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CONCEPTUAL MODELLING OF THE RAINFALL-RUNOFF PROCESS IN SEMI-ARID CATCHMENTS IN SOUTH AFRICA

André Hermann Matheus Görgens

A thesis submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

March 1983

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DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

.....
(A H M Görgens)

15th day of March, 1983

ABSTRACT

This thesis comprises a study of the ability of mathematical conceptual models to simulate the hydrological response of semi-arid catchments to rainfall. Some of the conceptual rainfall-runoff models typically used by water resources engineers in South Africa and specific problems related to the application of such models in the semi-arid environment form the focal points of the research. For this purpose a set of seven conceptual models of differing complexity and with different requirements in respect of time resolution of input data was selected. The set of models consisted of three models developed at the Hydrological Research Unit, University of the Witwatersrand, Johannesburg, three models developed at the Hydrological Research Unit, Department of Geography, Rhodes University, Grahamstown and the Stanford Watershed Model. The data set used in the study was derived from three well-instrumented semi-arid research catchments (the "Ecca River catchments") in the Eastern Cape.

The suitability of the Ecca River data base for rainfall-runoff modelling research was investigated and a simple error analysis revealed ways in which hydrometeorological data thought be suitable for research purposes could be contaminated with sizable errors. The effects of typical input data errors on model output were explored by employment of the Stanford Model.

Various aspects of the use of automatic optimization routines for the estimation of model parameters, known as model calibration, were studied. A satisfactory calibration procedure based on the Rosenbrock algorithm was devised.

The effect of the choice of calibration data sample on the reliability of estimated model parameters was investigated by means of six years of concurrent rainfall and runoff records that are available for the Ecca River catchments, as well as by means of a 101-year synthetic flow series generated by the Stanford Model. For the generation of the synthetic flows a long rainfall record that is typical of the semi-arid environment in the Eastern Cape was used. The

results suggest that for the adequate calibration of both monthly-input and daily-input models in semi-arid catchments a calibration period length well in excess of ten years is required. Vast improvements in the ability of the models to accurately reproduce long-term characteristics of streamflow can be effected by expanding a calibration sample from, say, a seven-year record to a fifteen-year record.

An investigation into adequate levels of complexity of model structure and of model input requirements took the form of an intercomparison of the performance of the seven selected models. Four different performance tests were executed in which the ability of the models to reproduce the monthly and daily flow series in the Ecca River catchments was measured by a varied set of statistical criteria commonly used in water resources engineering. The results indicate that increased complexity of model input requirements does not necessarily lead to improved accuracy of estimation of monthly or daily flow totals. Some evidence was found of a correspondence between superiority of model performance and higher structural complexity of the models in the hourly and daily input categories. A minimum level of model complexity is indicated for the generation of daily and monthly flow series of acceptable accuracy.

The feasibility of estimating streamflows in catchments for which no flow records exist by transferring model parameter values from gauged catchments with similar physical characteristics was studied in the following way. For each model and for each of two of the Ecca River catchments model parameters estimated in the one catchment were used to generate flow series in the remaining two catchments. Deterioration of the values of the statistical performance criteria as compared with the original model calibrations in each catchment signified the degree of success achieved with each parameter transfer operation. In general, parameter transfer between two of the catchments was successful but between these two and the third produced poor results. These results can be explained by subtle, but measurable, differences in catchment characteristics. No evidence was found that either increased structural complexity or more complex input requirements of the models corresponded with superior transferability of parameter values.

Conceptual modelling emerges as an approach that is viable for semi-arid water resources studies but which requires careful and, often, subtle a priori decision-making with respect to a number of factors. The most important among the factors are the choice of calibration sample and parameter estimation procedure, the time resolution of model output required by the application in mind which in turn dictates the time resolution of input data, the highest level of model complexity that can be accommodated and, last but not least, the desired level of accuracy of the generated flow series.

"Let us at least work towards a situation where the trans-scientific judgements which practical hydrologists are forced to make are informed and sustained by a truly scientific hydrology: a sceptical science with a coherent intellectual content firmly based on the real phenomena."

Philip (1975, p.29)

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CHAPTER 1

GENERAL FRAMEWORK

1.1 INTRODUCTION

South Africa relies almost exclusively on surface water resources for all major water supplies for urban, industrial and irrigation development. Exploitable groundwater resources are limited and play only a small role in national or regional water resources planning. It is now generally accepted that only about 60 percent of South Africa's mean annual runoff of $54.10^9 m^3$ can be exploited by means of storage. However, the distribution of exploitable resources does not conform favourably to the distribution of water demands (Van der Riet, 1980). Water supply planners currently accept a time horizon of less than 25 years for the maximum exploitation of local surface water resources in some parts of the country (Hobbs, 1980). Currently, large-scale water resource planning, development and management present an unequalled challenge to South African water resources engineers and hydrologists.

During the planning phase of a project water resources engineers are faced with three basic needs:

(i) a need to extend or "patch" inadequate streamflow records,

(ii) a need to estimate streamflows in ungauged catchments,

(iii) a need to predict the long-term effects on water supplies of man-induced changes to a catchment.

During the water resource development and management phases two additional needs may arise:

(iv) a need to forecast the short-term response of a catchment to flood-producing rainstorms for the purposes of possible flood control or urban stormwater management,

(v) a need to forecast the quantitative and qualitative effects on streamflow of human manipulation of the river system, such as reservior releases, irrigation diversions and point effluent releases.

It is accepted practice that appraisal of the water resources of a particular river system, i.e. identifying river flow characteristics

and establishing relationships between reservoir capacity and yield, requires a long unbroken hydrograph representative of the complete flow regime of the river. Usually, these requirements imply a record length of 50 years or more. Unfortunately, long flow records are generally scarce and many records, affected by land-use changes, do not represent stationary time series.

In order to overcome these data problems and to meet the five basic needs outlined earlier, water resources engineers often have to resort to various forms of mathematical simulation or modelling of the hydrological response of catchments. Some of the models typically used by water resources engineers in South Africa and specific problems related to the use of such models form the focal points of the research reported in this thesis.

1.2 CONCEPTS AND DEFINITIONS

Models used in water resources engineering for the generation of streamflow (quantity and quality) can be broadly classified into two categories: statistical/stochastic or physical/deterministic. The statistical/stochastic approach recognizes the chance-dependence of hydrological processes while the physical/deterministic approach regards these processes as being chance-independent. Each of these categories can be subdivided into many classes of models. Hydrologists such as Clarke (1973 a,b) and Fleming (1975) have proposed more or less rigorous classification schemes in an attempt to bring order to the terminology used in the modelling field.

This thesis is concerned with a type of model generally known as conceptual rainfall-runoff models (conceptual catchment models), which falls in the physical/deterministic category. The conceptual models under consideration are of the "explicit moisture accounting" variety, one of three sub-classes of conceptual models defined in an international model intercomparison study by the World Meteorological Organization (WMO, 1975). In conceptual modelling the catchment is represented by one or more moisture storages through which rainfall inputs are routed by a process of moisture accounting, eventually to produce streamflow outputs. The storage sizes, the transfer of

moisture between storages and the exit of moisture as streamflow or evapotranspiration are all defined by mathematical relationships. The structures of the mathematical relationships are usually assumed to be constant for all catchments, but certain coefficients of these relationships, known as model parameters, are allowed to vary from catchment to catchment. The mathematical relationships are commonly devised in such a way that they describe (mostly empirically) the main processes known to occur in the land phase of the hydrological cycle. In this way, it is hoped, the model parameters can be expected to have physical meaning in terms of measurable catchment characteristics.

The procedure by which parameter values are determined for a specific catchment is known as the calibration of a model. Sometimes, certain model parameters can be derived by field observation of catchment processes; however, it is common practice to determine most parameter values by a trial-and-error procedure based on the correspondence between observed and simulated streamflows. If only one "average" set of parameters is specified for a whole catchment, the model concerned is known as a lumped-parameter model. Alternatively, the expression of the spatial variability common to all catchments in the form of different sets of parameters for different segments of a catchment is known as a distributed-parameter approach. This study is concerned specifically with the lumped-parameter conceptual modelling approach.

Conceptual models can be designed for either specific purpose or general purpose operation. Specific purpose models are developed to provide the highest level of simulation for those processes that are regarded as being important for the specific application of the model. Flood forecasting or low flow analysis models are typical examples in this category. Conceptual components unimportant to the specific purpose of the model are usually omitted from the model structure. General purpose models incorporate most of the flow components recognized in the land phase of the hydrological cycle and are often complex in structure. Such general models, in more or less complex form, have the potential to fulfill all five the needs of water resources engineers outlined in section 1.1 - given that certain minimum data requirements can be met.

1.3 CHANGING PERSPECTIVES ON CONCEPTUAL MODELLING

At the beginning of the seventies the "first generation" of conceptual rainfall-runoff models (Dawdy and O'Donnell, 1965; Crawford and Linsley, 1966) had been in use for about five years. At this point Nash and Sutcliffe (1970) described the central philosophy of conceptual modelling most succinctly: " The fact that a basin is not a random assembly of different parts, but a geomorphological system whose parts are related to each other by a long common history, encourages the hope that simplified concepts may be found adequate to describe the operation of the basin in converting rainfall to runoff. If in addition the relation between this operation and the physical features of the catchment can be recognised, the operation of even an ungauged catchment might be forecast from a study of these features". The Nash-Sutcliffe definition touched in a subtle way on the potential strengths and weaknesses of conceptual modelling, both of which, paradoxically, could be associated with the "hope" that simplified conceptualizations would provide adequate catchment models. Much of the hydrological literature of the ensuing decade concerns research into consolidation of the strengths and amelioration of the shortcomings implied above. Many aspects of this research are discussed and analysed, with ample referencing, in Chapters 5 and 6 of this thesis. At this juncture it may be appropriate to sketch the general perspectives on conceptual modelling existing at the end of the seventies (when this investigation was started).

By the end of the decade it was already clear that conceptual rainfall-runoff modelling had become a standard tool of non-specialist water resources engineering to a much greater extent than any statistical/stochastic technique. The "common sense" structure of the average conceptual model made the technique highly accessible to engineers and allowed them to develop a "feel" for operation of the models. Furthermore, ongoing research in developing countries such as South Africa and Australia, where hydrometeorological gauging networks have been relatively sparse until recent years, revealed that simpler models commensurate with the level of available input data could yield

results comparable with those of more complex models.

One of the dominant trends of the seventies concerns the last-mentioned point, i.e. a movement away from modelling the maximum number of physical processes. As Garrick, Cunnane and Nash (1978) have pointed out: "Experience in the current decade has indicated that it is 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". Researchers working with the more complex general purpose models sometimes found that such models were "over-determined", i.e. that the models had too many parameters, resulting in some parameters "absorbing" errors in the input data. Such models performed poorly when verified on data not used during the calibration process.

An area in which perspectives on conceptual modelling changed drastically during the seventies is that of the physical meaning of model parameters. As the Nash and Sutcliffe (1970) quotation at the head of this section reveals, it was initially expected that reasonable relationships between parameter values and measurable catchment characteristics would be forthcoming. In such a situation model parameters could be obtained with a high level of confidence from field observation. Model application to ungauged catchments as well as reliable estimation of the effects on streamflow of land-use changes (by suitable changes to physically-realistic parameters) were two of the expected benefits of parameter/catchment characteristic relationships. However, in many cases clear relationships between model parameter values and measurable catchment characteristics could not be established, giving rise to a degree of disillusionment in complex models purported to possess a high level of correspondence between model components and all physical catchment processes. A key aspect of this problem was the fact that it was often impossible to determine unique parameter sets for specific catchments and that very different sets of parameter values could produce comparable outputs.

The reasons for this "failure" of conceptual modelling are explored in depth in Chapters 5 and 6.

The general disillusionment caused by the lack of success of reliable parameter estimation from physical features of a catchment placed the ungauged catchment "problem" in a new light. The only alternative way to derive parameter values for an ungauged catchment is by direct transfer of the values derived through calibration of a model on a gauged catchment which is hydrologically as similar as possible to the ungauged one. This parameter transfer technique was first recommended by the developers of the classic Stanford Watershed Model (Crawford and Linsley, 1966), but seemed by the early seventies to have fallen into disrepute among specialist hydrologists. The accent on the need for physically-realistic parameter values, combined with a great upsurge in the development of models based on partial/variable source area theories of runoff generation (Kirkby, 1978), resulted in a lack of systematic research on parameter transfer possibilities. Nevertheless, practising engineers, accustomed to traditional hydrological techniques based on regionalization of statistical relationships among hydrological variables, continued to use parameter transfer to good effect. In fact, in South Africa the technique acquired so much respectability in engineering circles that parameter transfer became one of the cornerstones of a national survey of water resources in which application of a conceptual rainfall-runoff model, developed by Pitman (1973), played a key role (Hydrological Research Unit, 1981-1982).

During the seventies a start was made with using lumped-parameter conceptual rainfall-runoff models as the "carriers" of water quality sub-models. In South Africa this approach was shown to be useful for planning purposes at a macro-scale (Hall and Görgens, 1979) or in catchments where point or man-made sources of water quality constituents dominate the natural production of the catchment (Herold, 1981). As a forecasting technique, however, this use of conceptual models has made less of an impact generally. All the shortcomings of the basic rainfall-runoff model are of course also incorporated in the combined "piggy-back" water quality model: the lack of physical meaning of parameters, the problem of deriving representative and unique model parameters , and the uncertainties involved in parameter value transfer from gauged to ungauged catchments.

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1.4 THE ROLE OF COMPARATIVE STUDIES OF CONCEPTUAL MODELS

During the past fifteen years a plethora of lumped-parameter conceptual rainfall-runoff models have been reported in hydrological literature. This proliferation has been partially a response to the ever increasing complexity of modern water resources planning, design and management, partly a movement with the trend towards less complex models, and partly a consequence of the increasing availability of high-speed digital computers. The non-specialist engineer or hydrologist, needing a model to solve a specific water resources problem, may find it very difficult to make a judicious choice of a model suitable to his needs and to the level of available data. Often, there must be a temptation to follow the route of least inconvenience, namely to choose whatever model is at hand or is easily acquired or seems reasonably uncomplicated to use. For some time now there has been a continuing need that more of the available models should be objectively tested and their performance compared.

By the early seventies the WMO (1975) recognised that model intercomparison studies offered a solution to the dilemma of model selection. Hoping to promote the establishment of guidelines for model selection the WMO coordinated an ambitious international intercomparison of performance of conceptual models used in flood forecasting. The results of the WMO study can unfortunately not be generalized as the models used were all fairly complex, with short time interval input data requirements. During the ensuing years a number of conceptual model intercomparisons have been reported internationally, the most notable of which are listed in Table 1.1.

Table 1.1

Notable intercomparisons of conceptual rainfall-runoff models

Source	No. of models	No. of catchments	Countries	Climate range
WMO (1975)	10	6	6 different countries	wide range
Moore and Mein (1975)	3	4	Australia	wide range
Naef (1977, 1981)	10	3	Switzerland	similar climates
Black and Aitken (1977)	2	2	Australia	different climates
Pitman (1977, 1978)	4	3	South Africa	similar climates
Roberts (1978)	8	5	South Africa	similar climates
Weeks and Hebbert (1980)	5	3	Australia	similar climates
O'Connell and Clarke (1981)	4	1	U.K.	-
Moore and Clarke (1981)	2	4	U.K.	wide range

To enable a potential user of conceptual rainfall-runoff models to gain maximum benefit and guidance from a reported intercomparison of models on the same data set, the intercomparison should ideally meet four maximum requirements:

(i) The complete intercomparison should be executed by persons other than the developers of the models - to ensure true objectivity and independence and to give an indication of the effort required to obtain and transfer knowledge about each of the models.

(ii) The set of models should cover a range of complexities so that the minimum degree of complexity necessary for any specific model application can be inferred from the intercomparison.

(iii) The quality of the data set used should be of a research standard so that modelling errors do not obscure essential differences in performance among the respective models.

(iv) The comparison of model performance must at least partly be based on a verification data set, i.e. representative simultaneous input and output data series not used in the calibration of the models.

Obviously, further requirements can be formulated, but even measured by these four requirements only very few reported model comparisons would meet the information needs of a potential user searching, for example, for a reliable but time-efficient model to use in semi-arid water resources studies for which parameter transfers into ungauged catchments might be a necessity.

The need for research that will lead to the development of guidelines for the selection of suitable models for specific applications has been stressed by Dooge (1977): "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". In South Africa

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this need still exists today and it is hoped that the research reported in this document will contribute towards guidelines for the model selection process.

1.5 RESEARCH NEEDS IN SOUTH AFRICA

South African research needs in the field of lumped-parameter conceptual rainfall-runoff modelling can be expressed in terms of four interrelated factors:

(i) the predominance of climatic conditions in the semi-arid/near-semi-arid range,

(ii) the need for guidelines for the selection of adequate levels of conceptual model complexity for specific applications, using data from semi-arid regions,

(iii) the need for guidelines for the calibration of conceptual models in both gauged and ungauged semi-arid catchments,

(iv) the high variability of the quality of the national hydrometeorological data base.

1.5.1 Modelling in the semi-arid environment

Over 50 percent of the land surface of South Africa experiences a climate that can be described as semi-arid or near semi-arid. Consequently, research into rainfall-runoff modelling in semi-arid catchments is of great importance to the country. One aspect of the results of the WMO (1975) model intercomparison project (see Table 1.1) is of special relevance to the last-mentioned point: all seven moisture accounting models tested performed appreciably worse on the two semi-arid catchments than on the remaining four humid catchments. Regarding this finding Chapman (1975) cautions that "....It should not be inferred that matters would worsen further with increasing aridity, as the prediction errors are probably associated with failure to model the soil water status of the catchment, which can be done with the least error in catchments which are generally wet or generally dry. In

this regard, the most difficult catchments may well be those where the precipitation is in the range 30 to 60 percent of the potential evaporation".

Semi-arid rainfall-runoff modelling research in South Africa has been reported by Roberts (1978), Hall and Görgens (1979) and Murray and Görgens (1981). Though important in their own right, for various reasons none of these studies has produced definitive results. There is still a real need to assess the ability of typical general purpose conceptual models in use in South Africa to model semi-arid rainfall-runoff processes.

1.5.2 Model complexity

Pitman (1977, 1978) compared three of his own models of differing complexity with the Stanford Watershed Model using data from three temperate catchments near Johannesburg. The Stanford Model and the most complex Pitman model required hourly rainfall inputs, while the other two models required respectively daily and monthly rainfall inputs. The outcome of the study was that the two simpler models produced monthly and annual outputs at levels of accuracy comparable with those of the two complex models. Pitman concluded that his monthly model would be as suitable for water resources analysis as any of the more complex models.

The implications of Pitman's findings are far-reaching. The choice of a model that is just sufficiently complex in terms of input and structure to provide results at a level of accuracy that is adequate for the application in mind would minimize the cost of data collection and the time, effort and computer costs involved in familiarisation and calibration.

Inevitably the question arises as to whether Pitman's (1977, 1978) conclusion regarding model complexity is valid for the semi-arid environment. Phrased more generally, what is the minimum level of model complexity necessary for acceptable performance in terms of water resources analysis in semi-arid catchments? Roberts's (1978) investigation addressed this very point (see Table 1.1). The models

Roberts selected did not include Pitman's three models, but he arrived at a similar (tentative) conclusion - that simple models can produce output at a level of accuracy that is competitive with complex models. Unfortunately, three problems affected the merit of Roberts's conclusion. Firstly, he used relatively short records (17 months) which contained few flow events of which only one could be described as "sizable". Secondly, it has subsequently been discovered that the version of the model Roberts used to represent the complex end of his range of models, the Stanford Watershed Model, contained programming errors which seriously affected the performance of the model (see section 4.1.3). Thirdly, it has also been discovered that the flow records of two of the catchments Roberts included in his study, may have contained serious errors (see section 2.3.1).

There is another aspect of the model complexity issue which is of relevance to South Africa. During recent years Pitman's (1973, 1976) monthly and daily models have been rapidly gaining a reputation in water resources engineering circles as "standard" South African models (Hydrological Research Unit, 1981-1982). It is not too early to ask the question: how do their performances in semi-arid catchments compare with those of more complex models or indeed of simpler models? Research leading to an answer to this question would be of direct benefit to the South African water resources engineering fraternity and contribute to a general understanding of what level of conceptual model complexity is adequate for simulation of semi-arid rainfall-runoff processes.

1.5.3 Parameter estimation

It is now generally accepted that reliable parameter estimation in conceptual rainfall-runoff models is laden with pitfalls and complexities (see Chapters 5 and 6). At the same time there can be little doubt that such models will continue to enjoy widespread use in South Africa for many years, because more physically-based models require prohibitive numbers of field measurements prior to application, while the more empirical and the statistical/stochastic approaches offer little hope of benefits in terms of the ungauged catchment "problem" or estimation of the effects of land-use changes

on flow.

In this context research into parameter estimation techniques remains a necessity in South Africa, both for model calibration and for model application to ungauged catchments. Specifically, the technique of transferring parameter values from gauged to ungauged catchments needs to be explored in semi-arid catchments.

1.5.4. Quality of hydrometeorological data

The quality of the hydrometeorological data obtained from the national gauging networks of the Department of Environment Affairs and the Weather Bureau of the Department of Transport is highly variable, both spatially and temporally. Specifically in the semi-arid parts of the country, the quality of the data base is not satisfactory for in-depth rainfall-runoff modelling research (Görgens and Hughes, 1982). A common problem in many of these areas is non-stationarity of streamflow records due to changing land-use and other human interference with the flow regime.

For meaningful rainfall-runoff modelling research in South Africa the development of a growing data bank of hydrological processes observed over short time-intervals (eg. hourly) in research catchments in different climatic regions of the country is a dire necessity. The Ecca research catchments near Grahamstown (Roberts, 1978), maintained by the Hydrological Research Unit at Rhodes University, fulfill the aforementioned need in terms of the semi-arid environment. The Ecca River catchments are uncultivated, densely instrumented and fairly similar in climate, vegetation and lithology.

1.6 AIMS OF THE RESEARCH

The research described in this thesis was designed in terms of South African research needs in the field of conceptual rainfall-runoff modelling, as sketched in section 1 5. Care was also taken that all four requirements for meaningful comparative model studies, outlined in section 1.4, were met. Data needed for the project were derived from the hydrometeorological gauging networks in the semi-arid

Ecca research catchments. A summary of the aims of the research follows:

(i) To develop a hydrometeorological data bank of semi-arid rainfall-runoff processes suitable for testing of conceptual rainfall-runoff models. This would include an assessment of the accuracy of the various types of data (Chapters 2 and 6).

(ii) To examine for semi-arid conditions a selection of lumped-parameter conceptual rainfall-runoff models, developed in South Africa and covering a range of complexities and rainfall input requirements. This would include identifying inadequacies in the models under these conditions and incorporating any modifications thought to be necessary (Chapters 3 and 4).

(iii) To investigate problems associated with the estimation of parameter values for conceptual models in gauged catchments, otherwise known as model calibration. This would include both non-uniqueness of parameter values for a given data set (Chapter 5) and variability among parameter sets derived from different calibration samples for the same catchment (Chapter 6).

(iv) To compare the performance of the selected models within hourly, daily and monthly rainfall input categories in terms of selected statistical criteria. These criteria should include measures of performance commonly used in hydrological modelling, as well as error functions based on streamflow statistics commonly used in water resources engineering (Chapter 7).

(v) 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 (Chapter 7).

(vi) 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 measurements have been made (Chapter 8).

1.7 THE SELECTED MODELS

In order to pursue the above aims it is necessary to select models developed for South African conditions that comprise the following :

(i) A variety of uses. The selection should cover models designed for simulation of flow volume only as well as those designed to simulate the complete hydrograph.

(ii) A variety of time-intervals for input data, i.e. hourly, daily and monthly rainfall input requirements

(iii) Different complexities of model structure within each time-interval category for input; at least two models per category should be tested.

A selection of models was made with the above requirements in mind. These are discussed in Chapters 3 and 4 but are dealt with briefly here in descending order of complexity.

1.7.1 Hourly-input models

(i) Model FORD - a version of the Stanford Watershed Model by Crawford and Linsley (1966). Though not a South African model, this model was chosen because it is one of the most complex and most generally applicable conceptual models yet developed. As such its performance would provide a good "benchmark" against which the performance of all the South African models could be measured

(ii) Model PITH - a version of an hourly-input model by Pitman (Pitman and Basson, 1979), designed for flood modelling on a continuous input-output basis. Pitman's original model was considerably modified for this research (as described in Chapter 3)

(iii) Model PITR - a modification of model PITH incorporating important changes to the infiltration functions.

