0,12	0,24	0,12	-149,50	-85,10	-234,60	-1,28	0,74	-469,86
Daily									
SMDV	-0,20	-	-	-36,36	-50,67	-87,03	-0,72	-0,44	-175,42
PDAY	-0,27	-	-	-33,33	-40,66	-73,99	-0,35	-0,12	-148,72
HANS	-0,11	-	-	-36,36	2,11	-34,25	0,83	0,05	-67,73
DALT2	-0,04	-	-	-53,54	-60,63	-114,17	-0,68	-0,34	-229,40
TOTAL	-0,62	-	-	-159,59	-149,85	-309,44	-0,92	-0,85	-621,27

TABLE 20(b)

RANKING OF DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER(CATCHMENT Q9M22)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	4(3)	(3)	(3)	1	3	2	4	4	18
PORT	2(2)	(2)	(2)	2	4	3	2	2	15
BERG	6(4)	(4)	(4)	6	5	6	3	6	32
DALH2	1(1)	(1)	(1)	8	2	4	8	1	24
TOTAL	13	-	-	17	14	15	17	13	89
Daily									
SMDV	7	-	-	4	7	7	7	8	40
PDAY	8	-	-	3	6	5	5	5	32
HANS	5	-	-	4	1	1	1	3	15
DALT2	3	-	-	7	8	8	6	7	39
TOTAL	23	-	-	18	22	21	19	23	126

TABLE 21(a)

DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER
(CATCHMENT Q9M23)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	-0,45	-0,41	-0,86	-49,21	-74,37	-123,58	-0,27	-0,16	-248,04
PORT	-0,36	-0,09	-0,45	-75,66	-53,67	-129,33	-0,41	-0,31	-259,74
BERG	-0,21	-0,39	-0,60	-25,40	-28,39	-53,79	-0,07	-0,16	-108,02
DALH2	-0,38	0,44	0,06	-60,32	-24,75	-85,07	-0,31	0,37	-170,46
TOTAL	-1,40	-0,45	-1,85	-210,59	-181,18	-391,77	-1,06	-0,26	-786,26
Daily									
SMDV	-0,62	-	-	-63,49	-89,35	-152,84	-0,27	-0,21	-306,78
PDAY	-0,46	-	-	-65,08	-93,89	-158,97	-0,06	0,25	-318,21
HANS	-0,46	-	-	-86,24	-85,17	-171,41	-0,41	-0,03	-343,72
DALT2	-0,57	-	-	-70,90	-83,18	-154,08	-0,35	0,09	-308,99
TOTAL	-2,11	-	-	-285,71	-351,59	-637,30	-1,09	0,10	-1277,70

TABLE 21(b)

RANKING OF DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER(CATCHMENT Q9M23)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	4(4)	(4)	(4)	2	4	3	3	6	22
PORT	2(2)	(2)	(2)	7	3	4	8	8	32
BERG	1(1)	(3)	(3)	1	2	1	2	5	12
DALH2	3(3)	(1)	(1)	3	1	2	5	1	15
TOTAL	10	-	-	13	10	10	18	20	81
Daily									
SMDV	8	-	-	4	7	5	4	7	35
PDAY	5	-	-	5	8	7	1	2	28
HANS	5	-	-	8	6	8	7	4	38
DALT2	7	-	-	6	5	6	6	3	33
TOTAL	25	-	-	23	26	26	18	16	134

TABLE 22(a)

DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER (CATCHMENT Q9M24)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	-3,36	-2,92	-6,28	-353,39	-292,28	-645,67	-2,77	-10,69	-1308,16
PORT	-1,85	0,73	-1,12	-252,97	-14,80	-267,77	0,09	-0,23	-537,53
BERG	-2,22	-9,28	-11,50	-241,95	-487,26	-729,21	-4,15	-32,16	-1496,95
DALH2	-7,70	-13,18	-20,88	-785,59	-798,33	-1583,92	-6,88	-68,23	-3250,65
TOTAL	-15,13	-24,65	-39,78	-1633,90	-1592,67	-3226,57	-13,71	-111,31	-6593,29
Daily									
SMDV	-4,91	-	-	-502,97	-589,47	-1092,44	-2,29	-42,82	-2234,90
PDAY	-5,23	-	-	-570,76	-584,77	-1155,53	-0,97	-44,24	-2361,50
HANS	-3,42	-	-	-386,44	-323,13	-709,57	-1,58	-14,55	-1438,69
DALT2	-5,26	-	-	-540,25	-793,22	-1333,47	-2,23	-74,62	-2749,05
TOTAL	-18,82	-	-	-2000,42	-2290,59	-4291,01	-7,07	-176,23	-8784,14

TABLE 22(b)

RANKING OF DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER(CATCHMENT Q9M24)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	3(3)	(2)	(2)	3	2	2	6	2	18
PORT	1(1)	(1)	(1)	2	1	1	1	1	7
BERG	2(2)	(3)	(3)	1	4	4	7	4	22
DALH2	8(4)	(4)	(4)	8	8	8	8	7	47
TOTAL	14	-	-	14	15	15	22	14	94
Daily									
SMDV	5	-	-	5	6	5	5	5	31
PDAY	6	-	-	7	5	6	2	6	32
HANS	4	-	-	4	3	3	3	3	20
DALT2	7	-	-	6	7	7	4	8	39
TOTAL	22	-	-	22	21	21	14	22	122

TABLE 23

TOTAL DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER (ALL FOUR SUB-CATCHMENTS)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	-3,90	-3,26	-7,16	-421,79	-382,49	-804,28	-3,25	-10,92	-1626,63
PORT	-2,15	+0,78	-1,37	-349,84	-99,36	-449,20	-0,46	-0,47	-901,48
BERG	-2,64	-10,04	-12,68	-327,00	-564,56	-891,56	-4,51	-32,70	-1822,97
DALH2	-7,87	-12,53	-20,40	-937,05	-806,68	-1743,73	-8,16	-66,66	-3570,15
TOTAL	-16,56	-25,05	-41,61	-2035,68	-1853,09	-3888,77	-16,38	-110,75	-7921,23
Daily									
SMDV	-5,80	-	-	-623,49	-755,28	-1378,77	-3,40	-43,49	-2810,23
PDAY	-5,97	-	-	-672,87	-720,76	-1393,63	-1,39	-44,11	-2838,73
HANS	-4,21	-	-	-519,75	-418,00	-937,75	-0,95	-14,82	-1895,48
DALT2	-5,74	-	-	-698,27	-975,12	-1673,39	-3,46	-74,78	-3430,76
TOTAL	-21,72	-	-	-2514,38	-2869,16	-5383,54	-9,20	-177,20	-10975,20

TABLE 24

RANKING OF TOTAL DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER (ALL FOUR SUB-CATCHMENTS)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	3	2	2	3	2	2	4	2	2
PORT	1	1	1	2	1	1	1	1	1
BERG	2	3	3	1	4	3	7	4	3
DALH2	8	4	4	8	7	8	8	7	8
TOTAL	14	10	10	14	14	14	20	14	14
Daily									
SMDV	6	-	-	5	6	5	5	5	5
PDAY	7	-	-	6	5	6	3	6	6
HANS	4	-	-	4	3	4	2	3	4
DALT2	5	-	-	7	8	7	6	8	7
TOTAL	22	-	-	22	22	22	16	22	22

TABLE 25

AVERAGE DETERIORATION IN PERCENTAGE ERROR IN STATISTICS DUE TO PARAMETER TRANSFER

CATCHMENT	U2	U3	U4	U5	U6	U7	U8	U9
Hourly models								
Q9M21	+3	-5	-2	-10	+1	-9	-8	+2
Q9M22	-3	+6	+3	-37	-21	-58	-32	-18
Q9M23	-35	-11	-46	-53	-45	-98	-26	-6
Q9M24	-378	-616	-994	-408	-398	-806	-343	-2783
Daily models								
Q9M21	-4	-	-	-17	-19	-36	-3	-6
Q9M22	-15	-	-	-40	-37	-77	-23	-21
Q9M23	-53	-	-	-71	-88	-159	-27	+2
Q9M24	-470	-	-	-500	-573	-1073	-177	-4406

is within reasonable limits and the same applies for statistics U2, U3 and U4 in catchment Q9M22. However, the deterioration of the statistics in catchment Q9M23 is probably greater than could be tolerated for most applications and the deterioration in catchment Q9M24 could at best be described as excessive. The pattern of increasing deterioration in the statistics from catchment Q9M21 to Q9M24 is evident in the results for the daily models (Table 25), but there is a difference in that the deterioration is worse with the result that feasibility of parameter transfer becomes doubtful, even in catchment Q9M21. The reason for the increasing loss of transferability with increasing upstream distance of the measuring point from the main catchment outlet is not clear but it may be associated with a spatial trend in the errors involved in the spatial assessment of rainfall depths.

5.3.2 Comparison of performance in terms of complexity of model structure

The comparison of the parameter transfer results on the basis of the complexity of model structure within each group of models is best illustrated by reference to Table 24. As in the case of the short record tests, the simple model DALH2 is inferior to the other hourly models in terms of the level of parameter transfer. However the pattern of increasing deterioration in statistics with decreasing model complexity is not otherwise evident in any statistic in either the hourly or daily group of models. Consequently the third hypothesis stating; "Within any group of models requiring the same time-interval for rainfall input, the models of complex structure are more suitable for parameter transfer applications than the models of more simple structure." must be rejected.

The values for model PORT indicate that it is the best model in terms of parameter transfer with model FORD in second place but it is necessary to consider that Table 15(a) showed that the ability of model PORT to reproduce the observed values of the statistics in each catchment was consistently poor whereas the output for model FORD was consistently good. Hence the choice of a model from either the hourly or daily group for any particular engineering application that requires parameter transfer should be based on the ability of the model to produce output at an acceptable level in the gauged catchment and the parameter transferability as shown in Table 24 should be a secondary consideration. An interesting facet of Tables 19(a), 20(a), 21(a) and 22(a) is that occasionally there has been an improvement in the value of a statistic due to parameter transfer for a model in a particular catchment as illustrated by the positive values. The majority of improvements are associated with models PORT and DALH2 which indicates that the parameters derived by calibration for these models are less applicable to the full range of statistics than those for the other models.

5.3.3 Comparison of performance in terms of complexity of model input requirements

The most notable feature of the parameter transfer results is the evident influence of the time-interval used for input data on the deterioration in the values of the statistics. The values of the rankings for statistics U2, U5, U6, U7 and U9 in Table 24 illustrate that the hourly models are more suitable for parameter transfer than the daily models. It is of particular interest to note that the hourly models were superior to the daily models with respect to statistic U7 which was the objective function used for the daily models. The reason for the higher level of transferability of the hourly models must be ascribed primarily to the higher level of information contained in the input record. It may be that the difference would decrease with increasing length of record for calibration. In the light of the results obtained, the fourth hypothesis stating that; "The models that require hourly rainfall input are generally more suitable for parameter transfer applications than the models that require daily rainfall input." may be accepted as valid within the limits of the number of catchments, models and objective functions for which the hypothesis has been tested.

The only statistic that does not show superior transfer for the hourly models is U8 and an examination of Tables 19(b), 20(b), 21(b) and 22(b) shows that although there is general agreement in rankings of U8 and U9 there are major discrepancies for the simple models DALH2 and DALT2. It would appear that the statistic U8 becomes far more sensitive to increasing systematic error than U9 and this may be attributed to the inclusion of the base constant of the regression equation in U8. The discrepancy appears to be most marked in cases where there is little deviation of the regression coefficient from unity but a marked deviation of the base constant from zero.

5.4 Temporal Aspects of Parameter Transfer

The hourly models were calibrated for catchment Q9M20 with both the long record of 15 months and the short record of 1 month where the short record constitutes the first portion of the longer record. An indication of the suitability of using a calibration period of one month for the hourly models can be obtained if the parameter values derived by using the short record are used with the longer record. The values of the statistics obtained are compared with the values of the statistics after recalibration with the longer record. The temporal transfer of parameters from the short to the long record provides an indication of the deterioration in the statistics that may arise as a result of using parameters derived from a short record calibration. The results obtained are reflected in Table 26 and have been ranked in Table 27 for ease of comparison. All of the hourly models produce a deterioration in the value of the objective function U4 with the short record par-

TABLE 26

DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER FROM SHORT TO LONG RECORD(CATCHMENT Q9M20)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	-2,02	-57,67	-59,69	-211,93	-25,27	-237,20	-5,02	-0,81	-482,25
PORT	-2,23	-6,99	-9,22	-302,59	-31,72	-334,31	-7,14	-2,32	-680,31
BERG	+0,08	-0,34	-0,26	+23,23	+20,06	+43,29	-0,41	+0,01	+86,26
DALH2	-0,47	-0,22	-0,69	-14,52	+23,05	+8,53	+0,35	+0,20	+17,14
TOTAL	-4,64	-65,22	-69,86	-505,81	-13,88	-519,69	-12,22	-2,92	-1059,16

TABLE 27

RANKING OF DETERIORATION IN STATISTICS DUE TO PARAMETER TRANSFER FROM SHORT TO LONG RECORD(CATCHMENT Q9M20)

MODEL	U2	U3	U4	U5	U6	U7	U8	U9	TOTAL
Hourly									
FORD	3	4	4	3	3	3	3	3	26
PORT	4	3	3	4	4	4	4	4	30
BERG	1	2	1	1	2	1	2	2	12
DALH2	2	1	2	2	1	2	1	1	12

ameter values but the sum of deteriorations in all statistics for each model (Table 26) illustrates that the parameter values for the simple models DALH2 and BERG are not only more representative than those for the complex models FORD and PORT but actually give an overall improvement as shown by the positive signs. Consequently the fifth hypothesis must be rejected since it states that: "Within the group of models that require hourly rainfall input, the use of a very short calibration record (1 month) results in less representative parameter values for the models of simple structure than for the more complex models." It can be concluded that the use of an inadequate length of calibration record with the complex models can give rise to less realistic values for the parameters than those for the more simple models mainly because the complex interaction between parameters in the complex models can provide a greater range of parameter sets that give near equivalent output. The results indicate that models FORD and PORT are probably over-determined with respect to objective function U4 and the length of calibration record used resulting in a 'forced fit'. As Snyder, Mills and Stephens (1971, 443) have pointed out, "If the model is over-determined - that is, has an excess number of parameters - then optimization will cause some of these excess degrees of freedom to be used to absorb some of the random error always present in data."

5.5 Summary of Findings

The feasibility of model parameter transfer from the gauged to the ungauged catchment has been tested for a wide range of models under conditions that would appear to be most favourable. However the results have shown that apparent similarity in climate, vegetation and lithology may not be sufficient evidence of similarity in hydrological response. It is not known how much of the deterioration in model output during parameter transfer is due to differences in hydrological response and how much is due to errors in the input data but the evidence does indicate that simulated runoff data obtained by parameter transfer should be used with discretion.

The parameter transfer comparisons between models have illustrated that the most important factor affecting the level of transferability is the time-interval used for rainfall input data (the iterations of the model are equivalent to the time-interval for input). The use of hourly rainfall consistently provided less deterioration in all statistics than the use of daily rainfall. The complexity of model structure does not seem to have much influence on the level of transferability provided that a certain undefined level of complexity has been exceeded. The poor results for the simple models DALH2 and DALT2 (Table 24) indicate that the necessary level of complexity has not been attained in these models with respect to the requirements for parameter transfer. The average deterioration in the percentage error of the statistics in Table 25 suggests that the nature of the statistic being used as the objective function is not an important consideration for parameter transfer applications as no single statistic consistently deteriorated more markedly than the others. However, the deterioration in statistic U9 in catchment Q9M24 as compared with the other catchments indicates that the amount of deterioration in a statistic that could be expected for any one model is related to the sensitivity of the statistic at the level of simulation attained in the gauged catchment.

The results of the parameter transfer tests have not provided rigid guidelines to the best choice of model for parameter transfer purposes but the following general observations may be of assistance to the practising engineer or hydrologist.

(1) Fine time-intervals for input data provided better results than coarse time-intervals and consequently the user may benefit by using

finer time-intervals than would be necessary to provide adequate values of the objective function in the gauged catchment.

(2) The use of models with highly complex structure does not necessarily provide better results in the ungauged catchment than simple models provided that the model is sufficiently complex to produce acceptable results in the gauged catchment.

(3) If the length of calibration record in the gauged catchment is very short, the use of a model with relatively simple structure is more likely to produce representative parameters than a highly complex model.

The comparison of the performance of the selected models in Chapters 4 and 5 has provided valuable information about the relative merits of model complexity in its various forms. The comparison has also provided a framework for the assessment of each stage in the development of the DALT model described in Chapter 3 but the major limitations to the general applicability of both the results obtained and the model developed, are the use of data from catchments in the same area and the relatively short time-base of the data record. In order to overcome the problem of the limitations, the daily models will be tested in an additional catchment with a long data record in the following chapter. The need for the extension of the research to at least one more catchment, far removed from the Ecca catchments, is evident from a comment by Hillel (1975, 122): "One seemingly obvious fallacy of simulation is to construct a model to fit a specific set of data, and then to claim as a surprising achievement the good agreement of the model with the very data which it was forced to fit."

CHAPTER 6

APPLICATION OF THE DAILY MODELS TO THE MAREETSANE CATCHMENT

6.1 Introduction

The major limitation of the comparison of model performance in the previous chapters may be regarded as the relatively short record used for calibration. There is some doubt as to whether the observed pattern of relative model performance would remain unchanged if the calibration data contained a greater range of flood and drought conditions. Valuable information could be obtained by calibrating the models in an additional semi-arid catchment with a much longer record of calibration data. Unfortunately, a long record for testing the group of hourly models is not available but numerous catchments have been monitored on a daily basis for an adequate period of time and it will be possible to conduct more rigorous tests with the group of daily models. While it has been necessary to exclude the hourly models there is the consideration that hourly models are seldom used for generation of long records and that the structures of three of the hourly models are represented in the group of daily models.

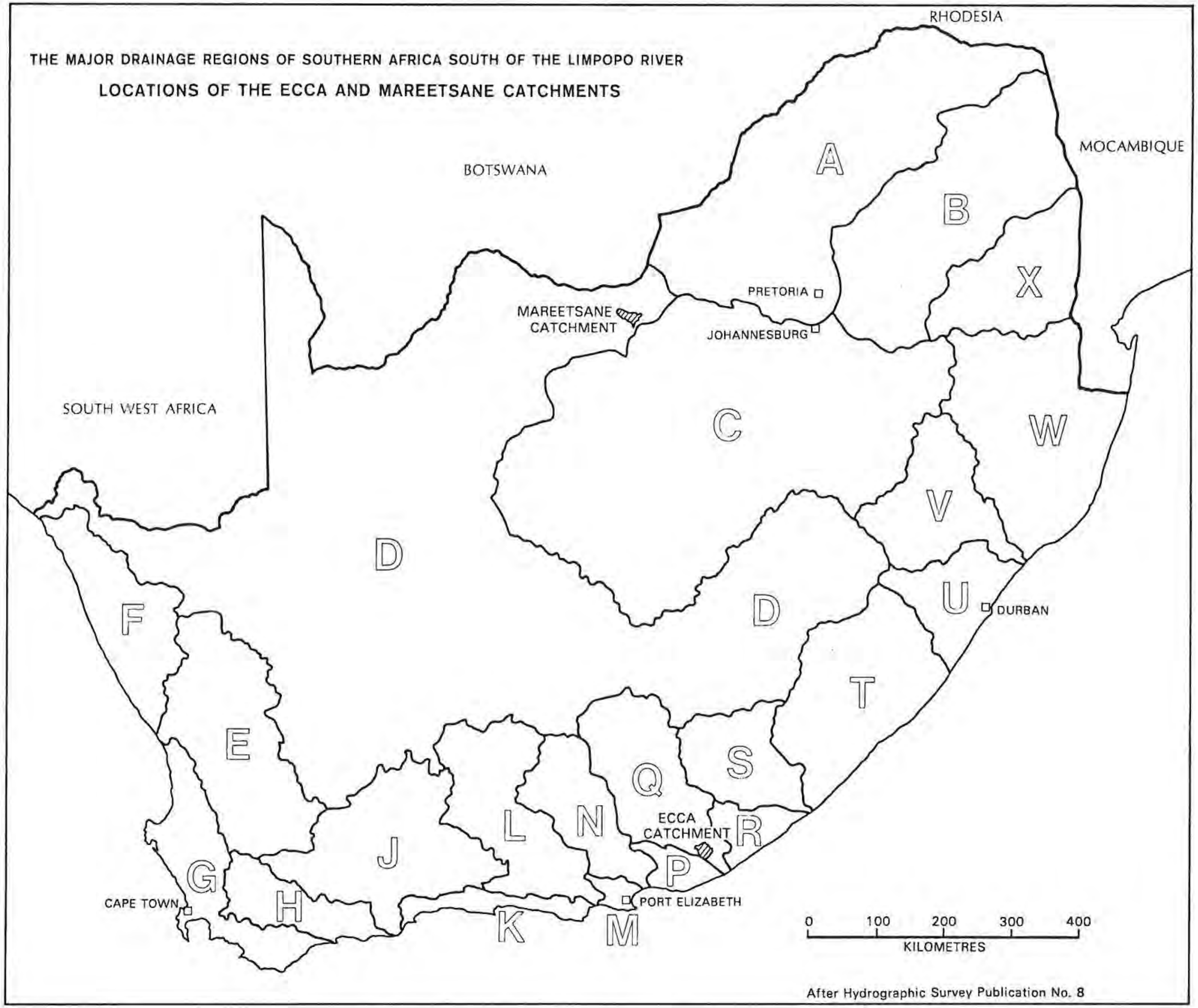
Semi-arid catchments that have been monitored on a daily basis in South Africa do not constitute 'research' or 'experimental' catchments but are part of the national network. The objective of the national network is to obtain assessments of the national water resources and as a result the hydrological data collected are not likely to be as accurate as those obtained for the Ecca catchments, both in terms of the density of the gauging network as well as the sophistication of the instruments used. A reduced level of accuracy in the calibration data will weaken the validity of the assumption that errors in the simulated discharge result from inadequacy of model structure rather than errors in calibration data. However, this consideration affects the testing of the adequacy of individual model structure for the particular hydrological regime more than the relative comparison of model performance which is the predominant aim. The disadvantages resulting from the use of less accurate calibration data are compensated for to a large extent by the increased length of record available and it must be remembered that such data are more representative of the quality of data that hydrologists have available for modelling applications in South Africa.

The catchment area chosen for further testing of the daily models was the semi-arid Mareetsane catchment in the Northern Cape Province (Figure 68). The hydrological data for the Mareetsane catchment were selected by P.S. Stickells as being suitable for a comparative study of daily models (research in progress at the Hydrological Research Unit, Rhodes University). Consequently the data were readily available in a suitable form and the benefit of calibrating the models in another semi-arid catchment could be achieved without further data gathering and preparation.

6.2 Description of the Mareetsane Catchment

The available daily rainfall and runoff data for the Mareetsane catchment cover the 38 year period from 1927 to 1964. The gauging structure at the catchment outlet is a weir (D4MO2 in the national network) at which daily observations have been recorded and the area drained in approximately 342 square kilometres. The river channel is emphemeral and the mean annual runoff has been estimated from the available records at approximately $3,3x10^6m^3$.

Daily rainfall has been recorded at three stations and the records indicate that the mean annual precipitation is approximately 477 millimetres. In order to compare the rainfall characteristics with those of


THE MAJOR DRAINAGE REGIONS OF SOUTHERN AFRICA SOUTH OF THE LIMPOPO RIVER

LOCATIONS OF THE ECCA AND MAREETSANE CATCHMENTS

After Hydrographic Survey Publication No. 8

FIGURE 68

the Ecca catchments, the record of areal estimates of daily rainfall (provided by Stickells) for the 38 year period was subjected to a run analysis by using program STAT (Appendix A) and the results are reflected in Table 28 and plotted in Figure 69. The lines drawn in Figure 69 illustrate the general similarity between the rainfall characteristics of the Ecca and Mareetsane catchments with the largest discrepancy being in the low threshold range where the effect of the stronger seasonal bias in rainfall distribution is more evident.

No measurements of daily pan evaporation are available for the Mareetsane catchment and as a result, estimates of daily potential evapotranspiration must be obtained from estimates of the average pan evaporation for each month. Values of average Symons Pan evaporation for each month were obtained from the publication of Pitman (1973) and disaggregated in proportion to obtain estimates for each day of the month.

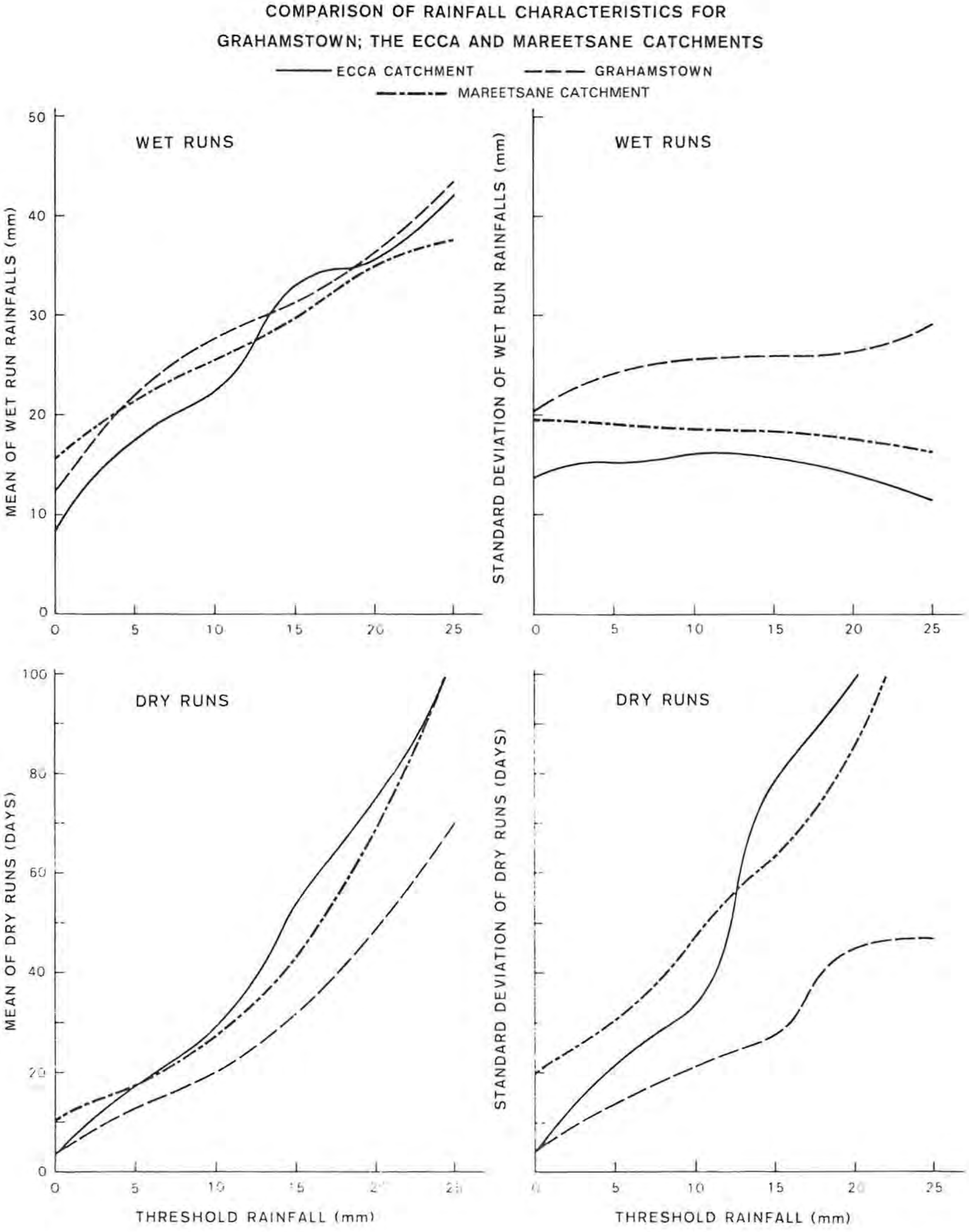
The Mareetsane catchment is similar to the Ecca catchment in that it is relatively homgeneous and relatively stable with respect to vegetation cover and land use. However, in contrast to the highly dissected Ecca catchment with its cover of Fish River Valley bushveld, the Mareetsane catchment is typical of an inselberg terrain and has been described by Stickells (personal communication) as a rather monotonous, slightly undulating plain interrupted by isolated outcrops. The catchment is covered by open Kalahari Thornveld with tall grassland and is underlain predominantly by granite and granitic gneiss. Perhaps the most important feature from a hydrological point of view is the fact that the gentle slopes are covered by surface deposits of sand; a combination that is likely to give a hydrological response more typical of the arid rather than semi-arid regimes. A visual inspection of the available runoff record illustrates that the flood hydrographs are

TABLE 28

COMPARISON OF RAINFALL CHARACTERISTICS FOR THE ECCA AND MAREETSANE CATCHMENTS

ECCA RAINFALL

THRESHOLD DAILY RAINFALL (MM)	DRY RUNS(DAYS)		WET RUNS(DAYS)		WET RUN DEPTHS (MM)		
	MEAN	S.DEV	MEAN	S.DEV	MEAN	S.DEV	CofV
0	4	4	2	1	8,06	13,85	1,72
1	8	8	2	1	11,21	14,66	1,31
5	18	22	1	1	17,75	15,05	0,85
10	29	33	1	1	22,24	16,03	0,72
15	55	80	1	1	33,38	15,95	0,48
20	75	98	1	1	35,85	13,89	0,39
25	106	125	1	1	42,30	11,70	0,28
MAREETSANE RAINFALL							
0	10	20	2	1	15,82	19,63	1,24
1	11	22	2	1	17,03	19,49	1,14
5	17	30	2	1	21,32	19,15	0,90
10	27	47	1	1	25,57	18,70	0,73
15	43	63	1	1	29,99	18,49	0,62
20	70	85	1	1	35,09	17,80	0,51
25	104	127	1	1	37,95	16,78	0,44



COMPARISON OF RAINFALL CHARACTERISTICS FOR GRAHAMSTOWN; THE ECCA AND MAREETSANE CATCHMENTS

WET RUNS

WET RUNS

DRY RUNS

DRY RUNS

FIGURE 69

more peaked with base flow of shorter duration than those observed in the Ecca catchments and the regime is more orientated to 'flash flood' response. The implications of the 'arid' characteristics of the flow regime with respect to model calibration may be drawn from recent research done by Pitman (1973). A conceptual model of the rainfall-runoff process was tested (with monthly data) in 46 diverse catchments in South Africa by Pitman and one of the conclusions drawn was that soil moisture state was a poor indicator of runoff in the more arid catchments. Consequently the data for the Mareetsane catchment will provide an exacting test of the general applicability of those models in which runoff is highly dependent on antecedent conditions.

6.3 Parameter Transfer from the Ecca to the Mareetsane Catchment

The first phase of the application of the daily models in the Mareetsane catchment involved an assessment of the difference in hydrological response between the Mareetsane and Ecca catchments. Only those model parameters that are not optimized in the calibration process were adjusted for the Mareetsane catchment and the remaining parameters were given the same values as those obtained by calibration in the Ecca catchment Q9M20. A parameter transfer between two catchments differing in topography and vegetation and so far removed from each other would not normally be attempted for practical applications but the purpose of the transfer in this instance was to obtain a numerical assessment of the difference in yield as a guide to optimization. The results obtained are of particular interest and have been listed in Table 29(a) and ranked in Table 29(b). The very simple model DALT1 has a single parameter value that represents the maximum moisture deficit averaged over the catchment and the use of the value of this parameter obtained by calibration in the Ecca catchment produced simulated output that has less than one percent error in the mean of the daily discharge values

TABLE 29(a)

GOODNESS OF FIT STATISTICS FOR MAREETSANE CATCHMENT USING ECCA PARAMETERS

MODEL	U2	U5	U6	U7	U8	U9
SMDV	1,18	20,09	-32,36	52,45	-0,65	-1,36
PDAY	1,14	10,15	-48,59	58,74	-0,74	-1,91
HANS	1,27	35,34	-15,81	51,15	-0,78	-1,11
DALT4	1,55	6,77	-186,55	193,32	-0,67	-7,81
DALT3	1,56	6,94	-187,10	194,04	-0,69	-7,86
DALT2	1,59	8,28	-198,37	206,65	-0,69	-8,54
DALT1	1,71	0,14	-247,17	247,31	-0,66	-11,65

TABLE 29(b)

RANKINGS OF GOODNESS OF FIT STATISTICS FOR MAREETSANE CATCHMENT (ECCA PARAMETER VALUES)

MODEL	U2	U5	U6	U7	U8	U9
SMDV	2	6	2	2	1	2
PDAY	1	5	3	3	6	3
HANS	3	7	1	1	7	1
DALT4	4	2	4	4	3	4
DALT3	5	3	5	5	4	5
DALT2	6	4	6	6	5	6
DALT1	7	1	7	7	2	7

(U5) for the Mareetsane catchment. In view of the fact that the model has a single parameter it is unlikely that the model was over-determined with respect to the data and objective function used for calibration in the Ecca catchment. Consequently it may be assumed that the yield per unit area in the two catchments is remarkably similar. Another interesting facet of the values obtained for statistic U5 in Table 29(a) is that the simple models DALT1 to DALT4 gave errors of less than 10 percent whereas the more complex models HANS, PDAY and SMDV gave errors in excess of 10 percent. However the pattern for statistic U6 (standard deviation of daily discharge values) is reversed with the simple models giving errors approaching or exceeding 200 percent whereas the more complex models have provided errors of less than 50 percent. It would appear that the more complex multiple storage models are less able to provide realistic average storage capacity but the use of multiple storages provides more realistic simulation of antecedent conditions (storage levels) and consequently better reproduction of the variance. The values for U6 show that the standard deviation of daily discharge has been exaggerated by all the models with the high flows being overestimated and the lower flows underestimated. Although the long term yield has been reproduced with reasonable accuracy by using 'Ecca' parameter values, the values of statistics U2, U8 and U9 show a very poor one-to-one correspondence between simulated and observed runoff.

6.4 The Calibration of the Models with Mareetsane Data

All the daily models were then calibrated with the 38 years of data available for the Mareetsane catchment and the derived values of the relevant statistics have been reflected in Table 30(a) and ranked in Table 30(b). During the calibration of the DALT range of models the deep percolation function was rendered inactive to conform with the

TABLE 30(a)

BEST FIT STATISTICS FOR MAREETSANE CATCHMENT (WITHOUT PERCOLATION FUNCTION IN DALT MODELS)

MODEL	U2	U5	U6	U7	U8	U9
SMDV	1,20	0,74	-19,95	20,69	-0,63	-1,04
PDAY	1,11	0,81	-4,94	5,75	-0,68	-0,76
HANS	1,28	3,82	-4,78	8,60	-0,69	-0,77
DALT4	1,46	4,19	-106,25	110,44	-0,69	-3,87
DALT3	1,49	0,61	-99,25	99,86	-0,63	-3,51
DALT2	1,54	1,43	-121,84	123,27	-0,68	-4,52
DALT1	1,71	0,14	-247,17	247,31	-0,66	-11,65

TABLE 30(b)

RANKING OF BEST FIT STATISTICS FOR MAREETSANE CATCHMENT (WITHOUT PERCOLATION FUNCTION)

MODEL	U2	U5	U6	U7	U8	U9
SMDV	2	3	3	3	1	3
PDAY	1	4	2	1	4	1
HANS	3	6	1	2	6	2
DALT4	4	7	5	5	7	5
DALT3	5	2	4	4	2	4
DALT2	6	5	6	6	5	6
DALT1	7	1	7	7	3	7

procedure adopted during the calibrations in the Ecca catchments. However, an examination of the values for U6 in Table 30(a) clearly illustrates a structural deficiency in the DALT models as the error in the standard deviation is still of the order of 100 percent. The desired effect of reducing the variance in soil moisture state was achieved to a limited extent by exaggerating the soil moisture response during low flow periods with the non-linear storage functions of models DALT3 and DALT4 but the reduction of soil moisture levels during high flows was inadequate. The solution was to improve the performance of the loss rate functions by activating the deep percolation loss function in models DALT2, DALT3 and DALT4, thereby introducing an additional parameter into the calibration process.

The final values of statistics U2, U5, U6, U7, U8 and U9 obtained by calibration of the daily models are reflected in Table 31(a) and ranked in Table 31(b). The values of U7, which was the objective function used in the calibration process, show that the addition of the deep percolation function in the DALT models was justified and that the simple models DALT2, DALT3 and DALT4 are competitive with the more complex models. All the models with the exception of DALT1 have accurately reproduced the mean and standard deviation of daily discharge values. During the optimization of U7 in the calibration process with the more complex models, the major parameter changes (with respect to 'Ecca' parameter values) involve increases in depression storage and it is evident that the need for larger depression storage is associated with the very gentle slopes and the surface deposits of wind blown sand. The additional storage requirements were met to a limited degree in the DALT models by increasing the maximum capacity of the single 'lumped' storage but the evaporation function for the single storage did not provide sufficient moisture loss. The effect of increasing the depres-

TABLE 31(a)

BEST FIT STATISTICS FOR MAREETSANE CATCHMENT
(WITH PERCOLATION FUNCTION IN DALT MODELS)

MODEL	U2	U5	U6	U7	U8	U9
SMDV	1,20	0,74	-19,95	20,69	-0,63	-1,04
PDAY	1,11	0,81	-4,94	5,75	-0,68	-0,76
HANS	1,28	3,82	-4,78	8,60	-0,69	-0,77
DALT4	1,04	0,98	-6,66	7,64	-0,32	-0,54
DALT3	1,02	0,82	-2,01	2,83	-0,47	-0,50
DALT2	1,07	0,26	-7,54	7,80	-0,47	-0,60
DALT1	1,71	0,14	-247,17	247,31	-0,66	-11,65

TABLE 31(b)

RANKING OF BEST FIT STATISTICS FOR MAREETSANE CATCHMENT (WITH PERCOLATION FUNCTION)

MODEL	U2	U5	U6	U7	U8	U9	TOTAL
SMDV	5	3	6	6	4	6	30
PDAY	4	4	3	2	6	4	23
HANS	6	7	2	5	7	5	32
DALT4	2	6	4	3	1	2	18
DALT3	1	5	1	1	2	1	11
DALT2	3	2	5	4	2	3	19
DALT1	7	1	7	7	5	7	34

sion storage in the more complex models was to provide increased moisture loss due to evaporation at the potential rate from surface storage but in the DALT models the additional moisture loss had to be accomodated in the form of deep percolation loss. The relatively poor result obtained for U7 by the Stanford Model SMDV can be attributed mainly to the inadequacy of the lower zone function (Figure 24, Chapter 3) for arid and semi-arid regimes as previously discussed. During the calibrations of the Stanford Models FORD and SMDV in both catchment areas it became apparent that one of the disadvantages of the Stanford Model lies in the fact that it is not as easy to control contributions to ground water storage as it is in the other models.