1.7.2 Daily-input models

(i) Model PITD - a model by Pitman (1976) which is similar in structure to PITH.

(ii) Model DALT - a model developed by Roberts (1978). The model is very simple in structure and was designed to be "just sufficiently complex to compete (in terms of accuracy of output) with the complex models" (Roberts, 1978).

1.7.3 Monthly-input models

(i) Model PITM - a model by Pitman (1973) designed specifically for water resources analysis.

(ii) Model DALM - a monthly-input version of model DALT by Roberts (1978).

CHAPTER 2

THE ECCA RESEARCH CATCHMENTS AND THE HYDROMETEOROLOGICAL DATA BASE

2.1 INTRODUCTION

During the years 1974 and 1975 the Geography Department of Rhodes University, Grahamstown, instrumented five nested catchments in a semi-arid zone about 20km from Grahamstown, with the express purpose of establishing a growing data bank for use in research on rainfall-runoff processes in a semi-arid environment. These research catchments vary in area from 1,1km^2 to 73,1km^2 and are all drained by tributaries of the Ecca River (previously known as the Brak River), a tributary of the Great Fish River, which drains the semi-arid eastern flank of the Karoo region of South Africa.

Fig. 2.1 depicts the Ecca catchments' location, configuration and hydrometeorological gauging network. Although all five catchments have been assigned code numbers by the Department of Environment Affairs (DEA) according to the national river gauging network code system, in this report the Hydrological Research Unit (HRU) codes A, B, C, D and E are used (see Table 2.1). The areas of the five catchments are listed in Table 2.1. The range of catchment sizes originally chosen for the Ecca monitoring network represents a rational compromise between the economic considerations of establishing and maintaining a gauging network of above average density, the need for reasonable homogeneity over the group of catchments and the objective that the catchments should be small enough to allow the rigorous testing of short time increment (e.g. hourly) modelling of land surface processes (Roberts, 1978).

In the context of the aims of this study set out in Chapter 1 the Ecca research catchments offer an excellent opportunity for the testing of explicit-soil-moisture-accounting conceptual rainfall-runoff models. Because of their relative smallness and their nested configuration, the Ecca catchments appear fairly similar in terms of climate, vegetation and lithology. The only prevailing form of land use is small livestock farming, which is practised in a stable manner.

Table 2.1
Ecca research catchment sizes

Catchment DEA code*1	HRU code	Area (km^2)
Q9M20	A	73,1
Q9M21	B	9 1
Q9M22	C	2,0
Q9M23	D	1,1
Q9M24	E	23,1

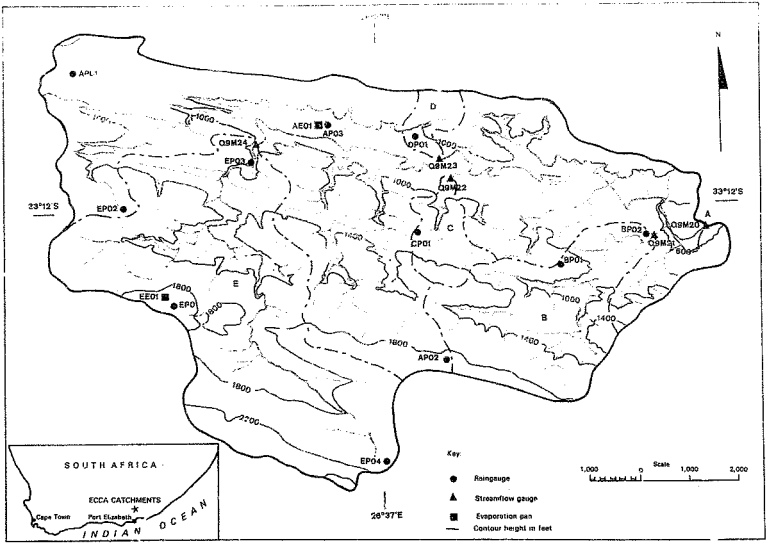
*1 Department of Environment Affairs

Table 2.2
Climate statistics for the Ecca research area

Month	Long-term mean rainfall (mm)	7-Year mean rainfall (mm)	Long-term free surface evaporation (mm)	Symons pan factor	7-Year free surface evaporation	A-pan factor (smoothed)	Regional A-pan factor
Jan.	37	41	173	0,96	167	0,76	0,75
Feb.	40	64	134	0,96	136	0,77	0,77
March	49	63	118	0,91	122	0,75	0,70
April	35	32	90	0,95	92	0,74	0,74
May	33	33	77	0,96	74	0,74	0,74
June	20	20	64	0,92	67	0,74	0,74
July	20	36	77	0,96	75	0,74	0,74
Aug.	25	36	91	0,96	90	0,72	0,73
Sep.	36	32	96	0,96	87	0,69	0,69
Oct.	43	41	125	0,96	128	0,71	0,71
Nov.	45	41	144	0,96	153	0,74	0,76
Dec.	37	49	173	0,90	173	0,75	0,74
Total	420	487	1362		1364		

*1 Based on a 92-year reconstruction by Roberts (1978).
*2 Estimated from Symons pan values (Pitman, 1973) with regional conversion factors (Roberts, 1978) applied.
*3 Estimated from Class A-pan observations with smoothed regional conversion factors applied.
*4 Regional conversion factors used by Directorate of Water Affairs.

Figure 2.1 *The Ecca River research catchments and the gauging network - scale in meters*
(see overleaf)


APL1
AE01
AP03
OP01
OSM24
EP03
OSM23
OSM22
EP02
33°12'S
33°12'S
OSM20
OSM21
BP02
CP01
BP01
EE01
EP01
AP02
EP04
26°37'E
N
A
B
C
D
E
1000
1200
1400
1600
1800
2000
Key:
Raingauge
Streamflow gauge
Evaporation pan
Contour height in feet
Scale
1,000
0
1,000
2,000
SOUTH AFRICA
ECCA CATCHMENTS
Cape Town
Port Elizabeth
INDIAN OCEAN

The vegetation is of a type (see section 2 2.2) that does not undergo appreciable transformations from season to season, nor is it very sensitive to grazing. All these characteristics render the Ecca catchments as unchanging and apparently as homogeneous as a general model user could hope to find in practice.

The Ecca catchments and the available data base are discussed in detail in subsequent sections. In the process extensive use will be made of the excellent physical description of the catchments by Roberts (1978), who processed a large volume of morphometric and physiographic data to provide a unified picture of the research area.

2.2 DESCRIPTION OF THE ECCA CATCHMENTS

2.2.1 General climate

The climate of the research area is harsh, with large differences between seasonal and daily extreme and average temperatures. According to synthetically reconstructed histories of rainfall in the lower Great Fish River catchment, the long-term mean annual precipitation (MAP) of the greater Ecca catchment is between 420mm (Midgley and Pitman, 1969) and 532mm (HRU, 1981, Volume 5). Records from the raingauge network (discussed later in this chapter) in the Ecca catchment since 1975 yield a seven-year average annual rainfall of 487mm with a standard deviation of 99mm. Rain-days (daily fall > 0.1mm)averaged 101 per year during the 1975-1981 period. Long-term mean annual free water surface evaporation is estimated at approximately 1362mm, using monthly Symons pan figures from Pitman (1973) and regional conversion factors supplied by the Department of Environment Affairs (Roberts, 1978). The seven-year average annual free water surface evaporation measured by two Class A pans (and after applying regional conversion factors) amounts to 1364mm, with a standard deviation of 94mm.

Table 2.2 provides information on the monthly distribution of the above mean annual climate statistics. According to both the long term estimates and the seven-year observed period the major part of the annual rainfall occurs in the "summer" months (October to March - the

mean "summer" falls being 59,8% and 61,8% of the MAP, respectively. The dominant rainfall-producing mechanisms in summer and winter differ substantially. Convectional or convergence thunderstorm systems cause most of the summer rainfall, while winter rain is usually associated with large-scale frontal systems sweeping along the south coast of the South African sub-continent.

The analysis of the spatial distribution of both long-term mean point precipitation and major storms as observed with the raingauge network reveal a roughly consistent pattern of spatial variation in the rainfall. Fig. 2.2 illustrates the overall pattern of progressive decrease of raingauge catch from south to north, as well as from west to east. This variation in rainfall is also depicted in some of the isohyetal maps of the individual storms analysed for flood hydrograph prediction in Chapter 3 and shown as Figs. 3.2(a) to (i). As is clear from the latter group of figures some rainfall events deviate from the pattern shown in Fig. 2.2. These deviations are usually associated with convectional thunderstorms which produce random spatial distributions of falls, while the overall spatial trends in Fig. 2.2 are essentially due to frontal rainfall that "fades" in the north-easterly direction. The prevalence of cold fronts during the period April to October is the cause of the *surprisingly large (for a semi-arid environment)* average number of rain-days (101) reported earlier. These storms are typified by relatively small falls spread over a number of days.

The "mixed" and highly variable nature of the general climate of the Ecca area is illustrated by Table 2.3 and can be related to the catchments' location in a climatic zone transitioning from the sub-humid all-year rainfall region of the southwest to the more arid *summer rainfall regions of the northwest* to the temperate summer rainfall regions of the east. On a regional scale the general climate of the Ecca area is typical, albeit somewhat more arid than the rest of the Albany/Border area and somewhat less arid that the northern parts of the Great Fish River catchment. On a national scale the MAP and mean annual free surface evaporation are close to the average values calculated for the Republic of South Africa (Commission of Enquiry into Water Matters, 1970).

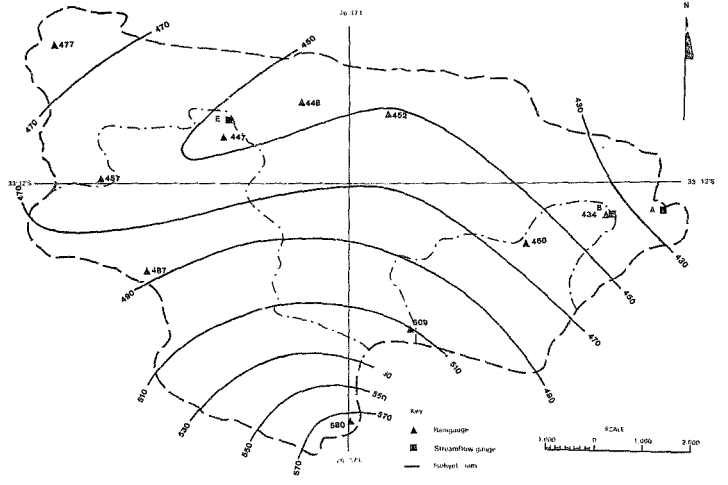
Table 2.3

Observed average rainfall and class A-pan evaporation in Ecca catchment A

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
						Rainfall (mm)							
1975	31,0*	49,7	60,9	6,6	3,0	41,9	10,1	17,5	89,3	3,6	19,0	57,6	390,2
1976	55,6	81,4	155,3	12,3	24,8	10,9	36,2	8,7	16,5	62,0	39,8	23,7	527,2
1977	17,9	134,6	21,2	49,2	71,0	4,8	2,0	9,7	33,3	6,8	75,0	104,4	529,9
1978	56,5	31,5	32,2	11,9	17,2	25,3	2,0	11,9	13,4	81,4	35,7	49,4	468,7
1979	46,3	96,8	16,3	2,3	43,0	24,5	189,8	130,1	30,3	44,8	12,8	12,1	649,1
1980	33,9	37,1	43,3	27,4	0,8	23,4	1,6	10,3	27,6	23,3	79,6	39,0	347,3
1981	44,6	19,2	116,3	9,9	67,4	11,0	0,3	62,2	12,0	73,4	28,6	54,0	498,9
Mean	40,9	64,3	63,9	31,7	32,7	20,5	34,6	35,6	31,7	42,4	41,4	48,7	487,4
%Total	8,4	13,2	13,1	6,5	6,7	4,2	7,1	7,3	6,5	8,7	8,5	10,0	100,0
						Class A-pan evaporation (mm)							
1975	186*	177	179	155	122	102	128	169	95	244	230	211	1990
1976	207	167	128	93	77	106	91	112	120	155	239	287	1782
1977	265	169	161	123	104	113	125	142	122	191	196	229	1939
1978	198	185	193	116	107	81	81	132	154	158	221	223	1850
1979	235	214	191	130	91	83	86	92	123	171	222	262	1899
1980	263	177	169	138	123	80	102	114	128	181	178	197	1849
1981	184	155	132	117	72	64	100	90	136	171	181	205	1605
Mean	220	177	164	124	100	91	102	122	126	181	209	231	1846
%Total	11,9	9,6	8,9	6,7	5,4	4,9	5,5	6,6	6,8	9,8	11,3	12,5	100,0

* Values estimated from Grahamstown data

Figure 2.2 Mean annual precipitation
over the research area (1975-1981)
- scale in meters
(see overleaf)


N
477
470
460
448
452
447
457
434
460
487
480
509
510
530
550
570
580
470
460
450
Key
Raingauge
StreamFlow gauge
Isohyet - mm
SCALE
1,000
0
1,000
2,000

2.2.2 Vegetation

Acocks (1953) classified the vegetation of the Ecca region under "Karoo and Karroid Bushveld Type iv", known as Valley Bushveld. The vegetation consists of tall sub-succulent bush in upper catchment areas and on the lower slopes of incised tributaries; this thins out to low succulent shrub on flatter areas and the lower parts of catchments B and A. There is a fair proportion of bare ground throughout the year, as was shown by Roberts (1978) who found, by detailed mapping from aerial and ground photographs, that the "ground cover" on 53% of catchment A could be described as "sparse" (or worse), while the "canopy cover" over 26% of the area fell in the same category. A "dense" classification for ground cover was given to 11% of the area, as opposed to 26% for canopy cover. Fig. 2.3 depicts the approximate spatial distribution of the vegetation categories.

2.2.3 Geology

As Fig. 2.4 illustrates, three major geological units are found in the Ecca area, namely the Witteberg Group, belonging to the Cape Supergroup, and the Dwyka and Ecca Groups, representing the Karoo Supergroup. Roberts (1978) describes the geological structure as "...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 of the formations is west/northwest to east/southeast. Two of the hardest formations present (Johnson, 1976), the Witteberg quartzite and the Dwyka tillite, together form the southern watershed of the research area (and the Great Fish River) while a broad band of the hardest of the shales (Johnson 1976), the Fort Brown shales (Ecca Group), forms the northern boundary. From Fig. 2.4 it is clear that about 90% of the surface geological formations of the research area represent the Karoo Supergroup. In this sense the research catchments can be regarded as fairly representative, geologically, of the middle to lower Great Fish River catchment (Tordiffe, 1978).

2.2.4 Physical features

The general physiography of the Ecca catchments is shown in Fig. 2.1. The Witteberg quartzite at Botha's Ridge in the south forms the highest ground at 738 metres, giving a maximum basin relief of 570 metres. The approximately west/east line of the main channel follows the strike of the rock formations and as a result of the alternating shale and sandstone bands (Fig. 2.4), the area is highly intersected, with the main tributaries forming deeply incised valleys at right angles to the strike. Soils tend to be shallow and stoney on hilltops and -slopes and extensive rock outcrops are fairly common; however, suprisingly deep (+2m) colluvial deposits occur in the valley bottoms of the major tributaries. In more than one area the main channel cuts through a rudimentary flood plain formed by alluvial deposits. All stream channels are ephemeral and on average during the period 1975 to 1978 three to four discrete runoff events per year were observed.

Roberts (1978) compiled a slope map of the research area to illustrate the degree of dissection in the catchments. For this map, shown in Fig. 2.5, areas falling into five slope categories were delimited (condensed to three categories in Fig. 2.5 for clarity). Noteworthy are the flat "uplands" of catchment E and the extremely steep hillslopes where major tributaries break through the shale/sandstone bands of the Ecca Group. Sediment movement and, presumably, yield have been observed to vary considerably among sub-catchments. According to the sediment yield map for South Africa, developed by Rooseboom (1978) after comprehensive analyses of available reservoir sedimentation and soils data, a maximum annual yield of 200t/km^2 can be expected from "medium to large" catchments in the Ecca region. Both on a regional and national scale this figure can be regarded as moderate.

2.3 HYDROMETEOROLOGICAL DATA BASE

2.3.1 Gauging network

The hydrometeorological gauging network in the Ecca catchments is

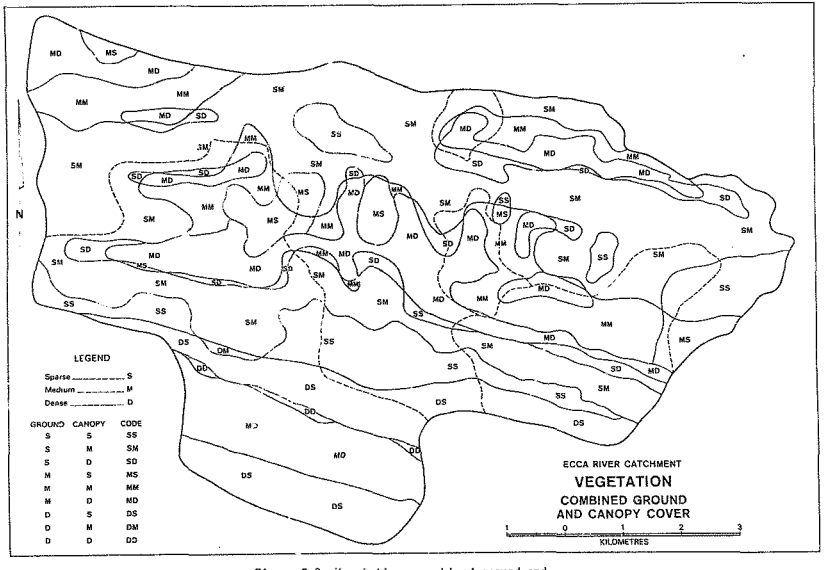
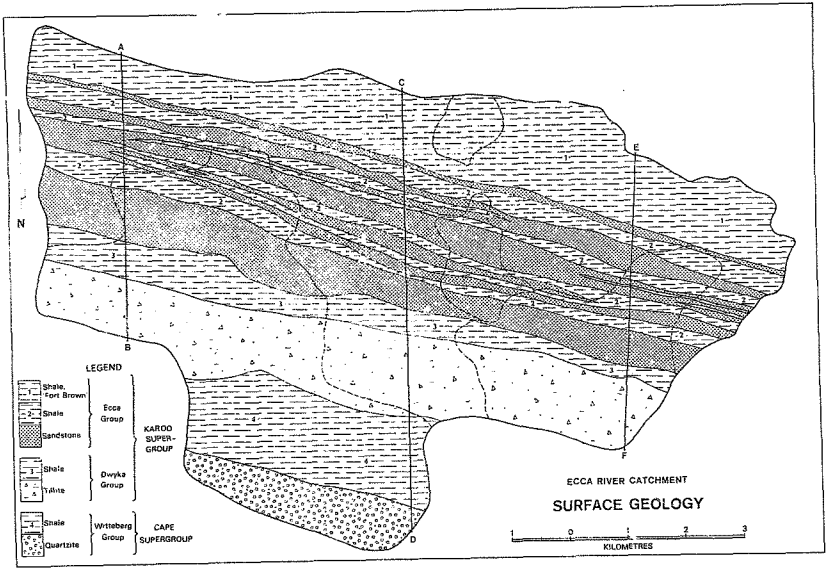


Figure 2.3 Vegetation : combined ground and canopy cover (from Roberts, 1978)



Figur. ' Surface geology of the Ecca catchments
(from Roberts, 1978)

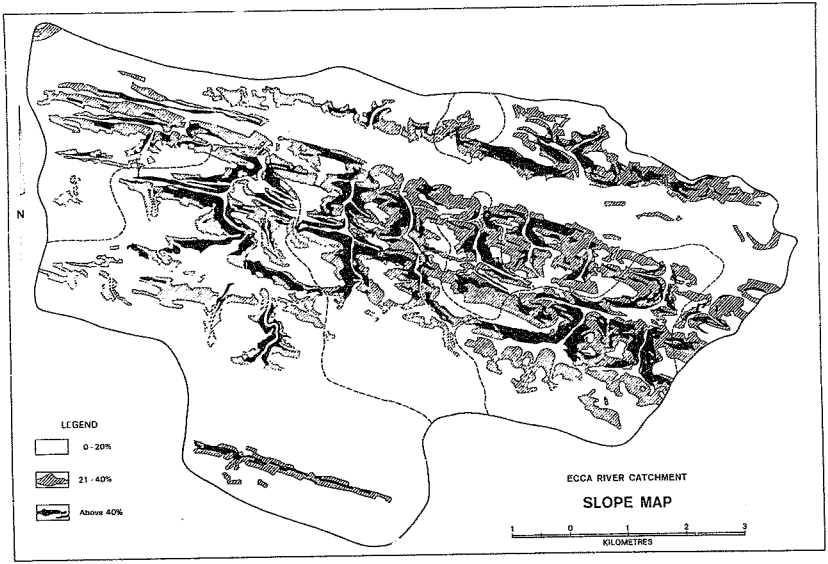


Figure 2.5 Slope map of the Ecca catchments
(from Roberts, 1978)

depicted in Fig. 2.1 and detailed in Table 2.4. As can be seen from Table 2.4 not all the gauges have been in operation over the same period. Raingauge BP01 was closed down at the end of February 1980 because, being atop a very steep high hilltop, it was extremely difficult to reach during wet periods. Even in good weather the journey to the gauge made extreme demands on driver and vehicle, because the "track" to it was almost non-existent. It was decided to re-locate this gauge at the site CP01, which was close to a tarred road and easily accessible. Care was taken to choose a site with approximately the same altitude and exposure as BP01. The location of CP01 solved another problem - the lack of a rainfall gauging point in catchment C.

The success of rainfall-runoff modelling depends strongly on areal assessment of rainfall over the modelled catchment. Some (by now) classic investigations of this problem by Dawdy and Bergman (1969), Chapman (1970) and Ibbitt (1972) underlined the necessity for accurate rainfall estimates in modelling. In a much-quoted study Johanson (1971), in a catchment of about 1000km^2 with 49 raingauges, found, somewhat suprisingly, that the number of raingauges required for "adequate" rainfall-runoff simulation was relatively independent of the area of the catchment, and suggested a general minimum of 4 raingauges per catchment. However, more recent evidence of the necessity for high accuracy in rainfall inputs for catchment models is provided in reports by Basson (1978, Chapter 2), Wilson, Valdes and Rodriguez-Iturbe (1979) and Boughton (1981). Furthermore, Hall and Barclay (1975) warned in their thought-provoking synthesis of information on areal rainfall determination that "Areal rainfall estimates based on point observations should only be regarded as an index of the true mean rainfall over a catchment and errors between 10 and 20 percent can be regarded as normal. Where strong wind effects or mountainous catchments are being considered, errors up to 60 percent can be experienced".

In the light of these findings and given the existence of deeply incised terrain causing likely rainshadows during frontal storms in winter, as well as the prevalence of localized, "patchy" thunderstorms in summer, the highest possible density of raingauges in

Table 2.4

Details of hydrometeorological gauging network

Variable	Gauge code	Gauge type	Observation period
Rainfall	AP01	Casella : Syphoning, autographic, no wind shields	Feb. 1975 - present
	AP02	ditto	ditto
	AP03	ditto	ditto
	BP01	ditto	Feb. 1975 - Feb. 1980
	BP02	ditto	Feb. 1975 - present
	CP01	ditto	March 1980 - present
	DP01	ditto	Feb. 1975 - present
	EP01	ditto	ditto
	EP02	ditto	ditto
	EP03	ditto	ditto
	EP04	ditto	ditto
Streamflow	AR01	Multiple-notch, sharp-crested weir; continuous stage recording	Jan. 1976 - present
	BR01	ditto	ditto
	CR01	Crump weir flanked by broad-crested weir; continuous stage recording	Nov. 1980 - present
	DR01	ditto	ditto
	ER01	Multiple-notch, sharp-crested weir; continuous stage recording	Jan. 1976 - present
Evaporation	AE01	U.S. Weather Bureau Class A evaporation pan; read weekly	Feb. 1975 - present
	EE01	ditto	Feb. 1980 - present

the research catchment would clearly be desirable. The existing network provides densities ranging from one raingauge per 0,7km^2 for catchment C to one raingauge per 7,3km^2 for catchment A. These densities compare most favourably with those employed in rainfall-runoff modelling research elsewhere in South Africa such as University of Zululand (5,0km^2 per gauge - Hope and Mulder, 1979) and the Bethlehem rainfall augmentation area (1,8km^2 to 13,3km^2 per gauge - Cousens, 1980) as well as in typical research catchments in the United Kingdom (1,0km^2 to 19,7km^2 per raingauge - Douglas, Clarke and Newton, 1976), Switzerland (0,5km^2 to 12,0km^2 per raingauge - Naef, 1977) and Australia (14,2km^2 per gauge - Boughton, 1981). The raingauge density is of course only a partial indication of adequacy of the rainfall monitoring network, as actual spatial distribution of the gauges is equally important. Scrutiny of the raingauge network in Fig. 2.1 will reveal that the present distribution of gauges in the whole easterly zone of the research area is weak compared with the rest of the area. As indicated before, this is the unfortunate result of limited accessibility.

The streamflow gauging sites, CR01 and DR01, have also undergone extensive modifications. During 1975 trapezoidal flumes were built at these two sites for flow gauging. Given the evidently high sediment yield from these catchments, it was hoped that the self-cleansing characteristics of the flumes would prevent serious sedimentation during large flow events (Roberts, 1978). Unfortunately, it was discovered in 1979 that the stage-discharge table that Roberts (1978) had used for the flumes was completely unsuitable, as it had been empirically developed for a structure of very different dimensions. After studying the problem, Prof. A. Rooseboom of Pretoria University advised that the flumes were in any case poor measuring devices as they were not acting as proper hydraulic controls during medium to large flow events. Consequently the occurrence of super-critical flow in the throats of the flumes was common. On his advice the flumes were subsequently modified into low Crump weirs (for low to medium flow rates), flanked by broad-crested weirs (for high flow rates). Stage recording at these sites was resumed in November 1980. Attempts were made to assess the inaccuracies in the flume-gauged stage records by applying the backwater model developed by Weiss and Midgley (1975)

to the catchment D stream channel. It was hoped that these valuable data could be salvaged to some extent. This study, based on some fifteen cross-sections upstream and downstream of the flume, was, however, fraught with so many uncertainties that the attempt had to be abandoned. Consequently, the stage records at CR01 and DR01 for the period January 1976 to September 1980 were regarded as being unfit for research purposes. This effectively reduced the number of catchments with reasonable length of record to three - catchments A, B and E.

It will be noted from Table 2.4 that evaporation pan EE01 has a much shorter record than pan AE01. It was installed in early 1980 to provide improved estimates of free water surface evaporation in the research area and its location was dictated by the need to have evaporation data representing the higher ground of the Ecca area, given that AF01 was situated on low ground in the Kat valley.

2.3.2 Data assembly and processing

Raingauge charts are replaced weekly, as are stage recorder charts. Evaporation pan readings are also taken on a weekly basis. All charts are digitized by means of a micro-computer system at the Rhodes Hydrological Research Unit (HRU). From the start of the project until December 1980 digitization was simply at one-hour increments. Since January 1981, however, break-point digitization has been employed. The programs were developed by Dr. D. Hughes of the Rhodes HRU.

"Missing" rainfall data at any gauge site are "synthesized" by simple replacement, on an hourly basis, from the geographically closest gauge. Average catchment falls are calculated by Thiessen polygon weighting of individual point falls on an hourly basis. The past and present Thiessen weightings for catchments A, B and E are listed in Table 2.5. There are, of course, numerous methods of estimating areal average rainfall from point raingauge measurements The most common of these are: arithmetic averaging, Thiessen weighting, isohyetal mapping, interpolation to a regular grid, trend surface analysis, multiple regression and correlation analysis. Hall (1972) reviewed 15 versions of these six techniques and concluded that

provided there is a dense network of reasonably evenly spaced raingauges, there is little to choose among these methods. The isohyetal and interpolation techniques not practicable for calculation of "continuous" inputs to rainfall-runoff models while the trend surface and regression techniques, though suitable for modelling use, require relatively long records (±15 - 25 years) for estimation of stable statistical coefficients. In view of the foregoing and given the relative brevity of the Ecca records as well as the fact that the research area does have a dense network of raingauges, the Thiessen weighting technique was an obvious choice for this study. (This point is explored further in section 2.3.3).

In years to come, when continuing monitoring has provided longer rainfall records in the research area, the weightings in Table 2.5 can themselves be "improved" on some rational basis. For instance, each gauge weight can be adjusted by the ratio of its annual mean to the catchment annual mean, or, even better, twelve Thiessen weighting matrixes can be developed from Table 2.5 by adjusting each gauge weight by the ratio of its mean for each calendar month to the equivalent catchment (calender) monthly mean. These adjustments take into account (to a certain extent) the orographic and exposure influences on individual sites, and, in the monthly adjustment case, even the seasonal effects, such as dominant storm types.

Daily and monthly totals of average catchment rainfall and streamflow are calculated directly from the hourly average catchment falls and the hourly instantaneous discharges. Daily values of pan evaporation are derived from the weekly readings by simple proportion with weekly values obtained from a pan of the same type, installed on the Rhodes campus and read every day. Monthly pan evaporation totals are calculated from the derived daily values. Estimates of daily or monthly potential evaporation in the form of free water surface evaporation, which is a required input variable to all the models used in this study, are achieved by multiplying each daily or monthly pan evaporation total by a pan-to-free-water-surface conversion factor for that calender month. A set of twelve such factors, one for each calender month, and derived for the lower Great Fish River region, was obtained from the Directorate of Water Affairs (see Table 2.2).

Table 2.5

Thiessen polygon weightings for estimation of average catchment rainfall

Raingauge	Catchment					
	A		B		E	
	1975-79	1980-82	1975-79	1980-82	1975-79	1980-82
APO1	0,059	0,060	0,0	0,0	0,0	0,0
APO2	0,114	0,111	0,317	0,614	0,014	0,006
APO3	0,071	0,052	0,0	0,0	0,0	0,0
BPO1	0,126	-	0,593	-	0,0	-
BPO2	0,078	0,147	0,089	0,350	0,0	0,0
CPO1	-	0,152	-	0,036	-	0,056
DPO1	0,119	0,089	0,0	0,0	0,0	0,0
EPO1	0,122	0,138	0,0	0,0	0,0	0,0
EPO2	0,087	0,090	0,0	0,0	0,359	0,444
EPO3	0,140	0,079	0,0	0,0	0,615	0,087
EPO4	0,085	0,084	0,0	0,0	0,	0,262

The erratic nature of these regional factors seemed inexplicable and so they were subjectively smoothed for this study.

2.3.3 Data quality, uncertainties and errors

In order properly to evaluate the results of the rainfall-runoff modelling investigations discussed in later chapters, it was essential to assess the quality of and uncertainties in input data used in the models, i.e. the quality of hydrometeorological data provided by the Ecca gauging network. A theme that is becoming progressively more common in rainfall-runoff modelling is echoed in a conclusion reached by Boughton (1981) after studying the effects of rainfall variability on modelling: ".. errors in (input) data are probably of the same order of magnitude as errors within the modelling process and now form a barrier to further accuracy in rainfall-runoff modelling".

(a) Rainfall:

As all the models used in this study require "lumped" values of areal rainfall input - i.e. point rainfalls in some way averaged over the catchment - areal rainfall errors deserve special attention. Total areal rainfall errors may result from a combination of different individual types of errors. Hall and Barclay (1975) consider areal rainfall errors as ".... a systematic measurement error of a single (point) rainfall catch, systematic spatial and elevation variations of rainfall and a random error which is dependent on the type of storm, the raingauge density and the extent to which each gauge represents the area to which it is ascribed".

(i) Errors in point measurements: Contemplation of the extensive international literature dealing with the accuracy of measurement of rainfall, some of which is contained in an annotated bibliography by the WMO (1973), as well as in a comprehensive review by Larson and Peck (1974), leads to the inevitable conclusion that the likely magnitude of systematic errors in point measurements by standard vertical raingauges must be expected to be -5% to -20%, mainly caused by over-exposure to wind and deficient catches of inclined rainfall. A

recent South African study disclosed average errors of between -25% and -32% over 37 individual storms (De Villiers, 1980). Considering the fact that the Ecca raingauges are all standard and vertically-mounted, with variable exposure and without wind shields, then at least a degree of point rainfall underestimation must be prevalent - especially during rainstorms associated with cold fronts when strong southwesterly winds may prevail.

(ii) Areal extrapolation errors: These errors can be systematic and/or random. Systematic errors arise when the raingauge distribution and density are inadequate to capture a systematic spatial variation of rainfall (e.g. winter storms in the Eccal. Random errors arise as variations in the actual rainfall pattern during a storm and from storm to storm cause the representativeness of each gauge of the area to which it is ascribed to fluctuate randomly. Clearly, the latter type of error relates to the averaging technique used.

In this research project, systematic errors may be introduced by virtue of the fact, mentioned before, that the easterly zone, i.e. the more arid part, of the research area is less densely gauged than the remainder. Perusal of Thiessen weightings in Table 2.5 reveals that switching rainfall gauging from site BP01 to site CP01 (see Fig. 2.1) reduced total "eastern-input" weighting from 0,204 to 0,147 in catchment A and from 0,682 to 0,350 in catchment B. Given the known trend of decreasing rainfall (Fig. 2.2) from south to north and from west to east, this weighting change probably decreased the accuracy of areal rainfall estimates over catchment A. However, the weighting change may actually have improved catchment B estimates as its headwater areas had formerly been underrepresented . For catchment E estimates, the weighting change may have been a mixed blessing: it reduced the former importance of gauging site EP03 which was a poor site, being in a narrow "blind" valley surrounded by hills 80 to 150 metres high. On the other hand it may have exaggerated the importance of the headwater gauges, EP01 and EP04. An in-depth study by Huff and Schickedanz (1972) may provide some clues towards evaluating how serious the variable density of raingauges over the research area may be in terms of areal rainfall errors. Investigating the errors

inherent in sparse, relative to dense networks of gauges, they showed that the error in measuring areal hourly average rainfall decreased from ±11% for a gauge density of 21km^2/gauge, to ±4% at a gauge density of 2,6km^2/gauge. It seems that errors related to gauge density during any storm may be expected to vary from less than ±5% in the west of the Ecca research area to about double that in the east.

A *simple assessment of errors (systematic and random)* attributable to the chosen averaging technique, Thiessen weighting, was made by comparing Thiessen averages of a limited sample of observed rainstorms over catchment A with isohyetal and arithmetic averages. The 21 selected events were representative of all types of storms that have produced runoff in the Ecca catchments. The comparison is shown in Table 2.6 and the isohyetal representation of some of the storms can be seen in Figs. 3.3(a) to (i) in Chapter 3. If one accepts the assumption that the isohyetal representation of rainfall distribution is one of the most accurate averaging approaches available (if done with due recognition of orographic effects, *exposure and seasonal* controls), then it appears from Table 2.6 that both the Thiessen polygon and arithmetic average techniques may be slightly underestimating the catchment average falls. Over the 21 storms the mean Thiessen under-estimation was -3,4% while the mean arithmetic average "error" was -4,2%. *These "errors" were dominated* however, by two events, viz. the storms of 6/3/77 and 10/1/78. These two typical thunderstorms each straddled only a portion of catchment A, with the result that there were zero readings at certain raingauges. Without these two storms, the mean "errors" drop to -2,2% for Thiessen and -2,8% for arithmetic averaging respectively. According to the t-test, however, none of the differences is significant at the 5% level. The foregoing analysis indicates that, based on storm totals and except for extremely localised thunderstorms, the Thiessen approach is as satisfactory as any for the purposes of this study and, at worst, leads to only minimal under-estimation.

Errors introduced by the exact "mix" of raingauges producing the catchment average relate both to the final distribution of gauges and

Table 2.6

Comparison of catchment rainfall averages (in mm) calculated by different averaging techniques (runoff-producing storms only)

Storm starting date	Isohyetal mapping	Thiessen polygon	Arithmetical average
20/3/76	57,0	54,0	53,3
28/3/76	16,0	14,4	14,6
4/10/76	14,0	15,8	13,1
27/2/77	31,0	30,8	30,3
28/2/77	26,0	25,8	25,5
6/3/77	12,0	7,0	6,9
6/5/77	37,0	34,8	33,9
7/5/77	25,0	20,9	21,9
1/12/77	17,0	15,8	16,0
30/12/77	53,0	52,1	51,3
9/1/78	19,7	19,4	19,4
10/1/78	15,0	8,0	8,8
3/2/78	21,0	22,4	22,0
19/4/78	44,0	45,3	44,4
21/4/78	35,0	35,5	35,7
5/10/78	45,0	41,6	41,5
1/11/78	22,0	21,2	21,5
28/2/79	25,0	27,0	26,6
20/7/79	159,6	154,3	157,1
23/7/79	29,0	28,6	28,5
19/8/79	95,0	93,2	94,1
Average	38,0	36,7	36,4
St. deviation	33,9	33,2	33,8

to the missing data "patching" technique used - in this case, substituting hourly totals from the "nearest neighbour". Due to the dusty and harsh conditions in the Ecca, syphon and clock failures - in spite of weekly maintenance - result in between 5 and 20 missed gauge-periods of one or more hours each per normal month, and these patched in the aforementioned way. Almost the only way to quantify the effects of any particular "mix" of raingauges on the accuracy of the output from any rainfall-runoff model is to operate the calibrated model on rainfall derived from different subsets of the total network and then to compare these model outputs with the original model outputs stemming from "total network" inputs. This is also a fruitful avenue along which to explore the relative importance of systematic or random errors in rainfall or evaporation input data in terms of their effects on model outputs: contaminate the original model inputs by the required error type and observe changes in model outputs. Such an exercise, using the Ecca data base and the Stanford Watershed Model (Crawford and Linsley, 1966), is discussed in paragraph 2.3.3(e).

(b) Streamflow: In an analysis of South African streamflow-gauging practice, Muller (1977) evaluates the errors inherent to the records produced by the best flow-gauging structures in the national network of the Directorate of Water Affairs (including stage-discharge rating errors) as between ±5% and ±10%. The multiple-notch, sharp-crested weirs used for gauging the outputs from catchments A, B and E are on a par with the best in South Africa. Consequently, flow records of these catchments can confidently be expected to be in error by no more than ±5% to ±10% at least for monthly totals. The compound Crump/broad-crested weirs serving catchments C and D may have an even higher accuracy than the above three weirs, but may suffer a deterioration in low-flow accuracy during large events that deposit large amounts of sediment in their relatively small weir-pools. Sediment deposition is in fact the single most serious threat to accurate flow-gauging in the Ecca catchments because it reduces the stilling-pond effect required to bring approach velocities to zero. Although the weir-pools at the outlets of catchments A, B and E are sizeable, the latter two had to be excavated after massive deposits of sediment during a flood in August 1979.

In summary, the quality of the flow records for catchments A, B and E can be regarded as very good, by South African standards, with the only suspect data belonging to the latter part of the August 1979 flood in catchments B and E. There were no periods of missing data in these three catchments.

(c) Evaporation: For a comprehensive review on the suitability, advantages and disadvantages of the use of pans for evaporation estimation, the reader is referred to Gangopadhyaya et al. (1966). There are four primary sources of errors in the use of evaporation pans for areal potential evaporation estimates: inadequate distribution of measuring sites, effects of the wind regime on individual pans, effects of advection of heat energy not representative of the natural environment,and the pan factor, i.e. the relationship of pan evaporation to free water surface or "lake" evaporation, commonly assumed to be equal to potential evaporation. Some random errors can also be related to pan discolouring and the observation time interval.

(i) Distribution of measuring sites: During the period February 1975 to January 1980 evaporation gauging took place at only one site in the research area, namely at AE01 (see Fig. 2.1). Table 2.7 compares the 4-weekly totals of weekly evaporation readings at AE01 with those at EE01, the pan installed in January 1980. Over the 32-month period the mean monthly evaporation has been slightly higher at EE01 than at AE01, viz. 126,2mm as opposed to 122,0mm. The t-test applied to pairs of 4-weekly totals could only detect a difference between the two samples at a probability level of 20%, which is commonly regarded as too high to exclude the possibility that the differences between the two sets of pan readings are due to chance alone. However, the monthly distribution of differences between the two sites as listed in Table 2.7 does suggest a pattern: pan evaporation at site EE01 appears to be higher in early to mid-winter and vice versa in early to mid-summer.

(ii) Effects of wind regime: Errors caused by wind patterns over the pan are likely to fluctuate in time and could be either random or systematic. A systematic error would be caused by a site

Table 2.7

Difference*1 (in %) of 4-weekly evaporation totals read at pan EE01 relative to readings at pan AE01

Month	1980	1981	1982	Mean
January	.	+14,1	-9,3	+2,4
February	-0,6	0	-6,2	-3,4
March	+8,6	+1,7	+1,3	+3,9
April	+3,8	-3,7	-3,3	-1,1
May	+8,4	+4,8	+12,2	+8,5
June	-3,3	+11,1	+15,0	+7,6
July	+21,3	+8,1	+6,8	+12,1
August	+8,5	-10,5	-0,9	-1,0
September	+1,9	-18,2	0	-5,4
October	-6,5	-7,6	.	-7,1
November	-6,0	-10,2	.	-8,1
December	-0,1	-6,7	.	-3,4

*1 Difference = 100.(EE01 - AE01)/AE01

Table 2.8

Weightings applied to evaporation pan data for estimation of catchment average evaporation*1

Catchments	A	B	C	D	E
Pan AE01	0,58	0,58	0,74	1,0	0,21
Pan EE01	0,42	0,42	0,26	0,0	0,79

*1 In effect from February 1980.

that is over- or under-exposed relative to the major part of the catchment. Because of its altitude and greater exposure, a different wind regime almost certainly prevails in the EE01 meso-environment compared to the AE01 meso-environment. However, it was felt that an altitude/physiographic zone over the whole research area could probably be defined with a wind regime reasonably similar to that of EE01 and that EE01 evaporation values would be representative of wind-related evaporation from such a zone. After careful consideration and based on subjective assessment of advection and catchment conditions, all catchment areas above the 426,7m (1400ft) contour were classified as having EE01 evaporations and the rest of the research area as having AE01 evaporations. The resultant weightings of the two pans are listed in Table 2.8. This rather subjective weighting of data from the two pans could possibly be an additional source of systematic error, given the apparent systematic evaporation differences between the two pans evident in Table 2.7.

(iii) Advection effects: The location of AE01 in a deep valley almost certainly ensures a higher degree of advection than that experienced by EE01 on the flatter uplands. Higher advection leads to higher evaporation values, explaining perhaps the higher evaporation totals observed in summer at AE01. Along with consideration of the wind regime, the advection phenomena of the meso-environments of the two pans played a role in area-related weightings of the two evaporation records (Table 2.8)

(iv) Pan factors: The twelve monthly pan factors provided by the Directorate of Water Affairs (see Table 2.2) are of unknown accuracy. They were determined by comparing evaporation values in floating pans on certain large dams in the Great Fish River catchment with estimated dam evaporation losses. These estimates are based on a monthly mass balance of the dams, calculated from measured in-and outflows and assuming certain seepage losses. The errors involved in this form of mass balance are usually large, but even if one assumes that levels of accuracy can be reached equivalent to those achieved by the most accurate method for estimating dam evaporation, i.e. by complete energy budgeting, then one still has to accept errors of $\pm$15% on a monthly basis (Winter, 1981). The pan factors can therefore be expected to contain errors larger than $\pm$15% and their use on a daily basis will increase this error further. On an annual

basis the error should drop to below ±10% (Winter, 1981). The discontinuous change in pan factor from one month to the next is also likely to be a source of random and/or systematic error, as is the rather subjective smoothing of the original pan factors, mentioned earlier. A further systematic error would be introduced if the meso-environment of the Ecca pans are not representative of the environments of the regional dams used for the determination of the regional factors. On the basis of all the above facts, it does seem as if the errors in daily values introduced by the use of smoothed regional monthly pan factors in this project are unlikely to be smaller than ±20%.

(v) Effects of discolouring: The harsh and dusty conditions of the research area rapidly cause discolouring even of freshly painted or washed pans. Dust forms a layer on the bottom of the pans and along with discolouring and algal growth changes the albedo of the pans. Errors caused by these problems would be random, but could be sizeable. Gangopadhyaya et al. (1966) report a study on the effects of colour (albedo) where eight pans of different colours were compared with a new galvanized pan. The extremes of the differences between the pans were represented by an unpainted copper pan, +7% of the control pan's evaporation, and a white pan, -17% of the control pan evaporation.

(vi) Observation interval: The proportioning of weekly pan readings in the Ecca area by daily pan readings in Grahamstown could cause sizeable errors in daily evaporation data used in this project. In summer these errors would be small and random - probably about ±5% - but in winter the errors would be larger and could be systematic; up to ±20% would be possible. The winter/summer difference is due to the fact that in winter Grahamstown often experiences a light drizzle over a few consecutive days while the research area may be experiencing relatively hot, sunny weather.

(d) Error summary: In evaluating the foregoing discussion of

uncertainties and errors present in data produced by the hydrometeorological gauging network in the Ecca catchments, it is important to keep the percentages and time frames mentioned in perspective. A large percent difference in small numbers, for example, may not represent much water, but a small percent difference in large numbers can involve a considerable quantity of water. Also long term averages generally have smaller errors of estimation than short term averages.

To summarize, and to integrate the errors in all aspects of the gauged hydrology of the research area, three sets of simple error estimates were made using Ecca data and representing a daily, a monthly and an annual time frame, respectively. For the daily time frame the event with the biggest daily runoff total was chosen, viz. 21-22 August 1979, for the monthly case the month containing the biggest daily event, August 1979, which also happens to be the highest runoff month, and for the annual case the year 1979. Details of the error estimates are contained in Table 2.9. Individual error percentages are based on typical values gleaned from literature referred to earlier, tempered by subjective assessment of the Ecca network. For each of the hydrological components, precipitation streamflow and evaporation, a "total error" was derived following the principle (Winter, 1981) that the propagation of error in a measurement can be approximated by summing the variances and covariances of the measurement errors introduced by individual components of that measurement. Streamflow can be used as an example. In section 2.3.3(b) it was stated that there are two known sources of error in the Ecca flow-gauging procedure: inherent errors associated with the combination of weir and stage/discharge relationship used (WSD) and errors introduced by weir-pool sedimentation (WPS). The propagation of streamflow (SF) error can now be written as:

$$Var(e_{SF}) = Var(e_{WSD}) + Var(e_{WPS}) + 2Cov(e_{WSD}, e_{WPS}) \quad \ldots\ldots\ldots\ldots\ldots (2.1)$$

where e = error at each error source
Var = variance
Cov = covariance

The covariance term can be ignored because the two sources of streamflow errors are independent. By means of the volumetric errors derived from the percentages shown in Table 2.9, the total volumetric error in streamflow gauging during the 21-22 August 1979 event can be *estimated*:

$$e_{SF} \approx (3,0^2 + 3,0^2)0,5 = 4,2\text{mm}.$$

An identical procedure is used to calculate the total volumetric error in precipitation and evaporation measurements.

The question arises as to how the total volumetric errors in the measurement of the three hydrometeorological data sets used in this study can be related to rainfall-runoff model performance. This can be done by following a procedure similar to that represented by 2.1, namely by approximating the "overall error" to which a model using the Ecca data set would be exposed by the variances and covariances of the individual total errors in each separate data set used. This leads to the equation:

$$\text{Var}(e_{OE}) = \text{Var}(e_P) + \text{Var}(e_E) + \text{Var}(e_{SF}) + 2\text{Cov}(e_P,e_E) + 2\text{Cov}(e_P,e_{SF}) + 2\text{Cov}(e_E,e_{SF}) \quad \text{.....(2.2)}$$

where OE = overall error
P = precipitation
E = evaporation
SF = streamflow

Because measurement of each hydrometeorological component is *considered independent of the measurement* of the other components, covariances can be ignored. By substituting the total volumetric compound errors from Table 2.9 into equation 2.2, overall errors which would affect a rainfall-runoff model during calibration or verification can be approximated. For instance, the overall volumetric error a model would "see" during simulation of the event of 21-22 August 1979 would be:

Table 2.9

Typical estimates of likely errors in hydrometeorological data used in this study

Component or error source	2-daily total 21/22 Aug.1979		Monthly total August 1979		Annual total 1979	
	Error (%)	Error (mm) or gauged value (mm)	Error (%)	Error (mm) or gauged value (mm)	Error (%)	Error (mm) or gauged value (mm)
PRECIPITATION		85,0		130,1		649,0
Gauge placement	7,5	6,4	7,5	9.8	7,5	48,7
Gauge density	7,5	6,4	5	6,5	2,5	16,2
Areal averaging	5	4,3	4	,2	2,5	16,2
Data patching	6	5,1	3		3	19,5
TOTAL ERROR		11,2		,5		57,2
STREAMFLOW		29,8		60,4		117,1
Sharp-crested weir	10	3,0	5	3,0	5	5,9
Weir-pool sediment	10	3,0	5	3,0	2,5	2,9
TOTAL ERROR		4.2		4,2		6,6
EVAPORATION		1,3		91,5		1899
Class A pan	10	0,1	10	9,2	7,5	142,4
Pan factor	30	0,4	20	18,3	5	95,0
Gauge density	15	0,2	10	9,2	5	95,0
Areal averaging	10	0,1	7,5	6,9	2,5	47,5
Daily proportion	10	0,1	0	0	0	0
TOTAL ERROR		0,5		23,5		201,5
OVERALL ERROR		12,0		27,4		209,6

overall error $\approx (11,2^2 + 4,2^2 + 0,5^2)^{0,5} = 12,0$mm

The results in Table 2.9 put all statements made in later chapters of this document relating to the accuracy of hydrograph simulations, the soundness of model performances and the consequent representativeness of model structures and parameters, into a specific perspective: inherent overall volumetric errors in the total data set used can be more that 10mm per individual major runoff event, more that 25mm for large monthly totals and more that 200mm for large annual totals.