An important aspect of Table 31(a) is that the values obtained for statistics U2, U8 and U9 show a very poor level of one-to-one correspondence between individual simulated and observed values and that there is a strong systematic error present in the discharge produced by all the models. Although the base constant of the regression equation approached its optimum value of zero, in no instance did either the correlation or regression coefficient exceed a value of 0,3. The statistic U2 shows that the sum of the discrepancies between simulated and observed monthly discharge values was generally of the same order of magnitude as the total discharge for the entire simulation period of 38 years. The poor correspondence is also evident in the annual discharge values plotted in Figures 70 to 76 inclusive. In seeking an explanation of the poor one-to-one correspondence, a part of the error term must be ascribed to errors in calibration data particularly in view of;

(1) the relatively low density of the raingauge network,

(2) the fact that the capacity of the runoff gauging structure was repeatedly exceeded,

SIMULATED AND OBSERVED ANNUAL DISCHARGE
MAREETSANE CATCHMENT
MODEL SMDV

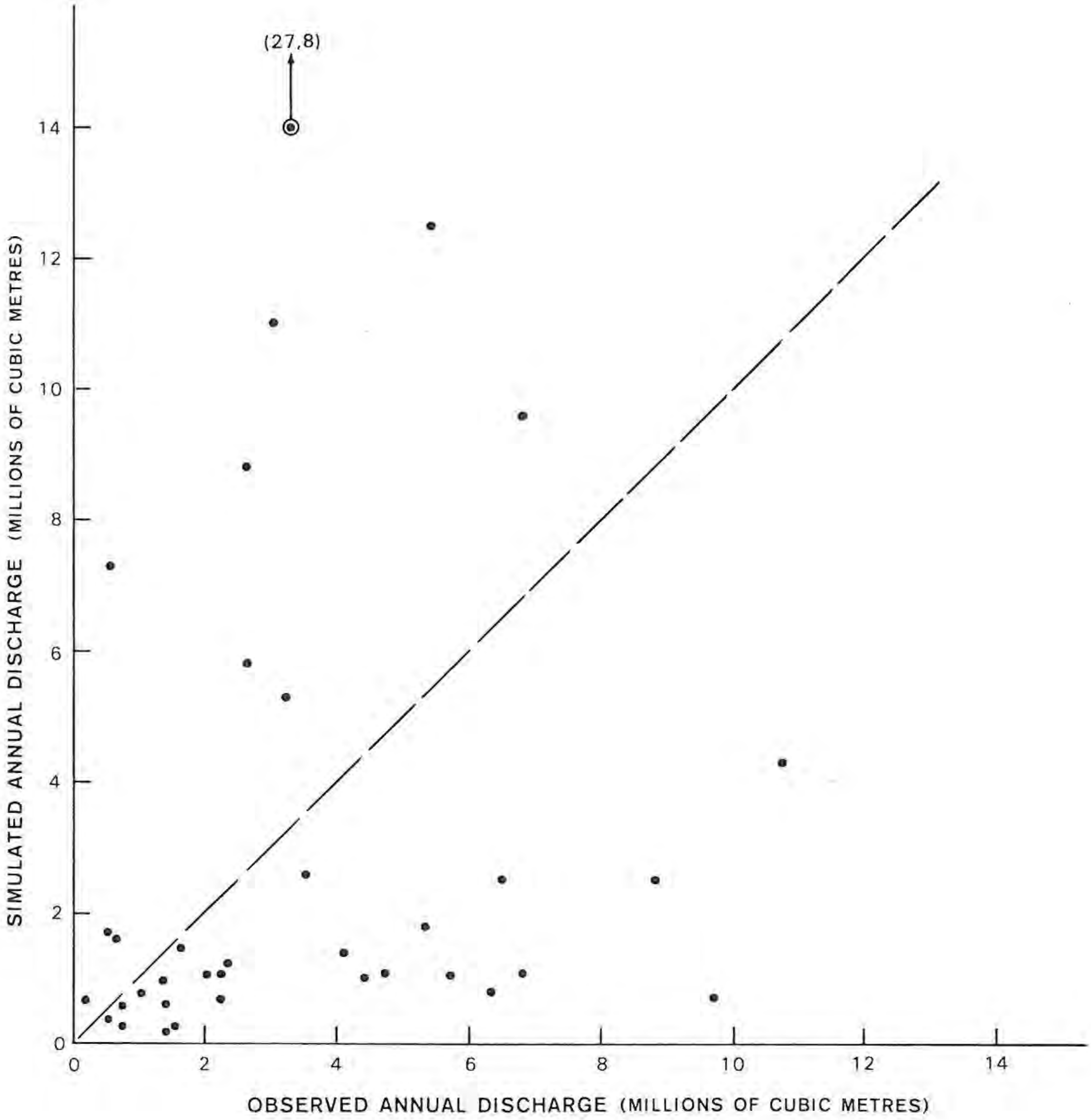


FIGURE 70

SIMULATED AND OBSERVED ANNUAL DISCHARGE
MAREETSANE CATCHMENT

MODEL PDAY

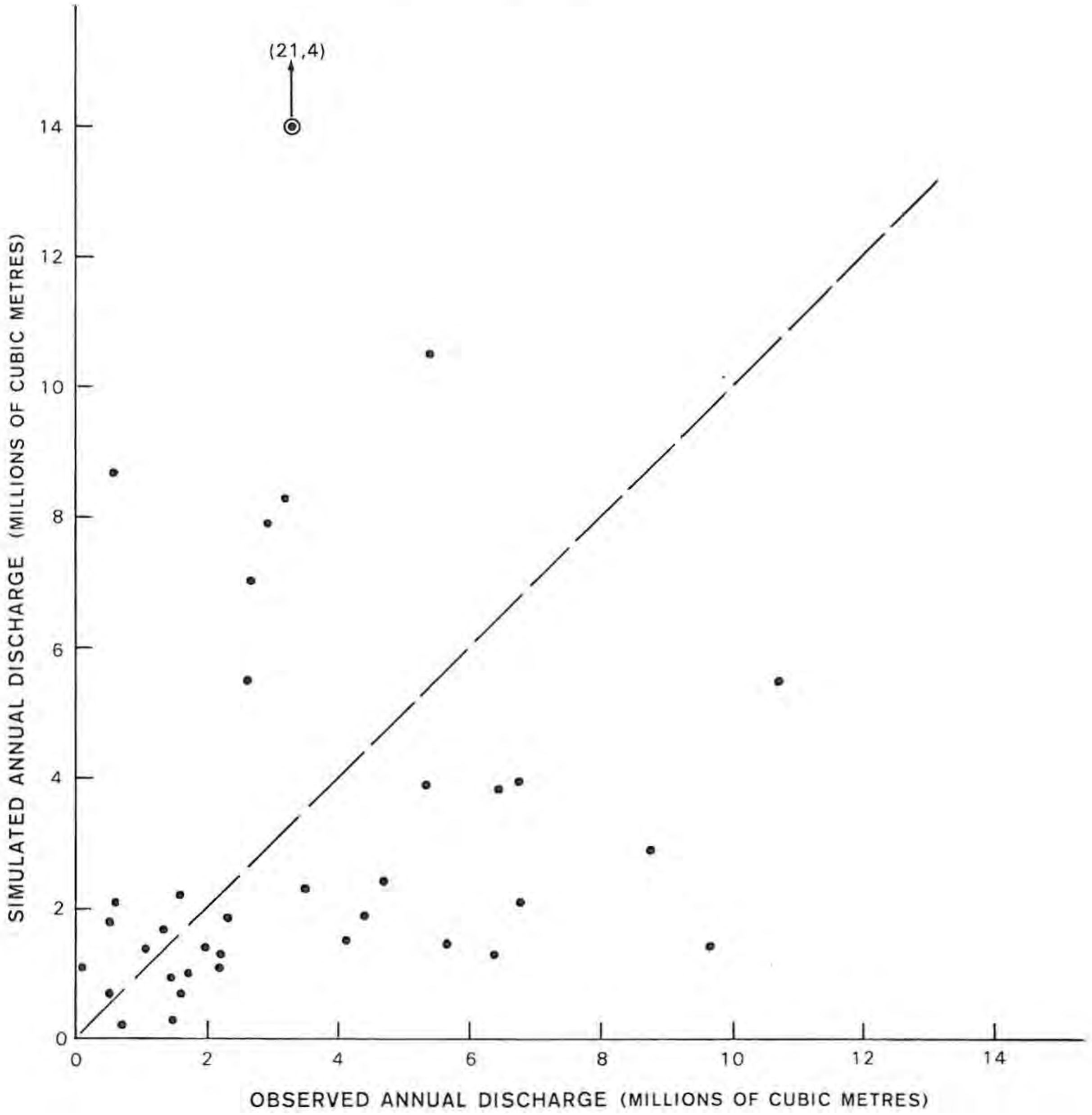


FIGURE 71

SIMULATED AND OBSERVED ANNUAL DISCHARGE
MAREETSANE CATCHMENT
MODEL HANS

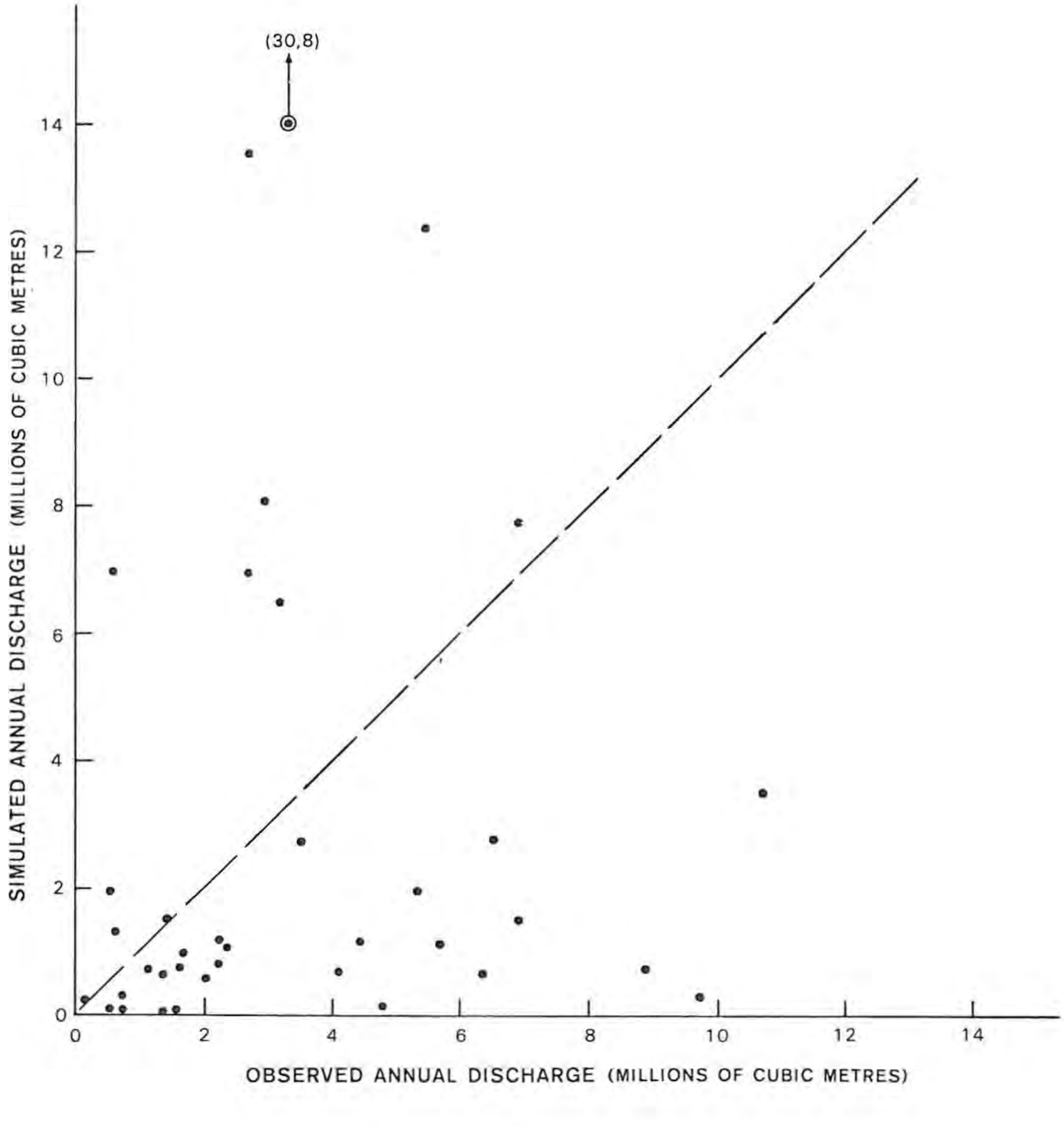


FIGURE 72

SIMULATED AND OBSERVED ANNUAL DISCHARGE-
MAREETSANE CATCHMENT

MODEL DALT4

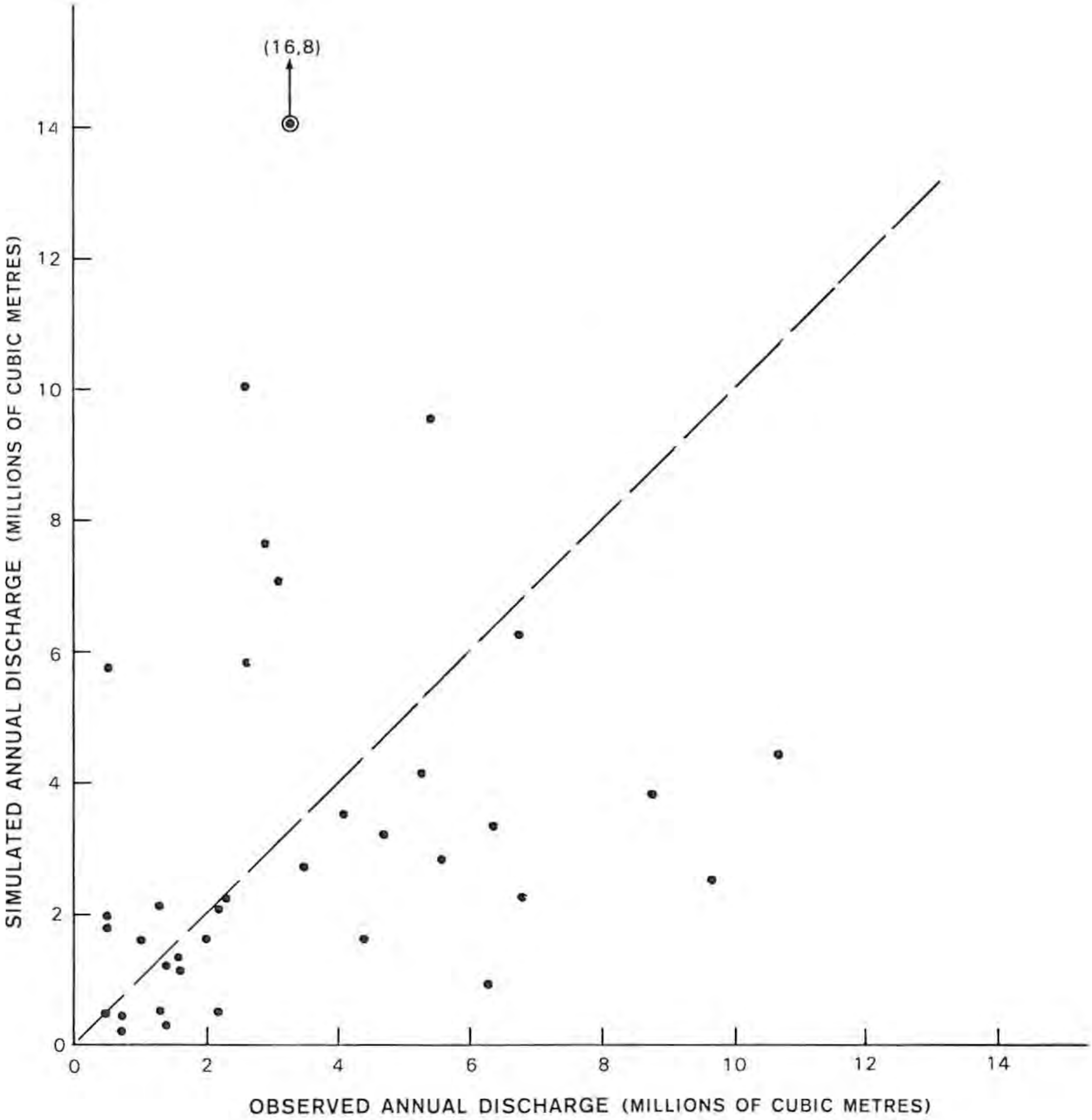


FIGURE 73

SIMULATED AND OBSERVED ANNUAL DISCHARGE
MAREETSANE CATCHMENT
MODEL DALT3

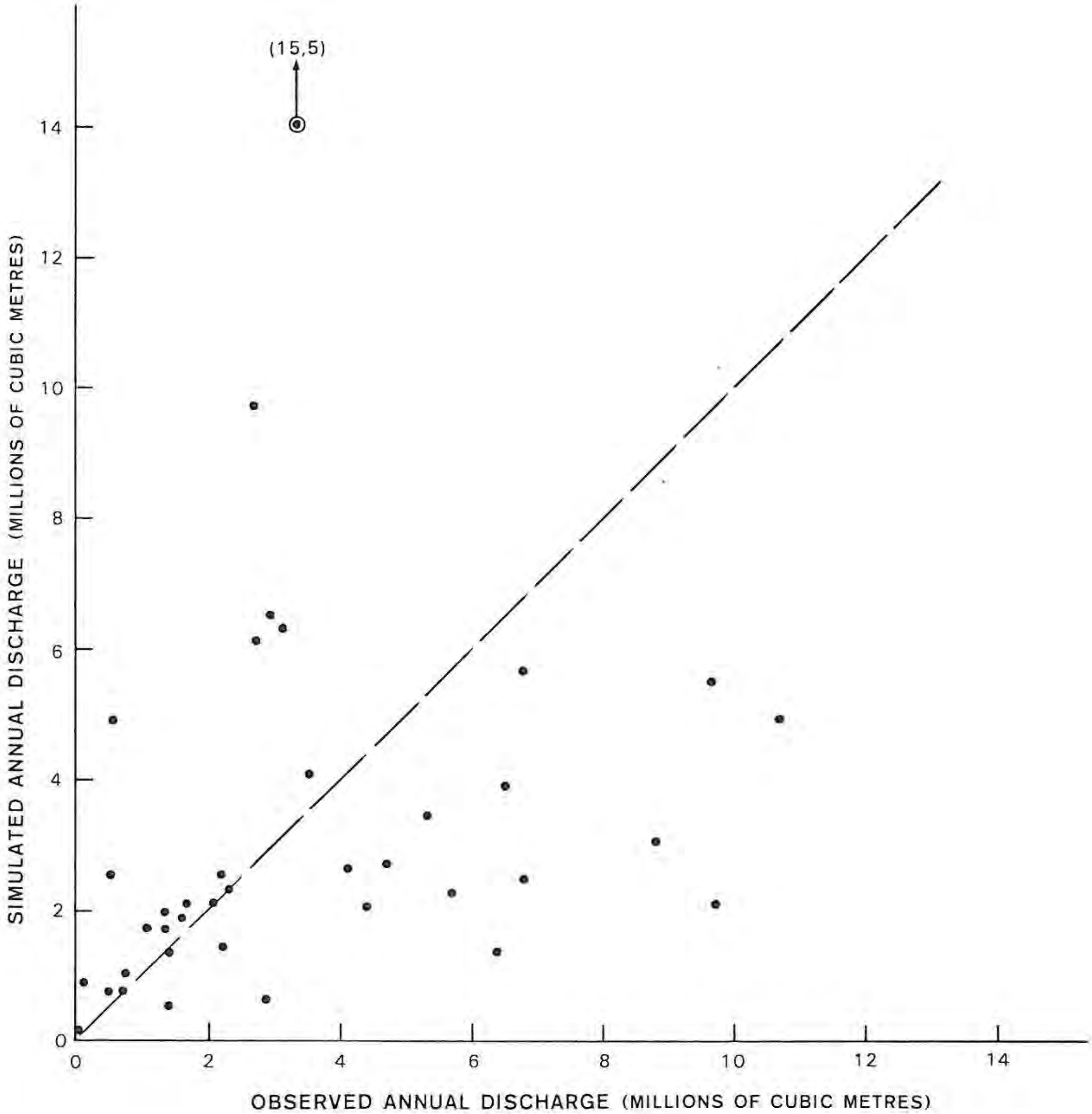


FIGURE 74

SIMULATED AND OBSERVED ANNUAL DISCHARGE
MAREETSANE CATCHMENT
MODEL DALT2

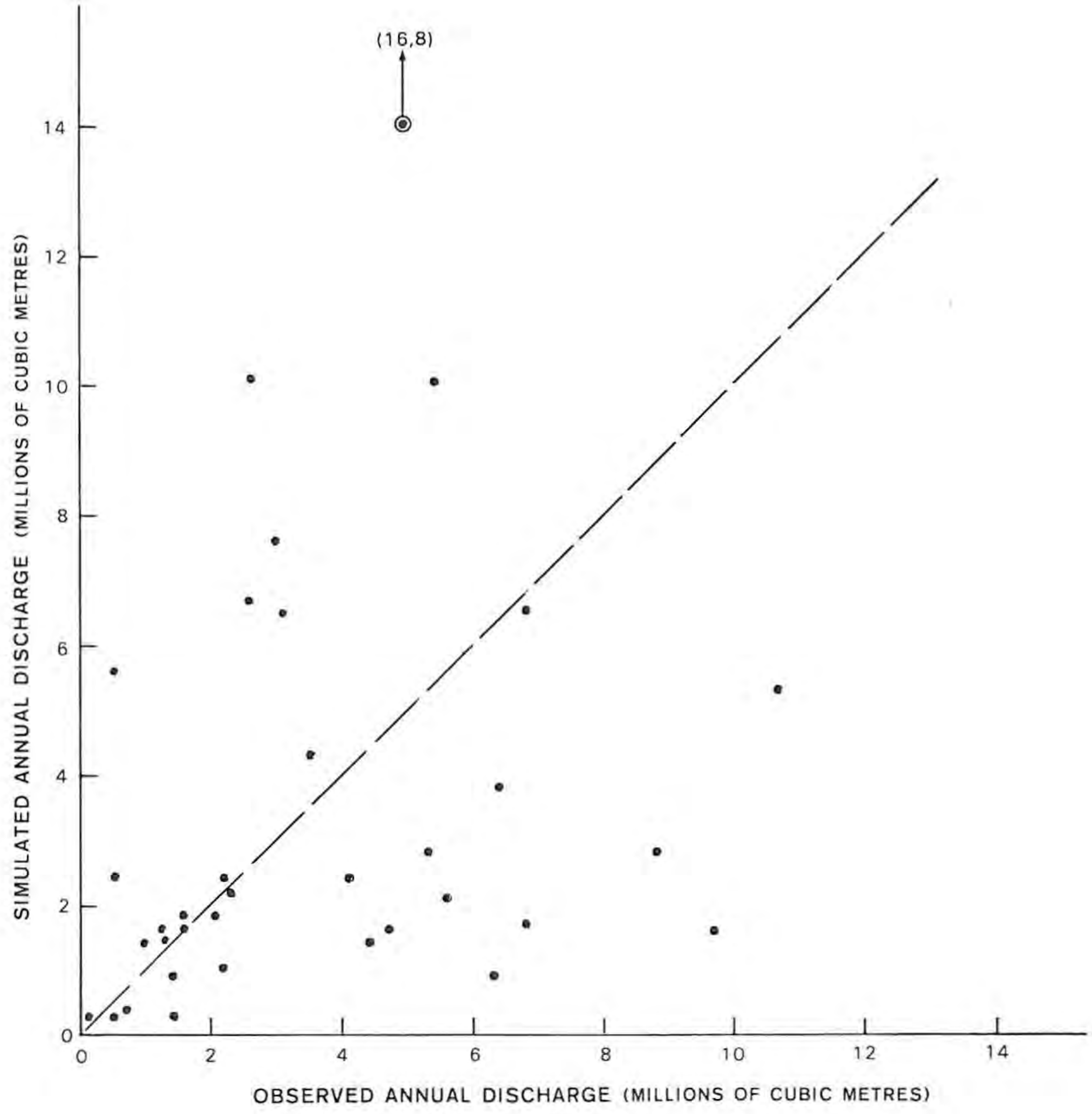


FIGURE 75

SIMULATED AND OBSERVED ANNUAL DISCHARGE
MAREETSANE CATCHMENT

MODEL DALT1

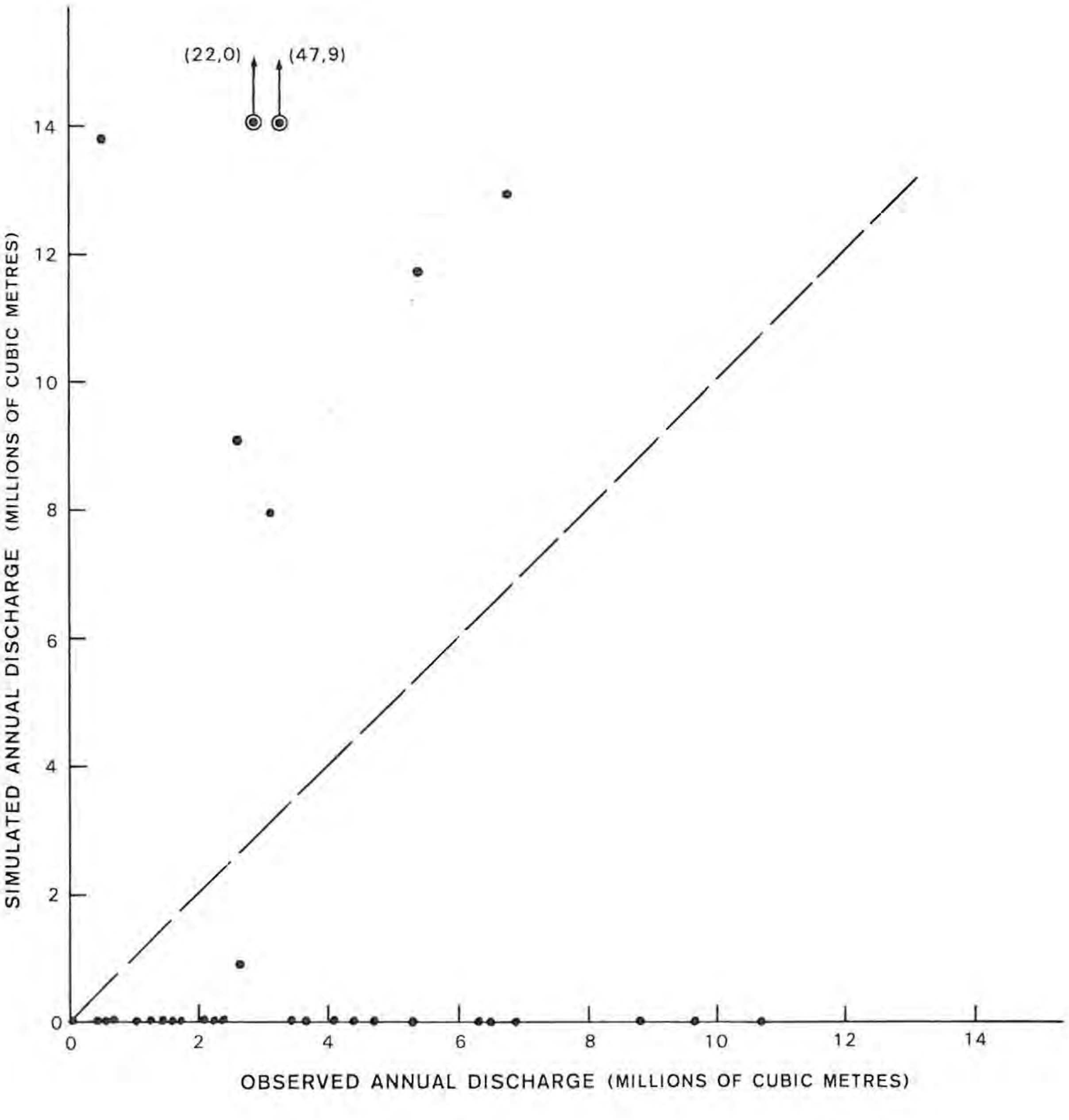


FIGURE 76

(3) the use of estimates of average monthly evaporation and

(4) the lack of autographic instrumentation for both rainfall and runoff data.

However, part of the error term must be attributed to inadequacy of model structure for the particular hydrological regime. Perhaps the greatest deficiency in the structure of all of the models for the more arid regimes is the relatively high level of dependence on soil moisture status for determining contributions of surface runoff to channel flow in any time-interval. There is a need for research on the suitability of various conceptual model structures for the more arid regimes and it is evident from the research done by Pitman (1973) that the approach to the simulation of excess rain in arid regions should be orientated particularly to the development of absorbtion functions that are independent of soil moisture status for any time-interval. In view of the fact that runoff records for the more arid catchments contain long periods of zero flow, an additional approach for further research could include a combination of conceptual and regression models. Travares (1975) conducted model comparison studies with the Stanford Watershed Model and various regression models (on a daily basis) and concluded that the drier the study period, the smaller is the variance explained by regression models, whereas the opposite tendency was observed with the Stanford Model.

6.5 Summary of Findings

The calibration of the daily models in the Mareetsane catchment has provided results that support the relevant conclusions reached during the comparison of model performance in the Ecca catchments. It has been shown that the model DALT1 is too simple in structure to provide adequate simulation for most purposes but the simple model DALT2 has again provided results that are competitive with the more complex models and the relatively simple model DALT3 provided the best results overall. In general, the models were able to reproduce accurately the mean and variance of daily discharge values but the poor one-to-one correspondence illustrates the need for further research on the suitability of various conceptual model structures for the more arid catchments.

CHAPTER 7

SUMMARY AND CONCLUSION

7.1 Summary of Results

The research undertaken is a contribution to the long term objective of providing detailed guidelines for the selection and application of hydrological models. Of necessity the contribution made is limited in terms of the number of models tested, the variety of catchments monitored and the length of the data base used for model calibration. However, any research contributing towards a long term objective should be regarded primarily as a 'report of research in progress' rather than a self-contained document.

In view of the fact that hydologists need to make use of simulation models for a broad range of applications under a variety of hydrological regimes, it would be unrealistic to formulate explicit guidelines from the results obtained even for the semi-arid range of catchments. However the results have provided valuable indications of the merits of various model characteristics which incorporate important implications for the practising hydrologist. The following tentative guidelines have been drawn from the comparison of the performance of the selected models in the Ecca catchments.

1) For any particular application the user of hydrological models should choose a model that is relatively simple in structure rather than one of the highly complex models. The results show that simple models can produce output at a level of accuracy that is competitive with the complex models and so provide marked savings in terms of both user time and computer costs. An additional advantage, indicated by the results, is that the use of a simple model is less likely to result in the model becoming over-determined with respect to the length and nature

of the data record available for calibration. The choice of a simple model should however be qualified by the indications obtained that there is a certain level of structural complexity below which the model is likely to become inadequate for the production of an acceptable value for the objective function.

2) The results have indicated that models requiring hourly time-intervals for rainfall input data do not necessarily provide more accurate output with respect to most of the statistics calculated than models that require daily rainfall. The implication is that users should generally choose a model that requires a time-interval for rainfall input that corresponds to the largest time-interval in the output permitted by the objective function. For example, if daily values of runoff are required, there appears to be little justification for using hourly rather than daily rainfall as model input. However the results indicate that in cases where the application requires parameter transfer or close correspondence between individual values of simulated and observed runoff, the user could benefit by using finer time-intervals for input data.

The general principle of selecting models that are relatively simple in terms of both structure and input requirements is complicated by the fact that the minimum level of complexity is not known in advance. In this respect the approach adopted in the development of the DALT and DALH models is particularly useful. These relatively simple models not only provide flexibility in terms of input requirements but flexibility in structural complexity as well. The user is free to increase progressively the complexity to the desired level without additional programing and consequently the costly process of abandoning the model to start again with a different model may well be avoided.

The comparison of the performance of the group of daily models was extended to the Mareetsane catchment where 38 years of data were available. The results obtained in the Mareetsane catchment substantiated the results obtained in the Ecca catchment, namely, that the models of complex structure do not necessarily provide more accurate output than the simple models and that the simple model DALT2 was competitive with the complex models using data that were not used in the development process. The extension of the comparison of model performance to the Mareetsane catchment also served to illustrate the need for further research on the applicability of various forms of conceptual model structure for use in the more arid hydrological regimes. In particular, there is a need for the development of a moisture absorption function that is not largely dependent on antecedent conditions.

The feasibility of parameter transfer from the gauged to the ungauged catchment has been tested under favourable conditions in the Ecca catchments with data that are probably more accurate than normally would be available to the hydrologist. It was found that in at least two of the catchments studied, the parameter transfer process resulted in excessive deterioration of the statistics expressing the accuracy of the simulated runoff. The reasons for the increasing difference in hydrological response with increasing distance upstream of the gauging point are not immediately clear. It might be expected that the feasibility of parameter transfer would decrease with increasing catchment size due to decreasing homogeneity but the trend observed in the Ecca catchments is not related to catchment size. The indications are that apparent similarity in climate, vegetation and lithology may not be sufficient for the assumption of equivalent hydrological response.

7.2 The Need for Further Research

A logical extension of the research in the Ecca catchments would be to repeat the comparison of model performance (including parameter transfer aspects) with a longer record of rainfall and runoff when the necessary data become available. The process would permit more rigorous testing of the models and would provide more comprehensive information about the minimum length of calibration record necessary for various combinations of models and objective functions. There is also a need for extension of the research on the feasibility of parameter transfer and the identification of additional characteristics that influence the feasibility of the parameter transfer process.

If the models studied are to be of general use in South Africa it is equally important that the models should be tested in a wide range of hydrological regimes so that;

(1) the suitability of the structure of each model may be assessed for a wider range of conditions,

(2) the change in parameter values may be observed and the level of physical interpretation of the parameters improved and

(3) the parameters may be related to physical and climatic characteristics of the catchments to improve the guidelines for the estimation of parameter values.

There are now a number of research catchments in South Africa where suitable data are being collected and these catchments cover a variety of hydrological regimes and incorporate various forms of land use.

The range of models selected for study is limited and there is a need to increase the range to include monthly and yearly models when sufficient data become available. In this respect, additional models should also include quasi-stochastic and stochastic models which are often more suitable for some applications than the conceptual models. In view of the large number of models available, it probably would be more productive to select existing models for further testing (such as those developed for use in South Africa by Pitman (1973, 1976 and 1977)) rather than to develop new models.

7.3 Conclusion

The comparison of model performance in the Ecca catchments near Grahamstown has led to the formulation of tentative guidelines that may assist the practising hydrologist in the selection of suitable models for various applications. The results have demonstrated that a judicious choice of model may give rise to large savings in both user time and computer costs. A simple model (DALT/DALH) has been developed that is not only flexible in terms of structure and input requirements but has provided output at a level of accuracy that is competitive with models that are far more complex and expensive to operate. As an additional aid to model users the models selected for comparison have in many cases been modified to increase their applicability to general South African conditions and have been presented in the form of computer programs. It is hoped that the presentation of the models in this form will also benefit those hydrologists and student hydrologists who wish to make use of the important heuristic properties of the models.

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APPENDIX A

THE COMPUTER PROGRAMS

A.1 Introduction

The computer programs have been written in standard Fortran IV so that the programs may be utilized at other computer centres with a minimum amount of reprograming to achieve compatibility with the particular compilers available. It is anticipated that the only changes that may be necessary at centres where Fortran IV compilers are available would involve specifications of input and output channels.

The use of a computer program that has been obtained from a publication or passed on by hand usually necessitates the reference to a program description that details the input requirements under various options that the program may offer. In the absence of an adequate program description, the user must spend a great deal of time studying the program itself to obtain clarity as to the exact nature of the input and the units required and this process is usually hampered by inadequate explanation in the program by way of comment statements. To overcome this problem, all the programs have been written as independent entities with full details of options and input requirements built in as comment blocks. All comment blocks that contain a general or introductory description of a routine in the program are zoned off by cards containing hash signs (#), comments that contain information about input requirements (read statements) are zoned off by stars (*) and comments about the steps in the program are zoned off by minus signs(-). This system facilitates the use of the programs in the absence of a program description but it should be pointed out that in the case of the models, the programs give identification of the parameters by way of comment statements but efficient use of the models can only be achieved if the user has gained a clear understanding of the interrelationships between parameters by studying the relevant texts.

A.2 The Hourly Models

The computer programs PORT, BERG, DALH, SMDV, PDAY, HANS and DALT that have been developed by the author to operate the models, form two groups of programs and the group characteristic will be discussed to aid the user in setting up an input data deck that can be used for any model in a particular group. The first group of programs comprises the models that require hourly rainfall input data (PORT, BERG and DALH) and the input/output framework of the models has been standardized so that the models all operate on the same basic data deck. The data deck consists of two sections where the first is the relatively small parameter section that contains the following cards:

	Description	Format
Card 1	Simulation period	2A8
	Catchment name	2A8
	No. of months of input data	I4
	Area of catchment (sq. km.)	F6.2

Card 2 contains information about the model storages and program control flags where the common control flag is MVAP which is given a value of 1 if average monthly values of pan evaporation are to be used in the model and a value of 2 for daily values of pan evaporation. Program DALH is a multimodel program and has the following additional control flags:

LINE = 1 for use of a linear storage
= 2 for use of a non-linear storage.

ILIM = 1 sets the operational range of the non-linear depth response function from storage level zero to the base flow threshold level SSB and

= 2 sets the operational range of the non-linear depth function from storage level zero to the storage capacity SSM.

LEVEL = 1 gives the history of the storage level (each hour) or the pseudo-storage level (if LINE = 2) as an aid to calibration and

= 2 suppresses the listing of the storage level for each hour.

The various models in the DALH range of models are obtained by setting the program control flags and the parameter SSB as follows:

DALH1	LINE = 1	ILIM = 2	SSB = SSM
DALH2	LINE = 1	ILIM = 2	SSB < SSM
DALH3	LINE = 2	ILIM = 2	SSB < SSM
DALH4	LINE = 2	ILIM = 1	SSB < SSM .

Card 3 contains the remaining model parameters and as in card 2, the information depends on the model itself and must be obtained from the program.

Card 4 contains 12 pan to free water surface conversion factors, one for each month in the order January to December in format 12F6.2 .

Card 5 contains 12 average monthly pan evaporation values in millimetres in the order January to December in format 12F6.1 . This card is required only if the control flag MVAP has been set to 1 .

Card 6 contains hourly translated flow values in cumecs (format 12F6.2) from the day preceeding the start of the simulation period and the number of values required is equal to the lag time in hours. This card is required only if the lag time set in card 3 is greater than or equal to one hour.

The second section of the data deck contains the rainfall and evaporation data which is common to all the hourly models. In order to minimise the computer core requirements of the programs, one month of data are read at a time where the rainfall data have two cards per day. Each card is set out as follows:

Description	Format
Record identification number	I2
Record description	7X (not read by the program)
Year	I3
Month	I3
Day	I3
Card code	I2 = 1 hours 1 to 12 = 2 hours 13 to 24
Hourly rainfall	12I5 .

The rainfall data are in integer values of tenths of a millimetre and in order to reduce the bulk of the data deck, any rainfall card that has 12 zero values of rainfall may be omitted. The rainfall data for each month are terminated by a card that contains the value 99 punched in the first two columns. This card should be a separate card and not the last data card containing rainfall values. As the first two values are read, the user should not use the value 99 as a record identification number. The format of rainfall data as described above coincides with the format of the Stanford Watershed Model FORD.

The rainfall data for each month are followed by the daily pan evaporation (millimetres per day) for the month if the program control flag MVAP has been set to 2 . The evaporation for the month is set out on three cards where each card is formatted as follows:

Description	Format
Record description	7X (not read by the program)
Year	I2
Month	I2

Card code I1 = 1 days 1 to 10
= 2 days 11 to 20
= 3 days 21 to last day of the month

Evaporation 11F6.2 .

The output from the hourly models has been standardized and for each month gives the following information:

1) The run identification, the month and year and (as a guide to calibration) the values of the model variables (at the beginning of the month) and parameter values being used.

2) The hourly flow values in cumecs (m^3/s) and the daily runoff volumes in thousands of cubic metres.

3) The total monthly runoff ($x10^3m^3$), the average daily runoff ($x10^3m^3$) and the average hourly flow (m^3/s).

4) The translated flow values at the end of the month (m^3/s) and the final values of model variables. This information allows the user to run relatively long records in a number of short, more manageable segments with continuity of variable values.

5) As an additional aid to the calibration process the monthly output also incorporates a data component summary where all the components are given in the same units (millimetres) and includes (where applicable);

(a) total rainfall,

(b) total runoff,

(c) total surface runoff,

(d) total interflow,

(e) total base flow,

(f) total potential evapotranspiration,

(g) total actual evapotranspiration as calculated by the model and

(h) total percolation to inactive groundwater.

A.3 The Daily Models

The second group of programs constitutes the daily models SMDV, PDAY, HANS and DALT where, as is the case in the hourly models, the input and output have been standardized and the input data can be divided into two sections. The first section is the parameter section that requires the following cards:

Card 1 contains the catchment name and/or run information in 32 columns in format 4A8 .

Card 2 AREA Catchment area (sq. kilometres) F8.2
NMON Number of months of input data I5 .

Program control flags where each flag has the format I5 and flags include the flag MVAP which has been described under the hourly group of models. Other flags that are common to all programs in this group are:

ISTAT = 1 to initiate a statistical package (subroutine CORK) to calculate measures of correspondence between simulated and observed runoff,
= 2 to suppress the statistical package.

IVAL = 1 for the use of actual values of runoff in the statistical package and
= 2 for the use of logarithmic values of runoff in the calculation of the statistics. The use of log. values is sometimes required to avoid giving too much weight to flood peaks in the calculation of some measures of correspondence.

IOUT = 1 formats the model output for short period calibration giving one month output per page together with information that can be used as a guide to calibration,
= 2 formats the model output for long record generation with

approximately 15 months output per page of printout and the listing of additional calibration information for each month is suppressed.

In addition to the above flags the program DALT has the flags LINE and ILIM which are the same as for the model DALH in the hourly group. The models DALT1, DALT2, DALT3 and DALT4 correspond to the models DALH1, DALH2, DALH3 and DALH4 respectively and are selected by setting the control flags in the same way as that described for the DALH range of models.

Card 3 and Card 4 contain the starting values of model variables and model parameter values that are unique to each model.

Card 5 contains 12 values of average monthly pan evaporation in millimetres in the order January to December in format 12F6.1 . This card is only required if flag MVAP has been set to 1 .

Card 6 contains translated runoff values in thousands of cubic metres for the period preceeding simulation in format 10F8.3 where the number of values is equal to the lag time in days. The card is not required if the lag time is zero days.

Card 7 contains 12 pan to free water surface evaporation constants, one for each month in the order January to December in format 12F5.3 .

The second group of data cards contain the daily rainfall, evaporation (optional) and observed runoff (optional) data. In order to limit the dimensions, one month of data are read at a time and this group of cards is common to all the daily models. As an aid to data control, all three types of data (i.e. rainfall, evaporation and runoff)have the same format requiring three cards per month for each type as follows:

Description	Format
Identification	7X (not read by the program)

Year	I2
Month	I2
Card code	I1 = 1 days 1 to 10 = 2 days 11 to 20 = 3 days 21 to the last day of the month
Rainfall, evaporation or runoff	11F6.2 .

The rainfall data (millimetres) are followed by evaporation (millimetres) data and then by observed runoff (thousands of cubic metres) data for each month. The evaporation cards are required only if flag MVAP = 2 and the runoff data are required only if flag ISTAT = 1 .

The output from the daily models has been standardized. At the beginning of the simulation period the programs list the parameter values, program control flag settings and the starting values of model variables. Thereafter, the output for each month depends on the control flag IOUT which if set to 1 gives the following information each month on one page of printout:

1) Run identification, that is, the month and year together with the period of simulation and the catchment name.

2) The simulated runoff and the observed runoff (zero values will appear if observed runoff not given in the input stream) for each day in thousands of cubic metres. In the case of the DALT range of models the storage level and pseudo-storage level are also given each day.

3) The total runoff for the month and the average daily runoff for both simulated and observed data.

4) A data component summary (as in the hourly models) where rainfall, potential evapotranspiration, actual evapotranspiration, surface runoff, interflow, base flow, total runoff and deep percolation for the month

are all expressed in millimetres.

If the model is being used to generate a long record of many years, the above format produces an excessive volume of printout and the printout in such cases can be reduced substantially by setting control flag IOUT = 2 in which case all the additional guides to calibration are suppressed and approximately 15 months of daily simulated runoff are given per page of printout. At the end of the simulation period the total simulated runoff for the entire period is given and if the simulation period exceeds five years, the programs will also calculate the simulated mean annual runoff. This is followed by a listing of all the statistics calculated in the statistical package if the flag ISTAT has been set to 1 . The statistics include the total, mean, standard deviation and variance of both simulated and observed runoff followed by the product moment correlation coefficient, student's T value, regression coefficient, base constant of regression equation and the coefficient of model efficiency.

The other program (STAT) listed in this Appendix cannot be included in the common program description but follows the format of comment statements as described and therefore can be used without the aid of a program description. The programs developed by the author for the data control system are too numerous to include in this thesis but may be obtained from the Hydrological Research Unit of the Department of Geography, Rhodes University. These programs include;

DETE a general program (FORTRAN IV) for producing a discharge table for a multiple notch, sharp crested, rectangular weir with a 90 degree V-notch section.