(e) Effects of data errors on model outputs: Studies of the effects of data errors on model outputs have been done for rainfall by Dawdy and Bergman (1969), Chapman (1970), Ibbitt (1972), Wilson et al. (1979), Boughton (1981); for evaporation by Parmele (1972) and Ibbitt (1972); for streamflow by Ibbitt (1972) and Sorooshian and Dracup (1980). Ibbitt (1972) found that the closeness of fit of simulated and observed runoff data was most influenced by random errors in the runoff record and least influenced by random errors in the evaporation record. It must be stressed that Ibbitt's finding is of a relative nature, as most of the researchers referred to the above showed in their efforts to quantify the sizeable errors in model outputs caused by input data errors. For instance, Parmele (1972) shows that in semi-arid catchments in Pennsylvania it may be necessary to estimate potential evapotranspiration to better than ±10% to achieve a reasonable fit between simulated and observed yields. The earlier discussion on errors in Ecca evaporation data makes one aware that Parmele's finding poses a formidable problem to modellers - a problem that can probably only be solved by using techniques of distributed modelling and mapping of potential evapotranspiration, such as developed by Schulze (1981) and Najjar, Ambroise and Mercier (1981).

As the main purpose of the earlier discussions on and analyses of the quality of the Ecca data sets was that evaluation of rainfall-runoff model performance may be facilitated, it follows logically that some of the foregoing ideas regarding model input data "contamination" by errors should be implemented by means of a modelling example. The well-known Stanford Watershed Model, as calibrated for Ecca catchment

A (discussed in Chapter 3), was chosen to explore briefly the importance of various input error types and sizes in final model performance. The calibrated Stanford model was operated with each of eleven consecutive treatments of the original input data and the treatment effects judged by observing changes in the shapes, volumes and peaks of six representative runoff hydrographs, as well as in the MAR over the five-year calibration period. Table 2.10 lists some of the results of the exercise: the April 1978 event represents the most important thunderstorm flood hydrograph on record while the August 1979 event was the largest flood caused by a frontal weather system. Fig. 2.6 gives a visual impression of the hydrograph shape changes caused by some of the data input treatments.

For the first two treatments indicated in Table 2.10 the model was first run with a subset of five Thiessen-averaged raingauge records as input, namely APO2, EP01, EP02, EP03 and EP04, and secondly, with the subset, APO2, BP01 and BP02. As can be expected, a raingauge configuration biased to the higher rainfall zones in the catchment, i e. treatment (1), will substantially increase the predicted MAR . The opposite volume and peak changes caused in the April 1978 event by treatments (1) and (2), reflect the storm pattern (Fig. 3.3(f)) that caused the runoff and illustrate the extent to which an unfavourable raingauge configuration can affect the simulation of individual events. Treatments (3), (4), (8) and (9) comprised constant proportional increases or decreases of hourly inputs in the case of rainfall and of daily inputs in the case of evaporation. It is worth noting that the model is much more sensitive to systematic errors in rainfall inputs than evaporation inputs, and also that in relative terms systematic under- or over-estimation of rainfall affects the simulation of smaller runoff events more than that of larger runoff events. This result can be related to the fact that soil-moisture-accounting models are usually highly non-linear (as are real-life catchments) in their response to rainfall while their moisture stores are still filling up, but become less non-linear under saturated conditions.

The "mixed" and random errors, introduced as treatments (5), (6), (7), (10) and (11), were selected from the error ranges shown on a

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Table 2.10

Changes (in %) in output from calibrated*1 Stanford Model due to error contamination of input data

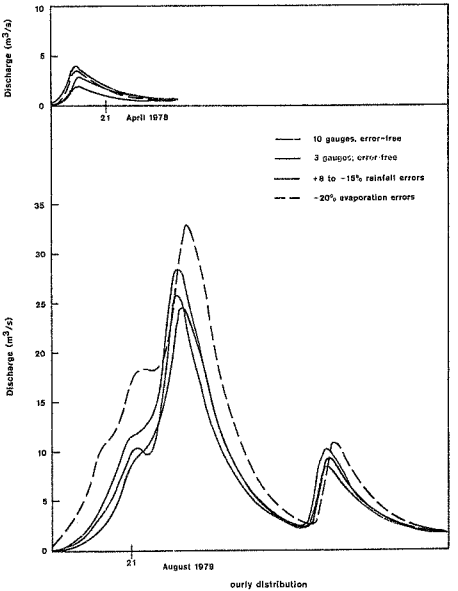
Data treatment	Event: April 1978*2		Event: August 1979*3		5-Year MAR
	Volume	Peak	Volume	Peak	
RAINFALL					
(1) 5 Raingauges	-26	-34	+7	-9	+10
(2) 3 Raingauges	+32	+42	-14	-9	-3
(3) -10% Systematic error	-71	-84	-30	-31	-28
(4) +5% Systematic error	+74	+95	+16	+15	+16
(5) +5 to -10% Mixed error	-23	-29	-7	-8	-9
(6) +8 to -15% Mixed error	-25	-30	-13	-14	-10
(7) +15 to -15% Random error	-42	-52	+1	+4	+1
EVAPORATION					
(8) -20% Systematic error	+23	+30	+25	+16	+15
(9) +20% Systematic error	-14	-17	-23	-20	-10
(10) +10 to -10% Random error	+1	+2	0	0	0
(11) +20 to -20% Random error	+1	+1	-6	-5	-2

*1 One warm-up year and five years calibration period used; discussed in Chapter 3.

*2 Thunderstorm event: Observed volume and peak are 2,33mm and 2,68m^3/s respectively.

*3 Frontal storm event: Observed volume and peak are 50,88mm and 35,40m^3/s respectively.

Figure 2.6 Changes in output from calibrated Stanford Model due to error contamination of input data (see overleaf)



ourly distribution

random basis by employing a pseudo-random number generator in the model computer program. Each of the five treatments under discussion was repeated a few times to ascertain the degree of variability caused by random errors. ch repeat of course produced different outputs because a different array of errors was introduced (albeit from an identical error range), but the five examples shown are fairly typical of the size and type of model output changes. Treatments (5) and (6) represent "mixed" error conditions: a small systematic bias (-2,5% to -3,5%) towards under-estimation of rainfall with random errors superimposed, which can be a common situation in catchment modelling. Results for these two treatments show that even small systematic errors cannot be expected to be neutralized by random errors. Treatments (7), (10) and (11) suggest that completely random errors do not affect the MAR very much but individual events may be substantially affected. Again the model responses to errors in smaller runoff-producing rainstorms were in relative terms much more affected than in the case of major storms. Although Table 2.10 does not show it, individual runoff events simulated during months with high evaporative demands - November to February - are considerably affected by random evaporation errors.

2.3.4 Summary of monthly and annual data used in this study

The lack of reliable flow gauging in catchments C and D before November 1980 meant that this study had to be confined to the three catchments A, B and E. Tables 2.11, 2.12 and 2.13 list full summaries of monthly totals of average catchment rainfall, average catchment pan evaporation and streamflow.

The runoff during July and August 1979 clearly dominates the runoff record of all three catchments. Each of these months experienced a major frontal storm lasting several days and producing multiple-peaked flood hydrographs. The highest daily fall of the July 1979 storm was estimated to have a return period of well over 50 years, based on a probability analysis of regional rainfall, while the August 1979 storm was awarded a return period well over 25 years. A 101-year flow series, synthetically generated for the Ecca catchments by means of the Stanford Watershed Model and discussed in Chapter 6,

Table 2.11

SUMMARY OF AVER.CATCH-WATR ABOVE Q9M20(MM)

PERIOD OF RECORD JAN. 1975 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
75	51.0	49.7	80.9	4.6	5.0	41.9	10.1	17.5	89.3	5.6	19.0	57.6	390.
76	33.0	81.4	155.3	14.3	24.8	10.9	36.2	8.7	16.3	62.0	39.6	25.7	527.
77	17.0	144.6	21.2	47.2	71.0	4.8	2.0	9.7	33.3	6.4	75.0	104.4	536.
78	56.3	11.5	32.2	110.9	17.4	65.5	2.0	11.9	13.4	81.4	35.7	49.4	469.
79	96.5	96.6	19.2	9.5	45.0	64.5	189.8	130.1	30.3	44.8	12.8	16.1	664.
80	33.2	17.1	43.5	27.4	0.8	23.4	1.0	19.3	27.5	23.3	79.6	39.0	347.
81	44.6	19.2	116.3	4.9	67.4	11.0	0.3	62.2	12.0	73.4	28.6	54.0	490.
XTOTAL	9.4	13.2	13.1	5.5	6.7	6.2	7.1	7.5	6.5	8.7	8.5	10.0	100.00

MEAN ANNUAL RAINFALL = 467.4 MM.

SUMMARY OF OBSERVED FLOWS AT Q9M20(THOUS.CUB.MET.)

PERIOD OF RECORD JAN. 1976 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
76	0.0	0.0	490.9	28.9	5.4	0.0	5.1	1.0	0.0	3.6	0.4	0.0	735.
77	0.0	27.1	131.8	0.0	81.6	0.1	0.0	0.0	0.0	0.0	35.5	0.5	276.
78	80.5	11.4	0.0	203.3	11.4	5.6	3.8	3.3	1.1	7.9	7.5	0.3	336.
79	0.0	2.6	6.7	0.0	0.0	0.0	349.2	441.5	542.7	96.2	8.2	0.3	8563.
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	25.2	30.
81	0.0	0.0	64.3	1.2	24.9	3.5	0.0	0.2	6.4	105.8	0.6	23.0	208.
XTOTAL	0.8	0.4	8.8	2.3	1.0	0.1	34.5	43.6	5.4	2.1	0.2	0.8	100.00

MEAN ANNUAL RUNOFF = 1690.9 THOUS. CUB. MET.

SUMMARY OF AVER.CATCH-EVAP ABOVE Q9M20(MM)(A-PAN)

PERIOD OF RECORD JAN. 1975 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
75	186.3	177.2	179.4	155.0	121.7	102.0	147.9	169.4	94.8	244.1	229.8	211.3	1999.
76	206.8	167.6	168.1	95.0	70.6	106.4	90.7	111.6	120.2	155.0	259.6	267.1	1782.
77	265.0	168.4	160.5	127.6	104.2	113.0	124.6	142.1	124.1	181.2	195.7	224.2	1939.
78	198.4	184.9	193.0	119.4	107.2	81.1	81.2	131.9	154.0	158.0	220.9	223.3	1850.
79	234.6	214.2	190.6	142.9	91.3	82.6	85.5	91.5	123.2	170.6	242.2	262.4	1899.
80	265.0	177.2	169.5	137.6	122.6	80.0	102.3	113.8	127.6	181.0	177.5	196.8	1849.
81	194.4	154.8	152.1	110.8	71.5	63.6	99.8	88.9	135.6	171.2	181.0	205.1	1603.
XTOTAL	11.9	9.6	8.9	6.7	5.4	4.9	5.5	6.6	6.8	9.8	11.3	12.5	100.00

MEAN ANNUAL EVAP. = 1840.0 MM.

Table 2.12

SUMMARY OF AVER.CATCH.RAIN ABOVE Q9M21(MM)
PERIOD OF RECORD JAN. 1975 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
75	10.3	55.9	52.3	8.7	[illegible]	47.4	11.7	14.6	95.4	1.9	16.5	56.7	564.
76	65.8	77.6	145.7	10.4	44.6	11.8	37.5	9.4	16.7	64.5	35.9	23.1	521.
77	14.9	139.5	26.1	55.0	86.4	9.5	2.5	9.4	52.1	0.3	76.6	104.2	538.
78	55.5	27.3	33.1	112.2	75.9	22.7	2.3	19.7	73.9	78.1	36.9	49.0	459.
79	44.6	62.7	14.3	3.0	45.0	24.4	193.9	123.6	29.1	69.0	13.2	12.5	637.
80	35.2	37.9	43.6	27.2	1.0	28.0	1.8	14.7	50.7	25.6	69.6	37.4	346.
81	39.1	16.6	115.0	10.1	96.9	10.6	0.4	62.9	22.3	64.5	30.8	52.3	481.
%TOTAL	7.7	12.7	12.9	6.8	6.3	4.5	7.5	7.1	7.2	8.7	8.4	10.0	100.00

MEAN ANNUAL RAINFALL = 478.0 MM.

SUMMARY OF OBSERVED FLOWS AT Q9M21(THOUS.CUB.MET.)
PERIOD OF RECORD JAN. 1976 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
76	5.1	0.6	67.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	73.
77	0.0	12.5	15.5	0.5	28.8	0.0	0.0	0.0	0.0	0.0	0.3	7.4	65.
78	3.2	0.0	0.0	17.5	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	21.
79	0.0	2.2	0.0	0.0	0.0	0.0	444.6	405.5	138.9	11.8	3.5	0.0	1007.
80	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	3.
81	0.0	0.0	5.0	0.0	0.3	0.0	0.0	0.5	0.7	6.7	0.3	3.9	17.
%TOTAL	0.7	1.3	7.4	1.5	2.5	0.0	37.5	34.2	11.8	1.6	0.4	1.1	100.00

MEAN ANNUAL RUNOFF = 197.7 THOUS. CUB. MET.

SUMMARY OF AVER.CATCH.EVAP ABOVE Q9M21(MM)(A-PAN)
PERIOD OF RECORD JAN. 1975 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
75	0.5	177.2	179.4	131.2	121.7	102.0	127.9	169.4	94.8	224.1	229.8	211.3	1769.
76	206.6	167.6	128.1	95.0	76.5	106.4	90.7	111.6	120.2	155.0	239.3	287.9	1785.
77	265.0	168.4	160.5	122.6	103.9	113.0	124.6	142.1	122.1	191.2	195.7	229.2	1938.
78	196.4	184.9	193.0	116.4	107.1	81.1	81.2	131.9	154.0	158.0	220.9	225.5	1850.
79	234.6	214.2	190.6	164.9	91.3	82.6	85.5	91.5	123.2	170.6	222.6	264.4	1809.
80	263.0	177.2	169.5	137.6	122.6	80.0	101.5	113.8	127.6	181.0	179.5	198.7	1850.
81	184.4	154.8	152.1	116.8	71.5	63.6	99.8	88.9	135.6	171.2	181.0	205.1	1605.
%TOTAL	10.7	9.8	9.1	6.7	5.5	5.0	5.6	6.7	6.9	9.9	11.6	12.7	100.00

MEAN ANNUAL EVAP. = 1815.4 MM.

Table 2.13

SUMMARY OF AVER.CATCH.RAIN ABOVE Q9M24(MM)
PERIOD OF RECORD JAN. 1975 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
75	42.0	51.3	65.7	7.5	5.6	47.8	11.7	15.6	98.5	4.1	43.0	65.2	465.
76	44.8	88.6	170.0	15.1	25.5	10.0	37.9	8.8	16.6	65.6	45.6	28.6	555.
77	17.0	132.6	55.1	92.0	84.7	5.7	1.6	13.1	33.1	8.2	74.8	104.9	539.
78	34.0	11.2	33.0	113.4	20.7	29.7	2.2	15.5	14.4	62.4	38.8	50.7	447.
79	53.9	111.4	19.3	3.1	44.7	28.0	189.8	135.0	35.5	40.1	12.8	10.5	682.
80	54.6	40.3	51.9	91.2	0.9	24.7	2.5	13.5	29.4	23.7	91.2	28.7	371.
81	40.9	23.9	126.0	11.0	87.5	12.1	0.3	67.9	15.7	86.3	24.5	56.5	553.
%TOTAL	8.3	15.2	15.2	8.3	7.2	4.3	6.6	7.3	6.7	8.8	8.5	9.4	100.00

MEAN ANNUAL RAINFALL = 520.3 MM.

SUMMARY OF OBSERVED FLOWS AT Q9M24(THOUS.CUB.MET.)
PERIOD OF RECORD JAN. 1976 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
76	0.0	0.0	98.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	98.7
77	0.0	0.0	0.0	0.0	8.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6
78	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
79	0.0	0.0	0.0	0.0	0.0	0.0	752.6	791.6	179.0	9.1	0.0	0.0	1732.3
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.1	1.6
81	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	14.8	16.2
%TOTAL	0.0	0.0	5.3	0.0	0.5	0.0	40.5	42.6	9.6	0.6	0.1	0.8	100.00

MEAN ANNUAL RUNOFF = 309.6 THOUS. CUB. MET.

SUMMARY OF AVER.CATCH.EVAP ABOVE Q9M24(MM)(A-PAN)
PERIOD OF RECORD JAN. 1975 TO DEC. 1981

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
75	186.3	177.2	179.4	150.0	121.7	102.0	147.9	169.4	94.8	224.1	229.8	211.3	1959.
76	208.6	167.4	168.1	93.0	76.6	102.9	90.7	111.6	120.2	155.0	239.5	287.9	1779.
77	265.0	188.4	160.5	122.6	103.9	113.0	124.6	142.1	122.1	191.2	195.7	229.2	1938.
78	196.4	184.9	193.0	116.4	107.1	81.1	81.2	131.9	134.0	158.0	220.9	225.3	1850.
79	234.0	214.2	190.6	129.9	91.3	82.6	85.5	91.5	123.2	170.6	222.2	262.4	1899.
80	263.0	175.2	174.4	139.5	126.3	79.9	109.7	117.4	128.4	176.5	173.4	198.1	1862.
81	192.5	152.5	134.9	118.3	74.2	68.1	102.6	86.3	126.1	166.4	174.3	199.8	1594.
%TOTAL	12.0	9.6	9.0	6.6	5.4	4.9	5.6	6.6	6.7	9.6	11.3	12.5	100.00

MEAN ANNUAL EVAP. = 1840.2 MM.

suggests that annual runoff of the order of magnitude of the 1979 total can be expected no more than two to three times in 100 years.

2.4 COMPARISON OF CHARACTERISTICS AFFECTING HYDROLOGICAL RESPONSE OF CATCHMENTS A, B and E

2.4.1 Introduction

One of the objectives of this study is to evaluate with how much success explicit soil moisture accounting rainfall-runoff models can be used in ungauged catchments to generate a runoff time series where no runoff record exists. Such an analysis is described in Chapter 8 in which the parameter values of the models calibrated in catchments A and B are transferred respectively to the remaining two catchments and runoff time series generated for these two catchments in each case. These flow series are then compared with the original observed flow series in these two catchments. Good correspondence between the observed and the new flow series (after parameter transfer) signifies successful parameter transfer and strengthens confidence in the usefulness of such a model in the ungauged situation.

The principal determinant of successful parameter transfer is the degree of hydrological similarity between the gauged and the ungauged catchments (Linsley,1976). This similarity must encompass the maximum possible number of catchment characteristics, such as climate, lithology, soils, vegetation, physiographic and geomorphic parameters, drainage patterns and land use. Here the underlying principle is that a high degree of similarity in the above factors would ensure similarity in hydrological response, which in turn would ensure similarity of model parameters. Clearly interpretation of the outcome of parameter transfer between catchments A, B and E, discussed in Chapter 8, would be much enhanced by a synthesis of all information that has a bearing on the hydrological response of these three catchments. Such a synthesis is attempted below.

2.4.2 Comparison of physical characteristics

Table 2.14 lists the numerical values of certain geomorphic and

physiographic characteristics of the three catchments under consideration, while Table 2.15 details the spatial distribution of geological, vegetation and slope categories. The Table 2.14 values were digitized by micro-computer from 1:50000 maps, aided by aerial photographs, while the values in Table 2.15 were taken from Roberts (1978). Hypsometric analyses, illustrating the relation of horizontal cross-sectional drainage basin areas to elevation of the cross-section relative to the basin outlets, were reported in Roberts (1978). The hypsometric relationships of all five Ecca catchments, taken from the latter source, are shown in Fig. 2.7. Cumulative area vs. slope curves, according to Roberts (1978), are depicted in Fig. 2.8. The reader is also reminded of maps showing the spatial distribution of vegetation density, geological formations and slopes referred to earlier as Figs. 2.3, 2.4 and 2.5, respectively. The only hydrologically important characteristic in which no quantified information exists is soil type and distribution. A limited soil survey is at the time of writing (October 1982) in progress, but the results will not be available until well into 1983. The following inferences regarding hydrologic response are possible from the foregoing tabulated and graphic information.

Catchment E is a substantially flatter catchment than the other two - both in terms of the mean catchment slope and the proportion of catchment area with mild slopes. Superposition of the geology map (Fig. 2.4) on the slopes map (Fig. 2.5) reveals that geomorphological control may be exercised by the Dwyka and Witteberg formations, resulting in the flat uplands of E. Of the three catchments, E has by far the greatest percentage of "dense" vegetation cover, as well as the lowest drainage density. Field experience suggests that, proportionally speaking, deeper, fine-textured soils are more common in E. *Without forcing the argument at this stage, the balance of the* above physical evidence points to the likelihood of larger catchment losses and a much more dampened hydrological response in catchment E than in the other two. (This does not imply that A and B are completely similar; indeed catchment B is steeper than A, is less efficiently drained and has a different distribution of geological formations.)

Table 2.14

Physiographic indices of the Ecca catchments

Characteristic*1	Catchment A	Catchment B	Catchment E
Catchment area (km^2)	73,1	9,1	23,1
Mean catchment slope	0,199	0,263	0,178
Catchment perimeter (km)	42,2	13,7	24,9
Maximum relief (m)	570	373	455
Median altitude above weir as proportion of max. relief	0,41	0,61	0,56
Length of main channel (km)	24,9	6,7	10,6
Centre of gravity of catchment: channel distance from weir (km)	9,8	4,4	6,3
Slope (10% : 85%) of main channel	0,016	0,037	0,030
Drainage density (km/km^2)	4,34	2,33	1,83
Elongation ratio	0,39	0,51	0,52
Lemniscate ratio	0,58	0,61	0,55

*1 Mean catch. slope = $\frac{\text{total contour length . contour interval}}{\text{catchment area}}$

Slope (10%:85%) of main channel = $(H_{85} - H_{10})/(0,75.\text{channel length})$
with H_c = height at point c% of channel length

Drainage density = total tributary length / catchment area

Elongation ration = $1,129.(\text{catch. area})^{0,5}$ / catchment length
= catch. shape compared with circle

Lemniscate ratio = $(\text{catch. length})^2$ / 4.catchment area
= catch. shape compared with pear shape

Table 2.15

Proportions (%) of catchment areas*1 belonging to various categories of physical characteristics

Characteristic	Category	Catchment		
		A	B	E
Geology	Shales	51	30	95
	Sandstone	27	30	16
	Tillite	18	40	25
	Quartzite	4	-	14
Vegetation density				
Ground cover	Dense	11	13	28
	Medium	36	37	39
	Sparse	53	50	33
Canopy cover	Dense	26	17	34
	Medium	48	54	29
	Sparse	26	29	37
Slopes	Less than 10%	39	23	44
	10% to 20%	30	29	35
	20% to 40%	19	29	13
	More than 40%	12	19	8

*1 After Roberts (1978)

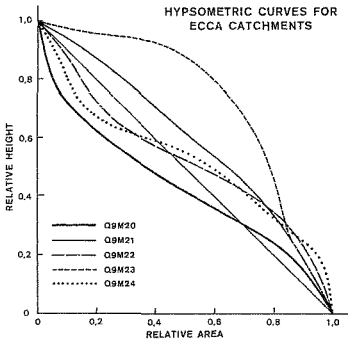


Figure 2.7 Hypsometric curves for the Ecca catchments (from Roberts, 1978)

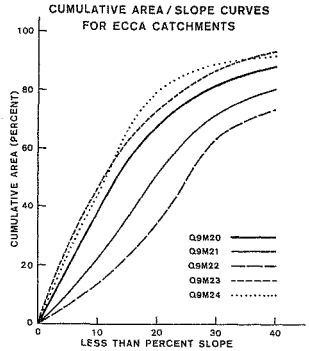


Figure 2.8 Cumulative area/slope curves for the Ecca catchments (from Roberts, 1978)

2.4.3 Comparison of observed rainfall-runoff behaviour

Preliminary analyses of all storm runoff events in the three catchments for the period 1976-1979 were reported by Görgens (1980) and Murray and Görgens (1981). Both these studies revealed that catchment E generated storm runoff (measurable at the weir) much less frequently than A and B, produced fewer small-volume runoff events, displayed on the average a tendency towards lower hydrological response (i.e. larger losses) per major runoff-producing storm and required on the average higher antecedent rainfalls before stormflow was initiated.

A summary of the observed hydrological behaviour of the three Ecca catchments is provided in Table 2.16, while their standardized flow duration curves have been plotted in Fig. 2.9. Data contained in both the table and the figure corroborate the suggestion made in the preceding section on the basis of physical catchment characteristics that catchment E is hydrologically dissimilar to catchments A and B. It must be stressed, however, that the dissimilarity is expressed in relative terms only, and that the range of hydrological response types exemplified by the three Ecca catchments is quite typical of South African semi-arid catchments seen on a macro-scale, if compared with the analysis by Görgens and Hughes (1982) of streamflow records from 30 semi-arid catchments in South Africa (selected on the basis of representativeness and reasonable data quality). For example, over the 30 catchments the mean long-term runoff coefficient came out at 4,8%, the mean MAR at 19,1mm, the mean monthly coefficient of variation at 5,62% and the mean percentage of zero-flow months at 37,1%. Nevertheless, on the basis of hydrological response types at the meso-scale, which is the scale relevant to the Ecca study, catchment E displays meaningful differences relative to catchments A and B. In terms of these differences the prognosis for parameter transfer between A, B and E must at this stage be that in general there should be more risk in transferring parameters to E from A or B than between A and B. Chapter 8 will address this question in depth.

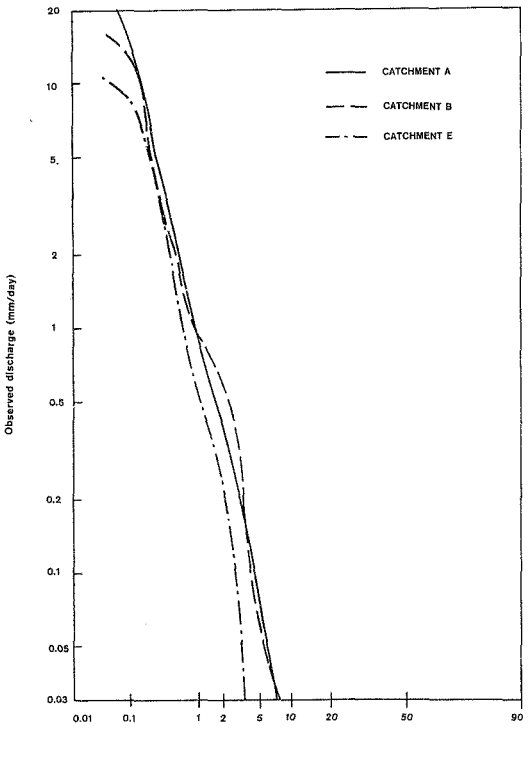


Figure 2.9 Standardized flow duration curves for the Ecca catchments

Table 2.16

Comparison of observed hydrological response variables

Variable	Catchment		
	A	B	E
Measured MAP (mm), 1975-1981	487	478	520
(Range)	347-649	346-637	371-682
Measured MAR (mm), 1976-1981	23,12	21,76	13,42
Measured MAR (10^3m^3), 1976-1981	1691	198	310
(Range)	30-8563	3-1007	0,3-1732
Measured MAR/MAP (%), 1976-1981	4,59	4,38	2,51
Zero-flow months (%), 1976-1981	41,7	58,3	81,9
Coef. of variation:monthly flows, 1976-1981	4,7	4,4	5,1
No. of discrete hydrograph rises, 1976-1979*	20	29	14
Mean runoff coefficient per stormflow event (%), 1976-1979*	4,89	3,06	4,04
Max. runoff coefficient (%), 1976-1979*	34,27	26,78	15,5
Max. instantaneous discharge (mm/h)*	1,67	1,67	1,48
Max. stormflow runoff event (mm)*	36,05	23,61	14,77

* From Murray and Görgens (1981)

CHAPTER 3

MODELS PITH AND PITR - PITMAN'S HOURLY MODEL MODIFIED IMPROVED AND COMPARED WITH THE STANFORD WATERSHED MODEL

3.1 HISTORY OF PITMAN'S HOURLY MODEL

During the period 1972-1977 a suite of three explicit soil moisture-accounting conceptual rainfall-runoff models was developed at the Hydrological Research Unit (HRU), University of the Witwatersrand (Pitman, 1973; 1976; 1977) under guidance of Prof. D.C. Midgley. The three models require respectively monthly, daily and hourly rainfall totals, as well as long-term mean monthly Symons pan evaporation values, as input streams. Pitman designed his suite of models to operate satisfactorily in terms of commonly-used water resources engineering criteria when using input data typically available to the South African user, viz. records from the national hydrometeorological monitoring networks of the Department of Environment Affairs, the Weather Bureau and the Department of Agriculture. The quality and accuracy of such data vary considerably and non-stationarities and periods of missing data are not uncommon. In the above context, Pitman thought it prudent to strive for simplicity in his models and considered the mathematical representations of the relevant hydrological processes as ".....just about sufficient for the purpose of simulating runoff to an acceptable degree of accuracy. Improvements in correlations between observed and simulated runoff could no doubt be achieved by introducing further more complex functions involving additional parameters but the task of calibrating such a model would be rendered highly complicated" (Pitman, 1976).

While the monthly and daily input versions of Pitman's model were intended for South African water resources analysis and planning purposes, the hourly model was specifically designed for flood forecasting application, as demonstrated in studies of flood forecasting for reservoir operation by Basson (1978) and Pitman and Basson (1979).

Figure 3.1 depicts the essential elements of the hourly model, as described in Pitman and Basson (1979). The following summary of the conceptualization of the model is taken directly from the latter source (pp. 2.1-2.3):

"The first storage that must be filled before rainfall reaches the ground is the interception store. Thereafter, water that does not infiltrate into the soil is held in depression storage as potential surface runoff. When this store (represented by parameter SU) is overtopped the surplus water becomes surface runoff.

"Water is evaporated from interception storage at the potential rate. Once this store is depleted evaporation takes place from the depression store, also at the potential rate. Evaporation from the soil itself is assumed to take place only when both interception and depression stores have been depleted.

"Spillage from depression storage is divided into surface flow and interflow. In modelling this separation it was assumed that low rates of spillage would generate a high proportion of the relatively slow response (interflow) and, conversely, that high rates of spillage would yield a high proportion of the quick response (surface flow)..... The parameter DIV can be envisaged as the limiting interflow rate....."

The hourly model was designed to be structurally similar to the daily model, so that the daily model could be used for initial calibration and for "warming-up" during pre-flood months. The internal variables in warmed-up status were then easily transferred from the daily to the hourly model a few days modelling time prior to the flood event to be simulated, so that the hourly model served for predictions during the flood proper. As this model was designed to operate in a practical real-time forecasting mode, its input data requirements were kept to a minimum, (i.e. long-term mean monthly Symons pan values). Furthermore, the use of the daily model during the warm-up period effected economies in both computer time and input data.

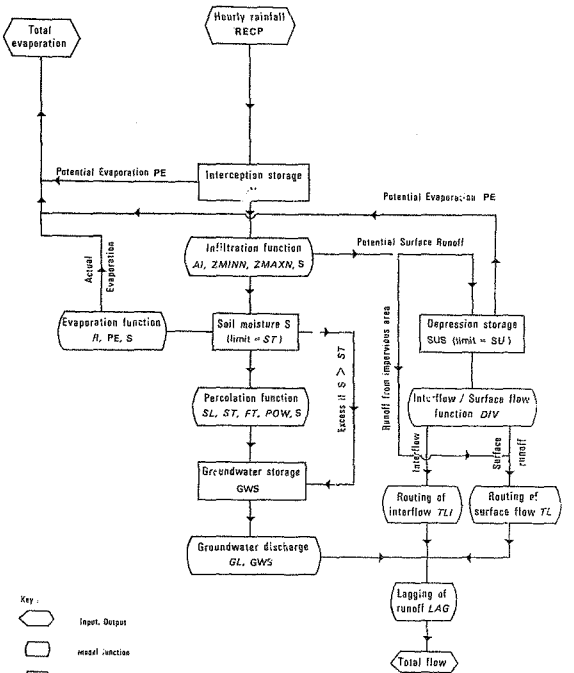


Figure 3.1 Flow diagram for Pitman's original hourly model (after Pitman and Bosson, 1978)

Using this "mixed" model, Pitman and Basson (1979) reported a high degree of success in simulating flood volumes in the Hartbeespoort Dam catchment, but less success in simulating flood peaks. In a comparison of his hourly model with the Stanford Watershed model using using data from the Jukskei catchment near Johannesburg, Pitman (1977) showed that as regards simulation of peak, volume and timing of flood hydrographs, the performance of the Stanford model was no better than that achieved by his hourly model. However, the two reported applications of Pitman's hourly model have revealed certain shortcomings in the performance of the model which needed further investigation with the view to improvements. These shortcomings can be summarised as follows:

Shortcoming 1: From the plots of simulated versus observed hydrographs in Pitman and Basson (1979, pp. 3.16-3.17) it appears that the model often failed to reproduce the later parts (both peak and volume) of composite flood hydrographs. Although inadequate representation of the distribution of storm rainfall, both in time and space, could account for some simulation errors, failure to reproduce the later parts of the composite hydrographs may be indicative of structural shortcomings in the model. As the later peaks of composite flood hydrographs usually represent the response of an already wet catchment to further rainfall (often neither much nor intense), those components of the model that dictate model output of quickflow during periods of exceedence of maximum soil moisture storage level, ST, perhaps need modification. The excess over ST, called SPILL, is added directly to the groundwater store, GWS. Conceptually, it may be more correct to divide SPILL between groundwater and quickflow.

Shortcoming 2: Rainfall of low intensity and prolonged duration caused simulation errors, because the mean monthly values of potential evaporation input resulted in serious overestimates of evaporation rates during such events, leading to underestimation of the consequent floods (Pitman and Basson, 1979, p. 3.20). However, this failure of the model could perhaps additionally be related to the model's inability to produce quickflow during wet catchment conditions, as stated in the previous paragraph. When using the model in forecast mode where the acquisition of potential evaporation data simultaneous

with incoming rainfall information may be difficult to arrange, the hourly evaporation values during storms, should perhaps be pre-set at some representatively low value, e.g. at an equivalent daily rate of between 0,1mm and 1,0mm.

Shortcoming 3: The model was "too sensitive" to high intensity rainfall (such as occurs in convectional thunderstorms) which led to exaggerated quick-flow generation (Pitman pers. comm., 1981). This problem implies inadequate infiltration and/or depression storage functions. There are two likely solutions to this problem. Firstly, the infiltration and depression storage functions could be reformulated to cope with high intensity rainfall. Secondly, these functions could remain unchanged, but the "potential surface runoff" already calculated could be allowed to undergo re-infiltration before being subjected to lagging and channel routing.

3.2 APPLICATION OF PITMAN'S ORIGINAL HOURLY MODEL IN SEMI-ARID CATCHMENTS

In the light of the aforementioned encouraging results of the applications of Pitman's hourly model to the Jukskei and Hartbeespoort Dam catchments, and taking cognisance of the fact that solutions might exist for all three of the model shortcomings outlined above, it was decided to make the attempted improvement of the model a special objective of this study. To this end, the computer program encompassing the hourly section of the forecast model algorithms was extracted from Pitman and Basson (1979). This program was then modified to run as an independent continuous catchment model with hourly rainfall inputs. To enhance accuracy further, the model was altered to accept inputs of daily A pan evaporation values and to spread each day's evaporation by a triangular distributuion between 07h00 and 19h00. The model component controlling actual evaporation as a function of soil moisture storage state and potential evaporation (see section 3.6.8 for details) was also made more flexible.

At this level of modification it was felt that the model was still basically identical to Pitman's original version and its ability to simulate runoff in the Ecca catchments had to be ascertained to

provide a "baseline" for attempted improvements. Two different tests of the model were undertaken. Firstly, the model program was modified to enable it to be fitted to selected flow events only, whereafter it was manually calibrated on the six most important flow events in Ecca catchments A and B respectively. The results of this exercise are discussed in the next few paragraphs. The second test took the form of an intercomparison of Pitman's hourly model with his daily and monthly models, as well as with the Stanford model, based on an analysis of their ability to reproduce the monthly and annual streamflow statistics of Ecca catchments A, B and E for the six years for which streamflow gaugings were available. The results of this second test are discussed in detail in Chapter 7. Suffice it to say that the hourly model produced, relatively speaking, the poorest performance of the four models. All three shortcomings outlined in the previous section were evident in this application of the model.

Table 3.1 lists the dates of the flow events in the Ecca catchments selected for testing the model in its original and modified modes. An impression of the results of fitting the original model to the selected flow events in the Ecca catchments A and B can be gained from Table 3.2, as well as Fig. 3.2. Figs. 3.3(a) to (i) provide isohyetal maps of all storms used in this exercise, while Figs. 3.4(a) to (c) depict the temporal distribution of each storm on the basis of average catchment falls. A warm-up period of one year was used and the calibration was based on optimizing the statistical measures of fit shown in Table 3.2, as well as on the visual comparison of simulated with observed hydrographs. Not much attention was paid to the absolute minimization of errors in mean annual runoff (MAR) and standard deviation of monthly runoff totals, nor to overall fitting criteria and no verification was attempted. This procedure was followed because the exercise was essentially exploratory in nature and aimed at revealing weaknesses in the model structure and behaviour. Consequently, the focus had to fall on individual hydrographs and not on overall statistics.

The criteria shown in Table 3.2 were chosen because it was thought they would provide a balanced overall impression of the ability of the model to simulate a range of flow events. An exact

mathematical definition of these criteria (and all other statistical criteria used in this report) can be found in Appendix A. The coefficient of efficiency is a measure of one-to-one fit which measures the model's success at simulating the hydrograph shapes while the peak-volume objective function is designed to give approximately equal weight to the errors in peak and volume and, when minimized, should provide a balanced measure of the fit of these two important hydrograph characteristics.

Table 3.2 and Fig. 3.2 reveal that the model fared better on catchment A than on B. However, in both cases the later parts of the composite hydrographs were poorly simulated. The large positive error in mean peak flow rates and volumes on B and the lack of improvement in the peak-volume objective function were mostly due to the exaggerated response of the model to high intensity short duration convectional thunderstorm rainfall input during the events of 27/28 February 1977 (peak hourly total of rainfall = 25,9mm). While the above test provided further evidence of the shortcomings outlined in the previous section, it also uncovered additional shortcomings, all of which represent conceptual errors of a more or less serious nature in the model stucture and the algorithms contained in the published computer program of the model (Pitman and Basson, 1979):

Shortcoming 4: Actual evaporation estimates are exaggerated because no provision was made in the computer program to ensure that evaporation from the soil store may take place only when both interception and depression stores have been depleted, and that in such a case only the residual potential evaporative demand was applied to the soil. This means that during time increments when the interception, depression and soil stores are all near full capacity, the actual evaporation for that time increment can be up to twice the input potential evaporation. This may be a simple oversight on the part of the model developer; nevertheless the evaporation algorithm in the model is conceptually very suspect, because the model effectively "creates" potential evaporation.

Shortcoming 5: Negative soil moisture states can occur in the

Table 3.1

Dates of selected flow events

Event No.	Catchment A	Catchment B	Catchment E
1	21/3/76-23/3/76	21/3/76-23/3/76	21/3/76-23/3/76
2	28/2/77- 1/3/77	27/2/77 28/2/77	7/5/77- 8/5/77
3	7/5/77- 8/5/77	7/5/77- 8/5/77	21/7/79-26/7/79
4	21/4/78-22/4/78	21/7/79-23/7/79	20/8/79-24/8/79
5	21/7/79-27/7/79	24/7/79-25/7/79	
6	20/8/79-25/8/79	20/8/79-23/8/79	

Table 3.2

Summary of overall results for Pitman's original hourly model fitted*1 to selected flow events

Statistical Criteria	Catchment A (73,1km ^{2})		Catchment B (9,1km ^{2})	
	No-model case*4	Pitman's model	No-model case	Pitman's model
Overall HCE*2	-0,79	0,57	-1,49	-0,01
Mean Peak Error (%)	-100,0	-0,8	-100,0	123,8
Mean Volume Error (%)	-100 0	-5,0	-100,0	284,8
Mean Peak Timing Error (hr)	-	+2	-	+1
Peak Volume O.F.*3 (m^3/s^2)	4591	538	101	102
No. of Calibration Runs	-	20	-	31

*1 All statistical criteria of fit are defined in Appendix A

*2 Overall coefficient of efficiency based on hourly values

*3 Peak-Volume Objective Function

*4 Value of the statistic when simulated flows all set to zero

Figure 3.2(a) Observed and simulated hydrographs:
catchment A (see overleaf)

Figure 3.2(a) Observed and simulated hydrographs:
catchment A (see overleaf)

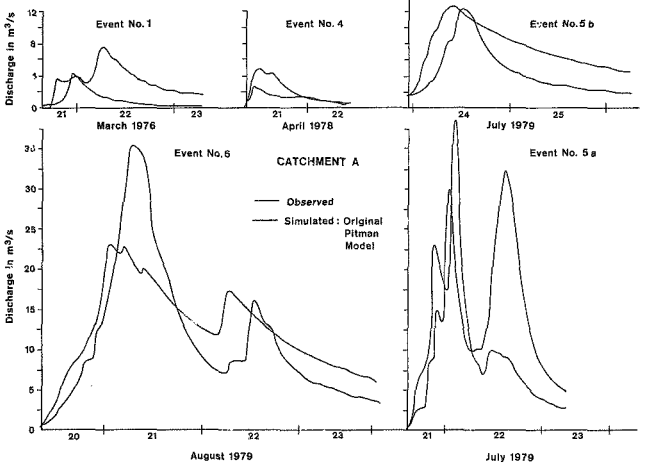

Discharge in m³/s
Event No. 1
March 1976
Event No. 4
April 1978
Event No. 5 b
July 1979
Event No. 6
August 1979
CATCHMENT A
Observed
Simulated : Original Pitman Model
Event No. 5 a
July 1979

Figure 3.2(b) Observed and simulated hydrographs:
catchment B (see overleaf)

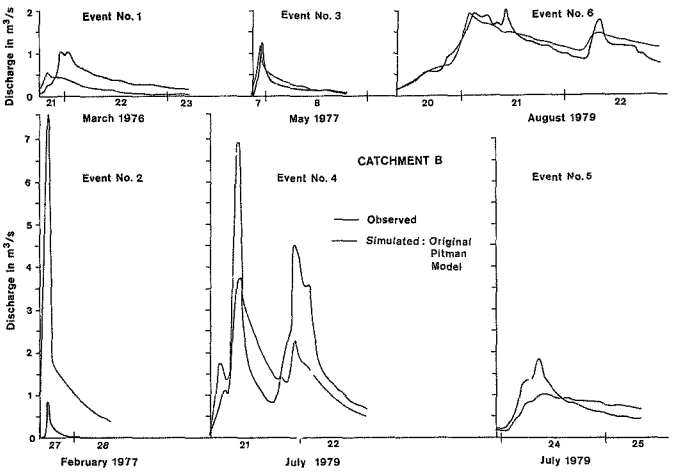
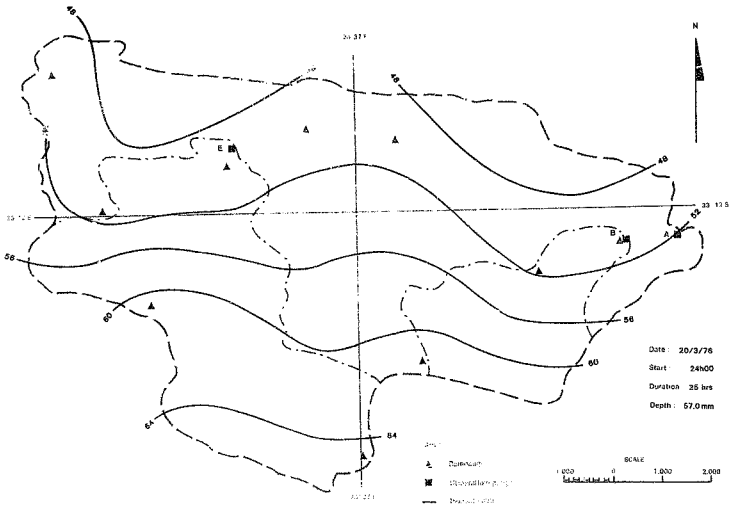
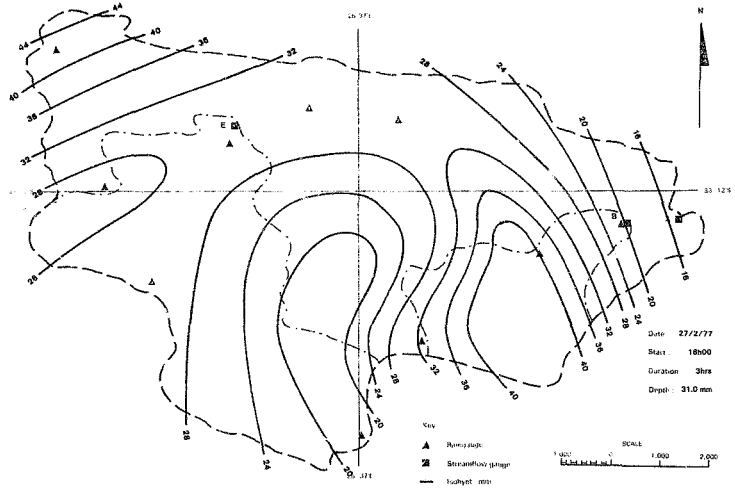
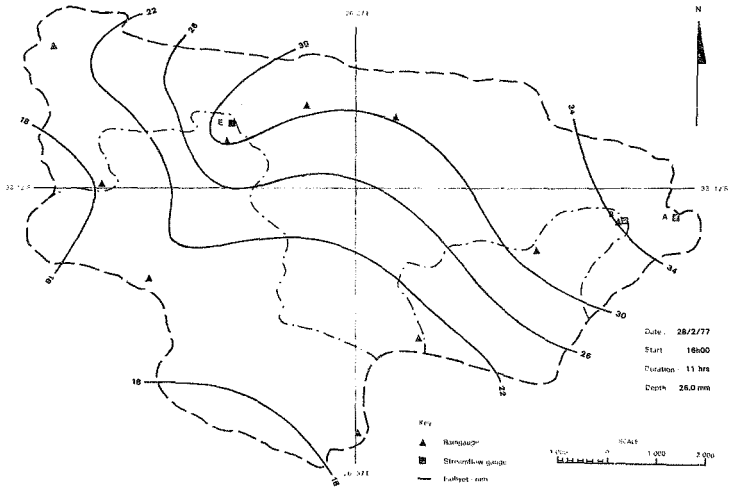
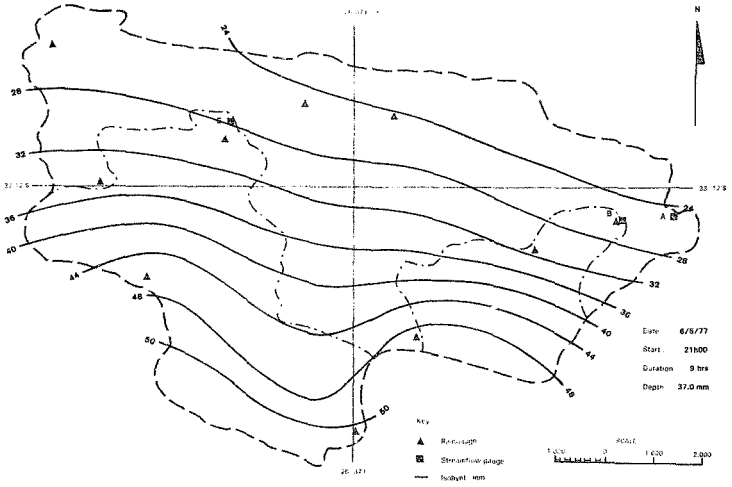