HOUR a general program (FORTRAN IV) for producing areal assessments of hourly and daily rainfall over a number of sub-catchments covered by a raingauge network of up to ten gauges. In addition the program provides daily and monthly summaries of both point and areal precipitation.

PSTP a program (FORTRAN IV) to provide a daily and monthly summary of hourly flow values.

MULITRACE the program (MULTI-TASK EXTENDED BASIC) used to extract rainfall information from multi-trace autographic raingauge charts.

FLOWTRACE the program (MULTI-TASK EXTENDED BASIC) used to extract runoff data from autographic stage recorder charts.

HOST, RAST and RUST the programs (COBOL, developed by R. Diederiks) used for inter-disc transfer and storage of rainfall and runoff data.

A.4 Program FORD

```
       DATE 31/10/78   TIME 15/41/45                          LISTING FOR:= HRP

FILE:   HRHRMAXIMOP     SUBFILE FORD IN CARD MODE

        SHORTLIST
       PROGRAM (FORD)
       INPUT 5=CR0
       OUTPUT 6=LP0
       OUTPUT 7=LP0
       COMPRESS INTEGER AND LOGICAL
       TRACE 2
       END
       MASTER FORD
C##################################################################
C     STANFORD WATERSHED MODEL  -- WEATHER BUREAU,ANDERSON VERSION
C     PROGRAM MODIFIED AT HRU RHODES UNIVERSITY
C     THIS VERSION SET UP FOR THE FOLLOWING
C     1 RAINGAUGE
C     1 FLOWPOINT
C     1 POTENTIAL EVAPOTRANSPIRATION STATION
C     48 HOURS OF TRANSLATED FLOW ARE RETAINED
C     THAT IS MAXL MUST BE (,LE,48)
C#####################################################################
C     THROUGHOUT PROGRAM  0 MEANS NO AND 1 MEANS YES WHEN APPROPRIATE
C#######################################################################
C     FORTRAN IDENTIFIER  FORMAT                  REMARKS
C     INFRO ( )          20A4     GENERAL RUN INFORMATION
C######################################################################
C     BASIN ( )          20A4     BASIN NAME
C#######################################################################
C     MO1                I5       FIRST MONTH AND LAST 2 DIGITS OF
C     YR1                I5       FIRST YEAR OF THE RUN
C     MO2                I5       SAME FOR LAST MONTH OF RUN
C     YR2                I5
C########################################################################
C     OUTHR              I5       OUTPUT HOURLY FLOWS ABOVE PRESET BASE?
C     AVEPE              I5       USE MEAN MONTHLY PE ?
C     IFORE              I5       INPUT DATA IS SET UP FOR FORECASTING?
C     POWER              F5,1     EXPONENT OF THE INFILTRATION CURVE
C                                 EQUATION  B=CB/((LZS/LZSN)**POWER)
C     SIXHR              I5       AVERAGE 6 HR,PRECIPITATION RATE USED?
C     CN6HR              I5       6 HR, PRECIPITATION USED AS INPUT?
C     TRSOUT             I5       TRANSLATED FLOW OUTPUT AT END OF MONTH?
C     TRSIN              I5       INPUT TRANSLATED FLOW FOR 1ST MONTH?
C     STORE              I5       STORES CHANNEL INFLOW ON DATA SET
C                                 DSRO IF YES
C     ROUTE              I5       ONLY ROUTING IF YES - CHANNEL INFLOW
C                                 MUST BE STORED
C     DSRO               I5       DATA SET WHERE CHANNEL INFLOW IS STORED
C                                 EQUAL TO ZERO IF NONE
C     VAREP              I5       VARY VALUE OF PE IF YES
C     UZSNWF             F5,2     WT, FACTOR IN EQUATION
C                                 UZSNT=UZSN+UZSNWF*AEPI
C     QUART              I5       15-MINUTE PRECIP USED IF YES
C                                 SIXHR AND CN6HR MUST BE 0
C#########################################################################
C     PEADJ ( )          12F5,3   MONTHLY PE ADJUSTMENT FACTOR
C#########################################################################
C     GAGEPE( )          F5,3     RAINGAGE PE ADJUSTMENT FACTOR
C######################################################################
```

```
C      EVAPM( )             12F5.3    AVERAGE MONTHLY PE -- ONLY IF AVEPE=1
C                                     DATA IN FORM OF AVERAGE DAILY PE IN
C                                     INCHES FOR EACH MONTH JAN - DEC
C##########################################################
C      SDEP                 F5.2      STANDARD DEVIATION OF PE IN PERCENT ONLY
C      EPBIAS               F5.2      PE BIAS IN PERCENT                    IF
C      IXEP                 I10       STARTING ODD INTEGER FOR R.N.    VAREP=1
C                                     GENERATION
C###########################################################
C      RGN( )               5A4       RAINGAGE NAME
C      K1                   F5.2
C      IMPV                 F5.2      LAND
C      EXPM                 F5.2
C      UZSN                 F5.1
C      LZSN                 F5.1      VOLUME
C      CB                   F5.2
C      CC                   F5.2
C      K3                   F5.2      PARAMETERS
C      K24L                 F5.2
C      K24EL                F5.2
C###########################################################
C      L                    20X,F5.0  LAND
C      SS                   F5.2
C      NN                   F5.2      TIMING
C      IRC                  F5.2
C      KK24                 F5.3      PARAMETERS
C      KV                   F5.2
C###########################################################
C      UZSI                 20X,F5.2
C      LZSI                 F5.2      LAND
C      SGWI                 F5.2
C      GWSI                 F5.2      INITIAL
C      RESI                 F5.2
C      SRGXI                F5.2      STORAGES
C      SCEPI                F5.2
C      AEPI                 F5.2      ANTECEDENT PE INDEX
C###########################################################
C###########################################################
C      FPN( )               7A4       FLOW-POINT NAME
C      AREA                 2X,F10.2  AREA-SQUARE MILES
C      KS1                  F5.2      CHANNEL ATTENUATION PARAMETER
C                                     CONSTANT K
C      VARK                 I5        VARIABLE K IF YES
C      VARL                 I5        VARIABLE LAG IF YES
C      RTEINT               I5        ROUTING INTERVAL -  HOURS
C                                     ROUTING INTERVALS OF LESS THAN ONE HOUR
C                                     MAY BE OBTAINED BY SETTING RTEINT
C                                     AS THE NEGATIVE OF THE DENOMINATOR
C                                     EG. RTEINT=-4 FOR QUARTER HOUR
C                                               =-2 FOR HALF HOUR ETC.
C      ELEMTS               I5        NO. OF ELEMENTS IN TIME-DELAY
C                                     HISTOGRAM
C###########################################################
C      BASEK                F10.0     VAR.  K INTERVAL - CFS  VARK=1
C      KSIV( )              10F5.2    VAR. K CURVE
C###########################################################
C      KSIV( )              10X,10F5.2  REMAINDER OF CURVE
C###########################################################
C      BASEL                F10.0     VAR. LAG,INTERVAL - CFS VARL=1
C      LAG( )               10I5      VAR. LAG, CURVE
C###########################################################
```

```
C     CHECK( )           30X,15    =1 IF OBSERVED SIX HOUR FLOW
C                                  =2 IF OBSERVED HOURLY FLOW
C                                  =0 IF NEITHER
C     COMPAR             I5        OBSERVED MEAN DAILY FLOW IF YES
C     PLOT               I5        PLOT MEAN DAILYS IF YES
C     PLOTHR             I5        PLOT HOURLY OR 6 HR. FLOWS IF YES
C     MINFW              F10,0     PRESET BASE FOR OUTPUT OF HOURLY FLOW
C     PLOTMX             F10,0     MAX, ORDINATE MEAN DAILY PLOT
C     PHRMX              F10,0     MAX, ORD HOURLY OR 6 HR, PLOT
C########################################################################
C     TIMEAR( )          30X,10F5,2  CHANNEL TIME DELAY HISTOGRAM
C########################################################################
C     PREVFI             2X,F8.0   INITIAL PREVIOUS FLOW =CFS, TRSIN=1
C     TRANSI( )          10F7.0    INITIAL TRANSLATED FLOW =CFS
C########################################################################
C     TRANSI( )          10X,10F7,0  FORM FOR ADDITIONAL CARDS
C#########################################################################
C#########################################################################
C     NEXT GROUP OF CARDS IS BY A WATER YEAR OR PART WATER YEAR BASIS
C     EVAP( )            DAILY     DAILY PE DATA - ONLY IF AVEPE=0
C     ACTFLW( )          INPUT     OBSERVED MEAN DAILY FLOW
C                     36 CARDS EACH
C########################################################################
C     DISP               I5        ONLY IF ROUTE=0
C                                  =0 IF PRECIP IS NOT TO BE STORED OR
C                                     IS STORED
C                                  =1 IF PRECIP IS TO BE STORED
C     DSN                I5        DATA SET NUMBER FOR PRECIP IF STORED
C     SKIP               I5        NO, OF RECORDS ON TAPE OR DISK TO
C                                  SKIP TO BE POSITIONED CORRECTLY
C                                  =0 IF CARDS
C########################################################################
C     PX( )              SWM CARD  HOURLY PRECIP DATA
C                        FORMAT    99(COL1=2) FOLLOWS EACH MONTH
C########################################################################
C     FLOW1              HOURLY    OBSERVED HOURLY FLOW FOR SELECTED
C                     FLOW FORMAT  DAYS, IF CHECK,EQ,2
C                                  99 CARD MARKS END OF EACH MONTH
C########################################################################
C     FLOW1           SIX HOUR     OBSERVED INSTAT, FLOWS FOR
C                     FLOW FORMAT  SELECTED DAYS - CFS
C                                  99 MARKS END OF EACH MONTH
C                                  ONLY IF CHECK =1
C########################################################################
C########################################################################
C     CARD FORMATS
C########################################################################
C     DAILY INPUT
C     IDENTIFICATION     7X
C     YR                 I2        LAST TWO DIGITS OF YEAR
C     MO                 I2        MONTH
C     CN                 I1        =1,DAYS 1-10 =2,DAYS 11-20 =3,DAYS
C                                  21-LAST
C     RECOBS( )          11F6,X    OBSERVED VALUE
C                                  X=3 FOR PE  X=0 FOR MEAN DAILY FLOWS
C########################################################################
C     SWM PRECIPITATION CARDS
C     SWM CAN HANDLE 6- HOUR,HOURLY OR 15-MINUTE PRECIP DATA
C     IN EACH CASE CARD FORMAT IS THE SAME:-
C########################################################################
C     STATE              I2        WEATHER BUREAU STATE NUMBER
```

```
C     IDENTIFICATION     7X
C     YR                 I3         LAST TWO DIGITS OF YEAR
C     MO                 I3         MONTH
C     DA                 I3         DAY
C     CN                 I2         CARD NO.--VALUE IS BETWEEN 1 & 8
C     RECPX( )           I4,12I5    OBSERVED PRECIP IN 1/10 MM
C#########################################################################
C     FOR 6-HOUR DATA THE 4 VALUES FOR EACH DAY ARE CODED IN THE FIRST
C     4 PLACES OF THE FIRST CARD(CN=1).  FOR HOURLY DATA TWO CARDS ARE
C     USED FOR A DAY'S INFO (CN=1 & 2).  FOR 15-MINUTE DATA ALL 8 CARDS
C     ARE USED, EACH COVERING A 3-HOUR PERIOD.
C     IN EVERY CASE A CARD IS ONLY REQD. IF PRECIP IS>0 FOR THAT CARD
C##########################################################################
C     HOURLY FLOW
C     STATE              I2         USGS STATE NUMBER
C     IDENTIFICATION     7X
C     MO                 I3         MONTH
C     DA                 I3         DAY
C     YR                 I3         YEAR
C     CN                 I2         =1 HOURS 1-6  =2 HOURS 7-12
C                                   =3 HOURS 13-18  =4 HOURS 19-24
C     HRFW( )            6F10.0     OBSERVED HOURLY FLOW -CFS- SELECTED DAYS
C##########################################################################
C     SIX HOUR FLOW
C     STATE              I2         USGS STATE NUMBER
C     IDENTIFICATION     7X
C     MO                 I3         MONTH
C     DA                 I3         DAY
C     YR                 I3         YEAR
C     RECFW( )           2X,F10.0 FLOW IN CFS AT 6 A.M.,NOON,6 P.M.,MID.
C     T1                 I3         24 HOUR CLOCK TIME   FOR FLOW AT TIMES
C     P1                 F7.0       FLOW CFS             OTHER THAN THOSE
C     T2                 I3         24 HOUR CLOCK TIME   MENTIONED UNDER
C     P2                 F7.0       FLOW CFS             RECFW( )
C##########################################################################
C MAIN PROGRAM VARIABLES
      INTEGER TITLE1,TITLE
      REAL INCHES(12),SGW1,RES1,LZS1,SRGX1,UZS1,SCEP1
C MAIN,INITL AND READER PROGRAM VARIABLES
      INTEGER YR2,COMPAR,BASE,CTEST,OUTHR,
     1PTEST,PLOT,PLOTHR,CKTEST,HRTEST,
     2DSRO,CN6HR,TRSOUT,STORE,ROUTE,
     3NUM(12),LASTDA(2,12),YR1,
     4MO1,MO2,IFORE,MO,INIT,NEWWY,YEAR,FINAL,LEAPYR,N
      REAL MINFW,MOCHAR(12),
     1SSF(12),SAF(12),AREA,
     4BASIN(20),RGNAME(5),INFRO(20)
      COMMON/MIR/YR2,COMPAR,BASE,CTEST,OUTHR,
     1PTEST,PLOT,PLOTHR,CKTEST,HRTEST,
     2DSRO,CN6HR,TRSOUT,STORE,ROUTE,
     3NUM,LASTDA,YR1,
     4MO1,MO2,IFORE,MO,INIT,NEWWY,
     5MINFW,MOCHAR,
     6INFRO,LEAPYR,N,YEAR,FINAL,
     7SSF,SAF,AREA,
     8BASIN,RGNAME
C MAIN,INITL,READER,HOURLY AND DAILY VARIABLES
      INTEGER FIRST,CHECK
      COMMON/MHD/FLOW1(744),PHRMX,FPNAME(7),PLOTMX,
     1ACTFLW(12,31),SIMFLW(12,31),FIRST,CHECK
C  MAIN,INITL,READER,LAND AND CHANNEL VARIABLES
```

```
      INTEGER ELE,ELEMTS,
     1RTEINT,AVEPE,VARK,
     2VARL,VAREP
      REAL IMPV,LZSN,K3,K24L,K24EL,KV,LKK4,
     1LIRC4,LZSI,KS1,KS1V(20),K24L
      COMMON/MCL/EPDIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
     1UZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,REPI,
     2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPE,SET,TIMEAR(16),PEADJ(12),
     5GAGEPE,POWER,BASEK,BASEL,IMPV,LZSN,K3,K24L,K24EL,KV,
     6LKK4,LIRC4,LZSI,KS1,KS1V,MAXL,MINL,LAG(10),
     7IE,MHR,MOHR1,MOHR2,ELE,ELEMTS,VAREP,SDEP,EPBIAS,IXEP,
     8TEST1,TEST2,RTEINT,AVEPE,VARK,VARL,UZSNWF,
     9AEPI
C     MAIN,LAND,CHANEL VARIABLES (II)
      INTEGER   PX(31,96),QUART
      INTEGER SIXHR
      REAL K1
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,
     1QUART,PX
C     INITIALISE VARIABLES AND READ IN BASIC RUN INFORMATION
  100 CALL INITL
C     END OF RUN,RAINGAGE AND FLOW-POINT INPUT DATA
 1051 MONTH=MO1
      YEAR=YR1
C     START OF MONTHLY LOOP
C     INITIAL MONTHLY VALUES
  105 LEAPYR=0
      IF ((YEAR-4*(YEAR/4)).EQ.0) LEAPYR=1
      LAST=LASTDA((LEAPYR+1),MONTH)
      UZS1=UZSI
      LZS1=LZSI
      SGW1=SGWI
      RES1=RESI
      SRGX1=SRGXI
      SCEP1=SCEPI
      SRO=0.0
      SROS=0.0
      SIMPV=0.0
      SINTF=0.0
      SGWF=0.0
      SRECH=0.0
      SPR=0.0
      SPE=0.0
  106 SET=0.0
C     INPUT OF MONTHLY DATA
      CALL READER
  122 IF (IFORE.EQ.0) GO TO 120
      READ(5,989) NSTR
      IF(INSTR.GT.1) READ(5,989) NSTR
  120 IF (ROUTE.EQ.0) GO TO 113
      GO TO 114
C     COMPUTATION OF SIMULATED CHANNEL INFLOW AND STREAMFLOW
  113 CALL LAND
  114 CALL CHANEL
C     MONTHLY SUMMARY
      IF (STORE.EQ.0) GO TO 1211
      WRITE (DSRO) RO
      GO TO 1210
 1211 IF (ROUTE.EQ.0) GO TO 1210
```

```
      GO TO 1258
 1210 WRITE(6,923) BASIN
      WRITE(6,924) MOCHAR(MONTH),YEAR
      WRITE(6,925)
      WRITE(6,940)
      WRITE(6,926)
C     OUTPUT LAND STORAGES AND FLOW COMPONENTS
      WRITE(6,927) RGNAME,SRO,SROS,SIMPV,
     1SINTF,SGWF,SRECH,SPR,SPE,
     2SET
      WRITE(6,941)
      WRITE(6,942)
      BAL=(LZSI+UZSI+RESI+SRGXI-LZS1-UZS1
     1-RES1-SRGX1)*(1.0-IMPV)+SGWI+SCEPI
     2-SGW1-SCEP1+SRO+SET+SRECH-SPR
      WRITE(6,943) RGNAME,UZSI,LZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,AEPI,BAL
 1258 IF(TRSOUT.EQ.0) GO TO 1257
      WRITE(6,983) MOCHAR(MONTH),YEAR
      WRITE(6,980)
      I=MAXL
      IF (I.GT.20) GO TO 1255
      WRITE(6,981) PREVFI,(TRANSI(IE),IE=1,I)
      GO TO 1257
 1255 WRITE(6,981) PREVFI,(TRANSI(IE),IE=1,20)
      IF (I.GT.40) GO TO 1256
      WRITE(6,982) (TRANSI(IE),IE=21,I)
      GO TO 1257
 1256 WRITE(6,982) (TRANSI(IE),IE=21,40)
      WRITE(6,982) (TRANSI(IE),IE=41,I)
C     COMPUTE MEAN DAILY SIMULATED FLOW
 1257 SSF(MONTH)=0.0
      DO 128 IDA=1,LAST
      I=(IDA-1)*24
      TEMPFL=0.0
      DO 127 IHR=1,24
      MHR=I+IHR
  127 TEMPFL=TEMPFL+FLOW(MHR)
      TEMPFL=TEMPFL/24.0
      SIMFLW(MONTH,IDA)=TEMPFL
  128 SSF(MONTH)=SSF(MONTH)+TEMPFL
C     OUTPUT HOURLY SIMULATED FLOWS ABOVE PRESET VALUE
      IF (OUTHR.EQ.0) GO TO 137
      TITLE=0
      TITLE1=0
      DO 140 IDA=1,LAST
      IF (SIMFLW(MONTH,IDA).LT.MINFW) GO TO 140
      IF (TITLE.EQ.1) GO TO 1391
      TITLE=1
      WRITE(6,900)
      WRITE(6,903) BASIN
      WRITE(6,924)MOCHAR(MONTH),YEAR
      WRITE(6,945)
 1391 IF (TITLE1.EQ.1) GO TO 1392
      TITLE1=1
      WRITE(6,946) FPNAME,MINFW
 1392 MOHR2=IDA*24-12
      MOHR1=MOHR2-11
      WRITE(6,947) IDA,(FLOW(MHR),MHR=MOHR1,MOHR2)
      MOHR1=MOHR1+12
      MOHR2=MOHR2+12
      WRITE(6,948) (FLOW(MHR),MHR=MOHR1,MOHR2),
```

```
     1SIMFLW(MONTH,IDA)
  140 CONTINUE
C     OUTPUT MEAN DAILY SIMULATED AND ACTUAL FLOWS
  137 WRITE(6,900)
      WRITE(6,903) BASIN
      WRITE(6,924) MOCHAR(MONTH),YEAR
      IF(CTEST.EQ.1) GO TO 131
      WRITE(6,928)
      WRITE(6,929)
      WRITE(6,903)
      DO 129 IDA=1,LAST
  129 WRITE(6,930) IDA,SIMFLW(MONTH,IDA)
      WRITE(6,935) SSF(MONTH)
      GO TO 1362
  131 WRITE(6,933)
      WRITE(6,934)
      WRITE(6,903)
      DO 136 IDA=1,LAST
  136 WRITE(6,931) IDA,SIMFLW(MONTH,IDA),ACTFLW(MONTH,IDA)
      WRITE(6,936) SSF(MONTH),SAF(MONTH)
C     PLOTTING OF HOURLY FLOW
 1362 IF((HRTEST.EQ.0).AND.(CKTEST.EQ.0)) GO TO 1363
      IF(PLOTHER.EQ.0) GO TO 1363
      CALL HOURLY(INFROW,MONTH,YEAR,FLOW)
C     WATER YEAR SUMMARY SECTION
 1363 IF (MONTH.NE.9) GO TO 1361
C     WATER YEAR SIMULATED FLOW SUMMARY TABLES
      WRITE(6,952) FPNAME
      WRITE(6,953) YEAR
      WRITE(6,954)
      WRITE(6,955)
      WRITE(6,956)
      N=28
      IF (LEAPYR.EQ.1) N=29
      DO 812 IDA=1,N
      WRITE(6,957) IDA,(SIMFLW(MO,IDA),MO=10,12),
     1(SIMFLW(MO,IDA),MO=1,9)
      IF ((IDA-5*(IDA/5)).EQ.0) WRITE(6,956)
  812 CONTINUE
      N=N+1
      DO 813 IDA=N,30
      WRITE(6,958) IDA,(SIMFLW(MO,IDA),MO=10,12),SIMFLW(1,IDA),
     1(SIMFLW(MO,IDA),MO=3,9)
  813 CONTINUE
      IDA=31
      WRITE(6,959) IDA,SIMFLW(10,31),SIMFLW(12,31),
     1SIMFLW(1,31),SIMFLW(3,31),SIMFLW(5,31),
     2SIMFLW(7,31),SIMFLW(8,31)
      CONV=26.9*AREA
      WYFLOW=0.0
      DO 814 MO=1,12
      TEMPFL=SSF(MO)
      INCHES(MO)=TEMPFL/CONV
  814 WYFLOW=WYFLOW+TEMPFL
      WRITE(6,960) (SSF(MO),MO=10,12),(SSF(MO),MO=1,9),WYFLOW
      WYFLOW=WYFLOW/CONV
      WRITE(6,961)(INCHES(MO),MO=10,12),(INCHES(MO),MO=1,9),WYFLOW
      WYFLOW=WYFLOW*CONV*1.986
      WRITE(6,962) WYFLOW
      IF (COMPAR.EQ.0) GO TO 810
      WYFLOW=0.0
```

```
      DO 815 MO=1,12
      TEMPFL=SAF(MO)
      INCHES(MO)=TEMFL/CONV
  815 WYFLOW=WYFLOW+TEMPFL
      WRITE(6,963) (SAF(MO),MO=10,12),(SAF(MO),MO=1,9),WYFLOW
      WYFLOW=WYFLOW/CONV
      WRITE(6,961) (INCHES(MO),MO=10,12),(INCHES(MO),MO=1,9),WYFLOW
      WYFLOW=WYFLOW*CONV*1.986
      WRITE(6,962) WYFLOW
C     PLOT OF SIMULATED VS OBSERVED MEAN DAILY FLOW--BY WATER YEAR
  810 IF (PTEST.EQ.0) GO TO 1361
      IF (FIRST.EQ.1) GO TO 800
      FIRST=1
  800 IF (PLOT.EQ.0) GO TO 801
      CALL DAILY(INFRO,MONTH,YEAR)
  801 CONTINUE
C     INCREMENT TO THE NEXT MONTH
 1361 IF ((YEAR.EQ.YR2).AND.(MONTH.EQ.MO2)) GO TO 130
      MONTH=MONTH+1
      IF (MONTH.LE.12) GO TO 105
      MONTH=1
      YEAR=YEAR+1
      GO TO 105
  130 CONTINUE
      IF (FIRST.EQ.1) WRITE(7,990)
C     PROGRAM FORMAT STATEMENTS
  900 FORMAT (1H1)
  903 FORMAT (1H ,20X,20A4)
  923 FORMAT (1H1,19HMONTHLY SUMMARY FOR,1X,20A4)
  924 FORMAT (1H0,A4,3H 19,I2)
  925 FORMAT (1H0,53X,16HRAINGAGE SUMMARY)
  926 FORMAT (1H0,6X,13HRAINGAGE NAME,10X,8HTOTAL RO,3X,
     110HSURFACE RO,3X,7HIMPV RO,3X,9HINTERFLOW,3X,7HGW FLOW,3X,
     28HRECHARGE,3X,6HPRECIP,3X,12HPOTENTIAL-ET,3X,9HACTUAL-ET)
  927 FORMAT (1H ,6X,5A4,F10.3,F12.3,4F11.3,F9.2,2F13.3)
  928 FORMAT (1H0,33HSIMULATED MEAN DAILY FLOW SUMMARY)
  929 FORMAT (1H0,5H DATE,8X,10HFLOW(CFSD))
  930 FORMAT (1H ,I5,5X,10F10.1)
  933 FORMAT(1H0,44HSIMULATED AND ACTUAL MEAN DAILY FLOW SUMMARY)
  934 FORMAT(1H0,5H DATE,10X,30HSIMULATED(CFSD)   ACTUAL(CFSD))
  931 FORMAT(1H ,I5,10X,F10.1,6X,F10.1)
  936 FORMAT (1H0,5HTOTAL,10X,F10.1,6X,F10.1)
  935 FORMAT(1H0,5HTOTAL,5X,10F10.1)
  940 FORMAT (1H0,34X,55HRUNOFF, PRECIPITATION AND EVAPOTRANSPIRATION CO
     1MPONENTS)
  941 FORMAT (1H0,52X,18HSTORAGE COMPONENTS)
  942 FORMAT (1H0,13HRAINGAGE NAME,16X,3HUZS,4X,3HLZS,4X,3HSGW,4X,
     13HGWS,4X,3HRES,3X,4HSRGX,3X,4HSCEP,3X,4HAEPI,4X,7HBALANCE)
  943 FORMAT (1H ,5A4,6X,8F7.2,F10.3)
  945 FORMAT (1H0,43X,29HSIMULATED HOURLY FLOW SUMMARY)
  946 FORMAT (1H0,7A4,10X,41HMINIMUM MEAN DAILY FLOW CAUSING OUTPUT IS,
     1F7.0,4H CFS)
  947 FORMAT (1H0,I3,3X,2HAM,6F9.1,4X,6F9.1)
  948 FORMAT (1H ,6X,2HPM,6F9.1,4X,6F9.1,F10.1)
  952 FORMAT (1H1,19X,24HWATER YEAR SUMMARY FOR--,7A4)
  953 FORMAT (1H0,37X,13HWATER YEAR 19,I2)
  954 FORMAT (1H0,28HMEAN DAILY DISCHARGE SUMMARY)
  955 FORMAT (1H0,3X,3HDAY,5X,3HOCT,6X,3HNOV,6X,3HDEC,6X,3HJAN,6X,3HFEB,
     14X,5HMARCH,4X,5HAPRIL,6X,3HMAY,5X,4HJUNE,5X,4HJULY,3X,6HAUGUST,5X,
     24HSEPT,7X,6HANNUAL)
  956 FORMAT (1H0)
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  957 FORMAT (1H ,I5,12F9.1)
  958 FORMAT (1H ,I5,4F9.1,9X,7F9.1)
  959 FORMAT (1H ,I5,F9.1,9X,2F9.1,9X,F9.1,9X,F9.1,9X,2F9.1)
  960 FORMAT (1H0,5HTOTAL,12F9.0,F10.0,5H CFSD)
  961 FORMAT (1H ,5X,12F9.3,F10.2,7H INCHES)
  962 FORMAT (1H ,113X,F10.0,8H ACRE-FT)
  963 FORMAT (1H0,5HACT. ,12F9.0,F10.0,5H CFSD)
  980 FORMAT (1H0,6X,5HPREVF,47X,15HTRANSLATED FLOW)
  981 FORMAT (1H ,3X,F7.0,2X,20F6.0)
  982 FORMAT (1H ,12X,20F6.0)
  983 FORMAT (1H1,31HCHANNEL TRANSITIONAL VALUES FOR,1X,A4,3H 19,I2)
  989 FORMAT(12I5)
  990 FORMAT (3X,2H99)
C     END OF MAIN PROGRAM
      STOP
      END
      BLOCK DATA
C     MAIN,INITL AND READER PROGRAM VARIABLES
      INTEGER YR2,COMPAR,BASE,CTEST,OUTHR,
     1PTEST,PLOT,PLOTHR,CKTEST,HRTEST,
     2DSRO,CN6HR,TRSOUT,STORE,ROUTE,
     3NUM(12),LASTDA(2,12),YR1,
     4MO1,MO2,IFORE,MO,INIT,NEWWY,YEAR,FINAL,LEAPTR,N
      REAL  MINFW,MOCHAR(12),
     1SSF(12),SAF(12),AREA,
     4BASIN(20),RGNAME(5),INFRO(20)
      COMMON/MIR/YR2,COMPAR,BASE,CTEST,OUTHR,
     1PTEST,PLOT,PLOTHR,CKTEST,HRTEST,
     2DSRO,CN6HR,TRSOUT,STORE,ROUTE,
     3NUM,LASTDA,YR1,
     4MO1,MO2,IFORE,MO,INIT,NEWWY,
     5MINFW,MOCHAR,
     6INFRO,LEAPYR,N,YEAR,FINAL,
     7SSF,SAF,AREA,
     8BASIN,RGNAME
      DATA MOCHAR/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,4HJUNE,4HJULY,3HAUG,
     14HSEPT,3HOCT,3HNOV,3HDEC/
      DATA LASTDA/31,31,28,29,31,31,30,30,31,31,30,30,31,31,31,31,30,30,
     131,31,30,30,31,31/
      DATA NUM/1,2,3,4,5,6,7,8,9,10,11,12/
      END
      SUBROUTINE INITL
C     INITIALISATION AND READ-IN OF GENERAL RUN INFORMATION
C     INITL SUBROUTINE VARIABLES
      INTEGER TRSIN
      REAL L,NN,IRC,KK24
C     MAIN,INITL AND READER PROGRAM VARIABLES
      INTEGER YR2,COMPAR,BASE,CTEST,OUTHR,
     1PTEST,PLOT,PLOTHR,CKTEST,HRTEST,
     2DSRO,CN6HR,TRSOUT,STORE,ROUTE,
     3NUM(12),LASTDA(2,12),YR1,
     4MO1,MO2,IFORE,MO,INIT,NEWWY,YEAR,FINAL,LEAPYR,N
      REAL   MINFW,MOCHAR(12),
     1SSF(12),SAF(12),AREA,
     4BASIN(20),RGNAME(5),INFRO(20)
      COMMON/MIR/YR2,COMPAR,BASE,CTEST,OUTHR,
     1PTEST,PLOT,PLOTHR,CKTEST,HRTEST,
     2DSRO,CN6HR,TRSOUT,STORE,ROUTE,
     3NUM,LASTDA,YR1,
     4MO1,MO2,IFORE,MO,INIT,NEWWY,
     5MINFW,MOCHAR,
```

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     6INFRO,LEAPYR,N,YEAR,FINAL,
     7SSF,SAF,AREA,
     8BASIN,RGNAME
C     MAIN,INITL,READER,HOURLY AND DAILY VARIABLES
      INTEGER FIRST,CHECK
      COMMON/MHD/FLOW1(744),PHRMX,FPNAME(7),PLOTMX,
     1ACTFLW(12,31),FIRST,CHECK
C     MAIN,INITL,READER,LAND AND CHANEL VARIABLES
      INTEGER ELE,ELEMTS,
     1RTEINT,AVEPE,VARK,
     2VARL,VAREP
      REAL IMPV,LZSN,K3,K24EL,KV,LKK4,
     1LIRC4,LZSI,KS1V(20),KS1,K24L
      COMMON/MCL/EPDIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
     1UZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,REPI,
     2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPE,SET,TIMEAR(16),PEADJ(12),
     5GAGEPE,POWER,BASEK,BASEL,IMPV,LZSN,K3,K24L,K24EL,KV,
     6LKK4,LIRC4,LZSI,KS1,KS1V,MAXL,MINL,LAG(10),
     7IE,MHR,MOHR1,MOHR2,ELE,ELEMTS,VAREP,SDEP,EPBIAS,IXEP,
     8TEST1,TEST2,RTEINT,AVEPE,VARK,VARL,UZSNWF,
     9AEPI
C     MAIN,LAND,CHANEL VARIABLES (II)
      INTEGER   PX(31,96),QUART
      INTEGER SIXHR
      REAL K1
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,
     1QUART,PX
C     INITIALIZATION OF DATA
      INIT=0
      FIRST=0
      NEWWY=0
      CTEST=0
      PTEST=0
      CKTEST=0
      HRTEST=0
      DO 100 I=1,24
  100 EPDIST(I)=0.0
      EPDIST(7)=0.019
      EPDIST(8)=0.041
      EPDIST(9)=0.067
      EPDIST(10)=0.088
      EPDIST(11)=0.102
      EPDIST(12)=0.11
      EPDIST(13)=0.11
      EPDIST(14)=0.11
      EPDIST(15)=0.105
      EPDIST(16)=0.095
      EPDIST(17)=0.081
      EPDIST(18)=0.055
      EPDIST(19)=0.017
C     RUN,RAINGAGE AND FLOW-POINT INPUT DATA
C     BASIC RUN INFORMATION
      READ(5,901) INFRO
      READ(5,901) BASIN
      WRITE(6,900)
      WRITE(6,903) BASIN
      WRITE(6,902) INFRO
      WRITE(6,904)
      READ(5,905) MO1,YR1,MO2,YR2
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      READ(5,950) OUTHR,AVEPE,IFORE,POWER,SIXHR,CN6HR,TRSOUT,TRSIN,
     1STORE,ROUTE,DSRO,VAREP,UZSNWF,QUART
      IF (DSRO.GT.0) REWIND DSRO
      IF (STORE.EQ.1) ROUTE=0
      IF (CN6HR.EQ.1) SIXHR=1
      READ(5,965) PEADJ
      READ(5,965) GAGEPE
      IF (AVEPE.EQ.0) GO TO 1003
      READ(5,965) EVAPM
      DO 1004 I=1,12
 1004 EVAPM(I)=EVAPM(I)*PEADJ(I)
 1003 LEAPYR=0
      IF (VAREP.EQ.1) READ(5,991) SDEP,EPBIAS,IXEP
      IF ((YR2-4*(YR2/4)).EQ.0) LEAPYR=1
      LAST=LASTDA((LEAPYR+1),MO2)
      WRITE(6,906) MOCHAR(MO1),YR1,MOCHAR(MO2),LAST,YR2
      WRITE(6,936)
 1005 WRITE(6,908)
C     BASIC RAINGAGE INFORMATION
      READ(5,909) RGNAME,K1,IMPV,EPXM,UZSN,LZSN,CB,CC,K3,K24L,K24EL
      READ(5,939) L,SS,NN,IRC,KK24,KV
      SRC=1020.0*SQRT(SS)/(NN*L)
      DEC=0.00982*((NN*L/SQRT(SS))**0.6)
      LKK4=1.0-(KK24**(1.0/96.0))
      LIRC4=1.0-(IRC**(1.0/96.0))
      READ(5,910) UZSI,LZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,AEPI
      REPI=0.0
      WRITE(6,911) RGNAME,K1,IMPV,EPXM,UZSN,LZSN,CB,CC,K3,K24L,K24EL,L,
     1SS,NN,IRC,KK24,KV
      WRITE(6,979) POWER,UZSNWF
      WRITE(6,937)
      WRITE(6,912)
      WRITE(6,913) RGNAME,UZSI,LZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,AEPI
 1022 WRITE(6,938)
      WRITE(6,914)
C     BASIC FLOW POINT INFORMATION
      READ(5,915) FPNAME,AREA,KS1,VARK,VARL,RTEINT,ELEMTS
      IF (VARK.EQ.0) GO TO 150
      READ(5,984) BASEK,(KS1V(I),I=1,10)
      READ(5,986) (KS1V(I),I=11,20)
      KS1=1.0
  150 IF (VARL.EQ.0) GO TO 1249
      READ(5,988) BASEL,(LAG(I),I=1,10)
 1249 READ(5,976) CHECK,COMPAR,PLOT,PLOTHR,MINFW,PLOTMX,PHRMX
      ELE=ELEMTS
      IF (COMPAR.EQ.1) GO TO 1241
      PLOT=0
      GO TO 1245
 1241 CTEST=1
 1245 IF (PLOT.EQ.0) GO TO 124
      PTEST=1
  124 IF (CHECK.EQ.1) GO TO 1246
      IF (CHECK.EQ.2) GO TO 1247
      PLOTHR=0
      GO TO 1248
 1246 CKTEST=1
      GO TO 1248
 1247 HRTEST=1
 1248 READ(5,917) (TIMEAR(IE),IE=1,ELE)
      CFSM=26.9*24.0*AREA
      WRITE(6,918) FPNAME,AREA,KS1,RTEINT,COMPAR,CHECK,(TIMEAR(IE),
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```
     1IE=1,ELE)
      IF (VARK.EQ.0) GO TO 1042
      WRITE(6,985) BASEK,(KS1V(I),I=1,20)
 1042 IF (VARL.EQ.0) GO TO 1041
      WRITE(6,987) BASEL,(LAG(I),I=1,10)
 1041 PREVFI=0.0
      IF (RTEINT.GE.0) GO TO 200
      INTR=-1*RTEINT
      KRX=ELEMTS-((ELEMTS/INTR)*INTR)
      ELE=ELEMTS/INTR
      IF (KRX.GT.0) ELE=ELE+1
      GO TO 210
  200 ELE=ELE*RTEINT
  210 MLAG=0
      IF (VARL.EQ.0) GO TO 1043
      DO 1044 I=1,10
      IF (LAG(I).GT.MLAG) MLAG=LAG(I)
 1044 CONTINUE
      DO 1045 I=2,10
      IF (LAG(I).EQ.0) GO TO 1045
      MINL=I
      GO TO 1043
 1045 CONTINUE
 1043 MAXL=ELE+MLAG
      ELE=ELE+MLAG
      DO 104 IE=1,ELE
  104 TRANSI(IE)=0.0
      IF (TRSIN.EQ.0) GO TO 1032
      N=MAXL/10+1
      DO 1035 I=1,N
      FINAL=I*10
      BASE=FINAL-9
      IF (I.EQ.N) FINAL=MAXL
      IF (I.GT.1) GO TO 1036
      READ(5,949) PREVFI,(TRANSI(IE),IE=BASE,FINAL)
      GO TO 1035
 1036 READ(5,964) (TRANSI(IE),IE=BASE,FINAL)
 1035 CONTINUE
 1032 WRITE(6,972)
      WRITE(6,973) (NUM(I),I=1,12)
      WRITE(6,974) (PEADJ(I),I=1,12)
      WRITE(6,975) GAGEPE
  900 FORMAT (1H1)
  901 FORMAT (20A4)
  902 FORMAT (1H0,20A4)
  903 FORMAT (1H ,20X,20A4)
  904 FORMAT (1H0,53X,21HBASIC RUN INFORMATION)
  905 FORMAT (7I5,5I3)
  906 FORMAT (1H0,10HRUN BEGINS,1X,A4,5H 1,19,I2,5X,8HRUN ENDS,1X,A4,1X,
     1I2,3H,19,I2)
  908 FORMAT (1H0,6X,13HRAINGAGE NAME,10X,2HK1,3X,4HIMPV,2X,
     14HEPXM,3X,4HUZSN,3X,4HLZSN,4X,2HCB,4X,2HCC,4X,2HK3,4X,4HK24L,2X,
     25HK24EL,4X,1HL,5X,2HSS,5X,2HNN,4X,3HIRC,4X,4HKK24,4X,2HKV)
  909 FORMAT (5A4,3F5.2,2F5.1,5F5.2)
  910 FORMAT (20X,8F5.2)
  911 FORMAT (1H ,6X,5A4,3F6.2,2F7.2,F7.3,2F6.2,2F7.2,F7.0,F6.2,
     1F7.2,F6.2,F7.3,F7.2)
  912 FORMAT (1H0,13HRAINGAGE NAME,16X,3HUZS,4X,3HLZS,4X,3HSGW,4X,
     13HGWS,4X,3HRES,3X,4HSRGX,3X,4HSCEP,3X,4HAEPI)
  913 FORMAT (1H ,5A4,6X,8F7.2)
  914 FORMAT (1H0,6X,15HFLOW-POINT NAME,17X,4HAREA,3X,3HKS1,2X,
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     14HRINT,2X,7HCOMPARE,2X,5HCHECK,2X,10HHISTOGRAMS)
 915 FORMAT (7A4,2X,F10.2,F5.2,4I5)
 917 FORMAT (16F5.2)
 918 FORMAT (1H ,6X,7A4,F8.2,F6.2,I5,2I7,5X,9HTIMEDELAY,/,16F5.2)
 919 FORMAT (1H ,72X,8HGAGEAREA,1X,10I5)
 920 FORMAT (1H ,72X,8HADDFLOW1,1X,10I5)
 921 FORMAT (1H ,72X,8HADDFLOW2,1X,10I5)
 936 FORMAT (1H0,53X,23HLAND SURFACE PARAMETERS)
 937 FORMAT (1H0,53X,16HINITIAL STORAGES)
 938 FORMAT (1H0,53X,21HFLOW-POINT PARAMETERS)
 939 FORMAT (20X,F5.0,3F5.2,F5.3,F5.2)
 949 FORMAT (2X,F8.0,10F7.0)
 950 FORMAT (3I5,F5.1,8I5,F5.2,I5)
 964 FORMAT (10X,10F7.0)
 965 FORMAT (12F5.3)
 972 FORMAT (1H0,43X,40HPOTENTIAL EVAPOTRANSPIRATION ADJUSTMENTS)
 973 FORMAT (1H0,19HSEASONAL ADJUSTMENT,10X,5HMONTH,6X,12I5)
 974 FORMAT (1H ,27X,10HADJUSTMENT,4X,12F5.2)
 975 FORMAT (1H0,19HRAINGAGE ADJUSTMENT,11X,F5.2)
 976 FORMAT (30X,4I5,3F10.0)
 979 FORMAT (1H0,10X,34HINFILTRATION CURVE POWER FACTOR IS,F5.1,10X,
     116HUZSN WT. FACTOR=,F5.2)
 984 FORMAT (F10.0,10F5.2)
 985 FORMAT (1H ,3X,17HVARIABLE K  BASE=,F6.0,3X,2HK=,20F5.2)
 986 FORMAT (10X,10F5.2)
 987 FORMAT (1H ,3X,20HVARIABLE LAG   BASE=,F6.0,3X,4HLAG=,10I5)
 988 FORMAT (F10.0,10I5)
 991 FORMAT (2F5.2,I10)
 934 FORMAT (30X,10I5)
     RETURN
     END
     SUBROUTINE READER
C    SUBROUTINE INVOKED EACH MONTH TO READ IN DATA
C    READER SUBROUTINE VARIABLES
     INTEGER WY,DISP,STATE,DSN,YR,T1,T2,SKIP,CN,DA,RECPX(12),PXSIX(4)
     REAL RECOBS(11),HRFW(6),RECFW(4)
C    MAIN ,INITL , AND READER PROGRAM VARIABLES
     INTEGER YR2,COMPAR,BASE,CTEST,OUTHR,PTEST,PLOT,PLOTHR,CKTEST,
    1HRTEST,DSRO,CN6HR,TRSOUT,STORE,ROUTE,NUM(12),LASTDA(2,12),YR1,
    2MO1,MO2,IFORE,MO,INIT,NEWWY,YEAR,FINAL,LEAPYR,N
     REAL MINFW,MOCHAR(12),SSF(12),SAF(12),AREA,BASIN(20),RGNAME(5),
    1INFRO(20)
     COMMON/MIR/YR2,COMPAR,BASE,CTEST,OUTHR,PTEST,PLOT,PLOTHR,CKTEST,
    1HRTEST,DSRO,CN6HR,TRSOUT,STORE,ROUTE,NUM,LASTDA,YR1,MO1,MO2,
    2IFORE,MO,INIT,NEWWY,MINFW,MOCHAR,INFRO,LEAPYR,N,YEAR,FINAL,
    3SSF,SAF,AREA,BASIN,RGNAME
C    MAIN,INITL,READER,HOURLY AND DAILY VARIABLES
     INTEGER FIRST,CHECK
     COMMON/MHD/FLOW1(744),PHRMX,FPNAME(7),PLOTMX,
    1ACTFLW(12,31),SIMFLW(12,31),FIRST,CHECK
C    MAIN,INITL,READER,LAND, AND CHANEL VARIABLES
     INTEGER ELE,ELEMTS,RTEINT,AVEPE,VARK,VARL,VAREP
     REAL IMPV,LZSN,K3,K24L,K24EL,KV,LKK4,LIRC4,LZSI,KS1,KS1V(20)
     COMMON/MCL/EPDIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
    1UZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,REPI,
    2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
    3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
    4SGWF,SRECH,SPR,SPE,SET,TIMEAR(16),PEADJ(12),
    5GAGEPE,POWER,BASEK,BASEL,IMPV,LZSN,K3,K24L,K24EL,KV,
    6LKK4,LIRC4,LZSI,KS1,KS1V,MAXL,MINL,LAG(10),
    7IE,MHR,MOHR1,MOHR2,ELE,ELEMTS,VAREP,SDEP,EPBIAS,IXEP,
```