Event No. 1
Event No. 3
Event No. 6
Discharge in m³/s
March 1976
May 1977
August 1979
CATCHMENT B
Event No. 2
Event No. 4
Event No. 5
Observed
Simulated : Original Pitman Model
Discharge in m³/s
February 1977
July 1979
July 1979

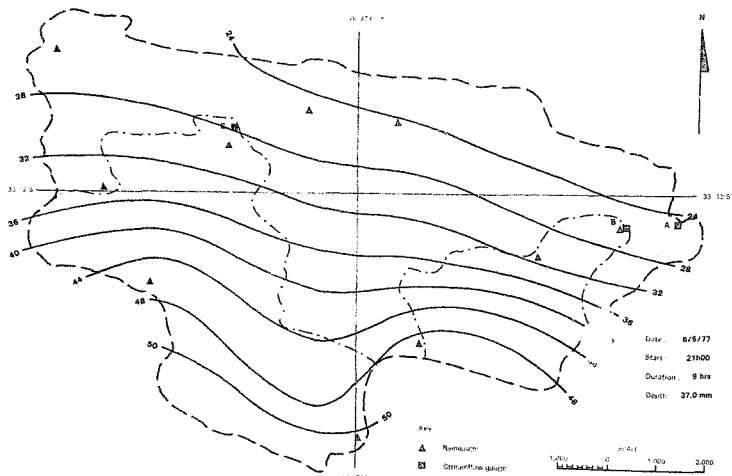
Figure 3.3(a) to 3.3(f) Isohyetal maps for all storms
used in hourly model tests (see following pages)
(scale in meters)

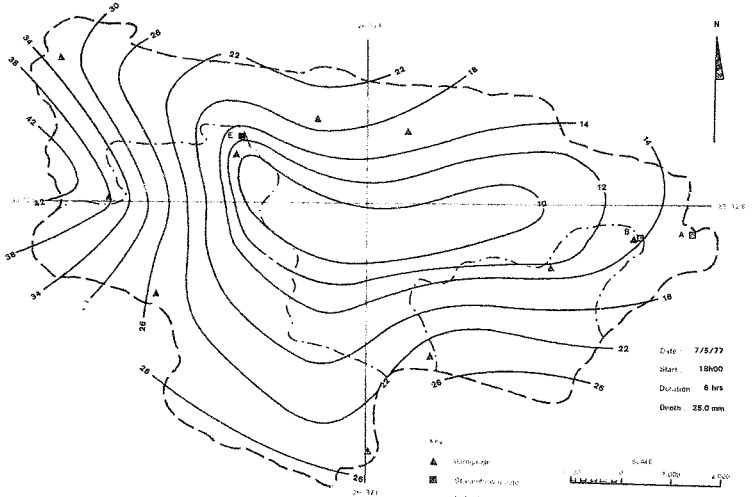

N
48
56
60
64
Date : 20/3/76
Start : 24h00
Duration 25 hrs
Depth : 57.0 mm
SCALE
1,000
0
1,000
2,000

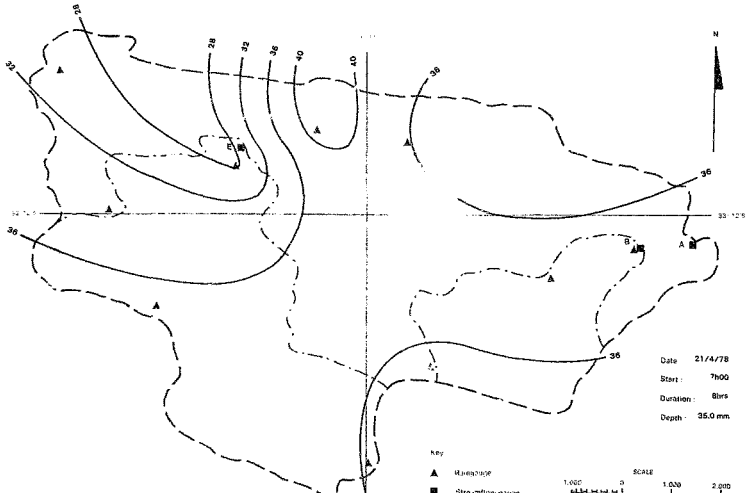

N
Date : 27/2/77
Start : 16h00
Duration : 3hrs
Depth : 31.0 mm
Key
Rain gauge
Streamflow gauge
Isohyet mm
SCALE
1 000
0
1 000
2 000

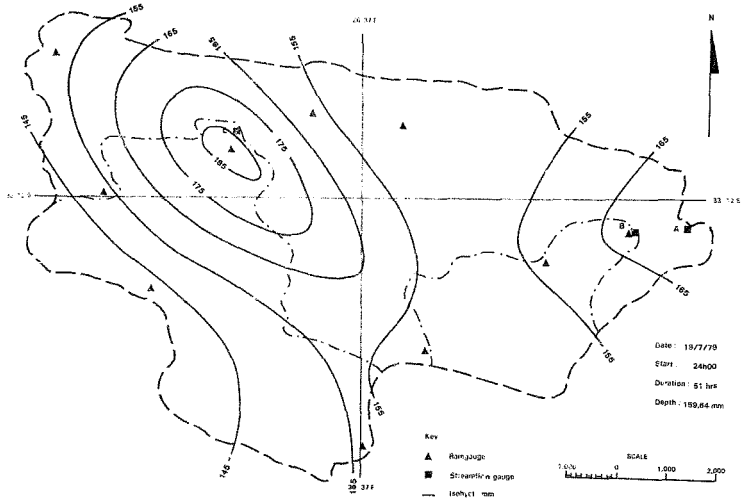

N
22
20
30
18
34
30
26
22
18
Date 28/2/77
Start 16h00
Duration 11 hrs
Depth 26.0 mm
Key
Raingauge
Streamflow gauge
Isohyet - mm
SCALE
1 000
2 000

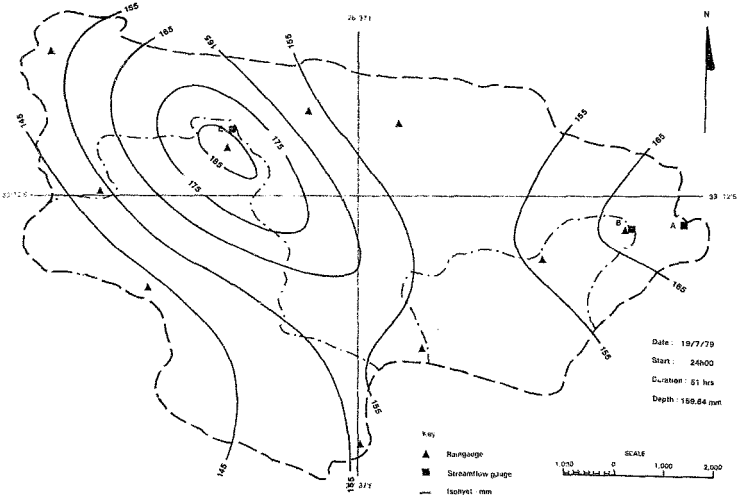

N
28
32
36
40
44
48
50
60
24
26
32
36
40
44
48
Date 6/6/77
Start 21h00
Duration 9 hrs
Depth 37.0 mm
Key
Raingauge
Streamflow gauge
Isohyet mm
SCALE
1 000
0
1 000
2 000

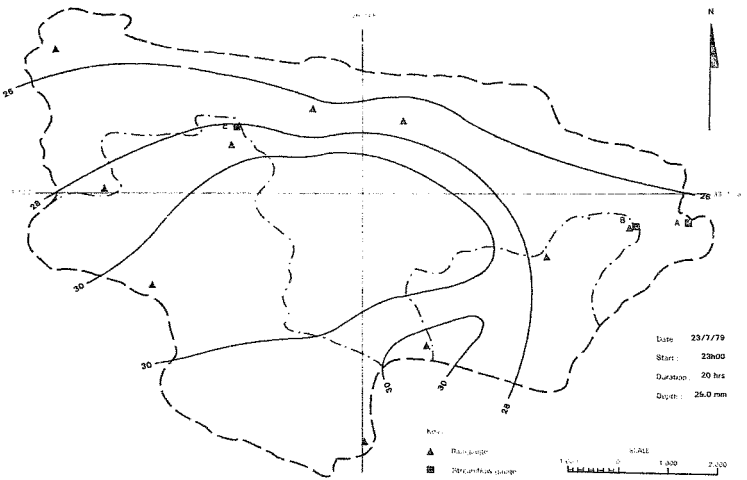

N
28
32
36
40
44
48
50
24
28
32
36
40
Date : 6/6/77
Start : 21h00
Duration : 9 hrs
Depth : 37.0 mm
Key
Raingauge
Catchment boundary
Isohyet mm
1,000
0
1,000
2,000


N
Date : 7/5/77
Start : 18h00
Duration : 6 hrs
Depth : 25.0 mm


N
20
28
32
36
40
40
36
36
36
Date 21/4/78
Start : 7h00
Duration : 6hrs
Depth : 35.0 mm
Key
Raingauge
Streamflow gauge
Isohyet mm
SCALE
1,000
0
1,000
2,000


N
185
175
165
155
145
A
B
Date : 19/7/79
Start : 24h00
Duration : 51 hrs
Depth : 189,64 mm
Key
Raingauge
Streamflow gauge
Isohyet mm
SCALE
0
1,000
2,000


N
155
165
175
185
145
Date : 19/7/79
Start : 24h00
Duration : 61 hrs
Depth : 188.64 mm
Key
Raingauge
Streamflow gauge
Isohyet - mm
SCALE
1,000
0
1,000
2,000


N
25
25
26
30
30
30
30
29
Date : 23/7/79
Start : 23h00
Duration : 20 hrs
Depth : 25.0 mm
SCALE
0
1 000
2 000

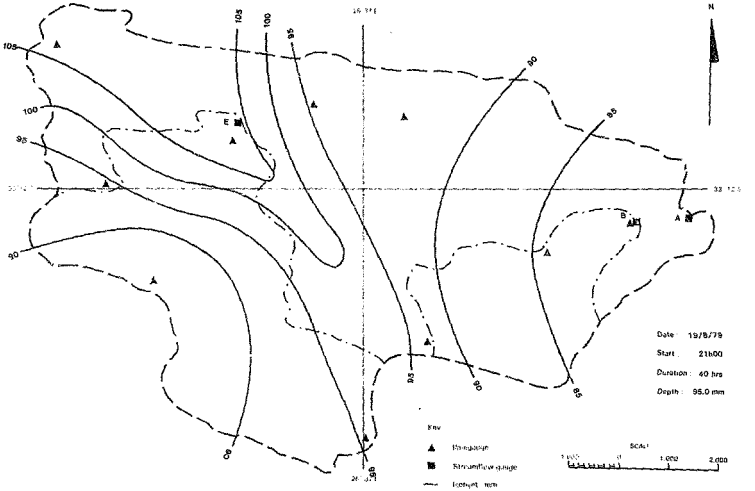
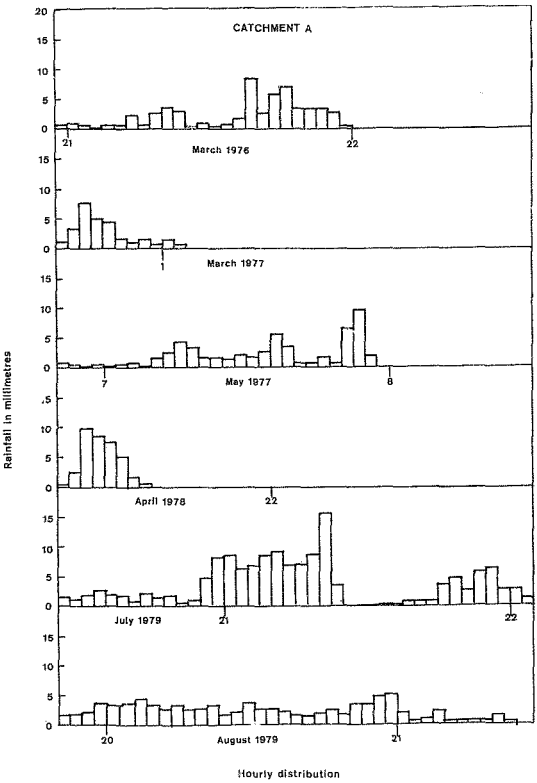
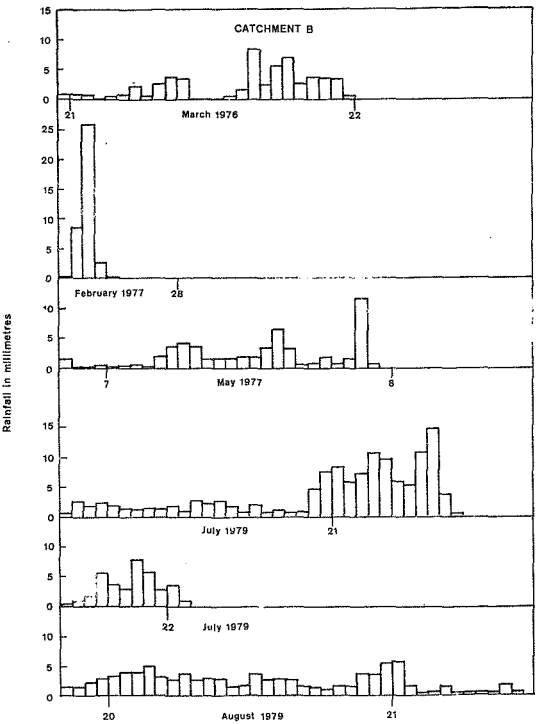
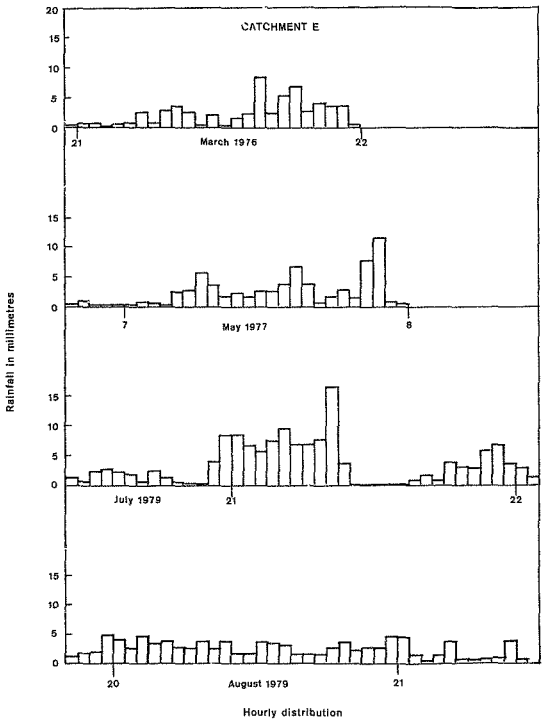

105
100
95
90
N
Date : 19/8/79
Start : 21h00
Duration : 40 hrs
Depth : 95.0 mm
Key
Raingauge
Stream flow gauge
Isohyet mm
Scale
1 000
2 000

Figure 3.4(a) to 3.4(c) Hourly distribution of selected storms : catchments A, B and E
(see following pages)


CATCHMENT A
March 1976
March 1977
May 1977
April 1976
July 1979
August 1979
Rainfall in millimetres
Hourly distribution


CATCHMENT B
Rainfall in millimetres
March 1976
February 1977
May 1977
July 1979
July 1979
August 1979
Hourly distribution


CATCHMENT E
Rainfall in millimetres
20
15
10
5
0
21
March 1976
22
7
May 1977
8
July 1979
21
22
20
August 1979
21
Hourly distribution

model, especially using semi-arid data, because the model program does not check for and correct this eventuality. Using a test parameter set and data from the Ecca catchments, it was found that negative soil moisture states actually do develop after prolonged dry spells. However, the effect on model simulations seems negligible for the data sets used. Nevertheless, though not serious in their model output consequences, negative soil moisture states are conceptually unacceptable.

Shortcoming 6: Only the surface flow part of the potential surface runoff of the model can be lagged. This implies that the model flow diagram given by Pitman and Basson (1979) is misleading (see Fig. 3.1). In this diagram the lagging function should appear in the surface runoff stream before the confluence of the three output streams. This error makes it *theoretically possible for the interflow* for a certain time increment to be output by the model before there *has been surface* flow for that time increment. Conceptually, this does not make sense, and the interflow component should be lagged as well.

Shortcoming 7: Outflow from the interflow linear store is calculated for a specific time increment from the storage state at the end of the previous time increment. This leads firstly to a built-in *lag of one time increment* in interflow which may or may not be acceptable and secondly, to a slightly erroneous interflow volume for any specific time interval. Analysis of simulated near-peak flow components revealed that interflow was often as important in the model's production of peaks as surface flow was - a fact confirmed by Pitman (pers. comm., 1982) for the Hartbeespoort Dam study as well. *It* is consequently important to improve the interflow component of the *model. Preferably, outflow from the interflow* linear store should be based upon the average storage state of the store for any time increment.

3.3 MODIFICATIONS TO PITMAN'S HOURLY MODEL : VERSIONS PITH AND PITR

Modifications to Pitman's hourly model that would overcome all the aforementioned shortcomings *would constitute a* major improvement

only if the inherent virtues - simplicity, ease of calibration and unambiguous conceptual meaning of model parameters - were not sacrificed in the process. The re-infiltration function proposed in the discussion of shortcoming 3 would certainly compromise the virtues much more than apparent solutions to the other six shortcomings. For this reason, it was decided to undertake modifications in three separate but overlapping steps:

(a) solutions to shortcomings 4 and 5 as a matter of necessity because they represent errors in the model program,

(b) in addition to (a), modifications to overcome all shortcomings including a re-infiltration function,

(c) in addition to (a), modifications to overcome shortcomings 1, 2, 6 and 7 only, i.e. excluding re-infiltration.

Pre-conditions to all modifications were (i) that introduction of new model parameters was to be avoided if possible and (ii) that retention of the maximum possible degree of compatibility with Pitman's daily model would be sought to ensure the structural equivalence required by the "mixed" model flood forecasting approach used by Pitman and Basson (1979).

Development work on all modifications, except the introduction of interflow-lagging, was done on catchment B events only. It was hoped the minimal attenuation and lag in response of the small catchment would allow the focus to remain on other aspects of the modelling process. Promising modifications were subsequently applied to selected events on catchments A and E and the overall performance assessed. Again a warm-up period of one year was used. Assessment criteria were the same as those defined in Table 3.2, but in addition percent error in MAR was minimized to ensure that the model did approximately simulate the overall water balance of the catchment. The more important modifications are outlined below:

(i) Re-infiltration of "potential surface runoff": Re-infiltration of overland flow generated on a hillslope during a storm

is a well-known phenomenon (Knapp , 1978; Dunne, 1978). Surface ponding occurs at a source area on a hillslope due either to continued exceedence of the average infiltration rate or to saturation of the surface soil layers at that site. This leads to overland flow under the influence of gravity, with rills and micro-gullies acting as the main conduits. However, some of this water soon flows over soil having higher infiltration capacity than that of the source area and infiltrates at these points. Furthermore, overland flow arriving in a local depression or being trapped by a small obstruction can also be subjected to additional infiltration. Introduction of a re-infiltration function in the model requires answers to two questions:

* at what point in the structure of the models should re-infiltration act on "potential surface runoff" - before it enters the depression store (along with the latter's contents), or after it spills over from the depression store and before lag-routing takes place (along with the contents of the depression store), or only on the contents of the depression store?

* which infiltration rates should hold for re-infiltration?

The former question was explored by calibrating the model individually with each of the three stated options on catchment B events. As will be seen in the discussion of the results of modification applications in section 3.4, the third option, namely re-infiltrating only the contents of the depression store, was clearly the best of the three options. The second question was more difficult to answer, but after attempting options such as using either a constant re-infiltration rate which is a function of that time increment's existing infiltration rate, or a special re-infiltration function requiring a *new model parameter (to be avoided)*, it was decided that the "tidiest", and perhaps conceptually safest, assumption would be that the model's original infiltration function (see section 3.4) should be re-employed at this point in the computer program. Inevitably, the incorporation of a re-infiltration function along these lines would affect the conceptual meaning of model parameters SU, ZMINN and ZMAXN (see Fig. 3.1).

At this juncture it may be informative to consider the little-known fact that the developers of the famous Stanford Watershed Model (Crawford and Linsley, 1966; Hydrocomp Inc., 1969) also employed the re-infiltration concept - albeit in an indirect way. Their solution to the twin problems of where re-infiltration fits into the model and at what rate it should take place was relatively pragmatic and simple. The Stanford model merely adds the contents of the "upper soil zone store" (roughly equivalent to Pitman's depression store, SU) at the start of any time increment to the residual incoming rainfall (after interception) for that time increment and then processes this combined moisture quantity through the infiltration function. It was felt that the three re-infiltration options outlined above for Pitman's model, though similar to the Stanford model approach, was conceptually more accurate.

(ii) Separation of spillage from soil moisture store, S: Given certain soil/slope/vegetation combinations, subsurface discharge can be a major contributor to the flood hydrograph (Hewlett and Hibbert, 1967; Dunne and Black, 1970; Weyman, 1973; Zaslavsky and Sinai, 1981). Such subsurface flow originates in up-slope soil zones that become saturated by infiltrating rainwater plus re-infiltrating overland flow particularly where there are favourable soil matrices or macro-pores to convey the water down-slope in the direction of the stream channel. Saturated subsurface flow can contribute to the rising limb, peak and early part of the falling limb of the flood hydrograph while unsaturated flow contributes to the hydrograph recession and even to the baseflow (Whipkey and Kirkby, 1978). Recharge of groundwater is obviously also enhanced by saturated soils. Conceptually, the variable SPILL, calculated in Pitman's hourly model as soil moisture excess over maximum soil store capacity ST, is roughly equivalent to potential subsurface discharge as described above. SPILL should therefore be divided into a quickflow component, as well as a delayed flow component, and not only the latter as in the original model version. Various formulations were rejected for failing adequately to simulate the multipeak hydrographs of July and August 1979 before the following successful approach was reached: SPILL is divided into

interflow and groundwater additions. In modelling this division the original assumption underlying interflow/surface flow separation (see section 3.1) was re-employed. It was assumed that low rates of spillage from the soil store would generate a high proportion of the relatively slow response (groundwater) and, conversely, that high rates of spillage would yield a high proportion of the quicker response (interflow). (These two model responses would then respectively represent real-life processes of unsaturated subsurface discharge plus groundwater recharge, and saturated subsurface stormflow.) The above separation needs to be governed by a model parameter, which in the case of interflow/surface flow separation in the original model, is the parameter DIV. In an endeavour to avoid the introduction of a new model parameter for groundwater/interflow separation, various unsuccessful attempts to relate this separation to some function of DIV was made. Ultimately, the incorporation of a new parameter, DIVG, had to be accepted as inevitable and the division of SPILL was represented by equation 3.12 (section 3.6.9).

(iii) Lagging and routing of the interflow components: Experimentation with separate lag parameters for interflow and surface flow, respectively, using selected floods in catchments A and E revealed that because most of the major flood hydrograph peaks comprised variable "mixtures" of these two flow components, the two optimum lag values always came out very close. Consequently, addition of another new parameter could be avoided by using the same lag parameter, LAG, for both surface runoff and interflow. The routing of interflow through a linear storage was furthermore modified such that release from storage is related to the average storage state during a time increment, instead of the starting storage state (original assumption). Equation 3.13 (section 3.6.10) represents this linear-storage routing of interflow.

In order to facilitate distinction between the modified model versions containing the three re-infiltration function options outlined above and the modified version without re-infiltration, the four versions were named PITR(1), PITR(2), PITR and PITH, respectively.

3.4 COMPARISON OF PERFORMANCE OF MODEL VERSIONS PITH AND PITR

The comparison of model versions PITH and PITR was based firstly on their ability to simulate individual selected flood hydrographs in Ecca catchments A, B and E, and secondly on their ability to reproduce overall annual, monthly and daily streamflow statistics for these three catchments. The latter comparison is reported in Chapter 7 as part of the general model intercomparison, while the former comparison is discussed below.

Interim and final results of various stages of model modifications are shown in Figs. 3.5(a) and (b), while Table 3.3 details the modification stages referred to in Fig. 3.5. Tables 3.4(a) and (b) contain values of goodness-of-fit criteria for the final calibration runs for each model/catchment combination. Optimum parameter sets are listed in Table 3.5, and Figs. 3.6(a), (b) and (c) provide comparisons of simulated with observed flood hydrographs as produced by the final calibration runs.