```
     8TEST1,TEST2,RTEINT,AVEPE,VARK,VARL,UZSNWF,AEPI
C     MAIN,LAND,CHANEL VARIABLES (II)
      INTEGER   PX(31,96),QUART
      INTEGER SIXHR
      REAL K1
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,QUART,PX
      IF (MONTH.EQ.10) GO TO 131
      IF ((YEAR.EQ.YR1).AND.(MONTH.EQ.MO1)) GO TO 1311
      GO TO 25
 1311 DO 1312 MO=1,12
      SSF(MO)=0.0
      DO 1312 IDA=1,31
 1312 SIMFLW(MO,IDA)=0.0
  131 WY=YEAR
C***** NEWWY HAS BEEN CHANGED FROM 1 TO ZERO
      NEWWY=0
      IF (MONTH.GT.9) WY=WY+1
      LEAPYR=0
      IF ((WY-4*(WY/4)).EQ.0) LEAPYR=1
C     DAILY POTENTIAL EVAPOTRANSPIRATION - BY WATER YEAR
      IF (AVEPE.EQ.1) GO TO 1331
      DO 133 I=1,36
      READ(5,931) MO,CN,RECOBS
      FINAL=CN*10
      BASE=FINAL-9
      IF (CN.EQ.3) FINAL=LASTDA((LEAPYR+1),MO)
      N=BASE-1
      DO 133 IDA=BASE,FINAL
  133 EVAP(MO,IDA)=RECOBS(IDA-N)
C     ACTUAL MEAN DAILY FLOWS -BY WATER YEAR
 1331 IF (CTEST.EQ.0) GO TO 25
      IF (COMPAR.EQ.1) GO TO 1342
      DO 1341 MO=1,12
      SAF(MO)=0.0
      DO 1341 IDA=1,31
 1341 ACTFLW(MO,IDA)=0.0
      GO TO 25
 1342 DO 1343 MO=1,12
 1343 SAF(MO)=0.0
      DO 135 I=1,36
      READ(5,932) MO,CN,RECOBS
      FINAL=CN*10
      BASE=FINAL-9
      IF (CN.EQ.3) FINAL=LASTDA((LEAPYR+1),MO)
      N=BASE-1
      DO 135 IDA=BASE,FINAL
      OBS=RECOBS(IDA-N)
      SAF(MO)=SAF(MO)+OBS
  135 ACTFLW(MO,IDA)=OBS
C     MONTHLY INPUT DATA
   25 IF (ROUTE.EQ.0) GO TO 1320
      READ (DSRO) RO
      GO TO 400
 1320 IF (NEWWY.EQ.0) GO TO 1321
      READ(5,978) DISP,DSN,SKIP
      IF ((DSN.GT.0).AND.(INIT.EQ.0)) REWIND DSN
      INIT=1
      NEWWY=0
      IF (SKIP.EQ.0) GO TO 1321
      DO 1329 I=1,SKIP
 1329 READ (DSN)
```

```
C       ESTABLISH NO OF VALUES IN PX( ) ARRAY THAT WE WILL USE
C       DEFAULT IS 24 -- FOR HOURLY DATA
 1321 KNO=24
      IF (SIXHR.EQ.1) KNO=4
      IF (QUART.EQ.1) KNO=96
      IF (DISP.EQ.1) GO TO 1330
      IF (DSN.GT.0) GO TO 1322
C       PRECIPITATION  --  BY MONTH
 1330 DO 109 IDA=1,31
      DO 109 NO=1,96
  109 PX(IDA,NO)=0
  110 READ(5,922) STATE,YR,MO,DA,CN,RECPX
      IF (STATE.EQ.99) GO TO 107
      IF (SIXHR.EQ.1) GO TO 1081
      BASE=(CN-1)*12
      DO 108 IHR=1,12
      NO=BASE+IHR
  108 PX(DA,NO)=RECPX(IHR)
      GO TO 110
 1081 IF (CN6HR.EQ.1) GO TO 1085
      BASE=(CN-1)*2
      PXSIX(1)=0
      PXSIX(2)=0
      DO 1082 I=1,6
 1082 PXSIX(1)=PXSIX(1)+RECPX(I)
      DO 1083 I=7,12
 1083 PXSIX(2)=PXSIX(2)+RECPX(I)
      DO 1084 IHR=1,2
      NO=BASE+IHR
 1084 PX(DA,NO)=PXSIX(IHR)
      GO TO 110
 1085 DO 1086 NO=1,4
      PX(DA,NO)=RECPX(NO)
 1086 CONTINUE
      GO TO 110
  107 IF (DISP.EQ.0) GO TO 400
 1327 WRITE (DSN) ((PX(IDA,NO),IDA=1,31),NO=1,KNO)
      GO TO 400
 1322 READ (DSN) ((PX(IDA,NO),IDA=1,31),NO=1,KNO)
C       INSTANTANEOUS ACTUAL FLOWS BY MONTH
C       HOURLY FLOW -- ONE STATION
  400 IF (HRTEST.EQ.0) GO TO 401
      IF (CHECK.NE.2) GO TO 401
      DO 402 I=1,744
  402 FLOW1(I)=0.0
  403 READ(5,971) STATE,YR,MO,DA,CN,HRFW
      IF (STATE.EQ.99) GO TO 401
      BASE=(DA-1)*24+(CN-1)*6
      DO 404 I=1,6
      MHR=BASE+I
  404 FLOW1(MHR)=HRFW(I)
      GO TO 403
  401 IF (CKTEST.EQ.0) RETURN
C       SIX HOUR FLOWS
      IF (CHECK.NE.1) RETURN
      DO 407 I=1,744
  407 FLOW1(I)=0.0
  408 READ(5,970) STATE,MO,DA,YR,RECFW,T1,P1,T2,P2
      IF (STATE.EQ.99) RETURN
      BASE=(DA-1)*24
      DO 409 I=1,4
```

```
      MHR=BASE+(I*6)
  409 FLOW1(MHR)=RECFW(I)
      IF (T1.EQ.0) GO TO 408
      MHR=BASE+T1
      FLOW1(MHR)=P1
      IF (T2.EQ.0) GO TO 408
      MHR=BASE+T2
      FLOW1(MHR)=P2
      GO TO 408
  922 FORMAT (I2,7X,3I3,I2,12I5)
  931 FORMAT (9X,I2,I1,11F6.3)
  932 FORMAT (9X,I2,I1,11F6.0)
  951 FORMAT (I2)
  970 FORMAT (I2,7X,3I3,2X,4F10.0,I3,F7.0,I3,F7.0)
  971 FORMAT (I2,7X,3I3,I2,6F10.0)
  978 FORMAT (3I5)
      END
      SUBROUTINE LAND
C     LAND SURFACE RUNOFF SUBROUTINE
C      LAND VARIABLES
      REAL LZS,INTF,INFIL,LZI,LOS,LNRAT,P(4)
C     MAIN,INITL,READER,LAND AND CHANEL VARIABLES
      INTEGER ELE,ELEMTS,RTEINT,AVEPE,VARK,VARL,VAREP
      REAL IMPV,LZSN,K3,K24L,K24EL,KV,LKK4,LIRC4,LZSI,KS1,KS1V(20)
      COMMON/MCL/EPDIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
     1UZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,REPI,
     2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPE,SET,TIMEAR(16),PEADJ(12),
     5GAGEPE,POWER,BASEK,BASEL,IMPV,LZSN,K3,K24L,K24EL,KV,
     6LKK4,LIRC4,LZSI,KS1,KS1V,MAXL,MINL,LAG(10),
     7IE,MHR,MOHR1,MOHR2,ELE,ELEMTS,VAREP,SDEP,EPBIAS,IXEP,
     8TEST1,TEST2,RTEINT,AVEPE,VARK,VARL,UZSNWF,
     9AEPI
C     MAIN,LAND,CHANEL VARIABLES (II)
      INTEGER    PX(31,96),QUART
      INTEGER SIXHR
      REAL K1
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,QUART,PX
C     LAND INITIAL VALUES
      SRO=0.0
      SROS=0.0
      SINTF=0.0
      SGWF=0.0
      SIMPV=0.0
      SRECH=0.0
      SET=0.0
      SPR=0.0
      SPE=0.0
C     INITIAL VALUES OF VARIABLES
      UZS=UZSI
      LZS=LZSI
      SGW=SGWI
      GWS=GWSI
      RES=RESI
      SRGX=SRGXI
      SCEP=SCEPI
      REP=REPI
      AEPIT=AEPI
C     INITIAL VALUES OF PARAMETERS
      AT=IMPV
```

```
      PA=1.0-AT
      IHR=1
      IDA=1
C     BEGINNING OF HOUR AND DAY LOOP
C     VALUES OF POT. EVAP. AND PRECIPITATION
  203 IF (IHR.NE.1) GO TO 206
      IF (KOHLER.EQ.1) GO TO 204
      IF (AVEPE.EQ.0) GO TO 205
      EP=EVAPM(MONTH)
      GO TO 2032
  205 EP=EVAP(MONTH,IDA)*PEADJ(MONTH)
      GO TO 2032
  204 EP=PE(IDA)*PEADJ(MONTH)
 2032 IF (VAREP.EQ.0) GO TO 202
      SD=EP*SDEP
      CALL IGAUSS(IXEP,SD,EP,TV)
      EP=TV+EPBIAS*EP
      IF (EP.LT.0.0) EP=0.0
  202 EP=EP*GAGEPE
      SPE=SPE+EP
      AEPIT=(AEPIT*0.9)+EP
  206 IF (QUART.EQ.0) GO TO 217
C     15-MINUTE DATA
      NO=(IHR-1)*4
      DO 218 I=1,4
      IN=NO+I
  218 P(I)=PX(IDA,IN)*K1
      GO TO 219
C     SIX-HOUR DATA
  217 IF (SIXHR.EQ.0) GO TO 208
      IS=(IHR+5)/6
      PX1=PX(IDA,IS)/6.0
      GO TO 207
C     HOURLY DATA
  208 PX1=PX(IDA,IHR)
  207 PX1=PX1*K1
      DO 233 I=1,4
  233 P(I)=PX1*0.25
C     PX1 IS HOURLY PRECIPITATION--PR IS 15 MINUTE PRECIPITATION
  219 RU=0.0
C     BEGINNING OF 15-MINUTE LOOP
      DO 209 I15=1,4
C     CONVERT 1/10 MM TO INCHES
      PR=P(I15)/254.
      SPR=SPR+PR
      IF (PR.GT.0.0) GO TO 210
 2121 IF (RES.EQ.0.0) GO TO 211
      P3=0.0
      GO TO 212
  211 IF (SRGX.EQ.0.0) GO TO 213
      P3=0.0
      ROS=0.0
      GO TO 214
  213 P3=0.0
      ROS=0.0
      INTF=0.0
      GO TO 215
C     INTERCEPTION STORAGE - SCEP IS INTERCEPTION STORAGE VOLUME
C                          - EPX IS INTERCEPTION STORAGE CAPACITY
  210 EPX=EPXM-SCEP
      IF (EPX.LT.0.0) EPX=0.0
```

```
      IF (PR.GE.EPX) GO TO 216
      SCEP=SCEP+PR
      P3=0.0
      GO TO 2121
  216 P3=PR-EPX
      SCEP=SCEP+EPX
C     P3 IS RAIN REACHING THE GROUND
C     UPPER ZONE CALCULATIONS
      SIMPV=SIMPV+P3*AT
C     P3*AT IS IMPERVIOUS AREA RUNOFF VOLUME
  212 LNRAT=LZS/LZSN
      P4=P3+RES
C     P4 IS P3 PLUS SURFACE DETENTION STORAGE
      D3FV=CB/((LNRAT)**POWER)
      D4F=0.25*D3FV
      RATIO=CC*(2.0**LNRAT)
      IF (RATIO.LT.1.0) RATIO=1.0
      IF (P4.GE.D4F)GO TO 220
      SHRD=P4*P4/(2.0*D4F)
      GO TO 221
  220 SHRD=P4-0.5*D4F
  221 INFIL=P4-SHRD
C     INFIL IS INFILTRATION VOLUME
      IF (P4.GE.(D4F*RATIO)) GO TO 222
      RXX=P4*P4/(2.0*D4F*RATIO)
      GO TO 223
222   RXX=P4-0.5*D4F*RATIO
C RXX IS THE POTENTIAL INCREASE TO OVERLAND FLOW AND SURFACE DETENTION
223   RGXX=SHRD-RXX
C RGXX IS THE POTENTIAL INCREASE TO INTERFLOW DETENTION
      UZSNT=UZSN+UZSNWF*AEPIT
      IF (UZS.GE.(2.0*UZSNT)) GO TO 224
      UZI=2.0*ABS(0.5*(UZS/UZSNT)-1.0)+1.0
      PRE=(0.5*UZS/UZSNT)*(1.0/(1.0+UZI))**UZI
      GO TO 225
224   UZI=2.0*ABS(((UZS/UZSNT)-1.0)-1.0)+1.0
      PRE=1.0-(1.0/(1.0+UZI))**UZI
C PRE IS THE PERCENT OF RXX AND RGXX NOT RETAINED IN UPPER ZONE STORAGE
225   RGX=RGXX*PRE
C RGX IS THE VOLUME TO INTERFLOW DETENTION STORAGE
      RX=RXX*PRE
C RX IS THE VOLUME TO OVERLAND FLOW AND SURFACE DETENTION
      UZS=UZS+SHRD-RGX-RX
C UZS IS UPPER ZONE STORAGE VOLUME
C OVERLAND FLOW
      IF (RX.LE.RES) GO TO 226
      DE=DEC*((RX-RES)**0.6)
C DE IS SURFACE DETENTION AT EQUILIBRIUM
      GO TO 227
226   DE=(RES+RX)/2.0
227   D=(RES+RX)/2.0
C D IS AVERAGE SURFACE DETENTION
      IF (D.GT.DE) DE=D
      IF (D.LE.0.005) GO TO 228
      ROS=0.25*SRC*(D**1.67)*((1.0+0.6*((D/DE)**3.0))**1.67)
      GO TO 229
228   ROS=0.0
229   IF (ROS.GT.(0.75*RX)) ROS=0.75*RX
C ROS IS OVERLAND FLOW VOLUME
      SROS=SROS+ROS
      RES=RX-ROS
```

```
C RES IS SURFACE DETENTION STORAGE VOLUME
      IF (RES.GE.0.001) GO TO 230
      LZS=LZS+RES
      RES=0.0
C LOWER ZONE AND GROUNDWATER CALCULATIONS
230   LZI=1.5*ABS((LZS/LZSN)-1.0)+1.0
      PRE=(1.0/(1.0+LZI))**LZI
      IF (LZS.LT.LZSN) PRE=1.0-PRE*(LZS/LZSN)
C PRE IS THE PERCENT OF INFILTRATION RETAINED IN H
C PRE IS THE PERCENT OF INFILTRATION RETAINED IN THE LOWER ZONE
C F3 IS HELD IN LOWER ZONE -- F1 GOES TO GROUNDWATER DETENTION
      F3=PRE*INFIL
      LZS=LZS+F3
C LZS IS LOWER ZONE STORAGE VOLUME
      F1A=INFIL-F3
      F1=F1A*(1.0-K24L)*PA
      RECH=F1A*K24L*PA
C RECH IS DEEP GROUNDWATER RECHARGE
      SRECH=SRECH+RECH
      SGW=SGW+F1
C SGW IS GROUNDWATER STORAGE VOLUME
      GWS=GWS+F1
C GWS IS ANTECEDENT GW INFLOW INDEX
      SRGX=SRGX+RGX
C SRGX IS INTERFLOW DETENTION STORAGE
C INTERFLOW CALCULATIONS
214   INTF=LIRC4*SRGX
C INTF IS INTERFLOW VOLUME
      SINTF=SINTF+INTF
      SRGX=SRGX-INTF
      IF (SRGX.GE.0.0001) GO TO 215
      LZS=LZS+SRGX
      SRGX=0.0
C GROUNDWATER FLOW CALCULATIONS
215   IF (SGW.LE.0.0001) GO TO 231
      GWF=SGW*LKK4*(1.0+KV*GWS)
      GO TO 232
231   GWF=0.0
      GWS=SGW
C GWF IS GROUNDWATER FLOW VOLUME
232   SGWF=SGWF+GWF
      SGW=SGW-GWF
C RU IS TOTAL LAND SURFACE RUNOFF VOLUME
      RU=RU+(ROS+INTF)*PA+P3*AT+GWF
C EVAP-TRANS LOSS FROM INTERCEPTION AND UPPER ZONE STORAGES
      IF (I15.NE.1) GO TO 209
      EPHR=EPDIST(IHR)*EP
      IF (EPHR.EQ.0.0) GO TO 234
      IF (SCEP.LE.0.0) GO TO 235
      IF (SCEP.LE.EPHR) GO TO 236
      SCEP=SCEP-EPHR
      SET=SET+EPHR
      EPHR=0.0
      GO TO 234
236   SET=SET+SCEP
      EPHR=EPHR-SCEP
      SCEP=0.0
235   IF (UZS.LE.0.0) GO TO 237
      IF (UZS.LE.EPHR) GO TO 238
      SET=SET+PA*EPHR
      UZS=UZS-EPHR
```

```
      EPHR=0.0
      GO TO 234
238   SET=SET+UZS*PA
      EPHR=EPHR-UZS
      UZS=0.0
237   REP=REP+EPHR
C REP IS RESIDUAL POTENTIAL EVAPOTRANSPIRATION
C SLOW PERCOLATION FROM UPPER ZONE
234   UZSNT=UZSN+UZXNWF*AEPIT
      DEEPL=(UZS/UZSNT)-(LZS/LZSN)
      IF (DEEPL.LE.0.0) GO TO 239
      LNRAT=LZS/LZSN
      RECE=0.003*CB*UZSNT*(DEEPL**3.0)
      UZS=UZS-RECE
      LZI=1.5*ABS(LNRAT-1.0)+1.0
      PRE=(1.0/(1.0+LZI))**LZI
      IF (LZS.LT.LZSN) PRE=1.0-PRE*LNRAT
      F3=PRE*RECE
      F1A=(1.0-PRE)*RECE
      F1=F1A*(1.0-K24L)*PA
      RECH=F1A*K24L*PA
      SRECH=SRECH+RECH
      LZS=LZS+F3
      SGW=SGW+F1
      GWS=GWS+F1
C EVAP-TRANS FROM GROUNDWATER AND LOWER ZONE
239   IF (IHR.NE.21) GO TO 209
      IF (GWS.GT.0.0001) GWS=0.97*GWS
      EP=REP
      IF (EP.EQ.0.0) GO TO 209
      LOS=SGW*K24EL*EP*PA
C LOS IS GROUNDWATER EVAPOTRANSPIRATION VOLUME
      SET=SET+LOS
      SGW=SGW-LOS
      GWS=GWS-LOS
      IF (GWS.LT.0.0) GWS=0.0
      EP=EP-LOS
      LNRAT=LZS/LZSN
      IF (EP.GE.(K3*LNRAT)) GO TO 240
      AETR=EP*(1.0-(EP/(2.0*K3*LNRAT)))
      LZS=LZS-AETR
      GO TO 241
240   AETR=0.5*K3*LNRAT
      LZS=LZS-AETR
241   SET=SET+PA*AETR
C AETR IS LOWER ZONE EVAPOTRANSPIRATION VOLUME
      REP=0.0
209   CONTINUE
C END OF 15 MINUTE LOOP
      MHR=(IDA-1)*24+IHR
      RO(MHR)=RU
      SRO=SRO+RU
      IF ((IDA.EQ.LAST).AND.(IHR.EQ.24)) GO TO 246
      IHR=IHR+1
      IF (IHR.LE.24) GO TO 203
      IHR=1
      IDA=IDA+1
      GO TO 203
C END OF HOUR AND DAY LOOP
C LAND CARRY/VER VALUES
246   UZSI=UZS
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      LZSI=LZS
      SGWI=SGW
      GWSI=GWS
      RESI=RES
      SRGXI=SRGX
      SCEPI=SCEP
      REPI=REP
      AEPI=AEPIT
      RETURN
      END
      SUBROUTINE CHANEL
C CHANNEL ROUTING SUBROUTINE
C CHANEL VARIABLES
      INTEGER HALFR,DHR
      REAL IN,K
      DIMENSION TRS(792),XRS(50)
C MAIN,INITL,READER,LAND AND CHANEL VARIABLES
      INTEGER ELE,ELEMTS,
     1RTEINT,AVEPE,VARK,
     2VARL,VAREP
      REAL IMPV,LZSN,K3,K24L,K24EL,KV,LKK4,
     1LIRC4,LZSI,KS1,KS1V(20)
      COMMON/MCL/EODIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
     1UZSI,SGWI,GWSI,RESI,SRGXI,SCEPI,REPI,
     2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPE,SET,TIMEAR(16),PEADJ(12),
     5GAGEPE,POWER,BASEK,BASEL,IMPV,LZSN,K3,K24L,K24EL,KV,
     6LKK4,LIRC4,LZSI,KS1,KS1V,MAXL,MINL,LAG(10),
     7IE,MHR,MOHR1,MOHR2,ELE,ELEMTS,VAREP,SDEP,EPBIAS,IXEP,
     8TEST1,TEST2,RTEINT,AVEPE,VARK,VARL,UZSNWF,
     9AEPI
C MAIN,LAND,CHANEL VARIABLES (II)
      INTEGER   PX(31,96),QUART
      INTEGER SIXHR
      REAL K1
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,
     1QUART,PX
C CHANNEL INITIAL VALUES
      MOHR1=1
      MOHR2=LAST*24
      IE=MOHR2+48
      DO 3001 I=MOHR1,IE
3001  TRS(I)=0.0
      IF (RTEINT.LT.0) GO TO 100
      HALFR=(RTEINT-1)/2
      IF (VARK.EQ.0) GO TO 3004
3004  IF (VARL.EQ.0) GO TO 3002
C TRANSLATION IN TIME
3002  DO 304 MHR=MOHR1,MOHR2
      DHR=MHR+HALFR
      DO 304 IE=1,ELEMTS
      I=DHR+RTEINT*(IE-1)
304   TRS(I)=TRS(I)+RO(MHR)*CFSM*TIMEAR(IE)
      GO TO 305
  100 INTR=-1*RTEINT
      KRX=ELEMTS-((ELEMTS/INTR)*INTR)
      DO 110 MHR=MOHR1,MOHR2
      MR=MHR-1
      IM=0
      IX=0
```

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      CON=0.
      DO 120 IE=1,ELEMTS
      XRS(IE)=RO(MHR)*CFSM*TIMEAR(IE)
      CON=CON+XRS(IE)
      IX=IX+1
      IF (IX.LT.INTR) GO TO 120
      IM=IM+1
      I=MR+IM
      TRS(I)=CON+TRS(I)
      CON=0.
      IX=0
  120 CONTINUE
      IF (KRX.GT.0) TRS(I+1)=TRS(I+1)+CON
  110 CONTINUE
      RTEINT=1
      ELEMTS=ELEMTS/INTR
      IF (KRX.GT.0) ELEMTS=ELEMTS+1
      HALFR=0
305   IF (VARL.EQ.0) GO TO 3051
C VARIABLE LAG
      IE=MOHR2+HALFR+RTEINT*(ELEMTS-1)
      DO 51 IHR=MOHR1,IE
      MHR=IE+MOHR1-IHR
      R=(TRS(MHR)/BASEL)+1.0
      I=R
      IF (I.LT.MINL) GO TO 51
      IF (I.LE.10) GO TO 52
C INFLOW GREATER THAN 10*BASEL
      L=LAG(10)
      PART=TRS(MHR)-BASEL*10.0
      TRS(MHR)=TRS(MHR)-PART
      TRS(MHR+L)=TRS(MHR+L)+PART
      I=10
      GO TO 57
C INFLOW BETWEEN ((MINL-1)*BASEL) AND (BASEL*10.0)
 52   LTOP=LAG(I)
      LBOT=LAG(I-1)
      P=R-I
      IF (LTOP.LT.LBOT) GO TO 53
      IF (LBOT.EQ.0) GO TO 55
      LTOP=LBOT+(P*(LTOP-LBOT+1))
      PART=TRS(MHR)-BASEL*(I-1)
      TRS(MHR)=TRS(MHR)-PART
      PART=PART/((LTOP-LBOT)+1.0)
      DO 54 L=LBOT,LTOP
 54   TRS(MHR+L)=TRS(MHR+L)+PART
      GO TO 55
 53   LTOP=LTOP+1
      LTOP=LBOT-(P*(LBOT-LTOP+1))
      PART=TRS(MHR)-BASEL*(I-1)
      TRS(MHR)=TRS(MHR)-PART
      PART=PART/((LBOT-LTOP)+1.0)
      DO 56 L=LTOP,LBOT
 56   TRS(MHR+L)=TRS(MHR+L)+PART
 55   IF (I.EQ.MINL) GO TO 51
      I=I-1
 57   DO 58 I1=MINL,I
      I2=I+MINL-I1
      LTOP=LAG(I2)
      LBOT=LAG(I2-1)
      IF (LTOP.LT.LBOT) GO TO 59
```

```
      IF (LBOT.LT.LTOP) LBOT=LBOT+1
      IF (LBOT.EQ.3) GO TO 58
      TRS(MHR)=TRS(MHR)-BASEL
      PART=BASEL/((LTOP-LBOT)+1.0)
      DO 60 L=LBOT,LTOP
 60   TRS(MHR+L)=TRS(MHR+L)+PART
      GO TO 58
 59   LTOP=LTOP+1
      TRS(MHR)=TRS(MHR)-BASEL
      PART=BASEL/((LBOT-LTOP)+1.0)
      DO 61 L=LTOP,LBOT
 61   TRS(MHR+L)=TRS(MHR+L)+PART
 58   CONTINUE
 51   CONTINUE
3051  IE=MAXL
      DO 34 I=1,IE
      MHR=MOHR1+(I-1)
 34   TRS(MHR)=TRS(MHR)+TRANSI(I)
      PREV=PREVFI
C CHANNEL ATTENUATION
      IF (VARK.EQ.1) GO TO 3052
C CONSTANT K
      DO 309 MHR=MOHR1,MOHR2
      IN=TRS(MHR)
      FLOWT=IN-KS1*(IN-PREV)
      PREV=FLOWT
      IF (PREV.LT.0.01) PREV=0.0
309   FLOW(MHR)=FLOWT
      GO TO 3091
C VARIABLE K
3052  DO 30 MHR=MOHR1,MOHR2
      IN=TRS(MHR)
      I=(PREV/BASEK)+1.0
      IF  (I.GT.20) I=20
      K=KS1V(I)*KS1
      FLOWT=IN-K*(IN-PREV)
      PREV=FLOWT
      IF (PREV.LT.0.01) PREV=0.0
30    FLOW(MHR)=FLOWT
C CHANNEL CARRYOVER VALUES
3091  ELEMTS=MAXL
      PREVFI=PREV
      DO 311 IE=1,ELEMTS
311   TRANSI(IE)=TRS(MOHR2+IE)
      RETURN
      END
      SUBROUTINE IGAUSS(IX,S,AM,V)
C SUBROUTINE TO COMPUTE NORMAL RANDOM NUMBERS
C  IX=ODD INTEGER .LT.9 DIGITS TO BEGIN R.N. GENERATION S=
C  IX=ODD INTEGER .LT.9 DIGITS TO BEGIN R.N. GENERATION    S=STANDARD DE
C  AM=MEAN  V=VALUE OF COMPUTED NORMAL RANDOM NUMBER
      DOUBLE PRECISION X,Y,C
      A=0.0
      DO 50 I=1,12
C START RANDU
      IY=IX*65539
      IF (IY) 5,6,6
  5   IY=IY+7483647+1
 6    YFL=IY
      YFL=YFL*0.4656613E-9
C  END RANDU
```

```
      IX=IY
50    A=A+YFL
      V=(A-6.0)*S+AM
      RETURN
      END
      SUBROUTINE DAILY(INFRO,MONTH,YEAR)
C CALCULATION OF SCALED VALUES FOR MEAN DAILY FLOW PLOT
C PLOT CALLS CAN BE ADDED IF COMPUTER HAS PLOT ROUTINES
      INTEGER YEAR,START(2,12),YR1
      REAL INFRO(20),MOCHAR(12)
      DIMENSION LASTDA(2,12),A(2,12),YA(368),YS(368)
C MAIN,INITL,READER,HOURLY AND DAILY VARIABLES
      INTEGER FIRST,CHECK
      COMMON/MHD/FLOW1(744),PHRMX,FPNAME(7),PLOTMX,
     1ACTFLW(12,31),SIMFLW(12,31),FIRST,CHECK
      DATA MOCHAR/3HOCT,3HNOV,3HDEC,3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,
     13HJUN,3HJUL,3HAUG,3HSEP/
      DATA A/3.0,3.0,6.0,6.0,9.1,9.1,12.2,12.2,15.0,15.1,18.1,18.2,
     121.1,21.2,24.2,24.3,27.2,27.3,30.3,30.4,33.4,33.5,36.4,36.5/
      DATA LASTDA/31,31,28,29,31,31,30,30,31,31,30,30,31,31,31,31,30,30,
     131,31,30,30,31,31/
      DATA START/92,92,123,123,151,152,182,183,212,213,243,244,273,274,
     1304,305,335,336,0,0,31,31,61,61/
      LEAPYR=0
      IF ((YEAR-4*(YEAR/4)).EQ.0) LEAPYR=1
      N=12
      PMAX=PLOTMX
      DELTA=PMAX*0.1
      X1=0.0
      L=LEAPYR+1
      NPT=A(L,12)*10.0+1.0
      WRITE(7,900)N,DELTA,X1,NPT
      WRITE(7,901)(A(L,J),J=1,12)
      WRITE(7,902)MOCHAR
      WRITE(7,903)
      WRITE(7,904)FPNAME
      YR1=YEAR-1
      IF (YR1.LT.0) YR1=99
      WRITE(7,905)YR1,YEAR
      WRITE(7,906)INFRO
      WRITE(7,907)
C SCALE ACTUAL AND SIMULATED FLOW
      DO 801 MO=1,12
      LAST=LASTDA(L,MO)
      IBASE=START(L,MO)
      DO 801 IDA=1,LAST
      FA=(ACTFLW(MO,IDA)/PMAX)*10.0
      FS=(SIMFLW(MO,IDA)/PMAX)*10.0
      IF (FA.GT.10.0) FA=10.0
      IF (FS.GT.10.0) FS=10.0
      I=IBASE+IDA
      YA(I)=FA
      YS(I)=FS
801   CONTINUE
      N=365+LEAPYR
      WRITE(7,908)(YA(I),I=1,N)
      WRITE(7,908)(YS(I),I=1,N)
C FORMAT STATEMENTS
900   FORMAT (I5,F10.2,F5.1,I5)
901   FORMAT (12F5.1)
902   FORMAT (12A3)
```

```
903    FORMAT (20HMEAN DAILY FLOW-CFSD)
904    FORMAT (7A4)
905    FORMAT (13HWATER YEAR 19,I2,1H-,I2)
906    FORMAT (20A4)
907    FORMAT (35HBLACK IS OBSERVED--RED IS SIMULATED)
908    FORMAT (16F5.2)
       RETURN
       END
       SUBROUTINE HOURLY(INFRO,MONTH,YEAR,FLOW)
C SUBROUTINE GENERATES SCALED INPUT FOR AUXILIARY PLOT PROGRAM
       INTEGER YEAR,DA1,DA2
       REAL INFRO(20),MOCHAR(12)
       DIMENSION YA(752),YS(752),A(31),NUM(31),FLOW(744)
C MAIN,INITL,READER,HOURLY AND DAILY VARIABLES
       INTEGER FIRST,CHECK
       COMMON/MHD/FLOW1(744),PHRMX,FPNAME(7),PLOTMX,
      1ACTFLW(12,31),SIMFLW(12,31),FIRST,CHECK
       DATA MOCHAR/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,4HJUNE,4HJULY,3HAUG,
      14HSEPT,3HOCT,3HNOV,3HDEC/
       MOHR1=1
       M6=6
880    IF (CHECK.EQ.1) GO TO 855
C DETERMINE FIRST AND LAST HOUR OF PLOT AND NUMBER OF POINTS
C HOURLY FLOW
       DO 850 MHR=MOHR1,744
       IF (FLOW1(MHR).EQ.0.0) GO TO 850
       MOHR1=MHR
       GO TO 851
850    CONTINUE
       GO TO 899
851    FIRST=1
       DO 852 MHR=MOHR1,744
       IF (FLOW1(MHR).GT.0.0) GO TO 852
       MOHR2=MHR-1
       GO TO 870
852    CONTINUE
       MOHR2=744
       GO TO 870
C SIX HOUR FLOWS
855    DO 856 MHR=M6,744,6
       IF (FLOW1(MHR).EQ.0.0) GO TO 856
       M6=MHR
       GO TO 857
856    CONTINUE
       GO TO 899
857    FIRST=1
       DO 858 MHR=M6,744,6
       IF (FLOW(MHR).GT.0.0) GO TO 858
       MOHR2=MHR-6
       GO TO 859
858    CONTINUE
       MOHR2=744
859    MOHR1=M6-5
       DO 860 MHR=MOHR1,M6
       IF (FLOW1(MHR).EQ.0.0) GO TO 860
       MOHR1=MHR
       GO TO 861
860    CONTINUE
861    F1=FLOW(MOHR1)
       M1=MOHR1+1
864    DO 862 MHR=M1,MOHR2
```

```
      IF (FLOW1(MHR).EQ.0.0) GO TO 862
      M2=MHR
      F2=FLOW1(MHR)
      GO TO 863
862   CONTINUE
863   IF (M1.EQ.M2) GO TO 865
      FP=(F2-F1)/(M2-M1+1)
      I=M2-1
      DO 866 MHR=M1,I
      X1=MHR-M1+1
866   FLOW1(MHR)=F1+FP*X1
865   IF (M2.EQ.MOHR2) GO TO 870
      M1=M2+1
      F1=F2
      GO TO 864
870   NPT=MOHR2-MOHR1+1
      DA1=(MOHR1-1)/24+1
      DA2=(MOHR2-1)/24+1
      NDA=DA2-DA1+1
      I=MOHR1-(DA1-1)*24
      X1=I*0.1
      DO 871 I=1,NDA
      NUM(I)=DA1-1+I
871   A(I)=2.4*I
      PMAX=PHRMX
      DELTA=PMAX*0.1
      WRITE(7,900)NDA,DELTA,X1,NPT
      WRITE(7,901)(A(I),I=1,NDA)
      WRITE(7,902)(NUM(I),I=1,NDA)
      IF (CHECK.EQ.1) GO TO 872
      WRITE(7,903)
      GO TO 873
  872 WRITE(7,904)
  873 WRITE(7,905)FPNAME
      WRITE(7,906)MOCHAR(MONTH),YEAR
      WRITE(7,907)INFRO
      WRITE(7,908)
      DO 875 MHR=MOHR1,MOHR2
      I=MHR-MOHR1+1
      YA(I)=(FLOW1(MHR)/PMAX)*10.0
      YS(I)=(FLOW(MHR)/PMAX)*10.0
      IF (YA(I).GT.10.0) YA(I)=10.0
      IF (YS(I).GT.10.0) YS(I)=10.0
875   CONTINUE
      WRITE(7,909)(YA(I),I=1,NPT)
      WRITE(7,909)(YS(I),I=1,NPT)
      IF (MOHR2.EQ.744) GO TO 899
      MOHR1=MOHR2+1
      M6=MOHR2+6
      GO TO 880
899   CONTINUE
C HOURLY FORMAT STATEMENTS
900   FORMAT (I5,F10.2,F5.1,I5)
901   FORMAT(16F5.1)
902   FORMAT(20I3)
903   FORMAT(16HHOURLY FLOW--CFS)
904   FORMAT(20HSIX HOURLY FLOW--CFS)
905   FORMAT(7A4)
906   FORMAT(A4,3H 19,I2)
907   FORMAT(20A4)
908   FORMAT(35HBLACK IS OBSERVED--RED IS SIMULATED)
```

```
909    FORMAT(16F5.2)
       RETURN
       END
       FINISH
```