Before discussing the results in detail, a few remarks on the search for a suitable re-infiltration function would be in order. While testing the three re-infiltration options outlined in section 3.3 it was soon recognized that subjecting all "potential surface runoff" to re-infiltration either before entering, or after leaving the depression store, i e. PITR(1) and PITR(2), produced very similar outcomes. These two options caused exaggerated accretions to soil moisture storage - to the extent that, to maintain the same overall water balance, parameter ST had to be increased to values between 33 and 67 percent higher than those required by the other modified and unmodified versions of the model. (See Table 3.5). These two re-infiltration options had to be rejected because "optimum" ST/ZMAXN combinations caused most of the smaller flow events to be completely supressed while the later parts of larger composite flood hydrographs and/or groundwater flow were severely over-predicted. It was clear that these options made the infiltration process far too dominant in the model structure and that the conceptual content of parameters ST, ZMAXN, ZMINN and SU was unacceptably altered by the model changes.

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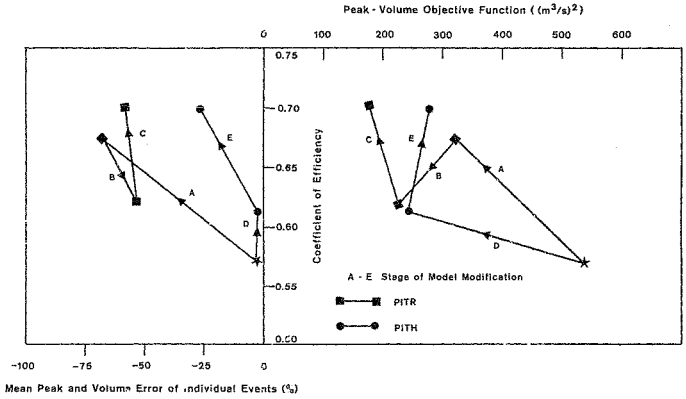


Figure 3.5(a) Results of model modifications by stages : catchment A

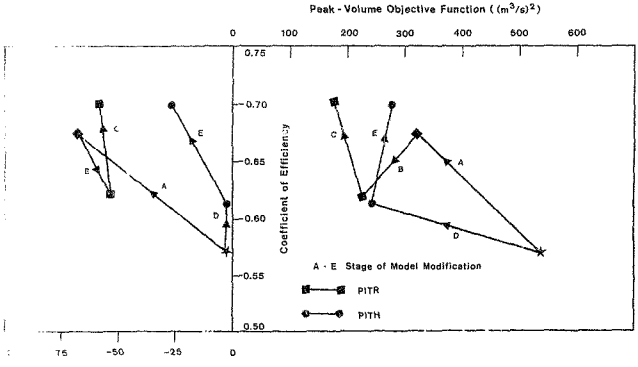


Figure 3.5(a) Results of model modifications by stages : catchment A

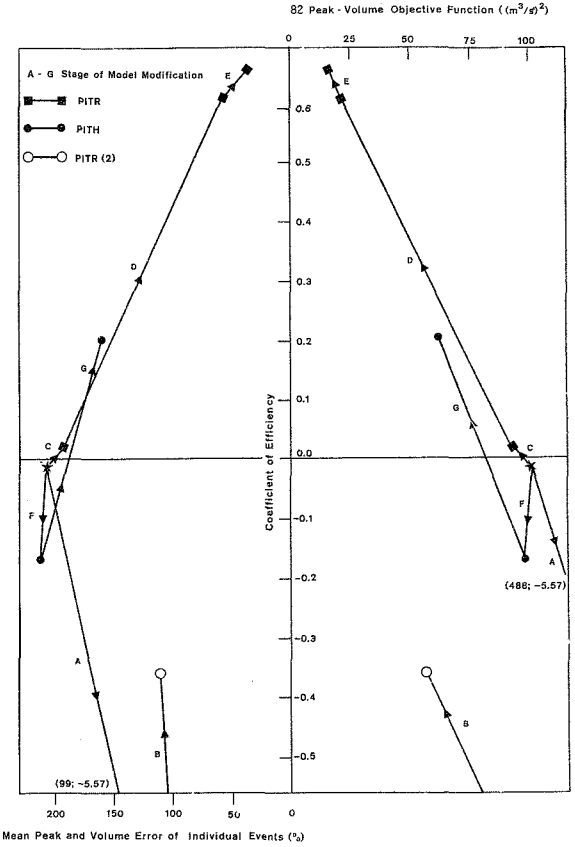


Figure 3.5(b) Results of model modifications by stages : catchment B

Table 7.3

Stages of model modifications and calibration runs

Catchment	Stage*	Details of stage	No. of calibration runs
A	Starting point	Calibrate Pitman's original hourly model (unmodified)	20
	A	Run PITR (depression storage re-infiltration) without interflow lag and routing modification, using parameters from the calibration of the original model	1
	B	Calibrate PITR without interflow lag and routing modification	27
	C	Calibrate PITR, including interflow lag and routing modification	10
	D	Run PITH (no re-infiltration) including all modifications, using parameters from the calibration of the original model	1
	E	Calibrate PITH including all modifications	10
B	Starting point	Calibrate Pitman's original hourly model (unmodified)	31
	A	Run PITR(2) (re-infiltration of spillage from depression store), using parameters from the calibration of the original model and all modifications included	1

Continued .....

Table 3.3 (continued)

Catchment	Stage*	Details of Stage	No. of calibration runs
B	B	Calibrate PITR(2), including all modifications	35
	C	Run PITR (depression store re-infiltration) using parameters from the calibration of the original model; all modifications, except SPILL division included	1
	D	Calibrate PITR, all modifications, except SPILL division included	41
	E	Calibrate PITR, incorporating SPILL division	10
	F	Run PITH (no re-infiltration); including all modifications; using parameters from the calibration of the original model	1
	G	Calibrate PITH, including all modifications	9
E	-	Calibrate PITR (depression store re-infiltration), including all modifications	14
	-	Calibrate PITH (no re-infiltration), including all modifications	14

* Refers to Fig. 3.5(a) and (b)

thereby threatening the desired compatibility with Pitman's daily model. In contrast, re-infiltrating only the contents of the depression store seemed to offer fewer of the above undesirable side-effects so this was chosen as the "best" re-infiltration approach, and led to model version PITR. Fig. 3.5 shows that the best combination of goodness-of-fit criteria values that could be achieved with PITR(2) falls far short of the best achieved with both PITH and PITR and required a number of calibration runs (Table 3.3) of the same order of magnitude for PITR and much fewer for PITH.

From a comparison of the overall outcome of the tests for goodness-of-fit of the final PITR and PITH model runs shown in Tables 3.4(a) and (b), it can be concluded that the PITR performance is superior in catchment B, PITH is superior in catchment E and the performance of the two models is similar in catchment A. However, looking in detail at the goodness-of-fit statistics, it is notable that PITR produced no runoff (error = 100 percent) in the case of five small events, a failure not exhibited [illegible]. A visual comparison of simulated with observed hydrographs, Figs. 3.6(a), (b) and (c), reveals that the larger, composite hydrographs of July and August 1979 were somewhat better simulated by PITH in catchments A and E, while PITR modelled the equivalent events better in catchment B. It is abundantly clear from Figs. 3.5(a) and (b) and Figs. 3.6(a) and (b) that as far as simulating major composite flood hydrographs in the Ecca catchments is concerned, both PITH and PITR are superior to Pitman's original model.

Another point worth noting in Table 3.4(a) and (b) is the exact magnitude of the peak and volume errors in the simulation of the major events - catchment A events no. 5 and 6, catchment B events no. 4, 5 and 6 and catchment E events no. 3 and 4. The average peak and volume errors for PITH are ±27% and ±23%, respectively, while the average equivalent errors for PITR are ±28% and ±30%, respectively. It appears that although the shapes of these complex hydrographs could often be simulated fairly closely, occasional large errors in either peak or volume estimation could not be avoided. During calibration it was noticed that, especially with PITH, it could have been possible to

achieve parameter sets that would have minimized the average volume error to the region of ±10%, but greatly increased errors in peak estimation would have resulted. The final parameter sets chosen as "optimum" tended to distribute any errors among peak, volume and shape (coefficient of efficiency).

Noteworthy about Table 3.5 is that final parameter values listed there are in the case of PITH fairly similar for catchments A and B as far as the main runoff volume control parameters - ST, ZMAXN, ZMINN and SU - are concerned, with catchment E requiring somewhat different values. However, in the case of PITR no such trend is discernible. Common to both PITH and PITR is the fact that the major model store ST is required to take on a value for catchment E that is more than 50% higher than for A and B. This may be a reflection of some of the physical inter-catchment differences discussed in section 2.4.

Specific criticisms of the performance of the two models can be summarised as follows:

PITR:

(a) Severe suppression of runoff from smaller rainstorms.

(b) Unrealistically sudden (and delayed) production of high rates for the July 1979 event.

(c) Exaggerated baseflow (groundwater flow) levels in catchment A.

(d) Requires more calibration runs than PITH (see Table 3.3) because the higher level of interdependence of model components makes it considerably more complex.

PITH:

(a) Too sensitive to very high rainfall intensities (see the February 1977 event in catchment B).

Table 3.4(a)

Tests for goodness-of fit on modified model PITR (with re-infiltration)

Item	Units	Event number						Mean or overall value	No-model case
		1	2	3	4	5	6		
				Catchment A					
Obs. peak	m^3/s	7,5	1,1	1,2	2,7	32,3	35,4		
Sim. peak	m^3/s	5,5	0,0	0,0	0,0	29,6	26,4		
Error	%	-27	-100	-100	-100	-8	-26	-60	-100
Obs. volume	mm	7,3	0,6	0,9	2,3	45,2	50,9		
Sim. volume	mm	2,9	0,0	0,0	0,0	53,6	51,9		
Error	%	-60	-100	-100	-100	+19	+2	-57	-100
Timing error	h	+3	.	.	.	-1	+1		
HCE		0,22	-2,88	-1,68	-0,92	0,59	0,81	0,70	-0,79
Peak-Vol. O.F.	$(m^3/s)^2$							176	4591
				Catchment B					
Obs. peak	m^3/s	1 0	0,9	1,2	4,5	1,8	2,0		
Sim. peak	m^3/s	0,2	2,5	0,0	3,2	1,7	2,4		
Error	%	-84	+194	-100	-29	-7	+19	-1	-100
Obs. volume	mm	5,8	0,6	2,2	25,4	11,7	31,1		
Sim. volume	mm	0,8	4,2	0,0	20,9	15,4	32,3		
Error	%	-86	+624	-100	-18	+32	+4	+76	-100
Timing error	h	+1	0	.	0	0	+1		
HCE		-0,53	-10,3	-0,32	0,76	0,61	0,85	0,66	-1 49
Peak-Vol. O.F.	$(m^3/s)^2$							17	101
				Catchment E					
Obs. peak	m^3/s	1,1	0,6	9,8	5,5				
Sim. peak	m^3/s	0,0	0,3	6,0	9,1				
Error	%	-100	-48	-39	+65			-30	-100
Obs. volume	mm	2,8	0,3	28,5	25,1				
Sim. volume	mm	0,0	0,3	10,6	43,3				
Error	%	-100	-17	-63	+72			-27	-100
Timing error	h	.	+1	0	+1				
HCE		-2,56	0,59	-0,14	-1,20			-0,46	-1,01
Peak-Vol. O.F.	$(m^3/s)^2$							79	233

Table 3.4 (b)

Tests for goodness-of-fit on modified model PITH (without re-infiltration)

Item	Units	Event number						Mean or overall value	No-model case
		1	2	3	4	5	6		
				Catchment A					
Obs. peak	m^3/s	7,5	1,1	1,2	2,7	32,3	35,4		
Sim. peak	m^3/s	3,3	0,4	1,0	3,4	46,0	35,9		
Error	%	-55	-68	-18	+27	+42	+2	-12	-100
Obs. volume	mm	7,3	0,6	0,9	2,3	45,2	50,9		
Sim. volume	mm	1,3	0,2	0,3	1,2	50,3	53,8		
Error	%	-83	-75	-66	-48	+11	+6	-42	-100
Timing error	h	+6	-4	-3	-4	+1	-1		
HCE		-0,27	-1,56	-0,61	-0,29	0,52	0,86	0,69	-0,79
Peak-Vol. O.F.	$(m^3/s)^2$							280	4591
				Catchment B					
Obs. peak	m^3/s	1,0	0,9	1,2	4,5	1,8	2,0		
Sim. peak	m^3/s	0,3	5,6	0,7	5,9	2,2	3,4		
Error	%	-67	+555	-41	+32	+18	+68	+94	-100
Obs. volume	mm	5,8	0,6	2,2	25,4	11,7	31,1		
Sim. volume	mm	1,4	8,6	1,8	26,2	16,3	39,9		
Error	%	-76	+1378	-17	+3	+40	+28	+226	-100
Timing error	h	+3	0	0	+1	+1	+1		
HCE		-0,21	-76,9	0,85	0,78	0,21	0,34	0,21	-1,49
Peak-Vol. O.F.	$(m^3/s)^2$							63	101
				Catchment E					
Obs. peak	m^3/s	1,1	0,6	9,8	5,5				
Sim. peak	m^3/s	0,3	1,1	9,6	6,8				
Error	%	-69	+94	-2	+25			+12	-100
Obs. volume	mm	2,8	0,3	28,5	25,1				
Sim. volume	mm	0,6	1,2	14,5	32,3				
Error	%	-77	+270	-49	+29			+43	-100
Timing error	h	-1	+1	0	0				
HCE		-0,99	-6,6	-0.11	0.15			-0,05	-1,01
Peak-Vol. O.F.	$(m^3/s)^2$							25	233

Table 3.4 (b)

Tests for goodness-of-fit on modified model PITH (without re-infiltration)

Item	Units	Event number						Mean or overall value	No-model case
		1	2	3	4	5	6		
				Catchment A					
Obs. peak	m^3/s	7,5	1,1	1,2	2,7	32,3	35,4		
Sim. peak	m^3/s	3,3	0,4	1,0	3,4	46,0	35,9		
Error	%	-55	-68	-18	+27	+42	+2	-12	-100
Obs. volume	mm	7,3	0,6	0,9	2,3	45,2	50,9		
Sim. volume	mm	1,3	0,2	0,3	1,2	50.3	53,8		
Error	%	-83	-75	-66	-48	+11	+6	-42	-100
Timing error	h	+6	-4	-3	-4	+1	-1		
HCE		-0,27	-1,56	-0,61	-0,29	0,52	0,86	0,69	-0,79
Peak-Vol. O.F.	$(m^3/s)^2$							280	4591
				Catchment B					
Obs. peak	m^3/s	1,0	0,9	1,2	4,5	1,8	2,0		
Sim. peak	m^3/s	0,3	5,6	0,7	5,9	2,2	3,4		
Error	%	-67	+555	-41	+32	+18	+68	+94	-100
Obs. volume	mm	5,8	0,6	2,2	25,4	11,7	31,1		
Sim. volume	mm	1,4	8,6	1,8	26,2	16,3	39,9		
Error	%	-76	+1378	-17	+3	+40	+28	+226	-100
Timing error	h	+3	0	0	+1	+1	+1		
HCE		-0,21	-76,9	0,85	0,78	0,21	0,34	0,21	-1,49
Peak-Vol. O.F.	$(m^3/s)^2$							63	101
				Catchment E					
Obs. peak	m^3/s	1,1	0,6	9,8	5,5				
Sim. peak	m^3/s	0,3	1,1	9,6	6,8				
Error	%	-69	+94	-2	+25			+12	-100
Obs. volume	mm	2,8	0,3	28,5	25,1				
Sim. volume	mm	0,6	1,2	14,5	32,3				
Error	%	-77	+270	-49	+29			+43	-100
Timing error	h	-1	+1	0	0				
HCE		-0,99	-6,6	-0,11	0,15			-0,05	-1,01
Peak-Vol. O.F.	$(m^3/s)^2$							25	233

Table 3.5

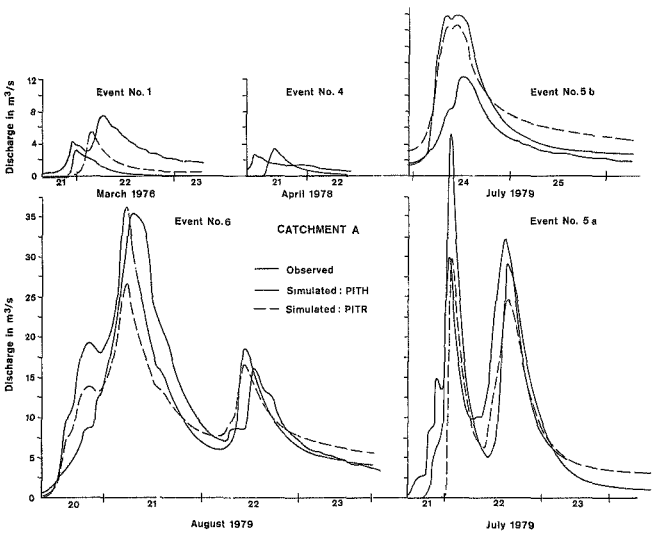
Adopted parameter set - different model versions*1

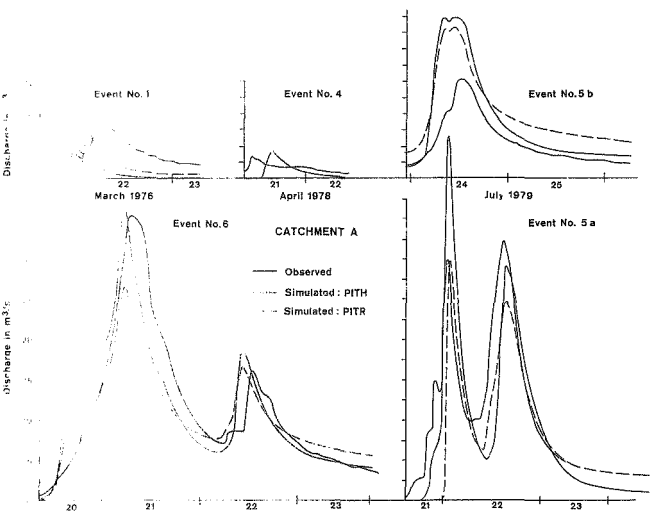
Parameter*2	Units	Catchment								
			A			B			E	
		Original	PITH	PITR	Original	PITH	PITR(2)	PITR	PITH	PITR
POW	-	2	2	2	2	2	2	2	2	2
SL	mm	0	0	0	0	0	0	0	0	0
FT	mm/day	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0.001
PI	mm	1,5	2,5	2,5	2,5	2,5	2,5	2,5	4,0	4,0
R	-	1	0,01	0,01	0,5	0,01	0,01	0,01	0,01	0,01
AI		0	0	0	0	0	0	0	0	0
ST	mm	165	148	140	150	148	250	135	240	210
ZMAXN	mm/h	11	11,5	7,5	9	11	7	11,5	9,5	10,5
ZMINN	mm/h	0	0,7	1,2	0,5	0,5	0,5	2,0	0,2	0,1
SU	mm	2	1,5	3,5	1,5	1,5	0,5	2,5	2,6	2,3
DIV	mm/h	10	10	9	20	20	16	14	8	8
DIVG	mm/h	-	4	10	-	6	4	8	3	4
TL	h	2	2	3	0,5	0,5	0,6	0,5	4	4
TLI	h	8	5	4	9	7	5	10	9	5
GL	day	1	2	2	2	2	8	4	3	4
LAG	h	5	4	4	0	0	0	0	1	1

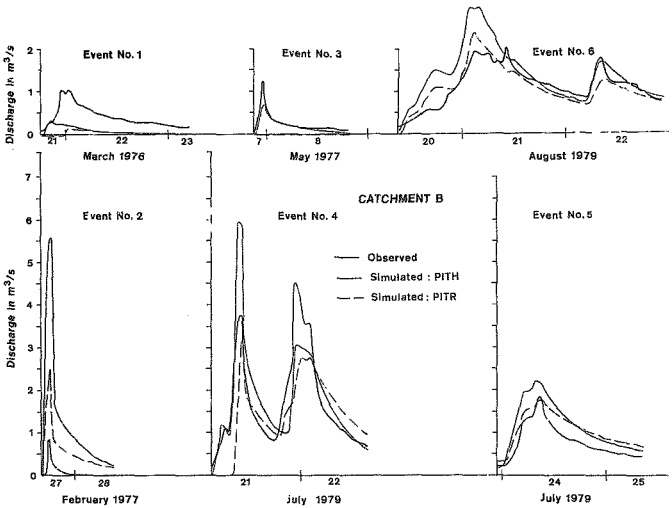
*1 Original - Pitman's original hourly model, essentially unmodified
PITR(2) - Spillage from depression store, as well as contents of depression store subjected to re-infiltration, plus all other modifications
PITR - Only contents of depression store subjected to re-infiltration, plus all other modifications
PITH - No re-infiltration function, but including all other modifications

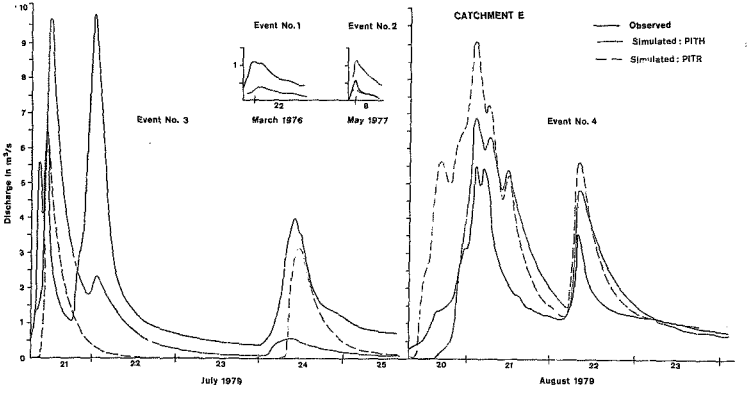
*2 See Figs. 3.7 and 3.8 and section 3.6.12 for definitions of parameters

Figure 3.6(a) to 3.6(c) Observed and simulated hydrographs : catchments A, B and E
(see following pages)


Discharge in m³/s
Event No. 1
March 1976
Event No. 4
April 1978
Event No. 5 b
July 1979
Event No. 6
August 1979
CATCHMENT A
Observed
Simulated : PITH
Simulated : PITR
Event No. 5 a
July 1979


Event No. 1
Event No. 4
Event No. 5 b
Event No. 6
CATCHMENT A
Observed
Simulated : PITH
Simulated : PITR
Event No. 5 a
Discharge in m³/s
March 1976
April 1978
July 1979
August 1979
July 1979


CATCHMENT B
Event No. 1
Event No. 3
Event No. 6
Event No. 2
Event No. 4
Event No. 5
Discharge in m³/s
Observed
Simulated : PITH
Simulated : PITR
March 1976
May 1977
August 1979
February 1977
July 1979
July 1979


CATCHMENT E
Observed
Simulated : PITH
Simulated : PITR
Event No.1
Event No.2
Event No. 3
Event No. 4
March 1976
May 1977
Discharge in m³/s
July 1979
August 1979

On the balance of evidence provided by this study of individual flood hydrograph simulation, model PITH must be preferred to model PITR for flood forecasting in small to medium-sized semi-arid catchments with a "mixed" convectional thunderstorm/frontal rainfall regime, similar to that experienced by the Ecca catchments. It may be that in a climatic region such as that in which the Hartbeespoort Dam catchment lies where according to Pitman and Basson (1979; p. 3.22) severe flooding is often caused by major localized convectional thunderstorms, model PITR may indeed prove to be preferable to PITH; PITR's re-infiltration function certainly controls the excess of "potential surface runoff" produced by rainfall of high intensity more effectively than does PITH, as shown by comparison of their respective reproductions of the February 1977 event in catchment B (Fig. 3.6(b)).

3.5 HOW WELL DOES PITMAN'S MODELLING APPROACH REPRESENT THE RAINFALL-RUNOFF PROCESS?

3.5.1 Introduction

As models PITH and PITR currently represent the most refined "statements" on the modelling philosophy and approach underlying the suite of Pitman models, a tentative answer to the above question may legitimately be demanded by a prospective user faced with a divergent and confusing array of models to choose from. Before venturing an answer, it may be prudent to reiterate four considerations that may have a bearing on such an answer:

(a) Pitman strived for model simplicity, ease of calibration and unambiguous parameter conceptualization. In attempting improvements to Pitman's original hourly model reported in this chapter, the endeavour was to remain faithful to his criteria.

(b) Pitman's models, though conceptual, are not physically-based in the true sense of the word. This means that apart from the assumption that a catchment may be represented mathematically by a series of different storages, no function or parameter of the model can be directly related to specific, measurable soil, physiographic or other physical catchment characteristics.