A.5 Program PORT

```
---------------------------------------------------------------------------------
       DATE 31/10/78   TIME 15/35/50                         LISTING FOR:- HRPR

FILE:   HRPRMAXIMOP     SUBFILE PORT IN CARD MODE

      LIST
      PROGRAM(PORT)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER PORT
C     ##################################################################
C     THIS PROGRAM GENERATES HOURLY FLOW VALUES FROM HOURLY RAINFALL
C     DATA (MM) AND DAILY PAN EVAPORATION (MM)
C     THE BASIC STRUCTURE OF THE MODEL HAS BEEN DRAWN FROM
C     THE MODEL OF PORTER AND MCMAHON (1971).
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSIY.
C     (P.J.T. ROBERTS 1975)
C     ##################################################################
      DIMENSION IRAIN(31,24),FLOW(31,24),RFLO(32,24),DTOT(31)
      DIMENSION EVAP(50),EDIS(24),KPPT(12),LS(12),Z(12),EVMO(12)
      DATA LS/31,28,31,30,31,30,31,31,30,31,30,31/
C     ******************************************************************
C     READ IN SIMULATION PERIOD (A8) AND CATCHMENT NAME (A8),
C     NUMBER OF MONTHS OF INPUT DATA AND CATCHMENT AREA (SQ.KM.).
C     ******************************************************************
      READ (5,1) H1,H2,H3,H4,NMON,AREA
    1 FORMAT (4A8,I4,F6.2)
C     ******************************************************************
C     READ IN STORAGE VALUES IN MM AND PROGRAM CONTROL FLAG MVAP.
C     VSL           INTERCEPTION STORAGE LEVEL
C     VSC           INTERCEPTION STORAGE CAPACITY (USUALY 1.5 MM)
C     DSL           DEPRESSION STORAGE LEVEL
C     DSC           DEPRESSION STORAGE CAPACITY
C     SSL           SOIL STORAGE LEVEL
C     SSC           SOIL STORAGE CAPACITY
C     GS            INITIAL GROUND WATER STORAGE LEVEL
C     MVAP          = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM)
C                   = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION (MM).
C     ******************************************************************
      READ (5,2) VSL,VSC,DSL,DSC,SSL,SSC,GS,MVAP
    2 FORMAT (7F6.0,I5)
C     ******************************************************************
C     READ IN MODEL PARAMETERS
C     BARE  PERCENTAGE BARE GROUND
C     X     CONSTANT IN SORPTIVITY-STORAGE RELATIONSHIP
C     P     CONSTANT IN SORPTIVITY-STORAGE RELATIONSHIP
C     A     CONSTANT IN PHILIPS INFILTRATION FORMULA
C     B     CONSTANT IN DEPRESSION STORAGE FUNCTION
C     Y     CONSTANT IN DEPRESSION STORAGE FUNCTION
C     UC    DIVERSION CONSTANT, SOIL TO CHANNEL STORAGE
C     UG    DIVERSION CONSTANT, SOIL TO GROUND WATER STORAGE
C     C     CONSTANT IN GROUND WATER STORAGE
C     XN    EXPONENT IN GROUND WATER STORAGE
C     RK    THE ROUTING CONSTANT
C     LAG   REQUIRED LAG TIME IN HOURS
C     Z     12 PAN TO FREE SURFACE EVAP. FACTORS (JAN-DEC)
C     ******************************************************************
      READ (5,3) BARE,X,P,A,B,Y,UC,UG,C,XN,RK,LAG,(Z(J),J=1,12)
```

```
    3 FORMAT (11F6.2,I5,/,12F6.2)
C     ******************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAPORATION(MM) JAN-DEC
C     ONLY IF MVAP = 1
C     ******************************************************************
      IF (MVAP.EQ.2) GO TO 761
      READ (5,766) (EVMO(NX),NX=1,12)
  766 FORMAT (12F6.1)
C     ******************************************************************
C     READ IN LAG NUMBER OF HOURS OF TRANSLATED FLOW (CUMECS)
C     FROM DAY PRECEEDING SIMULATION, ONLY IF LAG > 0
C     ******************************************************************
  761 IF (LAG.EQ.0) GO TO 760
      READ (5,6) (RFLO(1,LL),LL=1,LAG)
    6 FORMAT (12F6.2)
C     ------------------------------------------------------------------
C     INITIALISE VARIABLES
C     VT1 AND QT1 ARE THE RATE OF GENERATION OF EXCESS RAIN(CUMECS)
C     AND THE RUNOFF(CUMECS) RESPECTIVELY FOR HOUR PRECEEDING SIMULATION
C     ------------------------------------------------------------------
  760 TA=0.
      SSX=0.
      VT1=0.
      QT1=0.
      ICI=0
C     ------------------------------------------------------------------
C     MONTHLY RE-ENTRY POINT IN PROGRAM
C     ------------------------------------------------------------------
  666 DO 300 I=1,31
      DO 400 J=1,24
      IRAIN(I,J)=0
  400 CONTINUE
  300 CONTINUE
C     ******************************************************************
C     READ IN PRECIPITATION DATA IN TENTHS OF A MILLIMETER
C     TWO PRECIPITATION CARDS PER DAY AND CARDS WITH ZERO RAINFALL
C     FOR A 12 HOUR PERIOD MAY BE OMITTED.
C     THE PRECIPITATION DATA FOR EACH MONTH IS TERMINATED BY A
C     CARD CONTAINING THE VALUE 99 PUNCHED IN THE FIRST TWO COLUMNS.
C     THE FORMAT FOR EACH CARD IS AS FOLLOWS
C     STATE                I2
C     IDENTIFICATION       7X  (NOT READ BY PROGRAM)
C     YEAR                 I3  (IE. 75 FOR 1975)
C     MONTH                I3
C     DAY                  I3
C     CARD CODE            I2  =1  HOURS   0 TO 12
C                              =2  HOURS  13 TO 24
C     RAIN               12I5
C     ******************************************************************
  350 READ (5,4) NS,MY,MO,I,L,(KPPT(N),N=1,12)
    4 FORMAT (I2,7X,3I3,I2,12I5)
      IF (MO.GT.0) MX=MO
      IF (MY.GT.0) MZ=MY
      IF (NS.EQ.99) GO TO 505
      IF (L.EQ.2) GO TO 44
      NBEG=1
      NEND=12
      GO TO 45
   44 NBEG=13
      NEND=24
   45 DO 450 K=NBEG,NEND
```

```
      KL=K
      IF (NEND.EQ.24) KL=K-12
      IRAIN(I,K)=KPPT(KL)
  450 CONTINUE
      GO TO 350
C     ******************************************************************
C     READ IN EVAPORATION DATA IN MILLIMETRES PER DAY IF MVAP = 2
C     THREE CARDS PER MONTH IN THE FORMAT
C     IDENTIFICATION             7X  (NOT READ BY PROGRAM)
C     YEAR                       I2  (IE, 75 FOR 1975)
C     MONTH                      I2
C     CARD NO.                   I1  =1,    DAYS  1-10
C                                    =2,    DAYS 11-20
C                                    =3,    DAYS 21-LAST DAY OF MONTH
C     EVAP                   11F6.2
C     ******************************************************************
  505 NTOT=LS(MX)
      IF (((MZ-4*(MZ/4)).EQ.0).AND.(MX.EQ.2)) NTOT=NTOT+1
      IF (MVAP.EQ.1) GO TO 780
      NEND=10
      NBEG=1
      DO 500 NE=1,3
      READ (5,5) (EVAP(N),N=NBEG,NEND)
    5 FORMAT (12X,11F5.2)
      NEND=NEND+10
      NBEG=NEND-9
      IF (NE.EQ.2) NEND=NTOT
  500 CONTINUE
      GO TO 790
  780 DO 781 IZ=1,NTOT
      EVAP(IZ)=EVMO(MX)/FLOAT(NTOT)
  781 CONTINUE
C     --------------------------------------------------------------
C     SET HOURLY EVAP. DISTRIBUTION FACTOR (EDIS) FOR EACH HOUR
C     --------------------------------------------------------------
  790 DO 200 I=1,24
  200 EDIS(I)=0.00
      EDIS(7)=0.019
      EDIS(8)=0.041
      EDIS(9)=0.067
      EDIS(10)=0.088
      EDIS(11)=0.102
      EDIS(12)=0.110
      EDIS(13)=0.110
      EDIS(14)=0.110
      EDIS(15)=0.105
      EDIS(16)=0.095
      EDIS(17)=0.081
      EDIS(18)=0.055
      EDIS(19)=0.017
      XTOT=0.
      FSUR=0.
      FINT=0.
      FGRO=0.
      FSUM=0.
      FPPT=0.
      TPE=0.
      RES=0.
      XU=(1.0-(XN**(1.0/24.0)))
C     ------------------------------------------------------------------
C     LIST RUN INFORMATION, MODEL STORAGE AND PARAMETER VALUES
```

```
C     ------------------------------------------------------------
      WRITE (6,8) H3,H4
    8 FORMAT (1H1,30HHOURLY DISCHARGE (CUMECS) FOR ,2A8,/,1X,
     1 37HFLOW VOLUMES IN THOUSAND CUBIC METRES,/)
      WRITE (6,9) H1,H2
    9 FORMAT (1X,19HSIMULATION PERIOD  ,A8,4H TO ,A8,/)
      WRITE (6,22) MX,MZ
   22 FORMAT (1X,14HDATA FOR MONTH,I5,3X,4HYEAR,I5,/)
      WRITE (6,10)
   10 FORMAT (1X,14HSTORAGE VALUES,/,5X,3HVSL,5X,3HVSC,5X,3HDSL,5X,
     1 3HDSC,5X,3HSSL,5X,3HSSC,6X,2HGS)
      WRITE (6,11) VSL,VSC,DSL,DSC,SSL,SSC,GS
   11 FORMAT (7(2X,F6.0),//)
      WRITE (6,12)
   12 FORMAT (1X,16HMODEL PARAMETERS,/,6X,1HZ,2X,4HBARE,5X,1HX,5X,1HP,
     1 5X,1HA,5X,1HB,5X,1HY,4X,2HUC,4X,2HUG,5X,1HC,4X,2HXN,4X,2HRK,3X,
     2 3HLAG,2X,4HMVAP)
      WRITE (6,13) Z(MX),BARE,X,P,A,B,Y,UC,UG,C,XN,RK,LAG,MVAP
   13 FORMAT (1X,12F6.2,2I6,//)
      WRITE (6,14)
   14 FORMAT (1X,3HDAY,28X,26HHOURLY DISCHARGE IN CUMECS,50X,5HTOTAL,/)
C     ------------------------------------------------------------
C     START OF DAILY LOOP
C     ------------------------------------------------------------
      DO 100 NN=1,NTOT
C     ------------------------------------------------------------
C     START OF HOURLY LOOP
C     ------------------------------------------------------------
      DO 50 KK=1,24
C     ------------------------------------------------------------
C     CONVERT DAILY PAN EVAP TO HOURLY FREE SURFACE EVAP
C     AND DISTRIBUTE OVER 24 HOURS
C     ------------------------------------------------------------
      AVAP=EVAP(NN)*Z(MX)*EDIS(KK)
      TPE=TPE+AVAP
C     ------------------------------------------------------------
C     OPERATION OF INTERCEPTION STORAGE
C     ------------------------------------------------------------
      RAIN=FLOAT(IRAIN(NN,KK))/10.
      FPPT=FPPT+RAIN
      BAN=RAIN*(BARE/100.)
      VEG=RAIN-BAN
      CAN=VSC-VSL
      AVEG=VEG-CAN
      IF (AVEG.GE.0.) GO TO 15
      AVEG=0.
      CAN=VEG
   15 VSL=VSL+CAN
      IF (RAIN.GT.0.) GO TO 16
      XVSL=VSL-AVAP
      IF (XVSL.LT.0.) XVSL=0.
      IF (XVSL.GT.0.) AVAP=0.
      IF (AVAP.GT.VSL) AVAP=AVAP-VSL
      VSL=XVSL
   16 TOIF=BAN+AVEG
      T=1.
C     ------------------------------------------------------------
C     OPERATION OF INFILTRATION FUNCTION
C     ------------------------------------------------------------
      SSZ=SSL
      RED=(EVAP(NN)*Z(MX))+((SSX-SSL)*((SSC-SSL)/SSC))
```

```
      IF (RED.LT.0.)RED=0.
      SSX=SSX-RED
      IF (SSX.LT.SSL) SSX=SSL
      IF (SSX.GT.SSZ)SSZ=SSX
      XPC=-P*(SSZ/SSC)
      S=X*EXP(XPC)
      F=A+0.5*S*T**(-0.5)
      IF (TOIF.GT.F) GO TO 17
      IF (TA.GT.0.) GO TO 170
      GO TO 180
   17 TA=TA+T
      F=A+0.5*S*TA**(-0.5)
      FFF=F
      GO TO 180
  170 S= (FFF-A)/(0.5*T**(-0.5))
      SSX= (-SSC/P)*ALOG(S/X)
      IF (SSX.GT.SSC) SSX=SSC
      RED=(EVAP(NN)*Z(MX))+((SSX-SSL)*((SSC-SSL)/SSC))
      SSX=SSX-RED
      IF (SSX.LT.SSL) SSX=SSL
      XPC=-P*(SSX/SSC)
      S=X*EXP(XPC)
      F=A+0.5*S*T**(-0.5)
      TA=0.
  180 IF (TOIF.LT.F) F=TOIF
      TDSF=TOIF-F
C     ------------------------------------------------------------------
C     OPERATION OF DEPRESSION STORAGE FUNCTION
C     ------------------------------------------------------------------
      SM=DSC-DSL
      IF (SM.EQ.0.) GO TO 900
      D=B*2.7183**((-Y*DSL)/(DSC-DSL))*TDSF
  900 IF (SM.EQ.0.) D=0.
      DSL=DSL+D
      CS=TDSF-D
      IF (CS.LT.0.) CS=0.
      IF (AVAP.EQ.0.) GO TO 18
      XDSL=DSL-AVAP
      IF (DSL.GE.AVAP) AVAP=0.
      IF (XDSL.GE.0.) GO TO 19
      AVAP=AVAP-DSL
      XDSL=0.
   19 DSL=XDSL
   18 IF (F.LE.DSL) GO TO 20
      FD=DSL
      DSL=0.
   20 IF (F.GT.DSL) GO TO 21
      FD=F
      DSL=DSL-F
   21 IF (TOIF.GE.F) FD=0.
C     ------------------------------------------------------------------
C     CALCULATE OVERLAND FLOW
C     ------------------------------------------------------------------
      OVF=DSL-DSC
      IF (OVF.LT.0.) OVF=0.
      IF (OVF.GT.0.) DSL=DSC
      CS=CS+OVF
      FT=F+FD
C     ------------------------------------------------------------------
C     OPERATION OF SOIL MOISTURE FUNCTION
C     ------------------------------------------------------------------
```

```
      SC=UC*(SSL/SSC)*FT
      SG=UG*(SSL/SSC)*FT
      SSL=SSL+FT-(SC+SG)
      SLA=AVAP
      IF (SSL.GE.SLA) GO TO 48
      AVAP=AVAP-SSL
      SSL=0.
      GO TO 49
   48 AVAP=AVAP-SLA
      SSL=SSL-SLA
   49 RES=RES+AVAP
      OSL=SSL-SSC
      IF (OSL.LT.0.) OSL=0.
      IF (OSL.GT.0.)SSL=SSC
C     -----------------------------------------------------------------
C     OPERATION OF GROUND WATER FUNCTION
C     -----------------------------------------------------------------
      GS=GS+SG+OSL
      CG=C*GS*XU
C     -----------------------------------------------------------------
C     TOTAL CONTRIBUTION TO CHANNEL STORAGE
C     -----------------------------------------------------------------
      FSUR=FSUR+CS
      FINT=FINT+SC
      FGRO=FGRO+CG
      FSUM=FSUM+CS+SC+CG
      CS=CS+SC
      CT=CS+CG
      GS=GS-CG
      IF (GS.LT.0.) GS=0.
C     -----------------------------------------------------------------
C     ROUTING PROCEDURE
C     -----------------------------------------------------------------
      CC=1./2.7183**(1./RK)
      CA=1.-RK*(1.-CC)
      CB=RK*(1.-CC)-CC
      VT2=CT*AREA*10./36.
      FLOW(NN,KK)=CA*VT2+CB*VT1+CC*QT1
      VT1=VT2
      QT1=FLOW(NN,KK)
   50 CONTINUE
C     -----------------------------------------------------------------
C     END OF HOURLY LOOP
C     -----------------------------------------------------------------
  100 CONTINUE
C     -----------------------------------------------------------------
C     END OF DAY LOOP
C     -----------------------------------------------------------------
C     -----------------------------------------------------------------
C     START OF DIRECT LAG PROCEDURE
C     -----------------------------------------------------------------
      DO 600 I=1,NTOT
      LX=0
      DO 610 J=1,24
      K=J+LAG
      IF (K.GT.24) GO TO 620
      RFLO(I,K)=FLOW(I,J)
      GO TO 610
  620 LX=LX+1
      IF (LX.LT.2) M=I+1
      K=K-24
```

```
      RFLO(M,K)=FLOW(I,J)
  610 CONTINUE
  600 CONTINUE
      DO 625 JJ=1,NTOT
      DTOT(JJ)=0.
      DO 626 KK=1,24
  626 DTOT(JJ)=DTOT(JJ)+RFLO(JJ,KK)*3.6
      XTOT=XTOT+DTOT(JJ)
  625 CONTINUE
      DAVE=XTOT/FLOAT(NTOT)
      ZTOT=FLOAT(NTOT*24)
      HAVE=XTOT/ZTOT
C     ------------------------------------------------------------------
C     OUTPUT HOURLY FLOWS AND DAILY VOLUMES
C     ------------------------------------------------------------------
      DO 630 NN=1,NTOT
      WRITE (6,30) NN,(RFLO(NN,L),L=1,24),DTOT(NN)
   30 FORMAT (1X,I3,1X,2HAM,1X,12F8.2,/,5X,2HPM,1X,12F8.2,1X,F8.1,/)
  630 CONTINUE
      WRITE (6,40)    VSL,DSL,SSL,GS
   40 FORMAT (1X,1H(,20HFINAL STORAGE LEVELS,2X,5HVSL =,F6.0,2X,5HDSL =,
     1 F6.0,2X,5HSSL =,F6.0,2X,4HGS =,F6.0,1H),/)
      WRITE (6,31) XTOT
   31 FORMAT (1X,23HTOTAL FLOW FOR MONTH = ,F10.3,/)
      WRITE (6,32) DAVE,HAVE
   32 FORMAT (1X,21HDAILY AVERAGE FLOW = ,F10.3,//,1X,22HAVERAGE HOURLY
     1FLOW = ,F10.3,//)
      TAE=TPE-RES
      IF (LAG.EQ.0) GO TO 795
      M=NTOT+1
      WRITE (6,639) (RFLO(M,J),J=1,LAG)
  639 FORMAT (1X,15HTRANSLATED FLOW,//,8X,12F8.1,//)
C     --------------------------------------------------------------
C     OUTPUT DATA COMPONENT SUMMARY
C     --------------------------------------------------------------
  795 WRITE (6,640)
  640 FORMAT (1X,50HFLOW COMPONENT SUMMARY - ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,641) FPPT,TPE,TAE,FSUR,FINT,FGRO,FSUM
  641 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
     1 = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,15HSURFACE FLOW
     2= ,F8.2,//,1X,12HINTERFLOW = ,F8.2,//,1X,12HBASE FLOW = ,F8.2,
     3 //,1X,13HTOTAL FLOW = ,F8.2)
      IF (LAG.EQ.0) GO TO 796
      DO 650 J=1,LAG
      RFLO(1,J)=RFLO(M,J)
  650 CONTINUE
  796 ICI=ICI+1
      IF (ICI.NE.NMON) GO TO 666
      STOP
      END
      FINISH
```

A.6 Program BERG

```
        DATE 31/10/78   TIME 15/39/49                          LISTING FOR;= HRP

FILE:   HRPRMAXIMOP     SUBFILE BERG IN CARD MODE

      LIST
      PROGRAM(BERG)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER BERG
C     ##################################################################
C     THIS PROGRAM GENERATES HOURLY FLOW VALUES FROM HOURLY RAINFALL
C     DATA (MM) AND DAILY PAN EVAPORATION (MM)
C     THE BASIC STRUCTURE OF THE MODEL HAS BEEN DRAWN FROM
C     THE MODEL BY DAWDY,LICHTY AND BERGMANN (1972).
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY.
C     (P.J.T. ROBERTS 1975)
C     ##################################################################
      DIMENSION IRAIN(31,24),FLOW(31,24),RFLO(32,24),EVMO(12)
      DIMENSION EVAP(50),EDIS(24),KPPT(12),DTOT(31),LS(12),Z(12)
      DATA LS/31,28,31,30,31,30,31,31,30,31,30,31/
C     ******************************************************************
C     READ IN SIMULATION PERIOD(A8) AND CATCHMENT NAME(A8)
C     NUMBER OF MONTHS OF INPUT DATA AND CATCHMENT AREA  (SQ.KM.)
C     ******************************************************************
      READ (5,1) H1,H2,H3,H4,NMON,AREA
    1 FORMAT (4A8,I4,F6.2)
C     ******************************************************************
C     READ IN STORAGE VALUES IN MM AND PROGRAM CONTROL FLAG MVAP.
C     SMS     MOISTURE STORAGE IN SOIL SURFACE LAYER  (MM)
C     BMS     BASE SOIL MOISTURE STORAGE LEVEL  (MM)
C     BMSM    MAXIMUM SOIL MOISTURE STORAGE  (MM)
C     MVAP    = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM) OR
C             = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION (MM).
C     ******************************************************************
      READ (5,2) SMS,BMS,BMSM,MVAP
    2 FORMAT (3F6.0,I5)
C     ******************************************************************
C     READ IN MODEL PARAMETERS
C     SWF     SUCTION AT WETTED FRONT AT FIELD CAPACITY  (MM)
C     RGF     RATIO OF SUCTION AT WILTING POINT TO FIELD CAPACITY (MM)
C     XSAT    MINIMUM HYDRAULIC CONDUCTIVITY  (MM/HR)
C     DRN     DRAINAGE RATE FOR SOIL MOISTURE REDISTRIBUTION  (MM/HR)
C     RK      THE ROUTING CONSTANT
C     LAG     REQUIRED LAG TIME IN HOURS
C     Z       12 PAN TO FREE SURFACE EVAP. FACTORS (JAN-DEC)
C     ******************************************************************
      READ (5,3) SWF,RGF,XSAT,DRN,RK,LAG,(Z(J),J=1,12)
    3 FORMAT (5F6.2,I5,/,12F6.2)
C     ******************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAPORATION(MM) JAN-DEC
C     ONLY IF MVAP = 1
C     ******************************************************************
      IF (MVAP.EQ.2) GO TO 761
      READ (5,766) (EVMO(NX),NX=1,12)
  766 FORMAT (12F6.1)
C     ******************************************************************
C     READ IN LAG NUMBER OF HOURS OF TRANSLATED FLOW (CUMECS)
```

```
C     FROM DAY PRECEEDING SIMULATION, ONLY IF LAG > 0
C     ******************************************************************
  761 IF (LAG.EQ.0) GO TO 760
      READ (5,6) (RFLO(1,LL),LL=1,LAG)
    6 FORMAT (12F6.2)
C     ------------------------------------------------------------------
C     INITIALISE VARIABLES
C     VT1 AND QT1 ARE THE RATE OF GENERATION OF EXCESS RAIN(CUMECS)
C     AND FLOW(CUMECS) RESPECTIVELY FOR HOUR PRECEEDING SIMULATION
C     ------------------------------------------------------------------
  760 VT1=0.
      QT1=0.
      ICI=0
C     ----------------------------------------------------------------
C     MONTHLY RE-ENTRY POINT IN PROGRAM
C     ----------------------------------------------------------------
  666 DO 300 I=1,31
      DO 400 J=1,24
      IRAIN(I,J)=0
  400 CONTINUE
  300 CONTINUE
C     *****************************************************************
C     READ IN PRECIPITATION DATA IN TENTHS OF A MILLIMETER
C     PRECIPITATION CARDS WITH ZERO RAINFALL MAY BE OMITTED
C     THE FORMAT REQUIRES TWO CARDS PER DAY AND THE DATA FOR
C     EACH MONTH IS TERMINATED BY A CARD WITH THE VALUE 99 PUNCHED
C     IN THE FIRST TWO COLUMNS.
C     STATE                I2
C     IDENTIFICATION       7X  (NOT READ BY PROGRAM)
C     YEAR                 I3  (IE, 75 FOR 1975)
C     MONTH                I3
C     DAY                  I3
C     CARD CODE            I2  =1  HOURS  0 TO 12
C                              =2  HOURS 13 TO 24
C     RAIN               12I5
C     ****************************************************************
  350 READ (5,4) NS,MY,MO,I,L,(KPPT(N),N=1,12)
    4 FORMAT (I2,7X,3I3,I2,12I5)
      IF (MO.GT.0) MX=MO
      IF (MY.GT.0) MZ=MY
      IF (NS.EQ.99) GO TO 505
      IF (L.EQ.2) GO TO 44
      NBEG=1
      NEND=12
      GO TO 45
   44 NBEG=13
      NEND=24
   45 DO 450 K=NBEG,NEND
      KL=K
      IF (NEND.EQ.24) KL=K-12
      IRAIN(I,K)=KPPT(KL)
  450 CONTINUE
      GO TO 350
C     ******************************************************************
C     READ IN EVAPORATION DATA IN MILLIMETRES PER DAY IF MVAP = 2
C     THREE CARDS PER MONTH IN THE FORMAT
C     IDENTIFICATION            7X  (NOT READ BY PROGRAM)
C     YEAR                      I2  (IE, 75 FOR 1975)
C     MONTH                     I2
C     CARD NO.                  I1  =1,    DAYS  1-10
C                                   =2,    DAYS 11-20
```

```
C                                 =3,    DAYS 21=LAST DAY OF MONTH
C     EVAP                 11F6.2
C     ************************************************************************
  505 NTOT=LS(MX)
      IF (((MZ-4*(MZ/4)).EQ.0).AND.(MX.EQ.2)) NTOT=NTOT+1
      IF (MVAP.EQ.1) GO TO 780
      NEND=10
      NBEG=1
      DO 500 NE=1,3
      READ (5,5) (EVAP(N),N=NBEG,NEND)
    5 FORMAT (12X,11F5.2)
      NEND=NEND+10
      NBEG=NEND-9
      IF (NE.EQ.2) NEND=NTOT
  500 CONTINUE
      GO TO 790
  780 DO 781 IZ=1,NTOT
      EVAP(IZ)=EVMO(MX)/FLOAT(NTOT)
  781 CONTINUE
C     ----------------------------------------------------------------
C     SET HOURLY DISTRIBUTION FACTOR(EDIS) FOR EACH HOUR
C     ----------------------------------------------------------------
  790 DO 200 I=1,24
  200 EDIS(I)=0.00
      EDIS(7)=0.019
      EDIS(8)=0.041
      EDIS(9)=0.067
      EDIS(10)=0.088
      EDIS(11)=0.102
      EDIS(12)=0.110
      EDIS(13)=0.110
      EDIS(14)=0.110
      EDIS(15)=0.105
      EDIS(16)=0.095
      EDIS(17)=0.081
      EDIS(18)=0.055
      EDIS(19)=0.017
      FPPT=0.
      FSUM=0.
      FSPL=0.
      FSUR=0.
      TPE=0.
      XTOT=0.
C     -------------------------------------------------------------------
C     LIST RUN INFORMATION,MODEL STORAGE AND PARAMETER VALUES
C     -------------------------------------------------------------------
      WRITE (6,8) H3,H4
    8 FORMAT (1H1,30HHOURLY DISCHARGE (CUMECS) FOR ,2A8,/,1X,
     1 37HFLOW VOLUMES IN THOUSAND CUBIC METRES,/)
      WRITE (6,9) H1,H2
    9 FORMAT (1X,19HSIMULATION PERIOD  ,A8,4H TO ,A8,/)
      WRITE (6,22) MX,MZ
   22 FORMAT (1X,14HDATA FOR MONTH,I5,3X,4HYEAR,I5,/)
      WRITE (6,10)
   10 FORMAT (1X,14HSTORAGE VALUES,/,5X,3HSMS,5X,3HBMS,4X,4HBMSM)
      WRITE (6,11) SMS,BMS,BMSM
   11 FORMAT (3(2X,F6.0),//)
      WRITE (6,12)
   12 FORMAT (1X,16HMODEL PARAMETERS,/,4X,3HSWF,3X,3HRGF,2X,4HXSAT,5X,
     1 1HZ,3X,3HDRN,4X,2HRK,3X,3HLAG,2X,4HMVAP)
      WRITE (6,13) SWF,RGF,XSAT,Z(MX),DRN,RK,LAG,MVAP
```

```
   13 FORMAT (1X,6F6.2,2I6,//)
      WRITE (6,14)
   14 FORMAT (1X,3HDAY,28X,26HHOURLY DISCHARGE IN CUMECS,50X,5HTOTAL,/)
C     ------------------------------------------------------------------
C     START OF DAILY LOOP
C     ------------------------------------------------------------------
      DO 100 NN=1,NTOT
C     ------------------------------------------------------------------
C     START OF HOURLY LOOP
C     ------------------------------------------------------------------
      DO 50 KK=1,24
C     ------------------------------------------------------------------
C     CONVERT DAILY PAN EVAP TO HOURLY FREE SURFACE EVAP
C     AND DISTRIBUTE OVER 24 HOURS
C     ------------------------------------------------------------------
      AVAP=EVAP(NN)*Z(MX)*EDIS(KK)
      TPE=TPE+AVAP
C     ------------------------------------------------------------------
C     CALCULATE POINT INFILTRATION
C     ------------------------------------------------------------------
      RAIN=FLOAT(IRAIN(NN,KK))/10.
      FPPT=FPPT+RAIN
      PS=SWF*(RGF-(RGF-1.)*BMS/BMSM)
      IF (SMS.EQ.0.)GO TO 15
      FR=XSAT*(1.+PS/SMS)
   15 IF (SMS.EQ.0.) FR=XSAT*(1.+PS)
C     ------------------------------------------------------------------
C     CALCULATE EXCESS RAIN
C     ------------------------------------------------------------------
      IF (RAIN.LE.FR) QR=(RAIN**2.)/(2.*FR)
      IF (RAIN.GT.FR) QR=RAIN-FR/2.
C     ------------------------------------------------------------------
C     CONTRIBUTION TO SURFACE SOIL MOISTURE
C     ------------------------------------------------------------------
      FRX=RAIN-QR
      SMS=SMS+FRX
C     ------------------------------------------------------------------
C     EVAP. DEMANDS FIRST MET FROM SMS IF POSSIBLE
C     ------------------------------------------------------------------
      IF (AVAP.GT.SMS) GO TO 16
      SMS=SMS-AVAP
      AVAP=0.
   16 IF (AVAP.LE.SMS) GO TO 17
      AVAP=AVAP-SMS
      SMS=0.
   17 IF (SMS.LE.DRN) GO TO 18
      XSMS=SMS-DRN
      XDRN=DRN
   18 IF (SMS.GT.DRN) GO TO 19
      XDRN=SMS
      XSMS=0.
   19 SMS=XSMS
C     ------------------------------------------------------------------
C     DRAINAGE TO BMS AND EVAP LOSS IF NOT SATISFIED BY SMS
C     ------------------------------------------------------------------
      BMS=BMS+XDRN-AVAP
      IF (BMS.LT.0.) BMS=0.
C     ------------------------------------------------------------------
C     CALCULATE SPILL FROM SOIL MOISTURE
C     ------------------------------------------------------------------
      SPL=BMS-BMSM
```

```
      IF (SPL.GE.0.) BMS=BMSM
      IF (SPL.LT.0.) SPL=0.
C     ------------------------------------------------------
C     CALCULATE TOTAL CONTRIBUTION TO CHANNEL STORAGE
C     ------------------------------------------------------
      CT=QR+SPL
      FSUR=FSUR+QR
      FSPL=FSPL+SPL
      FSUM=FSUM+CT
C     ------------------------------------------------------
C     ROUTING PROCEDURE
C     ------------------------------------------------------
      CC=1./2.7183**(1./RK)
      CA=1.-RK*(1.-CC)
      CB=RK*(1.-CC)-CC
      VT2=CT*AREA*10./36.
      FLOW(NN,KK)=CA*VT2+CB*VT1+CC*QT1
      VT1=VT2
      QT1=FLOW(NN,KK)
   50 CONTINUE
C     ------------------------------------------------------
C     END OF HOUR LOOP
C     ------------------------------------------------------
  100 CONTINUE
C     ------------------------------------------------------
C     END OF DAY LOOP
C     ------------------------------------------------------
C     ------------------------------------------------------
C     START OF DIRECT LAG PROCEDURE
C     ------------------------------------------------------
      DO 600 I=1,NTOT
      LX=0
      DO 610 J=1,24
      K=J+LAG
      IF (K.GT.24) GO TO 620
      RFLO(I,K)=FLOW(I,J)
      GO TO 610
  620 LX=LX+1
      IF (LX.LT.2) M=I+1
      K=K-24
      RFLO(M,K)=FLOW(I,J)
  610 CONTINUE
  600 CONTINUE
      DO 625 JJ=1,NTOT
      DTOT(JJ)=0.
      DO 626 KK=1,24
  626 DTOT(JJ)=DTOT(JJ)+RFLO(JJ,KK)*3.6
      XTOT=XTOT+DTOT(JJ)
  625 CONTINUE
      DAVE=XTOT/FLOAT(NTOT)
      ZTOT=FLOAT(NTOT*24)
      HAVE=XTOT/ZTOT
C     ------------------------------------------------------
C     OUTPUT HOURLY FLOWS AND DAILY VOLUMES
C     ------------------------------------------------------
      DO 630 NN=1,NTOT
      WRITE (6,30) NN,(RFLO(NN,L),L=1,24),DTOT(NN)
   30 FORMAT (1X,I3,1X,2HAM,1X,12F8.2,/,5X,2HPM,1X,12F8.2,1X,F8.1,/)
  630 CONTINUE
      WRITE (6,40) SMS,BMS
   40 FORMAT (1X,1H(,20HFINAL STORAGE LEVELS,2X,5HSMS =,F6.0,2X,
```

```
     1 5HBMS =,F6.0,1H),/)
      WRITE (6,31) XTOT
   31 FORMAT (1X,23HTOTAL FLOW FOR MONTH = ,F10.3,/)
      WRITE (6,32) DAVE,HAVE
   32 FORMAT (1X,21HDAILY AVERAGE FLOW = ,F10.3,//,1X,22HAVERAGE HOURLY
     1FLOW = ,F10.3)
      IF (LAG.EQ.0) GO TO 795
      M=NTOT+1
      WRITE (6,639) (RFLO(M,J),J=1,LAG)
  639 FORMAT (1X,15HTRANSLATED FLOW,//,8X,12F8.1,//)
C     ------------------------------------------------------------------
C     OUTPUT DATA COMPONENT SUMMARY
C     ------------------------------------------------------------------
  795 WRITE (6,640)
  640 FORMAT (1X,50HDATA COMPONENT SUMMARY = ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,641) FPPT,TPE,FSUR,FSPL,FSUM
  641 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
     1 = ,F8.2,//,1X,15HSURFACE FLOW = ,F8.2,//,1X,16HSOIL SPILLAGE = ,
     2 F8.2,//,1X,13HTOTAL FLOW = ,F8.2)
      IF (LAG.EQ.0) GO TO 796
      DO 650 J=1,LAG
      RFLO(1,J)=RFLO(M,J)
  650 CONTINUE
  796 ICI=ICI+1
      IF (ICI.NE.NMON) GO TO 666
      STOP
      END
      FINISH
```

A.7 Program DALH

```
        DATE 31/10/78   TIME 15/33/57                         LISTING FOR:= HRPR

FILE:   HRPRMAXIMOP     SUBFILE DALH IN CARD MODE

      LIST
      PROGRAM(DALH)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER DALH
C     #################################################################
C     THIS PROGRAM GENERATES HOURLY FLOW VALUES FROM HOURLY RAINFALL
C     DATA (MM) AND DAILY PAN EVAPORATION (MM)
C     DALH IS AN HOURLY VERSION OF THE DAILY MODEL CALLED DALT.
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY.
C     (P.J.T. ROBERTS 1975)
C     #################################################################
      DIMENSION IRAIN(31,24),FLOW(31,24),RFLO(32,24),DTOT(31),Z(12)
      DIMENSION EVAP(50),EDIS(24),KPPT(12),OBFL(32,24),HL(31,24),LS(12)
      DIMENSION EVMO(12)
      DATA LS/31,28,31,30,31,30,31,31,30,31,30,31/
C     *****************************************************************
C     READ IN SIMULATION PERIOD (A8) AND CATCHMENT NAME (A8)
C     NUMBER OF MONTHS OF INPUT DATA AND CATCHMENT AREA (SQ.KM.)
C     *****************************************************************
      READ (5,1) H1,H2,H3,H4,NMON,AREA
    1 FORMAT (4A8,I4,F6.2)
C     *****************************************************************
C     READ IN STORAGE VALUES IN MM AMD PROGRAM CONTROL FLAGS.
C     SSL             SOIL STORAGE LEVEL
C     SSM             MAXIMUM STORAGE CAPACITY
C     SSB             STORAGE LEVEL AT WHICH BASE FLOW BEGINS
C     LINE            = 1 IF LINEAR STORAGE FUNCTION USED
C                     = 2 IF NON-LINEAR STORAGE FUNCTION REQUIRED AND
C     ILIM            = 1 SETS OPERATIONAL RANGE OF NON=LINEAR DEPTH
C                         FUNCTION FROM STORAGE LEVEL ZERO TO BASE
C                         FLOW LEVEL SSB,
C                     = 2 SETS OPERATIONAL RANGE OF NON-LINEAR DEPTH
C                         FUNCTION FROM STORAGE LEVEL ZERO TO STORAGE
C                         CAPACITY SSM AND
C     MVAP            = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM)
C                     = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION(MM)
C     LEVEL           = 1 TO OUTPUT HISTORY OF STORAGE LEVEL FOR MONTH
C                     = 2 TO SUPRESS OUTPUT OF STORAGE LEVELS.
C     NOTE. THE FLAG SETTINGS FOR THE DALH RANGE OF MODELS
C     ARE AS FOLLOWS.
C     DALH1  LINE=1  ILIM=2  SSB=SSM
C     DALH2  LINE=1  ILIM=2  SSB<SSM
C     DALH3  LINE=2  ILIM=2  SSB<SSM
C     DALH4  LINE=2  ILIM=1  SSB<SSM
C     *****************************************************************
      READ (5,2) SSL,SSM,SSB,LINE,ILIM,MVAP,LEVEL
    2 FORMAT (3F6.2,4I5)
C     *****************************************************************
C     READ IN MODEL PARAMETERS
C     RK    THE ROUTING CONSTANT
C     LAG   REQUIRED LAG TIME IN HOURS
C     POWER  POWER OF BASE FLOW FUNCTION
```

```
C     BCUR   POWER OF NON-LINEAR STORAGE DEPTH FUNCTION
C     AMAX   MAXIMUM VALUE OF STORAGE DEPTH FUNCTION
C     PERC   MAXIMUM FRACTION OF SOIL MOISTURE TO DEEP PERCOLATION
C     Z      12 PAN TO FREE SURFACE EVAP. FACTORS (JAN-DEC)
C     IF LINE=1 SET BCUR AND AMAX EQUAL TO 1
C     IF BASE FLOW FUNCTION NOT REQUIRED SET SSB=SSM
C     ******************************************************************
      READ (5,3) RK,POWER,BCUR,AMAX,PERC,LAG,(Z(J),J=1,12)
    3 FORMAT (5F6.2,I5,/,12F6.2)
C     ******************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAP(MM) JAN-DEC.
C     ONLY IF MVAP = 1.
C     ******************************************************************
      IF (MVAP.EQ.2) GO TO 761
      READ (5,766) (EVMO(NX),NX=1,12)
  766 FORMAT (12F6.1)
C     ******************************************************************
C     READ IN LAG NUMBER OF HOURS OF TRANSLATED FLOW (CUMECS)
C     FROM DAY PRECEEDING SIMULATION, ONLY IF LAG>0
C     ******************************************************************
  761 IF (LAG.EQ.0) GO TO 760
      READ (5,6) (RFLO(1,LL),LL=1,LAG)
    6 FORMAT (12F6.2)
C     ------------------------------------------------------------------
C     INITIALISE VARIABLES
C     VT1 AND QT1 ARE THE RATE OF GENERATION OF EXCESS RAIN(CUMECS)
C     AND THE FLOW(CUMECS) RESPECTIVELY FOR HOUR PRECEEDING SIMULATION.
C     ------------------------------------------------------------------
  760 VT1=0.
      QT1=0.
      ICI=0
      PSL=SSL
C     ------------------------------------------------------------------
C     MONTHLY RE-ENTRY POINT IN PROGRAM
C     ------------------------------------------------------------------
  301 DO 300 I=1,31
      DO 400 J=1,24
      IRAIN(I,J)=0
  400 CONTINUE
  300 CONTINUE
C     ******************************************************************
C     READ IN PRECIPITATION DATA IN TENTHS OF A MILLIMETER
C     PRECIPITATION CARDS WITH ZERO RAINFALL MAY BE OMITTED AND
C     DATA FOR EACH MONTH IS TERMINATED BY A CARD WITH
C     THE VALUE 99 PUNCHED IN THE FIRST TWO COLUMNS.
C     TWO CARDS PER DAY WITH FOLLOWING FORMAT FOR EACH CARD
C     STATE               I2
C     IDENTIFICATION      7X  (NOT READ BY PROGRAM)
C     YEAR                I3  (IE. 75 FOR 1975)
C     MONTH               I3
C     DAY                 I3
C     CARD CODE           I2    =1 HOURS  0 TO 12
C                               =2 HOURS 13 TO 24
C     RAIN               12I5
C     ******************************************************************
  350 READ (5,4) NS,MY,MO,I,L,(KPPT(N),N=1,12)
    4 FORMAT (I2,7X,3I3,I2,12I5)
      IF (MO.GT.0) MX=MO
      IF (MY.GT.0) MZ=MY
      IF (NS.EQ.99) GO TO 505
      IF (L.EQ.2) GO TO 44
```

```
      NBEG=1
      NEND=12
      GO TO 45
   44 NBEG=13
      NEND=24
   45 DO 450 K=NBEG,NEND
      KL=K
      IF (NEND.EQ.24) KL=K-12
      IRAIN(I,K)=KPPT(KL)
  450 CONTINUE
      GO TO 350
C     ****************************************************************
C     READ IN EVAPORATION DATA IN MILLIMETRES PER DAY IF MVAP = 2.
C     THREE CARDS PER MONTH IN THE FORMAT
C     IDENTIFICATION        7X  (NOT READ BY PROGRAM)
C     YEAR                  I2  (IE. 75 FOR 1975)
C     MONTH                 I2
C     CARD NO.              I1  =1,    DAYS  1-10
C                               =2,    DAYS 11-20
C                               =3,    DAYS 21-LAST DAY OF MONTH
C     EVAP              11F6.2
C     ****************************************************************
  505 NTOT=LS(MX)
      IF (((MZ-4*(MZ/4)).EQ.0).AND.(MX.EQ.2)) NTOT=NTOT+1
      IF (MVAP.EQ.1) GO TO 780
      NEND=10
      NBEG=1
      DO 500 NE=1,3
      READ (5,5) (EVAP(N),N=NBEG,NEND)
    5 FORMAT (12X,11F5.2)
      NEND=NEND+10
      NBEG=NEND-9
      IF (NE.EQ.2) NEND=NTOT
  500 CONTINUE
      GO TO 790
  780 DO 781 IZ=1,NTOT
      EVAP(IZ)=EVMO(MX)/FLOAT(NTOT)
  781 CONTINUE
C     ----------------------------------------------------------------
C     SET HOURLY EVAPORATION DISTRIBUTION FACTOR(EDIS) FOR EACH HOUR
C     ----------------------------------------------------------------
  790 DO 200 I=1,24
  200 EDIS(I)=0.00
      EDIS(7)=0.019
      EDIS(8)=0.041
      EDIS(9)=0.067
      EDIS(10)=0.088
      EDIS(11)=0.102
      EDIS(12)=0.110
      EDIS(13)=0.110
      EDIS(14)=0.110
      EDIS(15)=0.105
      EDIS(16)=0.095
      EDIS(17)=0.081
      EDIS(18)=0.055
      EDIS(19)=0.017
      XTOT=0.
      SROS=0.
      SGWF=0.
      TPER=0.
      FSUM=0.
```

```
      FPPT=0.
      TPE=0.
      TAE=0
      BRA=SSB/SSM
C     ------------------------------------------------------------------
C     LIST RUN INFORMATION,MODEL STORAGE AND PARAMETER VALUES
C     ------------------------------------------------------------------
      WRITE (6,8) H3,H4
    8 FORMAT (1H1,30HHOURLY DISCHARGE (CUMECS) FOR ,2A8,/,1X,
     1 37HFLOW VOLUMES IN THOUSAND CUBIC METRES,/)
      WRITE (6,9) H1,H2
    9 FORMAT (1X,19HSIMULATION PERIOD  ,A8,4H TO ,A8,/)
      WRITE (6,22) MX,MZ
   22 FORMAT (1X,14HDATA FOR MONTH,I5,3X,4HYEAR,I5,/)
      WRITE (6,10)
   10 FORMAT (1X,14HSTORAGE VALUES,/,5X,3HSSL,5X,3HSSM,5X,3HSSB)
      WRITE (6,11) SSL,SSM,SSB
   11 FORMAT (3(2X,F6.2),//)
      WRITE (6,12)
   12 FORMAT (1X,16HMODEL PARAMETERS,/,5X,1HZ,4X,2HRK,
     1 1X,5HPOWER,2X,4HBCUR,2X,4HAMAX,2X,4HPERC,3X,3HLAG,2X,4HLINE,
     2 2X,4HILIM,2X,4HMVAP,1X,5HLEVEL)
      WRITE(6,13)Z(MX),RK,POWER,BCUR,AMAX,PERC,LAG,LINE,ILIM,MVAP,LEVEL
   13 FORMAT (6F6.2,5I6,//)
      WRITE (6,14)
   14 FORMAT (1X,3HDAY,28X,26HHOURLY DISCHARGE IN CUMECS,50X,5HTOTAL,/)
C     ------------------------------------------------------------------
C     START OF DAILY LOOP
C     ------------------------------------------------------------------
      DO 100 NN=1,NTOT
C     ------------------------------------------------------------------
C     START OF HOURLY LOOP
C     ------------------------------------------------------------------
      DO 50 KK=1,24
C     ------------------------------------------------------------------
C     CONVERT DAILY PAN EVAP TO HOURLY FREE SURFACE EVAP
C     AND DISTRIBUTE OVER 24 HOURS
C     ------------------------------------------------------------------
      AVAP=EVAP(NN)*Z(MX)*EDIS(KK)
      TPE=TPE+AVAP
C     ------------------------------------------------------------------
C     OPERATION OF STORAGE
C     ------------------------------------------------------------------
      RAIN=FLOAT(IRAIN(NN,KK))/10.
      FPPT=FPPT+RAIN
      RAT=SSL/SSM
      PRE=(RAT**0.50)+((RAT**0.50)-RAT)
      AVAP=AVAP*PRE
      PLE=SSL+RAIN
      IF (PLE.LE.AVAP) GO TO 700
      TAE=TAE+AVAP
      PLE=PLE-AVAP
      GO TO 710
  700 TAE=TAE+PLE
      PLE=0.
  710 OVF=PLE-SSM
      IF (OVF.GT.0.) GO TO 720
      SSL=PLE
      CT=0.
      OVF=0.
      GO TO 730
```

```
  720 CT=OVF
      SROS=SROS+OVF
      SSL=SSM
C     -------------------------------------------------------------
C     THE NON-LINEAR DEPTH FUNCTION
C     -------------------------------------------------------------
  730 IF (ILIM.EQ.1) RANG=SSB
      IF (ILIM.EQ.2) RANG=SSM
      RAT=SSL/RANG
      IF (RAT.GT.1.0) RAT=1.0
      CR=RAIN-AVAP
      FAT=AMAX-((AMAX-1.0)*(RAT**BCUR))
      IF (LINE.EQ.1) FAT=1.0
      PSL=PSL+(CR*FAT)
      IF (PSL.GT.SSM) PSL=SSM
      IF (PSL.LT.SSL) PSL=SSL
      RAT=PSL/SSM
      HL(NN,KK)=PSL
      IF (RAT.GT.BRA) GO TO 740
      BF=0.
      GO TO 750
C     --------------------------------------------------------------
C     THE DEEP PERCOLATION FUNCTION
C     --------------------------------------------------------------
  740 HEAD=PSL-SSB
      POTH=SSM-SSB
      PLOS=HEAD*((HEAD/POTH)*PERC)
      SSL=SSL-PLOS
      PSL=PSL-PLOS*FAT
      RAT=PSL/SSM
      TPER=TPER+PLOS
C     --------------------------------------------------------------
C     THE BASE FLOW FUNCTION
C     --------------------------------------------------------------
      XBRA=RAT-BRA
      BF=(PSL-SSB)*(XBRA**POWER)
      IF (BF.GT.SSL) BF=SSL
      SGWF=SGWF+BF
      SSL=SSL-BF
      IF (SSL.LT.0.) SSL=0.
      PSL=PSL-BF*FAT
      CT=CT+BF
  750 FSUM=FSUM+CT
C     -----------------------------------------------------------------
C     ROUTING PROCEDURE
C     -----------------------------------------------------------------
      CC=1./2.7183**(1./RK)
      CA=1.-RK*(1.-CC)
      CB=RK*(1.-CC)-CC
      VT2=CT*AREA*10./36.
      FLOW(NN,KK)=CA*VT2+CB*VT1+CC*QT1
      VT1=VT2
      QT1=FLOW(NN,KK)
   50 CONTINUE
C     -----------------------------------------------------------------
C     END OF HOURLY LOOP
C     -----------------------------------------------------------------
  100 CONTINUE
C     -----------------------------------------------------------------
C     END OF DAY LOOP
C     -----------------------------------------------------------------
```

```
C     ----------------------------------------------------------------
C     START OF DIRECT LAG PROCEDURE
C     ----------------------------------------------------------------
      DO 600 I=1,NTOT
      LX=0
      DO 610 J=1,24
      K=J+LAG
      IF (K.GT.24) GO TO 620
      RFLO(I,K)=FLOW(I,J)
      GO TO 610
  620 LX=LX+1
      IF (LX.LT.2) M=I+1
      K=K-24
      RFLO(M,K)=FLOW(I,J)
  610 CONTINUE
  600 CONTINUE
      DO 625 JJ=1,NTOT
      DTOT(JJ)=0.
      DO 626 KK=1,24
  626 DTOT(JJ)=DTOT(JJ)+RFLO(JJ,KK)*3.6
      XTOT=XTOT+DTOT(JJ)
  625 CONTINUE
      DAVE=XTOT/FLOAT(NTOT)
      ZTOT=FLOAT(NTOT*24)
      HAVE=XTOT/ZTOT
C     -------------------------------------------------------------
C     OUTPUT HOURLY FLOWS AND DAILY VOLUMES
C     -------------------------------------------------------------
      DO 630 NN=1,NTOT
      WRITE (6,30) NN,(RFLO(NN,L),L=1,24),DTOT(NN)
   30 FORMAT (1X,I3,1X,2HAM,1X,12F8.3,/,5X,2HPM,1X,12F8.3,1X,F8.1,/)
  630 CONTINUE
      WRITE (6,40)    SSL
   40 FORMAT (1X,1H(,20HFINAL STORAGE LEVELS,2X,5HSSL =,F6.2,/)
      WRITE (6,31) XTOT
   31 FORMAT (1X,23HTOTAL FLOW FOR MONTH = ,F10.3,/)
      WRITE (6,32) DAVE,HAVE
   32 FORMAT (1X,21HDAILY AVERAGE FLOW = ,F10.3,//,1X,22HAVERAGE HOURLY
     1FLOW = ,F10.3,//)
      IF (LAG.EQ.0) GO TO 795
      M=NTOT+1
      WRITE (6,639) (RFLO(M,J),J=1,LAG)
  639 FORMAT (1X,15HTRANSLATED FLOW,//,8X,12F8.1,//)
C     -------------------------------------------------------------
C     OUTPUT DATA COMPONENT SUMMARY
C     -------------------------------------------------------------
  795 WRITE (6,640)
  640 FORMAT (1X,50HFLOW COMPONENT SUMMARY = ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,641) FPPT,TPE,TAE,SROS,SGWF,FSUM,TPER
  641 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
     1 = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,
     2 15HSURFACE FLOW = ,F8.2,//,1X,12HBASE FLOW = ,F8.2,//,1X,
     3 13HTOTAL FLOW = ,F8.2,//,1X,19HDEEP PERCOLATION = ,F8.2)
      IF (LEVEL.EQ.2) GO TO 797
C     -------------------------------------------------------------
C     OUTPUT HISTORY OF STORAGE LEVEL FOR MONTH
C     PSEUDO=LEVEL GIVEN IF LINE=2
C     -------------------------------------------------------------
      WRITE(6,800)
  800 FORMAT(1H1,1X,24HHISTORY OF STORAGE LEVEL,//)
```

```
    DO 801 JJJ=1,NTOT
    WRITE(6,802)JJJ,(HL(JJJ,LL),LL=1,24)
802 FORMAT(1X,I3,1X,2HAM,1X,12F8.2,/,5X,2HPM,1X,12F8.2,/)
801 CONTINUE
797 IF (LAG.EQ.0) GO TO 796
    DO 650 J=1,LAG
    RFLO(1,J)=RFLO(M,J)
650 CONTINUE
796 ICI=ICI+1
    IF (ICI.NE.NMON) GO TO 301
    STOP
    END
    FINISH
```

A.8 Program SMDV

```
      DATE 31/10/78   TIME 15/34/38                       LISTING FOR:= HRPR

FILE:   HRPRMAXIMOP     SUBFILE SMDV IN CARD MODE

      LIST
      PROGRAM(SMDV)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER SMDV
C     ################################################################
C     THIS PROGRAM GENERATES DAILY RUNOFF IN THOUSANDS OF CUBIC METERS
C     FROM DAILY RAINFALL (MM) AND DAILY PAN EVAPORATION (MM)..
C     THE BASIC STRUCTURE OF THE MODEL HAS BEEN DRAWN FROM THE STANFORD
C     WATERSHED MODEL 4 AND THE SAME PARAMETER IDENTIFIERS HAVE BEEN
C     RETAINED IN THIS PROGRAM WHERE FEASIBLE.
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY,
C     (P.J.T. ROBERTS 1975)
C     ################################################################
      REAL LZS,LZSN,INTF,INFIL,LZI,LOS,LNRAT,IMPV,K3,K24L,K24EL,KV,
     1 LKK4,LIRC4,IRC,KK24
      DIMENSION RAIN(31),EVAP(31),FLOW(31),RFLO(31),TRANS(20),LAST(12)
      DIMENSION PEADJ(12),TOBF(1000),TSIM(1000),OBFL(1000),SIMF(1000)
      DIMENSION EVMO(12)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C     ****************************************************************
C     READ IN CATCHMENT NAME OR RUN IDENTIFICATION - 32 COLUMNS
C     ****************************************************************
      READ (5,1) H1,H2,H3,H4
    1 FORMAT (4A8)
C     ****************************************************************
C     READ IN CATCHMENT AREA (SQ.KM) AND THE NUMBER OF MONTHS
C     OF INPUT DATA USED FOR SIMULATION AND
C     ISTAT = 1 TO INITIATE STATISTICAL PACKAGE AND
C           = 2 TO SUPPRESS STATISTICAL PACKAGE AND
C     IVAL  = 1 FOR USE OF ACTUAL VALUES IN STAT. PACK.
C           = 2 FOR USE OF LOG. VALUES IN STAT. PACK. AND
C     IOUT  = 1 FORMATS MODEL OUTPUT FOR SHORT PERIOD CALIBRATION
C             (ONE MONTH OUTPUT PER PAGE OF PRINTOUT)
C           = 2 FORMATS OUTPUT FOR LONG RECORD GENERATION
C             (APPROX. 15 MONTHS OUTPUT PER PAGE OF PRINTOUT) AND
C     MVAP  = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM)
C           = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION (MM)
C     IF ISTAT=2 SET IVAL=0
C     ****************************************************************
      READ (5,2) AREA,NMON,ISTAT,IVAL,IOUT,MVAP
    2 FORMAT (F8.2,5I5)
C     ****************************************************************
C     READ IN INITIAL LEVELS AND CAPACITIES FOR MODEL STORAGES
C     ALL VALUES IN MILLIMETERS
C     SCEP    INITIAL LEVEL OF INTERCEPTION STORAGE
C     EPXM    MAX. CAPACITY OF INTERCEPTION STORAGE
C     RES     INITIAL LEVEL OF DEPRESSION STORAGE
C     RESM    MAX. CAPACITY OF DEPRESSION STORAGE
C     UZS     INITIAL LEVEL OF UPPER ZONE STORAGE
C     UZSN    MEDIAN VALUE OF UPPER ZONE STORAGE
C     LZS     INITIAL LEVEL OF LOWER ZONE STORAGE
C     LZSN    MEDIAN VALUE OF LOWER ZONE STORAGE
```

```
C     SRGX    INITIAL LEVEL OF INTERFLOW STORAGE
C     SGW     INITIAL LEVEL OF GROUND WATER STORAGE
C     GWS     ANTECEDENT GROUND WATER LEVEL
C     *******************************************************************
      READ (5,3) SCEP,EPXM,RES,RESM,UZS,UZSN,LZS,LZSN,SRGX,SGW,GWS
    3 FORMAT (10F8.2,/,1F8.2)
C     *******************************************************************
C     READ IN MODEL PARAMETER VALUES
C     POWER   F5.2   EXPONENT OF INFILTRATION CURVE
C     CB      F5.2   INFILTRATION PARAMETER
C     CC      F5.2   SURFACE/INTERFLOW RATIO PARAMETER
C     IMPV    F5.2   IMPERVIOUS AREA FRACTION
C     K24L    F5.2   INACTIVE GROUND WATER CONTROL
C     K24EL   F5.2   GROUND WATER EVAP CONTROL
C     K3      F5.2   LOWER ZONE EVAP CONTROL
C     IRC     F5.2   INTERFLOW DECAY CONSTANT (OVER 24 HOURS)
C     KK24    F5.2   BASE FLOW DECAY CONSTANT (OVER 24 HOURS)
C     KV      F5.2   VARIABLE BASE FLOW DECAY PARAMETER
C     LAG       I5   REQUIRED LAG TIME IN DAYS
C     *******************************************************************
      READ (5,4) POWER,CB,CC,IMPV,K24L,K24EL,K3,IRC,KK24,KV,LAG
    4 FORMAT (F5.2,F5.3,8F5.2,I5)
C     *********************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAPORATION (MM)
C     JAN - DEC ONLY IF MVAP = 1
C     ******************************************************************
      IF(MVAP.EQ.2) GO TO 761
      READ(5,766)(EVMO(NX),NX=1,12)
  766 FORMAT(12F6.1)
  761 IF (LAG.EQ.0) GO TO 9
C     *******************************************************************
C     READ IN LAG NUMBER OF DAYS OF TRANSLATED FLOW (1000 CUBIC METERS)
C     FROM PREVIOUS MONTH----ONLY IF LAG IS REQUIRED
C     *******************************************************************
      READ (5,5) (TRANS(I),I=1,LAG)
    5 FORMAT (8F10.3)
C     *******************************************************************
C     READ IN PAN TO FREE WATER SURFACE EVAPORATION CONSTANTS
C     12 VALUES  JAN. TO DEC.
C     *******************************************************************
    9 READ (5,6) (PEADJ(K),K=1,12)
    6 FORMAT (12F5.3)
C     -------------------------------------------------------------------
C     INITIALISE PROGRAM VARIABLES AND LIST MODEL STORAGE LEVELS,
C     PARAMETER VALUES AND PROGRAM CONTROL FLAGS
C     -------------------------------------------------------------------
      AT=IMPV
      PA=1.0-AT
      LIRC4=1.0-IRC
      LKK4=1.0-KK24
      ICON=0
      RTOT=0.
      AMENX=0.
      AMENY=0.
      CCOF=0.
      TTEST=0.
      RECO=0.
      NOD=0
      BASE=0.
      SDEVY=0.
      WRITE (6,7) SCEP,EPXM,RES,RESM,UZS,UZSN,LZS,LZSN,SRGX,SGW,GWS
```

```
    7 FORMAT (1H1,1X,21HPARAMETER VALUES USED,//,5X,4HSCEP,5X,4HEPXM,
     1 6X,3HRES,5X,4HRESM,6X,3HUZS,5X,4HUZSN,6X,3HLZS,5X,4HLZSN,5X,
     2 4HSRGX,6X,3HSGW,6X,3HGWS,/,11(1X,F8.2),//)
      WRITE (6,8) POWER,CB,CC,IMPV,K24L,K24EL,K3,IRC,KK24,KV,LAG
    8 FORMAT (4X,5HPOWER,7X,2HCB,7X,2HCC,5X,4HIMPV,5X,4HK24L,4X,
     1 5HK24EL,7X,2HK3,6X,3HIRC,5X,4HKK24,7X,2HKV,6X,3HLAG,/,10(1X,F8.3)
     2 ,1X,I8,//)
      WRITE (6,623) ISTAT,IVAL,IOUT,MVAP
  623 FORMAT (1H0,1X,28HPROGRAM CONTROL FLAGS SET AS,//,
     1 4X,5HISTAT,5X,4HIVAL,5X,4HIOUT,5X,4HMVAP,/,4I9)
      DO 46 JK=1,31
      OBFL(JK)=0.0
   46 CONTINUE
      K3=K3*25.4
      IF (IOUT.EQ.1) GO TO 830
      WRITE (6,831) H1,H2,H3,H4
  831 FORMAT (1H1,1X,4A8,/)
      WRITE (6,310)
C     ------------------------------------------------------------------
C     START OF THE MONTHLY LOOP
C     ------------------------------------------------------------------
  830 DO 100 M=1,NMON
      SPR=0.
      SPE=0.
      SET=0.
      SROS=0.
      SINTF=0.
      SGWF=0.
      FSUM=0.
      TFLO=0.
      ZOB=0.
      SRECH=0.
C     ******************************************************************
C     READ IN ONE MONTH RAINFALL(MM),EVAPORATION(MM) AND RUNOFF DATA
C     OBSERVED RUNOFF DATA IN THOUSANDS OF CUBIC METERS
C     DAILY EVAPORATION DATA REQUIRED ONLY IF MVAP=2
C     RUNOFF DATA REQUIRED ONLY IF ISTAT=1
C     THREE CARDS PER MONTH FOR EACH TYPE OF INPUT DATA
C     FOLLOWING FORMAT USED FOR ALL THREE TYPES OF INPUT DATA
C     IDENTIFICATION     7X  (NOT READ BY PROGRAM)
C     YEAR               I2  (IE. 75 FOR 1975)
C     MONTH              I2
C     CARD CODE          I1  =1  DAYS   1 TO 10
C                            =2  DAYS  11 TO 20
C                            =3  DAYS  21 TO LAST DAY OF MONTH
C     R,E OR F       11F6.2  RAIN,EVAP OR RUNOFF DATA
C     RAINFALL FOLLOWED BY EVAP AND THEN RUNOFF FOR EACH MONTH
C     THE LENGTH OF RECORD FOR INPUT DATA IS UNLIMITED BUT
C     SHOULD NOT BE LESS THAN ONE MONTH.
C     *****************************************************************
      READ (5,10) NYR,NM,(RAIN(J),J=1,10)
   10 FORMAT (7X,2I2,1X,10F6.2)
      NEND=LAST(NM)
      IF (((NYR-4*(NYR/4)).EQ.0).AND.(NM.EQ.2)) NEND=NEND+1
      READ (5,11) (RAIN(J),J=11,NEND)
   11 FORMAT (12X,10F6.2,/,12X,11F6.2)
      IF (MVAP.EQ.2) GO TO 790
      DO 781 IZ=1,NEND
      EVAP(IZ) = EVMO(NM)/FLOAT(NEND)
  781 CONTINUE
      GO TO 795
```

```
  790 READ (5,12) (EVAP(K),K=1,NEND)
   12 FORMAT (12X,10F6.2,/,12X,10F6.2,/,12X,11F6.2)
  795 IF (ISTAT.EQ.2) GO TO 13
      READ (5,12) (OBFL(L),L=1,NEND)
C     -----------------------------------------------------------------
C     START OF THE DAY LOOP
C     -----------------------------------------------------------------
   13 DO 50 IDA=1,NEND
      EP=EVAP(IDA)*PEADJ(NM)
      SPE=SPE+EP
      PR=RAIN(IDA)
      SPR=SPR+PR
C     -----------------------------------------------------------------
C     OPERATION OF INTERCEPTION STORAGE
C     -----------------------------------------------------------------
      EPX=EPXM-SCEP
      IF (EPX.LT.0.0) EPX=0.0
      IF (PR.GE.EPX) GO TO 216
      SCEP=SCEP+PR
      P3=0.0
      GO TO 250
  216 P3=PR-EPX
      SCEP=SCEP+EPX
  250 SIMPV=SIMPV+P3*AT
      LNRAT=LZS/LZSN
      IF (LNRAT.LT.0.0001) LNRAT=0.0001
      P4=P3+RES
C     -----------------------------------------------------------------
C     OPERATION OF THE INFILTRATION FUNCTION
C     -----------------------------------------------------------------
      D3FV=CB/(LNRAT**POWER)
      D4F=D3FV*25.4
      RATIO=CC*(2.0**LNRAT)
      IF (RATIO.LT.1.0) RATIO=1.0
      IF (P4.GE.D4F) GO TO 220
      SHRD=P4*P4/(2.0*D4F)
      GO TO 221
  220 SHRD=P4-0.5*D4F
  221 INFIL=P4-SHRD
C     -----------------------------------------------------------------
C     CALCULATE INCREMENTS TO DEPRESSION,INTERFLOW AND
C     UPPER ZONE STORAGES
C     -----------------------------------------------------------------
      IF (P4.GE.(D4F*RATIO)) GO TO 222
      RXX=P4*P4/(2.0*D4F*RATIO)
      GO TO 223
  222 RXX=P4-0.5*D4F*RATIO
  223 RGXX=SHRD-RXX
      IF (UZS.GE.(2.0*UZSN)) GO TO 224
      UZI=2.0*ABS(0.5*(UZS/UZSN)-1.0)+1.0
      PRE=(0.5*UZS/UZSN)*(1.0/(1.0+UZI))**UZI
      GO TO 225
  224 UZI=2.0*ABS(((UZS/UZSN)-1.0)-1.0)+1.0
      PRE=1.0-(1.0/(1.0+UZI))**UZI
  225 RGX=RGXX*PRE
      RX=RXX*PRE
      UZS=UZS+SHRD-RGX-RX
C     -----------------------------------------------------------------
C     OPERATION OF THE DEPRESSION STORAGE
C     -----------------------------------------------------------------
      SPL=0.
```

```
      RES=RX
      IF (RES.LE.0.) GO TO 226
      IF (RES.LE.RESM) GO TO 228
      SPL=RES-RESM
      RES=RESM
  228 URR=RES/RESM
      IF (URR.GT.0.75) URR=0.75
      ROS=(RES*URR)+SPL
      RES=RES-ROS
      IF (SPL.GT.0.0) RES=0.25*RESM
      GO TO 227
  226 ROS=0.0
  227 SROS=SROS+ROS
C     -----------------------------------------------------------------
C     OPERATION OF THE INTERFLOW STORAGE
C     -----------------------------------------------------------------
      SRGX=SRGX+RGX
      INTF=LIRC4*SRGX
      SINTF=SINTF+INTF
      SRGX=SRGX-INTF
C     -----------------------------------------------------------------
C     LOWER ZONE CALCULATIONS
C     -----------------------------------------------------------------
      LZI=1.5*ABS((LZS/LZSN)-1.0)+1.0
      PRE=(1.0/(1.0+LZI))**LZI
      IF (LZS.LT.LZSN) PRE=1.0-PRE*(LZS/LZSN)
      F3=PRE*INFIL
      LZS=LZS+F3
      F1A=INFIL-F3
      F1=F1A*(1.0-K24L)*PA
      RECH=F1A*K24L*PA
      SRECH=SRECH+RECH
      SGW=SGW+F1
      GWS=GWS+F1
C     -----------------------------------------------------------------
C     GROUND WATER FLOW CALCULATIONS
C     -----------------------------------------------------------------
      IF (SGW.LE.0.0001) GO TO 231
      GWF=SGW*LKK4*(1.0+KV*GWS)
      GO TO 232
  231 GWF=0.0
      GWS=SGW
  232 SGWF=SGWF+GWF
      SGW=SGW-GWF
C     -----------------------------------------------------------------
C     TOTAL CHANNEL INFLOW FOR THE DAY
C     -----------------------------------------------------------------
      RU=(ROS+INTF)*PA+P3*AT+GWF
C     -----------------------------------------------------------------
C     EVAP LOSS FROM INTERCEPTION AND UPPER ZONE STORAGES
C     -----------------------------------------------------------------
      IF (EP.EQ.0.0) GO TO 237
      IF (SCEP.LE.0.0) GO TO 235
      IF (SCEP.LE.EP) GO TO 236
      SCEP=SCEP-EP
      SET=SET+EP
      EP=0.0
      GO TO 237
  236 SET=SET+SCEP
      EP=EP-SCEP
      SCEP=0.0
```

```
  235 IF (UZS.LE.0.0) GO TO 237
      IF (UZS.LE.EP) GO TO 238
      SET=SET+EP
      UZS=UZS-EP
      EP=0.0
      GO TO 237
  238 SET=SET+UZS
      EP=EP-UZS
      UZS=0.0
C     -----------------------------------------------------------------
C     SLOW PERCOLATION FROM UPPER ZONE
C     -----------------------------------------------------------------
  237 DEEPL=(UZS/UZSN)-(LZS/LZSN)
      IF (DEEPL.LE.0.0) GO TO 239
      LNRAT=LZS/LZSN
      IF (LNRAT.EQ.0.) LNRAT=0.0001
      RECE=0.003*CB*UZSN*(DEEPL**3.0)*25.4*24.0
      IF (RECE.GT.UZS) RECE=UZS
      UZS=UZS-RECE
      LZI=1.5*ABS(LNRAT-1.0)+1.0
      PRE=(1.0/(1.0+LZI))**LZI
      IF (LZS.LT.LZSN) PRE=1.0-PRE*LNRAT
      F3=PRE*RECE
      F1A=(1.0-PRE)*RECE
      F1=F1A*(1.0-K24L)*PA
      RECH=F1A*K24L*PA
      SRECH=SRECH+RECH
      LZS=LZS+F3
      SGW=SGW+F1
      GWS=GWS+F1
C     -----------------------------------------------------------------
C     EVAP-TRANS FROM GROUNDWATER AND LOWER ZONE
C     -----------------------------------------------------------------
  239 IF (GWS.GT.0.0001) GWS=0.97*GWS
      LOS=SGW*K24EL*EP*PA
      SET=SET+LOS
      SGW=SGW-LOS
      GWS=GWS-LOS
      IF (GWS.LT.0.0) GWS=0.0
      EP=EP-LOS
      LNRAT=LZS/LZSN
      IF (EP.GE.(K3*LNRAT)) GO TO 240
      AETR=EP*(1.0-(EP/(2.0*K3*LNRAT)))
      LZS=LZS-AETR
      IF (LZS.LT.0.) LZS=0.
      GO TO 241
  240 AETR=0.5*K3*LNRAT
      LZS=LZS-AETR
      IF (LZS.LT.0.) LZS=0.
  241 SET=SET+AETR
      FLOW(IDA)=RU*AREA
      FSUM=FSUM+RU
      IF (LAG.GT.0) GO TO 50
      TFLO=TFLO+FLOW(IDA)
      IF (ISTAT.EQ.2) GO TO 50
      ZOB=ZOB+OBFL(IDA)
   50 CONTINUE
C     -----------------------------------------------------------------
C     END OF DAY LOOP AND START OF TIME DELAY SECTION
C     -----------------------------------------------------------------
      IF (LAG.EQ.0) GO TO 99
```

```
      I=0
      DO 92 KK=1,LAG
      RFLO(KK)=TRANS(KK)
   92 CONTINUE
      DO 93 J=1,NEND
      K=J+LAG
      IF (K.GT.NEND) GO TO 94
      RFLO(K)=FLOW(J)
      GO TO 93
   94 I=I+1
      TRANS(I)=FLOW(J)
   93 CONTINUE
      DO 95 NJ=1,NEND
      TFLO=TFLO+RFLO(NJ)
   95 CONTINUE
   99 IF (IOUT.EQ.2) GO TO 800
C     ------------------------------------------------------------------
C     OUTPUT SECTION FOR SHORT PERIOD CALIBRATION
C     ------------------------------------------------------------------
      WRITE (6,300) NM,NYR,H1,H2,H3,H4
  300 FORMAT (1H1,1X,28HSIMULATED RUNOFF FOR MONTH  ,I2,9H  YEAR 19,I2,
     1 //,1X,4A8,//)
      WRITE (6,310)
  310 FORMAT (1X,48HRUNOFF VALUES GIVEN IN THOUSANDS OF CUBIC METERS,//)
      WRITE (6,320)
  320 FORMAT (10X,3HDAY,10X,16HSIMULATED RUNOFF,11X,
     1 15HOBSERVED RUNOFF,//)
      DO 90 J=1,NEND
      IF (LAG.EQ.0) GO TO 97
      WRITE (6,330) J,RFLO(J),OBFL(J)
      GO TO 90
   97 WRITE (6,330) J,FLOW(J),OBFL(J)
  330 FORMAT (11X,I2,16X,F10.3,16X,F10.3)
   90 CONTINUE
      GO TO 850
C     -----------------------------------------------------------------
C     OUTPUT SECTION FOR LONG RECORD GENERATION
C     -----------------------------------------------------------------
  800 AFLO=TFLO/FLOAT(NEND)
      IF (LAG.EQ.0) GO TO 805
      WRITE (6,810) NYR,NM,(RFLO(J),J=1,NEND)
  810 FORMAT (3X,I2,1X,I2,1X,10F8.3,/,9X,10F8.3,/,9X,11F8.3)
      WRITE (6,811) TFLO,AFLO
  811 FORMAT (9X,14HMONTH TOTAL = ,F9.3,3X,16HDAILY AVERAGE = ,F9.3,/)
      GO TO 815
  805 WRITE (6,810) NYR,NM,(FLOW(J),J=1,NEND)
      WRITE (6,811) TFLO,AFLO
  815 GO TO 860
  850 AFLO=TFLO/FLOAT(NEND)
      AZOB=ZOB/FLOAT(NEND)
      WRITE (6,340) TFLO,ZOB,AFLO,AZOB
  340 FORMAT (1H0,7X,5HTOTAL,2(16X,F10.3),//,
     1 6X,7HAVERAGE,2(16X,F10.3),//)
C     -----------------------------------------------------------------
C     OUTPUT OF DATA COMPONENT SUMMARY
C     -----------------------------------------------------------------
      WRITE (6,350)
  350 FORMAT (1X,50HDATA COMPONENT SUMMARY - ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,351) SPR,SPE,SET,SROS,SINTF,SGWF,FSUM,SRECH
  351 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
```

```
     1 = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,15HSURFACE FLOW
     2= ,F8.2,//,1X,12HINTERFLOW = ,F8.2,//,1X,12HBASE FLOW = ,F8.2,//,
     3 1X,13HTOTAL FLOW = ,F8.2,//,1X,23HINACTIVE GROUNDWATER = ,F8.2,
     4 //)
      WRITE (6,360) SCEP,RES,UZS,LZS,SRGX,SGW
  360 FORMAT (1X,30HSTORAGE LEVELS AT END OF MONTH,
     1 /,4X,4HSCEP,5X,3HRES,5X,3HUZS,5X,3HLZS,4X,4HSRGX,5X,3HSGW,/,
     2 6F8.2)
C     ------------------------------------------------------------------
C     CREATE CONTINUOUS ARRAYS FOR SIMULATED AND OBSERVED RUNOFF
C     ------------------------------------------------------------------
  860 RTOT=RTOT+TFLO
      NNT=NOD+1
      ICON=ICON+1
      IF ((12-(ICON/12)*12).EQ.0) ANT=RTOT
      IF (ISTAT.EQ.2) GO TO 100
      IF (LAG.GT.0) GO TO 400
      DO 401 ILK=1,NEND
  401 SIMF(ILK)=FLOW(ILK)
      GO TO 402
  400 DO 404 KLK=1,NEND
  404 SIMF(KLK)=RFLO(KLK)
  402 NOD=NOD+NEND
      IIC=0
      DO 500 NUM=NNT,NOD
      IIC=IIC+1
      TSIM(NUM)=SIMF(IIC)
      TOBF(NUM)=OBFL(IIC)
  500 CONTINUE
  100 CONTINUE
C     -------------------------------------------------------------------
C     END OF MONTH LOOP
C     -------------------------------------------------------------------
      WRITE (6,352) RTOT
  352 FORMAT (1H1,1X,37HTOTAL RUNOFF FOR SIMULATION PERIOD = ,F10.3,//)
      IF ((ICON/12).GT.4) GO TO 370
      WRITE (6,353)
  353 FORMAT (1X,39HNO M.A.R. CALCULATED - RECORD TOO SHORT,//)
      GO TO 375
  370 TMAR=ANT/FLOAT(ICON/12)
      WRITE (6,354) TMAR
  354 FORMAT (1X,21HMEAN ANNUAL RUNOFF = ,F10.3,//)
  375 WRITE (6,355) SCEP,RES,UZS,LZS,SRGX,SGW
  355 FORMAT (1X,42HSTORAGE LEVELS AT END OF SIMULATION PERIOD,//1X,
     1 12HINTERCEPTION,F10.2,//,3X,10HDEPRESSION,F10.2,//,3X,
     2 10HUPPER ZONE,F10.2,//,3X,10HLOWER ZONE,F10.2,//,3X,10HINTER FLOW
     3,F10.2,//,1X,12HGROUND WATER,F10.2,//)
      IF (LAG.GT.0) WRITE (6,356) (TRANS(I),I=1,LAG)
  356 FORMAT (5X,15HTRANSLATED FLOW,//,10X,10F10.3)
      IF (ISTAT.EQ.2) GO TO 450
      CALL CORK(TOBF,TSIM,NOD,IVAL)
  450 STOP
      END
C     ##########################################################
C     STATISTICAL PACKAGE TO CALCULATE MEASURES OF CORRESPONDENCE
C     BETWEEN OBSERVED AND SIMULATED FLOWS.
C     THE ACTUAL SIMULATED AND OBSERVED FLOWS WILL BE USED
C     UNLESS IVAL HAS BEEN SET TO 2 IN THE MAIN ROUTINE IN
C     WHICH CASE LOG. VALUES WILL BE USED SO AS TO AVOID
C     GIVING TOO MUCH WEIGHT TO THE HIGH FLOWS.
C     NO CALCULATION IS DONE IF ONE OR BOTH FLOW
```

```
C     ARRAYS CONSIST ENTIRELY OF ZERO FLOW.IN THIS CASE
C     ALL STATISTICS ARE SET TO ZERO AND THE LISTING OF STATISTICS
C     IS ABANDONED.
C     ###############################################################
      SUBROUTINE CORK(X,Y,N,L)
      DIMENSION X(1000),Y(1000)
      SPXY=0.
      SYSQ=0.
      SXSQ=0.
      SUMY=0.
      SUMX=0.
      SXMMX=0.
      SXMY=0.
      DO 10 I=1,N
      IF (L.EQ.1) GO TO 5
C     ---------------------------------------------------------------
C     CONVERT TO LOG. VALUES
C     ---------------------------------------------------------------
      X(I)=X(I)*1000.
      Y(I)=Y(I)*1000.
      IF (X(I).LT.1.0) X(I)=1.0
      IF (Y(I).LT.1.0) Y(I)=1.0
      XVAL=ALOG10(X(I))
      YVAL=ALOG10(Y(I))
      GO TO 6
    5 XVAL=X(I)
      YVAL=Y(I)
C     ----------------------------------------------------------------
C     CALCULATE ARRAY TOTALS,SUM OF SQUARES AND SUM
C     OF CROSS PRODUCTS
C     ----------------------------------------------------------------
    6 SUMX=SUMX+XVAL
      SUMY=SUMY+YVAL
      XSQ=XVAL**2.0
      YSQ=YVAL**2.0
      SXSQ=SXSQ+XSQ
      SYSQ=SYSQ+YSQ
      PXY=XVAL*YVAL
      SPXY=SPXY+PXY
   10 CONTINUE
C     -----------------------------------------------------------------
C     CHECK FOR ZERO ARRAYS
C     -----------------------------------------------------------------
      IF ((SUMX.GT.0.).AND.(SUMY.GT.0.)) GO TO 20
      AMENX=0.
      AMENY=0.
      CCOF=0.0
      TTEST=0.
      RECO=0.
      BASE=0.
      SDEVY=0.
      VARY=0.
      SDY=0.
      VARX=0.
      SDX=0.
      EVAL=0.
      SDIF=0.
      GO TO 30
C     ----------------------------------------------------------------
C     CALCULATE MEAN,STANDARD DEVIATION,VARIANCE,CORRELATION
C     COEFFICIENT,STUDENTS T VALUE,REGRESSION COEFFICIENT AND
```

```
C     BASE CONSTANT OF REGRESSION EQUATION.
C     -----------------------------------------------------------------
   20 AMENX=SUMX/FLOAT(N)
      AMENY=SUMY/FLOAT(N)
      AX=SXSQ-((SUMX**2.0)/FLOAT(N))
      AY=SYSQ-((SUMY**2.0)/FLOAT(N))
      TOP=SPXY-((SUMX*SUMY)/FLOAT(N))
      CCOF=TOP/((AX*AY)**0.5)
      NCC=N-2
      BNC=FLOAT(NCC)
      TTEST=CCOF*(BNC**0.5)/((1.0-(CCOF*CCOF))**0.50)
      RECO=TOP/AX
      BASE=AMENY-(RECO*AMENX)
      SDEVY=(AY**0.5)*((1.0-(CCOF*CCOF))**0.50)
      VARY=(SYSQ/NCC)-(AMENY*AMENY)
      VARX=(SXSQ/NCC)-(AMENX*AMENX)
      SDX=VARX**0.50
      SDY=VARY**0.50
      DO 50 J=1,N
      XMMX=(X(J)-AMENX)*(X(J)-AMENX)
      XMY=(X(J)-Y(J))*(X(J)-Y(J))
      SXMMX=SXMMX+XMMX
      SXMY=SXMY+XMY
C     -----------------------------------------------------------------
C     CALCULATE COEFFICIENT OF MODEL EFFICIENCY
C     -----------------------------------------------------------------
   50 CONTINUE
      EVAL=(SXMMX-SXMY)/SXMMX
      SDIF=((SDX-SDY)/SDX)*100.0
C     ----------------------------------------------------------------
C     LISTING OF STATISTICS
C     ----------------------------------------------------------------
      WRITE (6,420)
  420 FORMAT (1H0,42HCOMPARISON OF OBSERVED AND SIMULATED FLOWS,/,
     1 1X,36HSIMULATED FLOW IS DEPENDENT VARIABLE,//)
      IF (L.EQ.2) GO TO 405
      WRITE (6,400)
  400 FORMAT (1X,29HACTUAL VALUES USED THROUGHOUT,//)
      GO TO 415
  405 WRITE (6,410)
  410 FORMAT (1X,26HLOG VALUES USED THROUGHOUT,//)
  415 WRITE (6,414) SUMX,SUMY
  414 FORMAT (1X,23HTOTAL OBSERVED FLOWS = ,F10.3,//,
     1 1X,24HTOTAL SIMULATED FLOWS = ,F10.3,/)
      WRITE (6,421) AMENX,AMENY,CCOF,TTEST,RECO,BASE,SDEVY,
     1 VARX,VARY
  421 FORMAT (1X,25HMEAN OF OBSERVED FLOWS = ,F10.3,//,
     1 1X,26HMEAN OF SIMULATED FLOWS = ,F10.3,//,
     2 1X,26HCORRELATION COEFFICIENT = ,F10.3,//,
     3 1X,19HSTUDENTS T VALUE = ,F10.3,//,
     4 1X,25HREGRESSION COEFFICIENT = ,F10.3,//,
     5 1X,23HBASE CONSTANT FOR EQN = ,F10.3,//,
     6 1X,35HSTANDARD ERROR OF SIMULATED FLOW = ,F10.3,//,
     7 1X,30HVARIANCE OF OBSERVED VALUES = ,F10.3,//,
     8 1X,31HVARIANCE OF SIMULATED VALUES = ,F10.3,/)
      WRITE (6,422) SDX,SDY,SDIF,EVAL
  422 FORMAT (1X,33HSTANDARD DEVIATION OF X VALUES = ,F10.3,//,
     1 1X,33HSTANDARD DEVIATION OF Y VALUES = ,F10.3,//,
     2 1X,46HPERCENTAGE DIFFERENCE IN STANDARD DEVIATION = ,F10.3,//,
     3 1X,28HCOEFFICIENT OF EFFICIENCY = ,F10.3)
   30 RETURN
```

```
END
FINISH
```

A.9 Program PDAY

```
         DATE 31/10/78   TIME 15/47/55                       LISTING FOR:- HRP

FILE:   HRPRMAXIMOP     SUBFILE PDAY IN CARD MODE

      LIST
      PROGRAM(PDAY)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER PDAY
C     #################################################################
C     THIS PROGRAM GENERATES DAILY RUNOFF IN THOUSANDS OF CUBIC METERS
C     FROM DAILY RAINFALL (MM) AND DAILY PAN EVAPORATION (MM)..
C     THE BASIC STRUCTURE OF THE MODEL HAS BEEN DRAWN FROM THE
C     MODEL DESCRIBED BY PORTER AND MCMAHON (1971).
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY.
C     (P.J.T. ROBERTS 1975)
C     #################################################################
      DIMENSION RAIN(31),EVAP(31),FLOW(31),RFLO(31),TRANS(20),LAST(12)
      DIMENSION PEADJ(12),TOBF(1000),TSIM(1000),OBFL(1000),SIMF(1000)
      DIMENSION EVMO(12)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C     *****************************************************************
C     READ IN CATCHMENT NAME OR RUN IDENTIFICATION - 32 COLUMNS
C     *****************************************************************
      READ (5,1) H1,H2,H3,H4
    1 FORMAT (4A8)
C     *****************************************************************
C     READ IN CATCHMENT AREA (SQ.KM) AND THE NUMBER OF MONTHS
C     OF INPUT DATA USED FOR SIMULATION AND
C     ISTAT    = 1 TO INITIATE STATISTICAL PACKAGE AND
C              = 2 TO SUPPRESS STATISTICAL PACKAGE AND
C     IVAL     = 1 FOR USE OF ACTUAL VALUES IN STAT. PACK.
C              = 2 FOR USE OF LOG. VALUES IN STAT. PACK. AND
C     IOUT     = 1 FORMATS MODEL OUTPUT FOR SHORT PERIOD CALIBRATION
C                 (ONE MONTH OUTPUT PER PAGE OF PRINTOUT)
C              = 2 FORMATS OUTPUT FOR LONG RECORD GENERATION.
C                 (APPROX. 15 MONTHS OUTPUT PER PAGE OF PRINTOUT) AND
C     MVAP   = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM)
C            = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION (MM)
C     IF ISTAT = 2 SET IVAL = 0
C     *****************************************************************
      READ (5,2) AREA,NMON,ISTAT,IVAL,IOUT,MVAP
    2 FORMAT (F8.2,5I5)
C     *****************************************************************
C     READ IN STORAGE VALUES IN MM.
C     VSL            INTERCEPTION STORAGE LEVEL
C     VSC            INTERCEPTION STORAGE CAPACITY (USUALY 1.5 MM)
C     DSL            DEPRESSION STORAGE LEVEL
C     DSC            DEPRESSION STORAGE CAPACITY
C     SSL            SOIL STORAGE LEVEL
C     SSC            SOIL STORAGE CAPACITY
C     GS             INITIAL GROUND WATER STORAGE LEVEL
C     *****************************************************************
      READ (5,21) VSL,VSC,DSL,DSC,SSL,SSC,GS
   21 FORMAT (7F6.0)
C     *****************************************************************
C     READ IN MODEL PARAMETERS
```

```
C     BARE  PERCENTAGE BARE GROUND
C     X     CONSTANT IN SORPTIVITY-STORAGE RELATIONSHIP
C     P     CONSTANT IN SORPTIVITY-STORAGE RELATIONSHIP
C     A     CONSTANT IN PHILIPS INFILTRATION FUNCTION
C     B     CONSTANT IN DEPRESSION STORAGE FUNCTION
C     Y     CONSTANT IN DEPRESSION STORAGE FUNCTION
C     UC    DIVERSION CONSTANT, SOIL TO CHANNEL STORAGE
C     UG    DIVERSION CONSTANT, SOIL TO GROUND WATER STORAGE
C     C     CONSTANT IN GROUND WATER DECAY FUNCTION
C     XN    EXPONENT IN GROUND WATER DECAY FUNCTION
C     ******************************************************************
      READ (5,22) BARE,X,P,A,B,Y,UC,UG,C,XN
   22 FORMAT (10F6.2)
C     ******************************************************************
C     READ IN THE REQUIRED LAG TIME IN DAYS
C     ******************************************************************
      READ (5,4) LAG
    4 FORMAT (I5)
C     ******************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAPORATION (MM)
C     JAN - DEC ONLY IF MVAP = 1
C     ******************************************************************
      IF(MVAP.EQ.2) GO TO 761
      READ(5,766)(EVMO(NX),NX=1,12)
  766 FORMAT(12F6.1)
  761 IF (LAG.EQ.0) GO TO 9
C     ******************************************************************
C     READ IN LAG NUMBER OF DAYS OF TRANSLATED FLOW (1000 CUBIC METERS)
C     FROM PREVIOUS MONTH----ONLY IF LAG IS REQUIRED
C     ******************************************************************
      READ (5,5) (TRANS(I),I=1,LAG)
    5 FORMAT (8F10.3)
C     ******************************************************************
C     READ IN PAN TO FREE WATER SURFACE EVAPORATION CONSTANTS
C     12 VALUES  JAN. TO DEC.
C     ******************************************************************
    9 READ (5,6) (PEADJ(K),K=1,12)
    6 FORMAT (12F5.3)
C     ------------------------------------------------------------------
C     INITIALISE PROGRAM VARIABLES AND LIST MODEL STORAGES,
C     PARAMETER VALUES AND PROGRAM CONTROL FLAGS.
C     ------------------------------------------------------------------
      ICON=0
      XU=1.0-XN
      RTOT=0.
      T=1.
      AMENX=0.
      AMENY=0.
      CCOF=0.
      TTEST=0.
      RECO=0.
      NOD=0
      BASE=0.
      SDEVY=0.
      WRITE (6,42)
   42 FORMAT (1H1,1X,14HSTORAGE VALUES,/,5X,3HVSL,5X,3HVSC,5X,3HDSL,
     1 5X,3HDSC,5X,3HSSL,5X,3HSSC,6X,2HGS)
      WRITE (6,43) VSL,VSC,DSL,DSC,SSL,SSC,GS
   43 FORMAT (7(2X,F6.0),//)
      WRITE (6,44)
   44 FORMAT (1X,16HMODEL PARAMETERS,/,3X,4HBARE,5X,1HX,5X,1HP,
```

```
     1 5X,1HA,5X,1HB,5X,1HY,4X,2HUC,4X,2HUG,5X,1HC,4X,2HXN)
      WRITE (6,45) BARE,X,P,A,B,Y,UC,UG,C,XN
   45 FORMAT (1X,10F6.2,//)
      WRITE (6,623) ISTAT,IVAL,IOUT,MVAP
  623 FORMAT (1H0,1X,28HPROGRAM CONTROL FLAGS SET AS,//,
     1 4X,5HISTAT,5X,4HIVAL,5X,4HIOUT,5X,4HMVAP,/,4I9)
      DO 46 JK=1,31
      OBFL(JK)=0.0
   46 CONTINUE
      IF (IOUT.EQ.1) GO TO 830
      WRITE (6,831) H1,H2,H3,H4
  831 FORMAT (1H1,1X,4A8,/)
      WRITE (6,310)
C     ------------------------------------------------------------------
C     START OF THE MONTHLY LOOP
C     ------------------------------------------------------------------
  830 DO 100 M=1,NMON
      RES=0.
      SPR=0.
      SPE=0.
      SET=0.
      SROS=0.
      SINTF=0.
      SGWF=0.
      FSUM=0.
      TFLO=0.
      ZOB=0.
C     ******************************************************************
C     READ IN ONE MONTH RAINFALL(MM),EVAPORATION(MM) AND RUNOFF DATA
C     OBSERVED RUNOFF DATA IN THOUSANDS OF CUBIC METERS
C     DAILY EVAPORATION DATA REQUIRED ONLY IF MVAP=2
C     RUNOFF DATA REQUIRED ONLY IF ISTAT=1
C     THREE CARDS PER MONTH FOR EACH TYPE OF INPUT
C     FOLLOWING FORMAT USED FOR ALL THREE TYPES OF INPUT
C     IDENTIFICATION      7X  (NOT READ BY PROGRAM)
C     YEAR                I2  (IE, 75 FOR 1975)
C     MONTH               I2
C     CARD CODE           I1      =1  DAYS   1 TO 10
C                                 =2  DAYS  11 TO 20
C                                 =3  DAYS  21 TO LAST DAY OF MONTH
C     R,E OR F         11F6.2     RAIN,EVAP OR RUNOFF DATA
C     RAINFALL FOLLOWED BY EVAP AND THEN RUNOFF FOR EACH MONTH
C     THE LENGTH OF RECORD FOR INPUT DATA IS UNLIMITED BUT
C     SHOULD NOT BE LESS THAN ONE MONTH.
C     ******************************************************************
      READ (5,10) NYR,NM,(RAIN(J),J=1,10)
   10 FORMAT (7X,2I2,1X,10F6.2)
      NEND=LAST(NM)
      IF (((NYR-4*(NYR/4)).EQ.0).AND.(NM.EQ.2)) NEND=NEND+1
      READ (5,11) (RAIN(J),J=11,NEND)
   11 FORMAT (12X,10F6.2,/,12X,11F6.2)
      IF (MVAP.EQ.2) GO TO 790
      DO 781 IZ=1,NEND
      EVAP(IZ)=EVMO(NM)/FLOAT(NEND)
  781 CONTINUE
      GO TO 795
  790 READ (5,12) (EVAP(K),K=1,NEND)
   12 FORMAT (12X,10F6.2,/,12X,10F6.2,/,12X,11F6.2)
  795 IF (ISTAT.EQ.2) GO TO 13
      READ (5,12) (OBFL(L),L=1,NEND)
C     ------------------------------------------------------------------
```

```
C     START OF THE DAY LOOP
C     ----------------------------------------------------------------
   13 DO 50 IDA=1,NEND
      EP=EVAP(IDA)*PEADJ(NM)
      SPE=SPE+EP
      PR=RAIN(IDA)
      SPR=SPR+PR
C     ------------------------------------------------------------------
C     OPERATION OF INTERCEPTION STORAGE
C     ------------------------------------------------------------------
      BAN=PR*(BARE/100.)
      VEG=PR-BAN
      VSL=VSL+VEG
      IF (VSL.GT.VSC) GO TO 15
      AVEG=0.
      GO TO 16
   15 AVEG=VSL-VSC
      VSL=VSC
   16 IF (VSL.GT.EP) GO TO 17
      EP=EP-VSL
      VSL=0.
      GO TO 18
   17 VSL=VSL-EP
      EP=0.
   18 TOIF=AVEG+BAN
C     -----------------------------------------------------------------
C     OPERATION OF THE INFITRATION FUNCTION
C     -----------------------------------------------------------------
      XPC=-P*(SSL/SSC)
      S=X*EXP(XPC)
      F=A+0.5*S*T**(-0.50)
      IF (TOIF.LT.F) F=TOIF
      TDSF=TOIF-F
C     -----------------------------------------------------------------
C     OPERATION OF THE DEPRESSION STORAGE FUNCTION
C     -----------------------------------------------------------------
      SM=DSC-DSL
      IF (SM.EQ.0.) GO TO 900
      D=B*2.7183**((-Y*DSL)/(DSC-DSL))*TDSF
  900 IF (SM.EQ.0.) D=0.
      DSL=DSL+D
      CS=TDSF-D
      IF (CS.LT.0.) CS=0.
      IF (EP.EQ.0.) GO TO 19
      XDSL=DSL-EP
      IF (DSL.GE.EP) EP=0.
      IF(XDSL.GE.0.) GO TO 20
      EP=EP-DSL
      XDSL=0.
   20 DSL=XDSL
   19 IF (F.LE.DSL) GO TO 24
      FD=DSL
      DSL=0.
   24 IF (F.GT.DSL) GO TO 25
      FD=F
      DSL=DSL-F
   25 IF (TOIF.GE.F) FD=0.
C     ---------------------------------------------------------------
C     CALCULATE OVERLAND FLOW
C     ---------------------------------------------------------------
      OVF=DSL-DSC
```

```
      IF (OVF.LT.0.) OVF=0.
      IF (OVF.GT.0.) DSL=DSC
      CS=CS+OVF
      FT=F+FD
C     ------------------------------------------------------------
C     OPERATION OF SOIL MOISTURE FUNCTION
C     --------------------------------------------------------------
      SC=UC*(SSL/SSC)*FT
      SG=UG*(SSL/SSC)*FT
      SSL=SSL+FT-(SC+SG)
      SLA=EP
      IF (SSL.GE.SLA) GO TO 48
      EP=EP-SSL
      SSL=0.
      GO TO 49
   48 EP=EP-SLA
      SSL=SSL-SLA
   49 RES=RES+EP
      OSL=SSL-SSC
      IF (OSL.LT.0.) OSL=0.
      IF (OSL.GT.0.) SSL=SSC
C     -----------------------------------------------------------------
C     OPERATION OF GROUND WATER FUNCTION
C     -----------------------------------------------------------------
      GS=GS+SG+OSL
      CG=C*GS*XU
C     -----------------------------------------------------------------
C     TOTAL CONTRIBUTION TO CHANNEL STORAGE
C     -----------------------------------------------------------------
      SROS=SROS+CS
      SINTF=SINTF+SC
      SGWF=SGWF+CG
      FSUM=FSUM+CS+SC+CG
      CS=CS+SC
      CT=CS+CG
      GS=GS-CG
      IF (GS.LT.0.) GS=0.
      FLOW(IDA)=CT*AREA
      IF (LAG.GT.0) GO TO 50
      TFLO=TFLO+FLOW(IDA)
      IF (ISTAT.EQ.2) GO TO 50
      ZOB=ZOB+OBFL(IDA)
   50 CONTINUE
C     -----------------------------------------------------------------
C     END OF DAY LOOP AND START OF TIME DELAY SECTION
C     -----------------------------------------------------------------
      SET=SPE-RES
      IF (LAG.EQ.0) GO TO 99
      I=0
      DO 92 KK=1,LAG
      RFLO(KK)=TRANS(KK)
   92 CONTINUE
      DO 93 J=1,NEND
      K=J+LAG
      IF (K.GT.NEND) GO TO 94
      RFLO(K)=FLOW(J)
      GO TO 93
   94 I=I+1
      TRANS(I)=FLOW(J)
   93 CONTINUE
      DO 95 NJ=1,NEND
```

```
      TFLO=TFLO+RFLO(NJ)
   95 CONTINUE
   99 IF (IOUT.EQ.2) GO TO 800
C     ------------------------------------------------------------------
C     OUTPUT SECTION FOR SHORT PERIOD CALIBRATION
C     ------------------------------------------------------------------
      WRITE (6,300) NM,NYR,H1,H2,H3,H4
  300 FORMAT (1H1,1X,28HSIMULATED RUNOFF FOR MONTH  ,I2,9H  YEAR 19,I2,
     1 //,1X,4A8,//)
      WRITE (6,310)
  310 FORMAT (1X,48HRUNOFF VALUES GIVEN IN THOUSANDS OF CUBIC METERS,//)
      WRITE (6,320)
  320 FORMAT (10X,3HDAY,10X,16HSIMULATED RUNOFF,11X,
     1 15HOBSERVED RUNOFF,//)
      DO 90 J=1,NEND
      IF (LAG.EQ.0) GO TO 97
      WRITE (6,330) J,RFLO(J),OBFL(J)
      GO TO 90
   97 WRITE (6,330) J,FLOW(J),OBFL(J)
  330 FORMAT (11X,I2,16X,F10.3,16X,F10.3)
   90 CONTINUE
      GO TO 850
C     ------------------------------------------------------------------
C     OUTPUT SECTION FOR LONG RECORD GENERATION
C     ------------------------------------------------------------------
  800 AFLO=TFLO/FLOAT(NEND)
      IF (LAG.EQ.0) GO TO 805
      WRITE (6,810) NYR,NM,(RFLO(J),J=1,NEND)
  810 FORMAT (3X,I2,1X,I2,1X,10F8.3,/,9X,10F8.3,/,9X,11F8.3)
      WRITE (6,811) TFLO,AFLO
  811 FORMAT (9X,14HMONTH TOTAL = ,F9.3,3X,16HDAILY AVERAGE = ,F9.3,/)
      GO TO 815
  805 WRITE (6,810) NYR,NM,(FLOW(J),J=1,NEND)
      WRITE (6,811) TFLO,AFLO
  815 GO TO 860
  850 AFLO=TFLO/FLOAT(NEND)
      AZOB=ZOB/FLOAT(NEND)
      WRITE (6,340) TFLO,ZOB,AFLO,AZOB
  340 FORMAT (1H0,7X,5HTOTAL,2(16X,F10.3),//,
     1 6X,7HAVERAGE,2(16X,F10.3),//)
C     -----------------------------------------------------------------
C     OUTPUT OF DATA COMPONENT SUMMARY
C     -----------------------------------------------------------------
      WRITE (6,350)
  350 FORMAT (1X,50HDATA COMPONENT SUMMARY = ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,351) SPR,SPE,SET,SROS,SINTF,SGWF,FSUM
  351 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
     1 = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,15HSURFACE FLOW
     2= ,F8.2,//,1X,12HINTERFLOW = ,F8.2,//,1X,12HBASE FLOW = ,F8.2,//,
     3 1X,13HTOTAL FLOW = ,F8.2,//)
      WRITE (6,360) VSL,DSL,SSL,GS
  360 FORMAT (1X,30HSTORAGE LEVELS AT END OF MONTH,/,
     1 5X,3HVSL,5X,3HDSL,5X,3HSSL,6X,2HGS,/,4F8.2)
C     -----------------------------------------------------------------
C     CREATE CONTINUOUS ARRAYS FOR SIMULATED AND OBSERVED RUNOFF
C     -----------------------------------------------------------------
  860 RTOT=RTOT+TFLO
      NNT=NOD+1
      ICON=ICON+1
      IF ((12-(ICON/12)*12).EQ.0) ANT=RTOT
```

```
      IF (ISTAT.EQ.2) GO TO 100
      IF (LAG.GT.0) GO TO 400
      DO 401 ILK=1,NEND
  401 SIMF(ILK)=FLOW(ILK)
      GO TO 402
  400 DO 404 KLK=1,NEND
  404 SIMF(KLK)=RFLO(KLK)
  402 NOD=NOD+NEND
      IIC=0
      DO 500 NUM=NNT,NOD
      IIC=IIC+1
      TSIM(NUM)=SIMF(IIC)
      TOBF(NUM)=OBFL(IIC)
  500 CONTINUE
  100 CONTINUE
C     ------------------------------------------------------------------
C     END OF MONTH LOOP
C     ------------------------------------------------------------------
      WRITE (6,352) RTOT
  352 FORMAT (1H1,1X,37HTOTAL RUNOFF FOR SIMULATION PERIOD = ,F10.3,//)
      IF ((ICON/12).GT.4) GO TO 370
      WRITE (6,353)
  353 FORMAT (1X,39HNO M.A.R. CALCULATED - RECORD TOO SHORT,//)
      GO TO 375
  370 TMAR=ANT/FLOAT(ICON/12)
      WRITE (6,354) TMAR
  354 FORMAT (1X,21HMEAN ANNUAL RUNOFF = ,F10.3,//)
  375 WRITE (6,355) VSL,DSL,SSL,GS
  355 FORMAT (1X,42HSTORAGE LEVELS AT END OF SIMULATION PERIOD,//1X,
     1 12HINTERCEPTION,F10.2,//,3X,10HDEPRESSION,F10.2,//,9X,
     2 4HSOIL,F10.2,//,1X,12HGROUND WATER,F10.3,//)
      IF (LAG.GT.0) WRITE (6,356) (TRANS(I),I=1,LAG)
  356 FORMAT (5X,15HTRANSLATED FLOW,//,10X,10F10.3,//)
      IF (ISTAT.EQ.2) GO TO 450
      CALL CORK(TOBF,TSIM,NOD,IVAL)
  450 STOP
      END
C     ##################################################################
C     STATISTICAL PACKAGE TO CALCULATE MEASURES OF CORRESPONDENCE
C     BETWEEN OBSERVED AND SIMULATED FLOWS.
C     THE ACTUAL SIMULATED AND OBSERVED FLOWS WILL BE USED
C     UNLESS IVAL HAS BEEN SET TO 2 IN THE MAIN ROUTINE IN
C     WHICH CASE LOG. VALUES WILL BE USED SO AS TO AVOID
C     GIVING TOO MUCH WEIGHT TO THE HIGH FLOWS.
C     NO CALCULATION IS DONE IF ONE OR BOTH FLOW
C     ARRAYS CONSIST ENTIRELY OF ZERO FLOW. IN THIS CASE
C     ALL STATISTICS ARE SET TO ZERO AND THE LISTING OF
C     STATISTICS IS ABANDONED.
C     #################################################################
      SUBROUTINE CORK(X,Y,N,L)
      DIMENSION X(1000),Y(1000)
      SPXY=0.
      SYSQ=0.
      SXSQ=0.
      SUMY=0.
      SUMX=0.
      SXMMX=0.
      SXMY=0.
      DO 10 I=1,N
      IF (L.EQ.1) GO TO 5
C     -----------------------------------------------------------------
```

```
C     CONVERT TO LOG. VALUES
C     -------------------------------------------------------------
      X(I)=X(I)*1000.
      Y(I)=Y(I)*1000.
      IF (X(I).LT.1.0) X(I)=1.0
      IF (Y(I).LT.1.0) Y(I)=1.0
      XVAL=ALOG10(X(I))
      YVAL=ALOG10(Y(I))
      GO TO 6
    5 XVAL=X(I)
      YVAL=Y(I)
C     -------------------------------------------------------------
C     CALCULATE ARRAY TOTALS,SUM OF SQUARES AND SUM OF
C     CROSS PRODUCTS
C     -------------------------------------------------------------
    6 SUMX=SUMX+XVAL
      SUMY=SUMY+YVAL
      XSQ=XVAL**2.0
      YSQ=YVAL**2.0
      SXSQ=SXSQ+XSQ
      SYSQ=SYSQ+YSQ
      PXY=XVAL*YVAL
      SPXY=SPXY+PXY
   10 CONTINUE
C     -------------------------------------------------------------
C     CHECK FOR ZERO ARRAYS
C     -------------------------------------------------------------
      IF((SUMX.GT.0.).AND.(SUMY.GT.0.)) GO TO 20
      AMENX = 0.
      AMENY = 0.
      CCOF = 0.0
      TTEST = 0.
      RECO = 0.
      BASE = 0.
      SDEVY = 0.
      VARY=0.
      SDY=0.
      VARX=0.
      SDX=0.
      EVAL=0.
      SDIF=0.
      GO TO 30
C     -------------------------------------------------------------
C     CALCULATE MEAN,STANDARD DEVIATION,VARIANCE,CORRELATION
C     COEFFICIENT,STUDENTS T VALUE,REGRESSION COEFFICIENT
C     AND BASE CONSTANT OF REGRESSION EQUATION.
C     -------------------------------------------------------------
   20 AMENX=SUMX/FLOAT(N)
      AMENY=SUMY/FLOAT(N)
      AX=SXSQ-((SUMX**2.0)/FLOAT(N))
      AY=SYSQ-((SUMY**2.0)/FLOAT(N))
      TOP=SPXY-((SUMX*SUMY)/FLOAT(N))
      CCOF=TOP/((AX*AY)**0.5)
      NCC=N-2
      BNC=FLOAT(NCC)
      TTEST=CCOF*(BNC**0.50)/((1.0-(CCOF*CCOF))**0.50)
      RECO=TOP/AX
      BASE=AMENY-(RECO*AMENX)
      SDEVY=(AY**0.50)*((1.0-(CCOF*CCOF))**0.50)
      VARY=(SYSQ/NCC)-(AMENY*AMENY)
      VARX=(SXSQ/NCC)-(AMENX*AMENX)
```

```
      SDX=VARX**0.50
      SDY=VARY**0.50
      DO 50 J=1,N
      XMMX=(X(J)-AMENX)*(X(J)-AMENX)
      XMY=(X(J)-Y(J))*(X(J)-Y(J))
      SXMMX=SXMMX+XMMX
      SXMY=SXMY+XMY
C     -------------------------------------------------------------
C     CALCULATE COEFFICIENT OF MODEL EFFICIENCY
C     -------------------------------------------------------------
   50 CONTINUE
      EVAL=(SXMMX-SXMY)/SXMMX
      SDIF=((SDX-SDY)/SDX)*100.0
C     -------------------------------------------------------------
C     LISTING OF STATISTICS
C     -------------------------------------------------------------
      WRITE (6,420)
  420 FORMAT (1H0,42HCOMPARISON OF OBSERVED AND SIMULATED FLOWS,/,
     1 1X,36HSIMULATED FLOW IS DEPENDENT VARIABLE,//)
      IF (L.EQ.2) GO TO 405
      WRITE (6,400)
  400 FORMAT (1X,29HACTUAL VALUES USED THROUGHOUT,//)
      GO TO 415
  405 WRITE (6,410)
  410 FORMAT (1X,26HLOG VALUES USED THROUGHOUT,//)
  415 WRITE (6,414) SUMX,SUMY
  414 FORMAT (1X,23HTOTAL OBSERVED FLOWS = ,F10.3,//,
     1 1X,24HTOTAL SIMULATED FLOWS = ,F10.3,/)
      WRITE (6,421) AMENX,AMENY,CCOF,TTEST,RECO,BASE,SDEVY,
     1 VARX,VARY
  421 FORMAT (1X,25HMEAN OF OBSERVED FLOWS = ,F10.3,//,
     1 1X,26HMEAN OF SIMULATED FLOWS = ,F10.3,//,
     2 1X,26HCORRELATION COEFFICIENT = ,F10.3,//,
     3 1X,19HSTUDENTS T VALUE = ,F10.3,//,
     4 1X,25HREGRESSION COEFFICIENT = ,F10.3,//,
     5 1X,23HBASE CONSTANT FOR EQN = ,F10.3,//,
     6 1X,35HSTANDARD ERROR OF SIMULATED FLOWS = ,F10.3,//,
     7 1X,30HVARIANCE OF OBSERVED VALUES = ,F10.3,//,
     8 1X,31HVARIANCE OF SIMULATED VALUES = ,F10.3,/)
      WRITE (6,422) SDX,SDY,SDIF,EVAL
  422 FORMAT (1X,33HSTANDARD DEVIATION OF X VALUES = ,F10.3,//,
     1 1X,33HSTANDARD DEVIATION OF Y VALUES = ,F10.3,//,
     2 1X,46HPERCENTAGE DIFFERENCE IN STANDARD DEVIATION = ,F10.3,//,
     3 1X,28HCOEFFICIENT OF EFFICIENCY = ,F10.3,)
   30 RETURN
      END
      FINISH
```

A.10 Program HANS

```
       DATE 31/10/78   TIME 15/39/04                         LISTING FOR:- HRP

FILE:   HRPRMAXIMOP     SUBFILE HANS IN CARD MODE

      LIST
      PROGRAM(HANS)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER HANS
C     #################################################################
C     THIS PROGRAM GENERATES DAILY RUNOFF IN THOUSANDS OF CUBIC METERS
C     FROM DAILY RAINFALL (MM) AND DAILY PAN EVAPORATION (MM)..
C     THE BASIC STRUCTURE OF THE MODEL HAS BEEN DRAWN FROM THE
C     MODEL DESCRIBED BY NIELSEN AND HANSEN (1973),
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY,
C     (P.J.T. ROBERTS 1975)
C     #################################################################
      REAL LZR,LZM,INS
      DIMENSION RAIN(31),EVAP(31),FLOW(31),RFLO(31),TRANS(20),LAST(12)
      DIMENSION PEADJ(12),TOBF(1000),TSIM(1000),OBFL(1000),SIMF(1000)
      DIMENSION EVMO(12)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C     *****************************************************************
C     READ IN CATCHMENT NAME OR RUN IDENTIFICATION - 32 COLUMNS
C     *****************************************************************
      READ (5,1) H1,H2,H3,H4
    1 FORMAT (4A8)
C     *****************************************************************
C     READ IN CATCHMENT AREA (SQ.KM) AND THE NUMBER OF MONTHS
C     OF INPUT DATA USED FOR SIMULATION AND
C     ISTAT   = 1 TO INITIATE STATISTICAL PACKAGE AND
C             = 2 TO SUPPRESS STATISTICAL PACKAGE AND
C     IVAL    = 1 FOR USE OF ACTUAL VALUES IN STAT. PACK.
C             = 2 FOR USE OF LOG. VALUES IN STAT. PACK. AND
C     IOUT    = 1 FORMATS MODEL OUTPUT FOR SHORT PERIOD CALIBRATION
C               (ONE MONTH OUTPUT PER PAGE OF PRINTOUT)
C             = 2 FORMATS OUTPUT FOR LONG RECORD GENERATION
C               (APPROX. 15 MONTHS OUTPUT PER PAGE OF PRINTOUT) AND
C     MVAP  = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM)
C           = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION (MM)
C     IF ISTAT = 2 SET IVAL = 0
C     *****************************************************************
      READ (5,2) AREA,NMON,ISTAT,IVAL,IOUT,MVAP
    2 FORMAT (F8.2,5I5)
C     *****************************************************************
C     READ IN STORAGE VALUES
C     UZR = UPPER ZONE STORAGE LEVEL(STARTING VALUE)--MM
C     UZM = UPPER ZONE MAXIMUM STORAGE -- MM
C     LZR = LOWER ZONE STORAGE LEVEL(STARTING VALUE) --MM
C     LZM = LOWER ZONE MAXIMUM STORAGE -- MM
C     BFP = BASE FLOW VOLUME FOR THE DAY PRECEEDING SIMULATION PERIOD
C     BFP MUST BE IN THOUSAND CUBIC METERS
C     *****************************************************************
      READ (5,21) UZR,UZM,LZR,LZM,BFP
   21 FORMAT (4F6.0,F10.3)
C     *****************************************************************
C     READ IN FLOW PARAMETERS
```

```
C     COF,CLO,EKO  CONTROL OVERLAND FLOW
C     CIF,CLI,EKI  CONTROL INTERFLOW
C     EKB          CONTROLS BASE FLOW
C     *******************************************************************
      READ (5,22) COF,CLO,EKO,CIF,CLI,EKI,EKB
   22 FORMAT (7F8.2)
C     *******************************************************************
C     READ IN THE REQUIRED LAG TIME IN DAYS
C     *******************************************************************
      READ (5,4) LAG
    4 FORMAT (I5)
C     *******************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAPORATION (MM)
C     JAN - DEC ONLY IF MVAP=1
C     *******************************************************************
      IF(MVAP.EQ.2) GO TO 761
      READ(5,766)(EVMO(NX),NX=1,12)
  766 FORMAT(12F6.1)
  761 IF (LAG.EQ.0) GO TO 9
C     *******************************************************************
C     READ IN LAG NUMBER OF DAYS OF TRANSLATED FLOW (1000 CUBIC METERS)
C     FROM PREVIOUS MONTH----ONLY IF LAG IS REQUIRED
C     *******************************************************************
      READ (5,5) (TRANS(I),I=1,LAG)
    5 FORMAT (8F10.3)
C     *******************************************************************
C     READ IN PAN TO FREE WATER SURFACE EVAPORATION CONSTANTS
C     12 VALUES  JAN. TO DEC.
C     *******************************************************************
    9 READ (5,6) (PEADJ(K),K=1,12)
    6 FORMAT (12F5.3)
C     -------------------------------------------------------------------
C     INITIALISE PROGRAM VARIABLES AND LIST MODEL STORAGE LEVELS,
C     PARAMETER VALUES AND PROGRAM CONTROL FLAGS
C     -------------------------------------------------------------------
      ICON=0
      RTOT=0.
      INS=0.
      CON=0.
      TEST=0.
      NIC=0.
      TO=-1.
      TI=-1.
      OFD=0.
      AMENX=0.
      AMENY=0.
      CCOF=0.
      TTEST=0.
      RECO=0.
      NOD=0
      BASE=0.
      SDEVY=0.
      WRITE (6,42)
   42 FORMAT (1H1,1X,14HSTORAGE VALUES,/,5X,3HUZR,5X,3HUZM,5X,3HLZR,
     1 5X,3HLZM,9X,3HBFP)
      WRITE (6,43) UZR,UZM,LZR,LZM,BFP
   43 FORMAT (4(2X,F6.0),2X,F10.3,//)
      WRITE (6,44)
   44 FORMAT (16H FLOW PARAMETERS,/,7X,3HCOF,7X,3HCLO,7X,3HEKO,7X,3HCIF,
     1 7X,3HCLI,7X,3HEKI,7X,3HEKB)
      WRITE (6,45) COF,CLO,EKO,CIF,CLI,EKI,EKB
```

```
   45 FORMAT (7(2X,F8.2),//)
      WRITE (6,623) ISTAT,IVAL,IOUT,MVAP
  623 FORMAT (1H0,1X,28HPROGRAM CONTROL FLAGS SET AS,//,
     1 4X,5HISTAT,5X,4HIVAL,5X,4HIOUT,5X,4HMVAP,/,4I9)
      DO 46 JK=1,31
      OBFL(JK)=0.0
   46 CONTINUE
      IF (IOUT.EQ.1) GO TO 830
      WRITE (6,831) H1,H2,H3,H4
  831 FORMAT (1H1,1X,4A8,/)
      WRITE (6,310)
C     -------------------------------------------------------------------
C     START OF THE MONTHLY LOOP
C     -------------------------------------------------------------------
  830 DO 100 M=1,NMON
      SPR=0.
      SPE=0.
      SET=0.
      SROS=0.
      SINTF=0.
      SGWF=0.
      FSUM=0.
      TFLO=0.
      ZOB=0.
C     *******************************************************************
C     READ IN ONE MONTH RAINFALL(MM),EVAPORATION(MM) AND RUNOFF DATA
C     OBSERVED RUNOFF DATA IN THOUSANDS OF CUBIC METERS
C     DAILY EVAPORATION DATA REQUIRED ONLY IF MVAP=2
C     RUNOFF DATA REQUIRED ONLY IF ISTAT=1
C     THREE CARDS PER MONTH FOR EACH TYPE OF INPUT
C     FOLLOWING FORMAT USED FOR ALL THREE TYPES OF INPUT
C     IDENTIFICATION     7X  (NOT READ BY PROGRAM)
C     YEAR               I2  (IE, 75 FOR 1975)
C     MONTH              I2
C     CARD CODE          I1    =1   DAYS    1 TO 10
C                              =2   DAYS   11 TO 20
C                              =3   DAYS   21 TO LAST DAY OF MONTH
C     R,E OR F       11F6.2    RAIN,EVAP OR RUNOFF DATA
C     RAINFALL FOLLOWED BY EVAP AND THEN RUNOFF FOR EACH MONTH
C     THE LENGTH OF RECORD FOR INPUT DATA IS UNLIMITED BUT
C     SHOULD NOT BE LESS THAN ONE MONTH.
C     ******************************************************************
      READ (5,10) NYR,NM,(RAIN(J),J=1,10)
   10 FORMAT (7X,2I2,1X,10F6.2)
      NEND=LAST(NM)
      IF (((NYR-4*(NYR/4)).EQ.0).AND.(NM.EQ.2)) NEND=NEND+1
      READ (5,11) (RAIN(J),J=11,NEND)
   11 FORMAT (12X,10F6.2,/,12X,11F6.2)
      IF(MVAP.EQ.2) GO TO 790
      DO 781 IZ=1,NEND
      EVAP(IZ)=EVMO(NM)/FLOAT(NEND)
  781 CONTINUE
      GO TO 795
  790 READ (5,12) (EVAP(K),K=1,NEND)
   12 FORMAT (12X,10F6.2,/,12X,10F6.2,/,12X,11F6.2)
  795 IF (ISTAT.EQ.2) GO TO 13
      READ (5,12) (OBFL(L),L=1,NEND)
C     -------------------------------------------------------------------
C     START OF THE DAY LOOP
C     -------------------------------------------------------------------
   13 DO 50 IDA=1,NEND
```

```
      EP=EVAP(IDA)*PEADJ(NM)
      SPE=SPE+EP
      PR=RAIN(IDA)
      SPR=SPR+PR
      TO=TO+1.
      TI=TI+1.
C     -----------------------------------------------------------------
C     OPERATION OF THE UPPER ZONE STORAGE
C     -----------------------------------------------------------------
      A=LZR/LZM
      UZR=UZR+PR
      IF (UZR.GT.EP) GO TO 200
      SET=SET+UZR
      EP=EP-UZR
      UZR=0.
      GO TO 210
  200 SET=SET+EP
      UZR=UZR-EP
      EP=0.
  210 EXC=UZR-UZM
      IF (EXC.GT.0.) GO TO 220
      EXC=0.
      GO TO 230
  220 UZR=UZM
  230 OFL=COF*EXC*((A-CLO)/(1.0-CLO))
      IF (A.LE.CLO) OFL=0.
      SROS=SROS+OFL
      IF (OFL.EQ.0.0) GO TO 235
      TO=0.
  235 OFD=OFD+OFL
      SPS=OFD*((1.0/EKO)*2.7183**(-TO/EKO))
      ROS=SPS*AREA
      OFD=OFD-SPS
      IF (OFD.LT.0.0) OFD=0.0
C     -----------------------------------------------------------------
C     CALCULATE INTERFLOW
C     -----------------------------------------------------------------
      AINF=CIF*UZR*((A-CLI)/(1.0-CLI))
      IF (A.LE.CLI) AINF=0.
      IF (UZR.LE.TEST) GO TO 250
      TI=0.
  250 SINTF=SINTF+AINF
      INS=INS+AINF
      FIN=INS*((1.0/EKI)*2.7183**(-TI/EKI))
      INTF=FIN*AREA
      INS=INS-FIN
      IF (INS.LT.0.0) INS=0.0
      UZR=UZR-AINF
      IF (UZR.LT.0.0) UZR=0.0
      TEST=UZR
C     -----------------------------------------------------------------
C     CALCULATE INFILTRATION TO LOWER ZONE STORAGE
C     -----------------------------------------------------------------
      DL=(EXC-OFL)*(1.-A)
C     -----------------------------------------------------------------
C     CALCULATE PERCOLATION TO GROUNDWATER STORAGE
C     -----------------------------------------------------------------
      G=(EXC-OFL)*A
      GGG=G*AREA
      SGWF=SGWF+G
      RU=OFL+AINF+G
```

```
C     ------------------------------------------------------------------
C     OPERATION OF THE LOWER ZONE STORAGE
C     ------------------------------------------------------------------
      EA=EP*A
      LZR=(LZR+DL)-EA
      IF (LZR.GE.0.0) SET=SET+EA
      IF (LZR.LT.0.0) LZR=0.0
      IF (LZR.GT.LZM) LZR=LZM
C     ------------------------------------------------------------------
C     CALCULATE BASE FLOW
C     ------------------------------------------------------------------
      BF=(BFP*2.7183**(-1.0/EKB))+(GGG*(1.0-(2.7183**(-1.0/EKB))))
      BFP=BF
      FLOW(IDA)=ROS+INTF+BF
      FSUM=FSUM+RU
      IF (LAG.GT.0) GO TO 50
      TFLO=TFLO+FLOW(IDA)
      IF (ISTAT.EQ.2) GO TO 50
      ZOB=ZOB+OBFL(IDA)
   50 CONTINUE
C     ------------------------------------------------------------------
C     END OF DAY LOOP AND START OF TIME DELAY SECTION
C     ------------------------------------------------------------------
      IF (LAG.EQ.0) GO TO 99
      I=0
      DO 92 KK=1,LAG
      RFLO(KK)=TRANS(KK)
   92 CONTINUE
      DO 93 J=1,NEND
      K=J+LAG
      IF (K.GT.NEND) GO TO 94
      RFLO(K)=FLOW(J)
      GO TO 93
   94 I=I+1
      TRANS(I)=FLOW(J)
   93 CONTINUE
      DO 95 NJ=1,NEND
      TFLO=TFLO+RFLO(NJ)
   95 CONTINUE
   99 IF (IOUT.EQ.2) GO TO 800
C     ----------------------------------------------------------------
C     OUTPUT SECTION FOR SHORT PERIOD CALIBRATION
C     ----------------------------------------------------------------
      WRITE (6,300) NM,NYR,H1,H2,H3,H4
  300 FORMAT (1H1,1X,28HSIMULATED RUNOFF FOR MONTH  ,I2,9H  YEAR 19,I2,
     1 //,1X,4A8,//)
      WRITE (6,310)
  310 FORMAT (1X,48HRUNOFF VALUES GIVEN IN THOUSANDS OF CUBIC METERS,//)
      WRITE (6,320)
  320 FORMAT (10X,3HDAY,10X,16HSIMULATED RUNOFF,11X,
     1 15HOBSERVED RUNOFF,//)
      DO 90 J=1,NEND
      IF (LAG.EQ.0) GO TO 97
      WRITE (6,330) J,RFLO(J),OBFL(J)
      GO TO 90
   97 WRITE (6,330) J,FLOW(J),OBFL(J)
  330 FORMAT (11X,I2,16X,F10.3,16X,F10.3)
   90 CONTINUE
      GO TO 850
C     ---------------------------------------------------------------
C     OUTPUT SECTION FOR LONG RECORD GENERATION
```

```
C     ------------------------------------------------------------
  800 AFLO=TFLO/FLOAT(NEND)
      IF (LAG.EQ.0) GO TO 805
      WRITE (6,810) NYR,NM,(RFLO(J),J=1,NEND)
  810 FORMAT (3X,I2,1X,I2,1X,10F8.3,/,9X,10F8.3,/,9X,11F8.3)
      WRITE (6,811) TFLO,AFLO
  811 FORMAT (9X,14HMONTH TOTAL = ,F9.3,3X,16HDAILY AVERAGE = ,F9.3,/)
      GO TO 815
  805 WRITE (6,810) NYR,NM,(FLOW(J),J=1,NEND)
      WRITE (6,811) TFLO,AFLO
  815 GO TO 860
  850 AFLO=TFLO/FLOAT(NEND)
      AZOB=ZOB/FLOAT(NEND)
      WRITE (6,340) TFLO,ZOB,AFLO,AZOB
  340 FORMAT (1H0,7X,5HTOTAL,2(16X,F10.3),//,
     1 6X,7HAVERAGE,2(16X,F10.3),//)
C     ------------------------------------------------------------
C     OUTPUT OF DATA COMPONENT SUMMARY
C     ------------------------------------------------------------
      WRITE (6,350)
  350 FORMAT (1X,50HDATA COMPONENT SUMMARY = ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,351) SPR,SPE,SET,SROS,SINTF,SGWF,FSUM
  351 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
     1 = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,15HSURFACE FLOW
     2= ,F8.2,//,1X,12HINTERFLOW = ,F8.2,//,1X,12HBASE FLOW = ,F8.2,//,
     3 1X,13HTOTAL FLOW = ,F8.2,//)
      WRITE (6,360) UZR,LZR,BFP
  360 FORMAT (1X,30HSTORAGE LEVELS AT END OF MONTH,/,
     1 5X,3HUZR,5X,3HLZR,5X,3HBFP,/,3F8.3)
C     ------------------------------------------------------------
C     CREATE CONTINUOUS ARRAYS FOR SIMULATED AND OBSERVED RUNOFF
C     ------------------------------------------------------------
  860 RTOT=RTOT+TFLO
      NNT=NOD+1
      ICON=ICON+1
      IF ((12-(ICON/12)*12).EQ.0) ANT=RTOT
      IF (ISTAT.EQ.2) GO TO 100
      IF (LAG.GT.0) GO TO 400
      DO 401 ILK=1,NEND
  401 SIMF(ILK)=FLOW(ILK)
      GO TO 402
  400 DO 404 KLK=1,NEND
  404 SIMF(KLK)=RFLO(KLK)
  402 NOD=NOD+NEND
      IIC=0
      DO 500 NUM=NNT,NOD
      IIC=IIC+1
      TSIM(NUM)=SIMF(IIC)
      TOBF(NUM)=OBFL(IIC)
  500 CONTINUE
  100 CONTINUE
C     ------------------------------------------------------------
C     END OF MONTH LOOP
C     ------------------------------------------------------------
      WRITE (6,352) RTOT
  352 FORMAT (1H1,1X,37HTOTAL RUNOFF FOR SIMULATION PERIOD = ,F10.3,//)
      IF ((ICON/12).GT.4) GO TO 370
      WRITE (6,353)
  353 FORMAT (1X,39HNO M.A.R. CALCULATED - RECORD TOO SHORT,//)
      GO TO 375
```

```
  370 TMAR=ANT/FLOAT(ICON/12)
      WRITE (6,354) TMAR
  354 FORMAT (1X,21HMEAN ANNUAL RUNOFF = ,F10.3,//)
  375 WRITE (6,355) UZR,LZR,BFP
  355 FORMAT (1X,42HSTORAGE LEVELS AT END OF SIMULATION PERIOD,//3X,
     1 10HUPPER ZONE,F10.2,//,3X,10HLOWER ZONE,F10.2,//,1X,
     2 12HGROUND WATER,F10.3,//)
      IF (LAG.GT.0) WRITE (6,356) (TRANS(I),I=1,LAG)
  356 FORMAT (5X,15HTRANSLATED FLOW,//,10X,10F10.3,//)
      IF (ISTAT.EQ.2) GO TO 450
      CALL CORK(TOBF,TSIM,NOD,IVAL)
  450 STOP
      END
C     ##################################################################
C     STATISTICAL PACKAGE TO CALCULATE MEASURES OF CORRESPONDENCE
C     BETWEEN OBSERVED AND SIMULATED FLOWS.
C     THE ACTUAL SIMULATED AND OBSERVED FLOWS WILL BE USED
C     UNLESS IVAL HAS BEEN SET TO 2 IN THE MAIN ROUTINE IN
C     WHICH CASE LOG. VALUES WILL BE USED SO AS TO AVOID
C     GIVING TOO MUCH WEIGHT TO THE HIGH FLOWS.
C     NO CALCULATION IS DONE IF ONE OR BOTH FLOW
C     ARRAYS CONSIST ENTIRELY OF ZERO FLOW.IN THIS CASE
C     ALL STATISTICS ARE SET TO ZERO AND THE LISTING OF
C     STATISTICS IS ABANDONED.
C     #################################################################
      SUBROUTINE CORK(X,Y,N,L)
      DIMENSION X(1000),Y(1000)
      SPXY=0.
      SYSQ=0.
      SXSQ=0.
      SUMY=0.
      SUMX=0.
      SXMMX=0.
      SXMY=0.
      DO 10 I=1,N
      IF (L.EQ.1) GO TO 5
C     ----------------------------------------------------------------
C     CONVERT TO LOG. VALUES
C     ----------------------------------------------------------------
      X(I)=X(I)*1000.
      Y(I)=Y(I)*1000.
      IF (X(I).LT.1.0) X(I)=1.0
      IF (Y(I).LT.1.0) Y(I)=1.0
      XVAL=ALOG10(X(I))
      YVAL=ALOG10(Y(I))
      GO TO 6
    5 XVAL=X(I)
      YVAL=Y(I)
C     ---------------------------------------------------------------
C     CALCULATE ARRAY TOTALS,SUM OF SQUARES AND SUM OF
C     CROSS PRODUCTS
C     ---------------------------------------------------------------
    6 SUMX=SUMX+XVAL
      SUMY=SUMY+YVAL
      XSQ=XVAL**2.0
      YSQ=YVAL**2.0
      SXSQ=SXSQ+XSQ
      SYSQ=SYSQ+YSQ
      PXY=XVAL*YVAL
      SPXY=SPXY+PXY
   10 CONTINUE
```

```
C     ------------------------------------------------------------
C     CHECK FOR ZERO ARRAYS
C     ------------------------------------------------------------
      IF((SUMX.GT.0.).AND.(SUMY.GT.0.)) GO TO 20
      AMENX = 0.
      AMENY = 0.
      CCOF = 0.0
      TTEST = 0.
      RECO = 0.
      BASE = 0.
      SDEVY = 0.
      VARY=0.
      SDY=0.
      VARX=0.
      SDX=0.
      EVAL=0.
      SDIF=0.
      GO TO 30
C     ------------------------------------------------------------
C     CALCULATE MEAN,STANDARD DEVIATION,VARIANCE,CORRELATION
C     COEFFICIENT,STUDENTS T VALUE,REGRESSION COEFFICIENT
C     AND BASE CONSTANT OF REGRESSION EQUATION.
C     ------------------------------------------------------------
   20 AMENX=SUMX/FLOAT(N)
      AMENY=SUMY/FLOAT(N)
      AX=SXSQ-((SUMX**2.0)/FLOAT(N))
      AY=SYSQ-((SUMY**2.0)/FLOAT(N))
      TOP=SPXY-((SUMX*SUMY)/FLOAT(N))
      CCOF=TOP/((AX*AY)**0.5)
      NCC=N-2
      BNC=FLOAT(NCC)
      TTEST=CCOF*(BNC**0.50)/((1.0-(CCOF*CCOF))**0.50)
      RECO=TOP/AX
      BASE=AMENY-(RECO*AMENX)
      SDEVY=(AY**0.50)*((1.0-(CCOF*CCOF))**0.50)
      VARY=(SYSQ/NCC)-(AMENY*AMENY)
      VARX=(SXSQ/NCC)-(AMENX*AMENX)
      SDX=VARX**0.50
      SDY=VARY**0.50
C     ------------------------------------------------------------
C     CALCULATE COEFFICIENT OF MODEL EFFICIENCY
C     ------------------------------------------------------------
      DO 50 J=1,N
      XMMX=(X(J)-AMENX)*(X(J)-AMENX)
      XMY=(X(J)-Y(J))*(X(J)-Y(J))
      SXMMX=SXMMX+XMMX
      SXMY=SXMY+XMY
   50 CONTINUE
      EVAL=(SXMMX-SXMY)/SXMMX
      SDIF=((SDX-SDY)/SDX)*100.0
C     ------------------------------------------------------------
C     LISTING OF STATISTICS
C     ------------------------------------------------------------
      WRITE (6,420)
  420 FORMAT (1H0,42HCOMPARISON OF OBSERVED AND SIMULATED FLOWS,/,
     1 1X,36HSIMULATED FLOW IS DEPENDENT VARIABLE,//)
      IF (L.EQ.2) GO TO 405
      WRITE (6,400)
  400 FORMAT (1X,29HACTUAL VALUES USED THROUGHOUT,//)
      GO TO 415
  405 WRITE (6,410)
```

```
410 FORMAT (1X,26HLOG VALUES USED THROUGHOUT,//)
415 WRITE (6,414) SUMX,SUMY
414 FORMAT (1X,23HTOTAL OBSERVED FLOWS = ,F10.3,//,
   1 1X,24HTOTAL SIMULATED FLOWS = ,F10.3,/)
    WRITE (6,421) AMENX,AMENY,CCOF,TTEST,RECO,BASE,SDEVY,
   1 VARX,VARY
421 FORMAT (1X,25HMEAN OF OBSERVED FLOWS = ,F10.3,//,
   1 1X,26HMEAN OF SIMULATED FLOWS = ,F10.3,//,
   2 1X,26HCORRELATION COEFFICIENT = ,F10.3,//,
   3 1X,19HSTUDENTS T VALUE = ,F10.3,//,
   4 1X,25HREGRESSION COEFFICIENT = ,F10.3,//,
   5 1X,23HBASE CONSTANT FOR EQN = ,F10.3,//,
   6 1X,35HSTANDARD ERROR OF SIMULATED FLOW = ,F10.3,//,
   7 1X,30HVARIANCE OF OBSERVED VALUES = ,F10.3,//,
   8 1X,31HVARIANCE OF SIMULATED VALUES = ,F10.3,/)
    WRITE (6,422) SDX,SDY,SDIF,EVAL
422 FORMAT (1X,33HSTANDARD DEVIATION OF X VALUES = ,F10.3,//,
   1 1X,33HSTANDARD DEVIATION OF Y VALUES = ,F10.3,//,
   2 1X,46HPERCENTAGE DIFFERENCE IN STANDARD DEVIATION = ,F10.3,//,
   3 1X,28HCOEFFICIENT OF EFFICIENCY = ,F10.3,)
 30 RETURN
    END
    FINISH
```

A.11 Program DALT

```
        DATE 31/10/78   TIME 15/46/51                       LISTING FOR:- HRPR

FILE:   HRPRMAXIMOP     SUBFILE DALT IN CARD MODE

      LIST
      PROGRAM(DALT)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER DALT
C     ##################################################################
C     THIS PROGRAM GENERATES DAILY RUNOFF IN THOUSANDS OF CUBIC METERS
C     FROM DAILY RAINFALL (MM) AND DAILY PAN EVAPORATION (MM).,
C     THE BASIC STRUCTURE OF THE MODEL HAS BEEN DRAWN FROM THE
C     DALTON WATERSHED MODEL DESCRIBED BY DISKIN,BURAS AND ZAMIR (1973).
C     PROGRAM DEVELOPED AT THE HYDROLOGICAL RESEARCH UNIT OF THE
C     DEPARTMENT OF GEOGRAPHY, RHODES UNIVERSITY.
C     (P.J.T. ROBERTS 1975)
C     ##################################################################
      DIMENSION RAIN(31),EVAP(31),FLOW(31),RFLO(31),TRANS(20),LAST(12)
      DIMENSION PEADJ(12),DL(31),PL(31),TOBF(1000),TSIM(1000)
      DIMENSION OBFL(1000),SIMF(1000)
      DIMENSION EVMO(12)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C     ******************************************************************
C     READ IN CATCHMENT NAME OR RUN IDENTIFICATION - 32 COLUMNS
C     ******************************************************************
      READ (5,1) H1,H2,H3,H4
    1 FORMAT (4A8)
C     ******************************************************************
C     READ IN CATCHMENT AREA (SQ.KM) AND THE NUMBER OF MONTHS
C     OF INPUT DATA USED FOR SIMULATION AND
C     ISTAT = 1 TO INITIATE STATISTICAL PACKAGE AND
C           = 2 TO SUPPRESS STATISTICAL PACKAGE AND
C     IVAL  = 1 FOR USE OF ACTUAL VALUES IN STAT. PACK.
C           = 2 FOR USE OF LOG. VALUES IN STAT. PACK. AND
C     LINE  = 1 FOR USE OF LINEAR STORAGE
C           = 2 FOR NON-LINEAR STORAGE OPTION AND
C     ILIM  = 1 SETS OPERATIONAL RANGE OF NON-LINEAR DEPTH FUNCTION
C               FROM STORAGE LEVEL ZERO TO BASE FLOW LEVEL SSB
C           = 2 SETS OPERATIONAL RANGE OF NON-LINEAR DEPTH FUNCTION
C               FROM STORAGE LEVEL ZERO TO STORAGE CAPACITY SSM  AND
C     IOUT  = 1 FORMATS MODEL OUTPUT FOR SHORT PERIOD CALIBRATION
C             (ONE MONTH OUTPUT PER PAGE OF PRINTOUT)
C           = 2 FORMATS OUTPUT FOR LONG RECORD GENERATION
C             (APPROX. 15 MONTHS OUTPUT PER PAGE OF PRINTOUT) AND
C     MVAP  = 1 FOR USE OF AVERAGE MONTHLY VALUES OF PAN EVAP(MM)
C           = 2 FOR USE OF DAILY VALUES OF PAN EVAPORATION (MM)
C     ( IF ISTAT = 2 SET IVAL = 0 )
C     NOTE. THE FLAG SETTINGS FOR THE DALT RANGE OF MODELS
C     ARE AS FOLLOWS
C     DALT1   LINE=1   ILIM=2   SSB=SSM
C     DALT2   LINE=1   ILIM=2   SSB<SSM
C     DALT3   LINE=2   ILIM=2   SSB<SSM
C     DALT4   LINE=2   ILIM=1   SSB<SSM
C     ******************************************************************
      READ (5,2) AREA,NMON,ISTAT,IVAL,LINE,ILIM,IOUT,MVAP
    2 FORMAT (F8.2,7I5)
C     ******************************************************************
```

```
C     READ IN STORAGE PARAMETER VALUES
C     ALL STORAGE VALUES IN MILLIMETERS
C     SSL     INITIAL LEVEL OF STORAGE
C     SSM     MAXIMUM CAPACITY OF STORAGE
C     SSB     STORAGE LEVEL AT WHICH BASE FLOW BEGINS
C     POWER   POWER OF BASE FLOW FUNCTION
C     BCUR    POWER OF NON-LINEAR STORAGE DEPTH FUNCTION
C     AMAX    MAXIMUM VALUE OF STORAGE DEPTH FACTOR
C     PERC    MAXIMUM FRACTION OF SOIL MOISTURE TO DEEP PERCOLATION
C     IF LINE = 1 THEN SET BCUR AND AMAX EQUAL TO 1
C     IF BASE FLOW FUNCTION NOT REQUIRED SET SSB=SSM
C     ******************************************************************
      READ (5,3) SSL,SSM,SSB,POWER,BCUR,AMAX,PERC
    3 FORMAT (7F8.2)
C     ******************************************************************
C     READ IN THE REQUIRED LAG TIME IN DAYS
C     ******************************************************************
      READ (5,4) LAG
    4 FORMAT (I5)
C    *******************************************************************
C     READ IN 12 AVERAGE MONTHLY VALUES OF PAN EVAPORATION (MM)
C     JAN - DEC ONLY IF MVAP=1
C     ******************************************************************
      IF(MVAP.EQ.2) GO TO 761
      READ (5,766)(EVMO(NX),NX=1,12)
  766 FORMAT(12F6.1)
  761 IF (LAG.EQ.0) GO TO 9
C     ******************************************************************
C     READ IN LAG NUMBER OF DAYS OF TRANSLATED FLOW (1000 CUBIC METERS)
C     FROM PREVIOUS MONTH----ONLY IF LAG IS REQUIRED
C     ******************************************************************
      READ (5,5) (TRANS(I),I=1,LAG)
    5 FORMAT (8F10.3)
C     ******************************************************************
C     READ IN PAN TO FREE WATER SURFACE EVAPORATION CONSTANTS
C     12 VALUES  JAN. TO DEC.
C     ******************************************************************
    9 READ (5,6) (PEADJ(K),K=1,12)
    6 FORMAT (12F5.3)
C     ------------------------------------------------------------------
C     INITIALISE PROGRAM VARIABLES AND LIST MODEL STORAGE LEVEL,
C     PARAMETER VALUES AND PROGRAM CONTROL FLAGS.
C     ------------------------------------------------------------------
      BRA=SSB/SSM
      ICON=0
      RTOT=0.
      AMENX=0.
      AMENY=0.
      CCOF=0.
      TTEST=0.
      RECO=0.
      BASE=0.
      SDEVY=0.
      NOD=0
      PSL=SSL
      WRITE (6,7) SSL,SSM,SSB,POWER,BCUR,AMAX,PERC,LAG
    7 FORMAT (1H1,1X,21HPARAMETER VALUES USED,//,6X,3HSSL,6X,3HSSM,
     1 6X,3HSSB,4X,5HPOWER,5X,4HBCUR,5X,4HAMAX,5X,4HPERC,6X,3HLAG,/,
     2 7(1X,F8.2),4X,I5)
      WRITE (6,111) AREA,NMON,ISTAT,IVAL,LINE,ILIM,IOUT,MVAP
  111 FORMAT (1H0,1X,37HAREA AND PROGRAM CONTROL FLAGS SET AS,//,
```

```
     1 5X,4HAREA,5X,4HNMON,4X,5HISTAT,5X,4HIVAL,
     2 5X,4HLINE,5X,4HILIM,5X,4HIOUT,5X,4HMVAP,/,1X,F8.2,7(1X,I8))
      DO 46 JK=1,31
      OBFL(JK)=0.0
   46 CONTINUE
      IF (IOUT.EQ.1) GO TO 830
      WRITE (6,831) H1,H2,H3,H4
  831 FORMAT (1H1,1X,4A8,/)
      WRITE (6,310)
C     ------------------------------------------------------------------
C     START OF THE MONTHLY LOOP
C     ------------------------------------------------------------------
  830 DO 100 M=1,NMON
      SPR=0.
      SPE=0.
      SET=0.
      SROS=0.
      SGWF=0.
      FSUM=0.
      TFLO=0.
      TPER=0.
      ZOB=0.
C     ******************************************************************
C     READ IN ONE MONTH RAINFALL(MM),EVAPORATION(MM) AND RUNOFF DATA
C     OBSERVED RUNOFF DATA IN THOUSANDS OF CUBIC METERS
C     DAILY EVAPORATION DATA REQUIRED ONLY IF MVAP=2
C     RUNOFF DATA REQUIRED ONLY IF ISTAT=1
C     THREE CARDS PER MONTH FOR EACH TYPE OF INPUT
C     FOLLOWING FORMAT USED FOR ALL THREE TYPES OF INPUT
C     IDENTIFICATION      7X  (NOT READ BY PROGRAM)
C     YEAR                I2  (IE, 75 FOR 1975)
C     MONTH               I2
C     CARD CODE           I1    =1  DAYS  1 TO 10
C                               =2  DAYS 11 TO 20
C                               =3  DAYS 21 TO LAST DAY OF MONTH
C     R,E OR F        11F6.2    RAIN,EVAP OR RUNOFF DATA
C     RAINFALL FOLLOWED BY EVAP AND THEN RUNOFF FOR EACH MONTH
C     THE LENGTH OF RECORD FOR INPUT DATA IS UNLIMITED BUT
C     SHOULD NOT BE LESS THAN ONE MONTH.
C     ******************************************************************
      READ (5,10) NYR,NM,(RAIN(J),J=1,10)
   10 FORMAT (7X,2I2,1X,10F6.2)
      NEND=LAST(NM)
      IF (((NYR-4*(NYR/4)).EQ.0).AND.(NM.EQ.2)) NEND=NEND+1
      READ (5,11) (RAIN(J),J=11,NEND)
   11 FORMAT (12X,10F6.2,/,12X,11F6.2)
      IF(MVAP.EQ.2) GO TO 790
      DO 781 IZ= 1,NEND
      EVAP(IZ)=EVMO(NM)/FLOAT(NEND)
  781 CONTINUE
      GO TO 795
  790 READ (5,12) (EVAP(K),K=1,NEND)
   12 FORMAT (12X,10F6.2,/,12X,10F6.2,/,12X,11F6.2)
  795 IF (ISTAT.EQ.2) GO TO 13
      READ (5,12)(OBFL(L),L=1,NEND)
C     ------------------------------------------------------------------
C     START OF THE DAY LOOP
C     ------------------------------------------------------------------
   13 DO 50 IDA=1,NEND
      EP=EVAP(IDA)*PEADJ(NM)
      SPE=SPE+EP
```

```
      PR=RAIN(IDA)
      SPR=SPR+PR
C     -----------------------------------------------------------------
C     THE OPERATION OF THE STORAGE
C     -----------------------------------------------------------------
      RAT=SSL/SSM
      PRE=(RAT**0.50)+((RAT**0.50)-RAT)
      EP=EP*PRE
      PLE=SSL+PR
      IF (PLE.LE.EP) GO TO 200
      SET=SET+EP
      PLE=PLE-EP
      GO TO 210
  200 SET=SET+PLE
      PLE=0.
  210 OVF=PLE-SSM
      DL(IDA)=PLE
      IF (OVF.GT.0.) GO TO 220
      SSL=PLE
      FLOW(IDA)=0.
      OVF=0.
      GO TO 230
  220 FLOW(IDA)=OVF*AREA
      SROS=SROS+OVF
      SSL=SSM
C     -----------------------------------------------------------------
C     THE NON-LINEAR DEPTH FUNCTION
C     -----------------------------------------------------------------
  230 IF (ILIM.EQ.1) RANG=SSB
      IF (ILIM.EQ.2) RANG=SSM
      RAT=SSL/RANG
      IF (RAT.GT.1.0) RAT=1.0
      CR=RAIN(IDA)-EP
      FAT=AMAX-((AMAX-1.0)*(RAT**BCUR))
      IF (LINE.EQ.1) FAT=1.0
      PSL=PSL+(CR*FAT)
      IF (PSL.GT.SSM) PSL=SSM
      IF (PSL.LT.SSL) PSL=SSL
      RAT=PSL/SSM
      PL(IDA)=PSL
      IF (RAT.GT.BRA) GO TO 240
      BF=0.
      GO TO 250
C     -----------------------------------------------------------------
C     THE DEEP PERCOLATION FUNCTION
C     -----------------------------------------------------------------
  240 HEAD=PSL-SSB
      POTH=SSM-SSB
      PLOS=HEAD*((HEAD/POTH)*PERC)
      SSL=SSL-PLOS
      PSL=PSL-PLOS*FAT
      RAT=PSL/SSM
      TPER=TPER+PLOS
C     -----------------------------------------------------------------
C     THE BASE FLOW FUNCTION
C     -----------------------------------------------------------------
      XBRA=RAT-BRA
      BF=(PSL-SSB)*(XBRA**POWER)
      IF (BF.GT.SSL) BF=SSL
      SGWF=SGWF+BF
      SSL=SSL-BF
```

```
      IF (SSL.LT.0.) SSL=0.
      PSL=PSL-BF*FAT
      FLOW(IDA)=FLOW(IDA)+(BF*AREA)
      FSUM=FSUM+OVF+BF
  250 IF (LAG.GT.0) GO TO 50
      TFLO=TFLO+FLOW(IDA)
      IF (ISTAT.EQ.2) GO TO 50
      ZOB=ZOB+OBFL(IDA)
   50 CONTINUE
C     ------------------------------------------------------------------
C     END OF DAY LOOP AND START OF TIME DELAY SECTION
C     ------------------------------------------------------------------
      IF (LAG.EQ.0) GO TO 99
      I=0
      DO 92 KK=1,LAG
      RFLO(KK)=TRANS(KK)
   92 CONTINUE
      DO 93 J=1,NEND
      K=J+LAG
      IF (K.GT.NEND) GO TO 94
      RFLO(K)=FLOW(J)
      GO TO 93
   94 I=I+1
      TRANS(I)=FLOW(J)
   93 CONTINUE
      DO 95 NJ=1,NEND
      TFLO=TFLO+RFLO(NJ)
   95 CONTINUE
   99 IF (IOUT.EQ.2) GO TO 800
C     ----------------------------------------------------------------
C     OUTPUT SECTION FOR SHORT PERIOD CALIBRATION
C     ----------------------------------------------------------------
      WRITE (6,300) NM,NYR,H1,H2,H3,H4
  300 FORMAT (1H1,1X,28HSIMULATED RUNOFF FOR MONTH  ,I2,9H  YEAR 19,I2,
     1 //,1X,4A8,//)
      WRITE (6,310)
  310 FORMAT (1X,48HRUNOFF VALUES GIVEN IN THOUSANDS OF CUBIC METERS,//)
      WRITE (6,320)
  320 FORMAT (10X,3HDAY,5X,16HSIMULATED RUNOFF,8X,
     1 13HSTORAGE LEVEL,9X,12HPSEUDO LEVEL,6X,15HOBSERVED RUNOFF,//)
      DO 90 J=1,NEND
      IF (LAG.EQ.0) GO TO 97
      WRITE (6,330) J,RFLO(J),DL(J),PL(J),OBFL(J)
      GO TO 90
   97 WRITE (6,330) J,FLOW(J),DL(J),PL(J),OBFL(J)
  330 FORMAT (11X,I2,4(11X,F10.3))
   90 CONTINUE
      GO TO 850
C     ----------------------------------------------------------------
C     OUTPUT SECTION FOR LONG RECORD GENERATION
C     ----------------------------------------------------------------
  800 AFLO=TFLO/FLOAT(NEND)
      IF (LAG.EQ.0) GO TO 805
      WRITE (6,810) NYR,NM,(RFLO(J),J=1,NEND)
  810 FORMAT (3X,I2,1X,I2,1X,10F8.3,/,9X,10F8.3,/,9X,11F8.3)
      WRITE (6,811) TFLO,AFLO
  811 FORMAT (9X,14HMONTH TOTAL = ,F9.3,3X,16HDAILY AVERAGE = ,F9.3,/)
      GO TO 815
  805 WRITE (6,810) NYR,NM,(FLOW(J),J=1,NEND)
      WRITE (6,811) TFLO,AFLO
  815 GO TO 860
```

```
  850 AFLO=TFLO/FLOAT(NEND)
      AZOB=ZOB/FLOAT(NEND)
      WRITE (6,340) TFLO,ZOB,AFLO,AZOB
  340 FORMAT (1H0,7X,5HTOTAL,11X,F10.3,53X,F10.3,//,
     1 6X,7HAVERAGE,11X,F10.3,53X,F10.3,//)
C     ------------------------------------------------------------------
C     OUTPUT OF THE DATA COMPONENT SUMMARY
C     ------------------------------------------------------------------
      WRITE (6,350)
  350 FORMAT (1X,50HDATA COMPONENT SUMMARY - ALL VALUES IN MILLIMETERS,
     1 //)
      WRITE (6,351) SPR,SPE,SET,SROS,SGWF,FSUM,TPER
  351 FORMAT (1X,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRANS
     1 = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,
     2 15HSURFACE FLOW = ,F8.2,//,1X,12HBASE FLOW = ,F8.2,//,1X,
     3 13HTOTAL FLOW = ,F8.2,//,1X,19HDEEP PERCOLATION = ,F8.2)
C     -----------------------------------------------------------------
C     CREATE CONTINUOUS ARRAYS FOR SIMULATED AND OBSERVED RUNOFF
C     -----------------------------------------------------------------
  860 RTOT=RTOT+TFLO
      NNT=NOD+1
      ICON=ICON+1
      IF ((12-(ICON/12)*12).EQ.0) ANT=RTOT
      IF (ISTAT.EQ.2) GO TO 100
      IF (LAG.GT.0) GO TO 400
      DO 401 ILK=1,NEND
  401 SIMF(ILK)=FLOW(ILK)
      GO TO 402
  400 DO 404 KLK=1,NEND
  404 SIMF(KLK)=RFLO(KLK)
  402 NOD=NOD+NEND
      IIC=0
      DO 500 NUM=NNT,NOD
      IIC=IIC+1
      TSIM(NUM)=SIMF(IIC)
      TOBF(NUM)=OBFL(IIC)
  500 CONTINUE
  100 CONTINUE
C     --------------------------------------------------------------------
C     END OF MONTH LOOP
C     --------------------------------------------------------------------
      WRITE (6,352) RTOT
  352 FORMAT (1H1,1X,37HTOTAL RUNOFF FOR SIMULATION PERIOD = ,F10.3,//)
      IF ((ICON/12).GT.4) GO TO 370
      WRITE (6,353)
  353 FORMAT (1X,39HNO M.A.R. CALCULATED - RECORD TOO SHORT,//)
      GO TO 375
  370 TMAR=ANT/FLOAT(ICON/12)
      WRITE (6,354) TMAR
  354 FORMAT (1X,21HMEAN ANNUAL RUNOFF = ,F10.3,//)
  375 IF (LAG.GT.0) WRITE (6,356) (TRANS(I),I=1,LAG)
  356 FORMAT (5X,15HTRANSLATED FLOW,//,10X,10F10.3)
      IF (ISTAT.EQ.2) GO TO 450
      CALL CORK(TOBF,TSIM,NOD,IVAL)
  450 STOP
      END
C     ####################################################################
C     STATISTICAL PACKAGE TO CALCULATE MEASURES OF CORRESPONDENCE
C     BETWEEN OBSERVED AND SIMULATED FLOWS.
C     THE ACTUAL SIMULATED AND OBSERVED FLOWS WILL BE USED
C     UNLESS IVAL HAS BEEN SET TO 2 IN THE MAIN ROUTINE IN
```

```
C     WHICH CASE LOG. VALUES WILL BE USED SO AS TO AVOID
C     GIVING TOO MUCH WEIGHT TO THE HIGH FLOWS.
C     NO CALCULATION IS DONE IF ONE OR BOTH FLOW
C     ARRAYS CONSIST ENTIRELY OF ZERO FLOW.IN THIS CASE
C     ALL STATISTICS ARE SET TO ZERO AND THE LISTING OF STATISTICS
C     IS ABANDONED.
C     ##################################################################
      SUBROUTINE CORK(X,Y,N,L)
      DIMENSION X(1000),Y(1000)
      SPXY=0.
      SYSQ=0.
      SXSQ=0.
      SUMY=0.
      SUMX=0.
      SXMMX=0.
      SXMY=0.
      DO 10 I=1,N
      IF (L.EQ.1) GO TO 5
C     -----------------------------------------------------------------
C     CONVERT TO LOG. VALUES
C     -----------------------------------------------------------------
      X(I)=X(I)*1000.
      Y(I)=Y(I)*1000.
      IF (X(I).LT.1.0) X(I)=1.0
      IF (Y(I).LT.1.0) Y(I)=1.0
      XVAL=ALOG10(X(I))
      YVAL=ALOG10(Y(I))
      GO TO 6
    5 XVAL=X(I)
      YVAL=Y(I)
C     -----------------------------------------------------------------
C     CALCULATE ARRAY TOTALS,SUM OF SQUARES AND SUM OF CROSS PRODUCTS
C     -----------------------------------------------------------------
    6 SUMX=SUMX+XVAL
      SUMY=SUMY+YVAL
      XSQ=XVAL**2.0
      YSQ=YVAL**2.0
      SXSQ=SXSQ+XSQ
      SYSQ=SYSQ+YSQ
      PXY=XVAL*YVAL
      SPXY=SPXY+PXY
   10 CONTINUE
C     -----------------------------------------------------------------
C     CHECK FOR ZERO ARRAYS
C     -----------------------------------------------------------------
      IF ((SUMX.GT.0.).AND.(SUMY.GT.0.)) GO TO 20
      AMENX=0.
      AMENY=0.
      CCOF=0.
      TTEST=0.
      RECO=0.
      BASE=0.
      SDEVY=0.
      VARY=0.
      SDY=0.
      VARX=0.
      SDX=0.
      EVAL=0.
      SDIF=0.
      GO TO 30
C     -----------------------------------------------------------------
```

```
C     CALCULATE MEAN,STANDARD DEVIATION,VARIANCE,CORRELATION
C     COEFFICIENT,STUDENTS T VALUE,REGRESSION COEFFICIENT AND
C     BASE CONSTANT OF REGRESSION EQUATION.
C     ------------------------------------------------------------------
   20 AMENX=SUMX/FLOAT(N)
      AMENY=SUMY/FLOAT(N)
      AX=SXSQ-((SUMX**2.0)/FLOAT(N))
      AY=SYSQ-((SUMY**2.0)/FLOAT(N))
      TOP=SPXY-((SUMX*SUMY)/FLOAT(N))
      CCOF=TOP/((AX*AY)**0.5)
      NCC=N-2
      BNC=FLOAT(NCC)
      TTEST=CCOF*(BNC**0.5)/((1.0-(CCOF*CCOF))**0.50)
      RECO=TOP/AX
      BASE=AMENY-(RECO*AMENX)
      SDEVY=(AY**0.5)*((1.0-(CCOF*CCOF))**0.50)
      VARY=(SYSQ/NCC)-(AMENY*AMENY)
      VARX=(SXSQ/NCC)-(AMENX*AMENX)
      SDX=VARX**0.50
      SDY=VARY**0.50
      DO 50 J=1,N
      XMMX=(X(J)-AMENX)*(X(J)-AMENX)
      XMY=(X(J)-Y(J))*(X(J)-Y(J))
      SXMMX=SXMMX+XMMX
      SXMY=SXMY+XMY
C     ------------------------------------------------------------------
C     CALCULATE COEFFICIENT OF MODEL EFFICIENCY
C     ------------------------------------------------------------------
   50 CONTINUE
      EVAL=(SXMMX-SXMY)/SXMMX
      SDIF=((SDX-SDY)/SDX)*100.0
C     ------------------------------------------------------------------
C     LISTING OF STATISTICS
C     ------------------------------------------------------------------
      WRITE (6,420)
  420 FORMAT (1H0,42HCOMPARISON OF OBSERVED AND SIMULATED FLOWS,/,
     1 1X,36HSIMULATED FLOW IS DEPENDENT VARIABLE,//)
      IF (L.EQ.2) GO TO 405
      WRITE (6,400)
  400 FORMAT (1X,29HACTUAL VALUES USED THROUGHOUT,//)
      GO TO 415
  405 WRITE (6,410)
  410 FORMAT (1X,26HLOG VALUES USED THROUGHOUT,//)
  415 WRITE (6,414) SUMX,SUMY
  414 FORMAT (1X,23HTOTAL OBSERVED FLOWS = ,F10.3,//,
     1 1X,24HTOTAL SIMULATED FLOWS = ,F10.3,/)
      WRITE (6,421) AMENX,AMENY,CCOF,TTEST,RECO,BASE,SDEVY,
     1 VARX,VARY
  421 FORMAT (1X,25HMEAN OF OBSERVED FLOWS = ,F10.3,//,
     1 1X,26HMEAN OF SIMULATED FLOWS = ,F10.3,//,
     2 1X,26HCORRELATION COEFFICIENT = ,F10.3,//,
     3 1X,19HSTUDENTS T VALUE = ,F10.3,//,
     4 1X,25HREGRESSION COEFFICIENT = ,F10.3,//,
     5 1X,23HBASE CONSTANT FOR EQN = ,F10.3,//,
     6 1X,35HSTANDARD ERROR OF SIMULATED FLOW = ,F10.3,//,
     7 1X,30HVARIANCE OF OBSERVED VALUES = ,F10.3,//,
     8 1X,31HVARIANCE OF SIMULATED VALUES = ,F10.3,/)
      WRITE (6,422) SDX,SDY,SDIF,EVAL
  422 FORMAT (1X,33HSTANDARD DEVIATION OF X VALUES = ,F10.3,//,
     1 1X,33HSTANDARD DEVIATION OF Y VALUES = ,F10.3,//,
     2 1X,46HPERCENTAGE DIFFERENCE IN STANDARD DEVIATION = ,F10.3,//,
```

```
     3 1X,28HCOEFFICIENT OF EFFICIENCY = ,F10.3)
  30 RETURN
     END
     FINISH
```

A.12 Program STAT

```
       DATE 31/10/78    TIME 15/42/52                               LISTING FOR:- HRPR

FILE:   HRHRMAXIMOP     SUBFILE STAT IN CARD MODE

      LIST
      PROGRAM(STAT)
      INPUT 5=CR0
      OUTPUT 6=LP0
      TRACE 2
      END
      MASTER STAT
C     ##################################################################
C     THIS PROGRAM PROVIDES A RUN ANALYSIS OF A DAILY RAINFALL
C     RECORD(MM). A DRY RUN IS A NUMBER OF CONSECUTIVE DAYS WITH
C     RAINFALL LESS THAN OR EQUAL TO A PRESET THRESHOLD RAINFALL.
C     A WET RUN CONSISTS OF CONSECUTIVE DAYS WITH RAINFALL EXCEEDING
C     THE THRESHOLD. THE MEAN AND STANDARD DEVIATION OF DRY AND
C     WET RUNS IS GIVEN AS WELL AS THE MEAN AND STANDARD DEVIATION
C     OF WET RUN RAINFALL TOTALS.
C     PROGRAM DEVELOPED AT THE H.R.U. OF THE DEPT. OF GEOGRAPHY,
C     RHODES UNIVERSITY. (P.J.T. ROBERTS 1975).
C     ##################################################################
      DIMENSION IDRY(2000),IWET(2000),LAST(12),RAIN(32),RVOL(2000)
      DATA LAST/31,28,31,30,31,30,31,31,30,31,30,31/
C     ******************************************************************
C     READ IN THE NUMBER OF MONTHS OF RECORD (NMON) AND THE
C     THRESHOLD RAINFALL IN MM. (THRES).
C     ******************************************************************
      READ (5,200) NMON,THRES
  200 FORMAT (I5,F6.2)
      KCON=1
      ICON=1
      KD=1
      KW=1
      CHECK=0.
      CK=0.
      VOL=0.
C     ----------------------------------------------------------------
C     START OF THE MONTH LOOP
C     ----------------------------------------------------------------
      DO 10 KK=1,NMON
      NBEG=1
      NEND=10
C     ***************************************************************
C     READ IN ONE MONTH RAINFALL (MM) IN THREE CARDS AS FOLLOWS
C     IDENTIFICATION      7X   (NOT READ BY THE PROGRAM)
C     YEAR                I2   (I.E. 75 FOR 1975)
C     MONTH               I2
C     CARD CODE           I1   = 1  DAYS  1 TO 10
C                              = 2  DAYS 11 TO 20
C                              = 3  DAYS 21 TO LAST DAY OF MONTH
C     RAIN             11F6.2   DAILY RAINFALLS IN MM.
C     ******************************************************************
      DO 20 I=1,3
      READ(5,1)IY,M,(RAIN(J),J=NBEG,NEND)
    1 FORMAT(7X,2I2,1X,11F6.2)
      IF(I.EQ.1) MMM=M
      IF (I.EQ.1) KY=IY
      NBEG=NEND+1
      NEND=NEND+10
```

```
      IF(I.NE.2) GO TO 20
      NEND=LAST(MMM)
      IF(((KY-4*(KY/4)).EQ.0).AND.(MMM.EQ.2)) NEND=NEND+1
   20 CONTINUE
      NEND=LAST(MMM)
      IF(((KY-4*(KY/4)).EQ.0).AND.(MMM.EQ.2)) NEND=NEND+1
C     -----------------------------------------------------------------
C     COUNT NUMBER OF DAYS IN EACH DRY RUN
C     -----------------------------------------------------------------
      DO 50 J=1,NEND
      IF (RAIN(J).GT.THRES) GO TO 100
      IF(CHECK.NE.0.) GO TO 15
      RVOL(KW)=VOL
      VOL=0.0
      GO TO 3
   15 IF(ICON.LE.1) GO TO 3
      KD=KD+1
      RVOL(KW)=VOL
      VOL=0.
    3 IDRY(KD) = KCON
      KCON=KCON+1
      ICON=1
      CHECK=1.0
      GO TO 50
C     -----------------------------------------------------------------
C     COUNT NUMBER OF DAYS IN EACH WET RUN AND CALC. WET
C     RUN RAINFALL TOTALS.
C     -----------------------------------------------------------------
  100 IF(CK.EQ.0.) GO TO 4
      IF(KCON.GT.1) KW=KW+1
    4 IWET(KW)=ICON
      VOL=VOL+RAIN(J)
      ICON=ICON+1
      KCON=1
      CK=1.0
   50 CONTINUE
   10 CONTINUE
C     -----------------------------------------------------------------
C     END OF MONTH LOOP AND START OF SECTION TO CALC MEAN AND
C     ST. DEV. OF DRY AND WET RUN LENGTHS(DAYS) AS WELL AS
C     WET RUN RAINFALL TOTALS.
C     KD IS THE NUMBER OF DRY RUNS
C     KW IS THE NUMBER OF WET RUNS
C     -----------------------------------------------------------------
      ITD=0.
      DO 60 K=1,KD
      ITD=ITD+IDRY(K)
   60 CONTINUE
      RMD=FLOAT(ITD)/FLOAT(KD)
      ITW=0
      TT=0.
      DO 70 J=1,KW
      ITW=ITW+IWET(J)
      TT=TT+RVOL(J)
   70 CONTINUE
      RMW=FLOAT(ITW)/FLOAT(KW)
      RMV=TT/FLOAT(KW)
      TOPD=0.
      DO 80 KK=1,KD
      DUM=FLOAT(IDRY(KK))
      TOPD=TOPD+(DUM-RMD)*(DUM-RMD)
```

```
   80 CONTINUE
      RSDD=(TOPD/(KD-1))**0.5
      RTOP=0.
      TOPW=0.
      DO 90 JJ=1,KW
      ZZ=FLOAT(IWET(JJ))
      TOPW=TOPW+(ZZ-RMW)*(ZZ-RMW)
      RTOP=RTOP+(RVOL(JJ)-RMV)*(RVOL(JJ)-RMV)
   90 CONTINUE
      RSDW=(TOPW/(KW-1))**0.5
      SDV=(RTOP/(KW-1))**0.5
C     ------------------------------------------------------------
C     LIST THE DRY RUN LENGTHS (DAYS)
C     ------------------------------------------------------------
      WRITE(6,5)
    5 FORMAT(1H1,10X,21HDRY RUN LENGTHS(DAYS),//)
      WRITE(6,6)(IDRY(J),J=1,KD)
    6 FORMAT(10X,10I5,/)
      WRITE(6,7)RMD
    7 FORMAT(1H0,10X,23HMEAN OF DRY RUN LENGTHS,5X,F6.2,//)
      WRITE(6,8)RSDD
    8 FORMAT(1H0,10X,18HSTANDARD DEVIATION,5X,F6.2)
C     -----------------------------------------------------------
C     LIST THE WET RUN LENGTHS
C     -----------------------------------------------------------
      WRITE (6,9)
    9 FORMAT(1H1,10X,21HWET RUN LENGTHS(DAYS),//)
      WRITE(6,6)(IWET(K),K=1,KW)
      WRITE(6,11)RMW
   11 FORMAT(1H0,10X,23HMEAN OF WET RUN LENGTHS,5X,F6.2,//)
      WRITE(6,8)RSDW
C     -----------------------------------------------------------
C     LIST THE WET RUN RAINFALL TOTALS
C     -----------------------------------------------------------
      WRITE(6,12)
   12 FORMAT (1H1,10X,28HRAINFALL TOTALS FOR WET RUNS,//)
      WRITE(6,13)(RVOL(J),J=1,KW)
   13 FORMAT (10X,10F8.2,/)
      WRITE(6,14)RMV
   14 FORMAT (1H0,10X,23HMEAN OF RAINFALL TOTALS,5X,F6.2,//)
      WRITE(6,8)SDV
      STOP
      END
      FINISH
```