(c) The performance tests executed on PITH and PITR described in earlier sections included no verification checks, i.e. tests on data not included in the calibration sample, because the available number of reasonable flood hydrographs was too small. The aforementioned test results provide therefore only a partial indication of model adequacy.

(d) The performance test results reported earlier are difficult to interpret in isolation and will gain full significance only if they are compared with the results of applying to the same data another conceptual rainfall-runoff model of greater complexity and proven "respectability" (and which is preferably more physically-based).

The well known Stanford Watershed Model (Crawford and Linsley, 1966) represents in all respects a good "base-line" with which the performance of Pitman's modified model versions can be compared. The following section, in which the performance of PITH and PITR is compared with that of the Stanford model, should therefore cast further light on the adequacy of Pitman's modelling approach.

3.5.2 Comparison of Stanford Watershed Model with PITH and PITR

An hourly-input, single-catchment version of the Stanford Watershed Model, as modified by Anderson of the U.S. Weather Bureau (Roberts, 1978), was calibrated on the same runoff events as models PITH and PITR (Table 3.1), using the same statistical measures of fit. As the structure of this model is discussed in chapter 4 as model FORD, suffice it here to say that the model is more complex than Pitman's models, has a greater number of parameters and is more physically-based in terms of its overland flow and channel process components.

The Stanford model was considered to be calibrated after 63 calibration runs in the case of catchment A, 44 runs in the case of catchment B and 24 runs in the case of E. Though this may not be

reflected by the number of calibrations for each type of model, the author found the Stanford model more difficult both to analyse and to calibrate than either PITH or PITR. The final parameter sets adopted for the three catchments are listed in Table 3.6 (some trivial parameters are not shown). As with both PITH and PITR it was found that the major Stanford model moisture store LZSN - the nominal lower soil moisture storage - was required to take on a much larger value for catchment E than for A or B, larger in fact by more than 100%.

Table 3.7 contains goodness of-fit statistics for all three catchments while Figs. 3.7(a), (b) and (c) depict the actual hydrographs produced by the calibrated Stanford model. The figures also permit visual comparisons of the fit achieved by PITH and PITR.

Results in Table 3.7 disclose that the calibrated Stanford model produces no response in the case of at least five of the small events (among these, the problematic February 1977 event on B), but that it fared much better in the simulation of the major events - reproducing at least one major event in each catchment very well. The overall results in Table 3.7 are not notably different from those for PITR and PITH reported in Tables 3.4(a) and (b), respectively. However, comparison of the performance statistics of the three models as far as the major events are concerned, shown in Table 3.8, indicates that the Stanford model was more successful in simulating the actual flood events in the Ecca catchments. Especially in the reproduction of flood volumes and the one-to-one fits the Stanford model seems somewhat superior to the other two models. Visual comparison of simulated with observed hydrographs in Fig. 3.7 confirms the above finding.

It is likely, however, that this specific difference in performance among the models can not be viewed as being significant, given the small calibration sample, the lack of a verification sample, the similarity of overall performance statistics listed in Tables 3.4(a) and (b) and 3.7 and the fact that all three models produced notable failures and successes in simulating individual events. That model version PITH was in fact able to produce a more balanced simulation than the other two models of both small and major events, may outweigh the importance of the good reproduction of major events by the Stanford model. This "balanced" performance of model PITH may imply superior long-term soil moisture accounting ability and may bode

well for the continuous simulation model inter-comparison that forms the central theme of Chapter 7.

3.5.3 Conclusions

Re-addressing the question posed at the head of this section regarding the adequacy of Pitman's modelling approach, the following answer can now be offered.

By employing model versions which embody Pitman's modelling approach in its most refined form and using research level input data, it was found that major flood events in the semi-arid Ecca catchments could be reproduced with average errors in peaks and volumes of between $\pm$23% and $\pm$30%. The magnitude of these errors can be regarded as just acceptable by common engineering standards nevertheless, the more physically-based complex Stanford Watershed model was able to produce somewhat smaller equivalent errors. On the other hand, model version PITH yielded a better balance between smaller and larger flow event simulations than the more complex Stanford model. In general terms, therefore, it does seem as if Pitman's hourly model, in refined form, can simulate semi-arid rainfall-runoff processes at a level comparable with that achieved by a more complex more physically-based model. The implication is that Pitman's modelling philosophy of structural simplicity and conceptual unambiguity - appropriate to the modest to poor quality of input data expected in most applied modelling situations in South Africa - has been shown to be sound even in a research environment.

Conversely, it must be realized that the fact that sizeable simulation errors were not uncommon in the above application of Pitman's refined model does point to persistent inadequacies in the

Table 3.6

Adopted primary parameter values for the Stanford model

Parameter*1	Units	Catchment			
		A	B	E	
EPXM	inches	0,15	0,15	0,20	
UZSN	inches	0,93	0,87	0,90	
LZSN	inches	9,0	8,7	18,5	
POWER	-	1,6	2,1	2,1	
CB	inches/hr	0,002	0,004	0,004	Trial
CC	-	2,7	2,3	1,85	and
K3	inches	0,34	0,35	0,4	error
K24L	-	0,5	0,1	0,5	
K24EL	-	0,05	0,05	0,05	
KS1	-	0,87	0,82	0,75	
IRC	-	0,92	0,75	0,8	
KK24	-	0,85	0,20	0,97	
L	feet	2500	1800	2200	
SS	-	0,20	0,27	0,17	Physical
NN	-	0,35	0,35	0,35	

*1 Parameter definitions can be found in Chapter 4

Table 3.7

Tests for goodness-of-fit on the Stanford Watershed Model

Item	Units	Event number						Mean or overall value	No-model case
		1	2	3	4	5	6		
				Catchment A					
Obs. peak	m^3/s	7,5	1,1	1,2	2,7	32,3	35,4		
Sim. peak	m^3/s	2,5	0,1	0,1	2,8	35,4	28,5		
Error	%	-66	-93	-95	+3	+9	-20	-44	-100
Obs. volume	mm	7,3	0,6	0,9	2,3	45,2	50,9		
Sim. volume	mm	2,0	0,1	0,1	1,9	51,6	34,8		
Error	%	-73	-92	-87	-18	+14	-32	-48	-100
Timing error	h	+6	.	.	-3	+1	+4		
HCE		-0,09	-2,43	-1,21	0,58	0,73	0,63	0,66	-0,79
Peak-Vol. O F.	$(m^3/s)^2$							285	4591
				Catchment B					
Obs. peak	m^3/s	1,0	0,9	1,2	4,5	1,8	2,0		
Sim. peak	m^3/s	0,2	0,0	0,0	4,3	2,3	3,4		
Error	%	-81	-99	-97	-5	+23	+67	-32	-100
Obs. volume	mm	5,8	0,6	2,2	28,8	10,8	31,1		
Sim. volume	mm	1,8	0,0	0,3	31,3	14,1	28,6		
Error	%	-69	-92	-86	+9	+31	-8	-36	-100
Timing error	h	0	.	.	-2	+1	0		
HCE		-0,16	-0,15	-0,19	0,67	0,32	0,43	0,55	-1,49
Peak-Vol. O.F.	$(m^3/s)^2$							8	101
				Catchment E					
Obs. peak	m^3/s	1,1	0,6	9,8	5,5				
Sim. peak	m^3/s	0,2	0,0	4,9	5,6				
Error	%	-80	-96	-50	+2			-56	-100
Obs. volume	mm	2,8	0,3	28,5	25,1				
Sim. volume	mm	0,9	0,1	27,3	24,3				
Error	%	-68	-86	-4	-3			-40	-100
Timing error	h	-1	.	-2	0				
HCE		-0,99	-0,47	0,58	0,90			0,66	-1,01
Peak-Vol. O F.	$(m^3/s)^2$							28	233

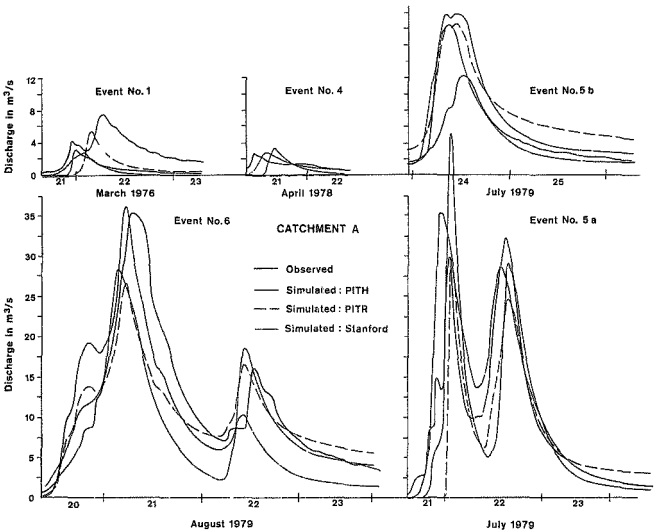
Table 3.8

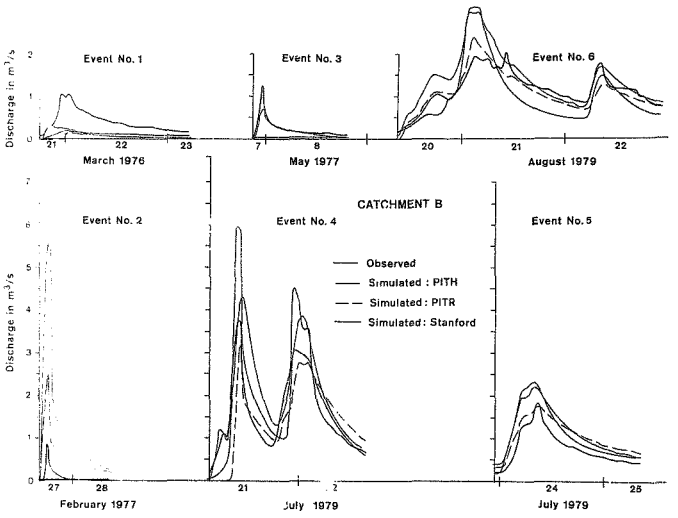
Summary of model performance in major flood events*1

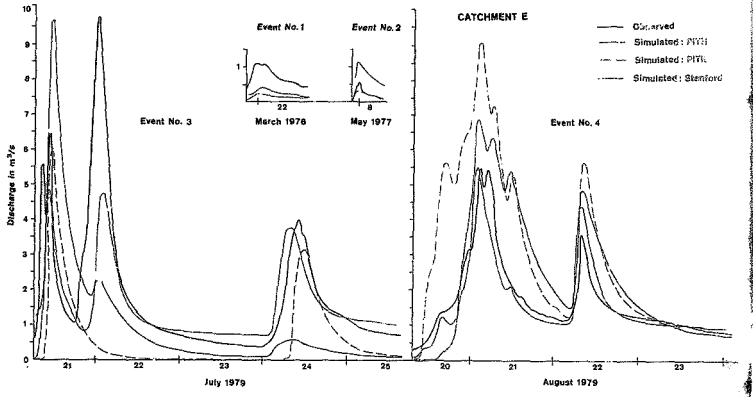
Model	Catchment	Mean peak error(%)	Mean volume error (%)	Mean HCE
PITR	A	±17	±11	0,70
	B	±18	±18	0,74
	E	±52	±68	-0,67
	Mean	±28	±30	0,33
PITH	A	±22	±9	0,69
	B	±39	±24	0,44
	E	±14	±39	0,02
	Mean	±27	±23	0,39
Stanford	A	±15	±23	0,68
	B	±32	±16	0,47
	E	±26	±4	0,74
	Mean	±25	±14	0,51

*1 Events 5 and 6 in catchment A
Events 4,5 and 6 in catchment B
Events 3 and 4 in catchment E

Figure 3.7(a) to 3.7(c) Observed and simulated
hydrographs : catchments A, B and E
(see following pages)


Discharge in m³/s
Event No. 1
Event No. 4
Event No. 5 b
March 1976
April 1978
July 1979
Event No. 6
CATCHMENT A
Observed
Simulated : PITH
Simulated : PITR
Simulated : Stanford
Event No. 5 a
August 1979
July 1979


CATCHMENT B
Event No. 1
Event No. 3
Event No. 6
Event No. 2
Event No. 4
Event No. 5
Observed
Simulated : PITH
Simulated : PITR
Simulated : Stanford
Discharge in m³/s
March 1976
May 1977
August 1979
February 1977
July 1979
July 1979


CATCHMENT E
Observed
Simulated : PITH
Simulated : PITL
Simulated : Stanford
Event No. 1
Event No. 2
Event No. 3
Event No. 4
March 1976
May 1977
Discharge in m³/s
July 1979
August 1979

general modelling procedure. If the presumption that a sound representation of storm rainfall is provided by the Ecca gauging network is accepted, then the above inadequacies can still be related to any combination of the following known problems: model structure inadequacy, illegitimate "lumping" of catchment areas and potential evaporation estimates of uncertain accuracy.

3.6 DESCRIPTION OF FINAL STRUCTURE OF PITH AND PITR

3.6.1 Introduction

Detailed descriptions of the main elements of Pitman's original hourly model can be found in Pitman (1976) while the interflow and depression storage functions are described in Pitman and Basson (1979). Taking into account the various modifications introduced into the model during this study, leading to model versions PITH and PITR, the inconvenience for a user of having a description spread over three different reports, as well as certain errors in the relevant text and computer program sections in Pitman and Basson (1979) (pp. 2.2, 2.3, 2.5, A6, A7, A8), it was deemed necessary to provide here a unified summarized description of all the model elements. In the description below many paragraphs relating to unmodified model elements are quoted or paraphrased directly from the original model descriptions in the aforementioned two reports, and descriptions of modifications are woven into the general text.

The essential elements of model version PITH appear in Fig. 3.8, while Fig. 3.9 depicts the elements of model version PITR. The computer program versions of PITR and PITH written in standard Fortran IV have been listed in Appendix B. Model parameters, variables and elements in the following description are referred to by the names appearing in the model computer program, and only in the case of re-infiltration is PITR distinguished from PITH. Model parameters are defined alphabetically in section 3.6.12.

3.6.2 Input data : Precipitation and evaporation

Hourly values of rainfall averaged over the catchment are

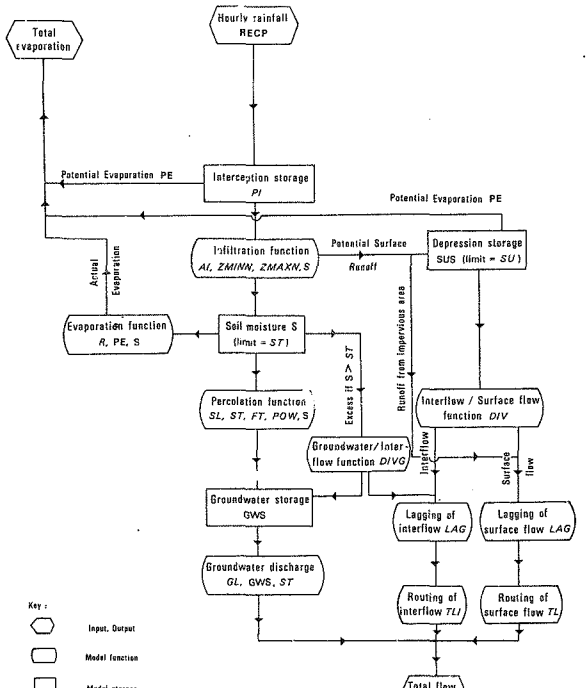


Figure 3.8 Flow diagram : model PITH

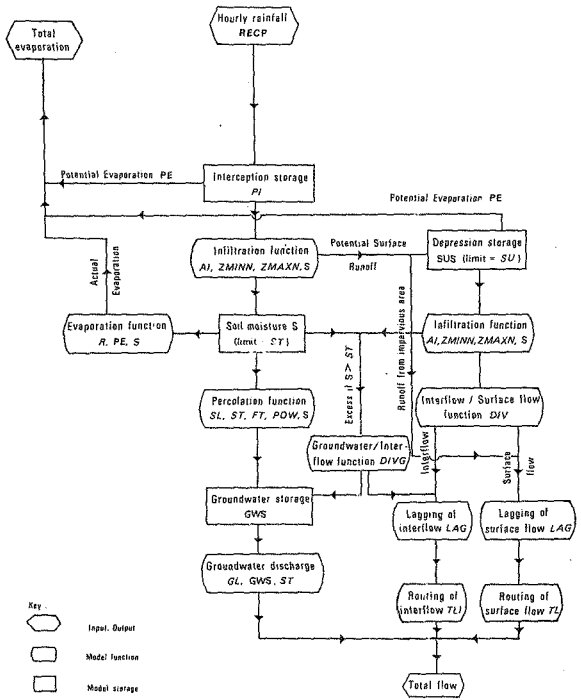


Figure 3.9 Flow diagram : model PITR

required as input data and are read in as variable RECP. No provision is made in the models for runoff from snowmelt. Daily values of A pan evaporation are also required as input data, from which values of daily potential evaporation (variable PE) are calculated by applying the regional monthly pan factors (variable ER). PE for each day is assumed to be symmetrically triangularly distributed between 07h00 and 19h00.

3.6.3 Interception

Vegetation and soil surfaces may be initially dry before a fall of rain and a small quantity of moisture is needed to wet these surfaces before runoff and infiltration can occur. This function is represented by an assumed interception storage (PI) which must be filled before precipitation is available for infiltration and runoff. Moisture from interception storage is removed at the potential evapotranspiration rate until exhausted (Pitman, 1976)

3.6.4 Surface runoff

Surface runoff is taken to be derived from two components, viz.:

(1) runoff from impervious areas and

(2) runoff resulting from rainfall that has not infiltrated.

Component (1) is computed by multiplying the rainfall available for infiltration and runoff by the area of catchment that is impervious The impervious area (AI) is the proportion of the catchment that contributes directly to surface runoff. Impervious surfaces not directly connected to water courses must flow over pervious area before reaching a stream channel. Isolated impervious areas are therefore not included in the parameter AI.

In computing the runoff in component (2) it was recognised that infiltration would be highly unlikely to be uniform throughout the catchment. The spatial distribution of infiltration rate is no doubt strongly influenced by physical features such as geology, soil type,

vegetation and many others too numerous to mention. In most natural catchments these factors would result in a considerable spatial variation in infiltration rate. It was felt by Pitman that a reasonable approximation could be reached by assuming a frequency distribution of infiltration rate, thus reducing to a manageable number the parameters associated with this phenomenon. As in the case of the monthly model a symmetrical triangular frequency distribution was adopted (Pitman, 1976). In this distribution the minimum infiltration rate is ZMIN (mm/h), the maximum ZMAX (mm/h) and the mean ZAVE = 0.5 (ZMIN + ZMAX)

For any given rainfall input rate, HP, the surface runoff rate, SURF, is given by the following equations, derived from the triangular probability distribution:

For ZMIN < HP < ZAVE:

$$SURF = \frac{2(HP - ZMIN)^3}{3(ZMAX - ZMIN)^2} \quad \text{.....(3.1)}$$

At HP = ZAVE:

$$SURF = \frac{1}{12}(ZMAX - ZMIN) \quad \text{.....(3.2)}$$

For ZAVE < HP < ZMAX:

$$SURF = HP - ZAVE + \frac{2(ZMAX - HP)^3}{3(ZMAX - ZMIN)^2} \quad \text{.....(3.3)}$$

At HP = ZMAX:

$$SURF = 0.5(ZMAX - ZMI \quad \text{.....(3.4)}$$

For HP > ZMAX:

$$SURF = HP - ZAVE \quad \text{.....(3.5)}$$

Apart from varying spatially, the infiltration rate will also depend on the wetness of the catchment; after several hours of rain,

infiltration rates will generally be lower than at the onset of rain. To adjust infiltration capacity as rainfall continues, the coefficients ZMIN, ZAVE and ZMAX must be decreased as the soil moisture (S) increases. The relevant functions ensuring this effect are:

$$ZMAX = \frac{4.\ ZMAXN}{2^{(2.S/ST)}} \qquad \ldots\ldots(3.6)$$

$$\text{and, } ZMIN = \frac{ZMINN}{ZMAXN} .ZMAX \qquad \ldots\ldots(3.7)$$

where,

ZMAXN = nominal maximum infiltration capacity (mm/h)
ZMINN = nominal minimum infiltration capacity (mm/h)
S = soil moisture (mm)
ST = soil moisture capacity (mm)

ZMAXN, ZMINN and ST are model parameters. Equation 3.6 bears a certain similarity to the infiltration function used in the original Stanford Watershed Model (Crawford and Linsley, 1966). Equation 3.7 implies the assumption that the ratio ZMAX:ZMIN remains constant under all conditions. Since by definition ZAVE = 0.5 (ZMAX + ZMIN), infiltration and surface runoff are determined by the three model parameters ZMINN, ZMAXN, ST and soil moisture, S.

3.6.5 Depression storage and re-infiltration

Water that does not infiltrate into the soil is held in depression storage as potential surface runoff (variable SURF). When the maximum capacity of this store (parameter SU) is exceeded, the surplus water (variable ADDSI) becomes surface runoff, ready to be separated into interflow and surface flow. In model PITR the average content of the depression store (0.5(SUS1 + SUS2)) for each hour is subjected to infiltration, re-employing the infiltration function and parameters ZMAXN, ZMINN and ST. This process is called "re-infiltration" and the infiltrate (variable DEPINF) is added to the soil moisture store. Model PITH has no re-infiltration function, but

in both models the content of the depression store is further diminished by the residual potential evaporation not satisfied by the interception store. Runoff derived from impervious areas bypasses depression storage (and is therefore subject only to lag and attenuation).

3.6.6 Interflow/surface flow function

Spillage from depression storage is divided into surface flow and interflow. In modelling this separation it is assumed that low rates of spillage generate a high proportion of the relatively slow response (interflow - variable FINT) and, conversely, that high rates of spillage yield a high proportion of the quick response (surface flow - variable TSURF).

This behaviour is represented by a function of the following form:-

$$DIVA = DIV / (DIV + ADDSI) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

where ADDSI = spillage from depression storage,
DIVA = proportion of ADDSI that becomes interflow
and DIV = model parameter controlling the interflow/surface flow split

(Since the model works at hourly time steps the variables in equation 3.8 all have mm/h units).

Fig. 3.10(a) illustrates for DI = 5mm/h the decreases of interflow proportion with increase in total runoff(surface flow + interflow). The parameter DIV can be envisaged as the limiting interflow rate as shown in Fig. 3.10(b) where both surface flow and interflow are shown to increase with increasing total flow (Pitman and Basson,1979).

3.6.8 Evaporation - soil moisture relationships

Pitman designed his original hourly model to require only twelve long-term monthly mean Symons pan values as evaporation inputs and

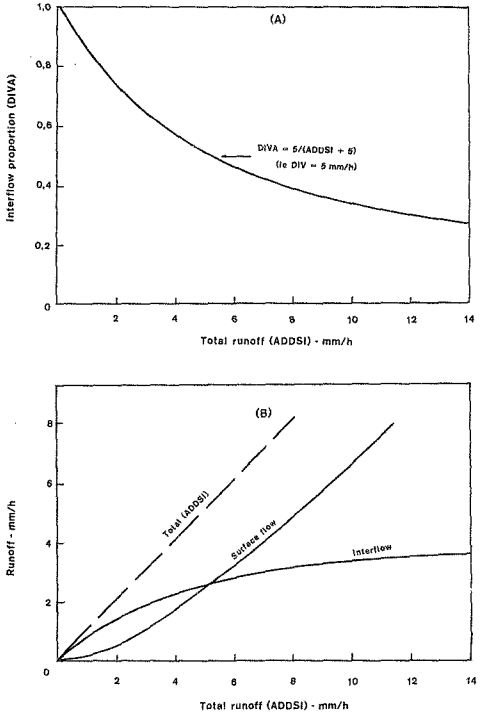


Figure 3.10 Interflow separation function
(after Pitman and Basson, 1979)

devised an evaporation-soil moisture relationship (Pitman, 1976) at a level of simplicity commensurate with the level of evaporation inputs. To operate with actual daily pan readings as input, the evaporation-soil moisture relationship had to be modified. To this end, the essential assumptions made by Pitman were accepted as necessary guidelines to preserve continuity in the original suite of models. These assumptions were:

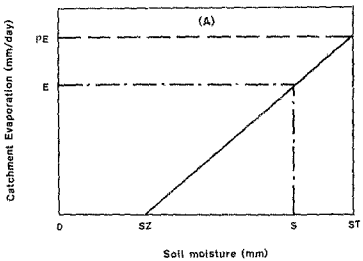
(a) actual evaporation (variable E) is a linear function of the level of soil moisture storage (S/ST) and potential evaporation PE;

(b) evaporation may cease at a S/ST ratio > zero;

(c) the evaporation-soil moisture relationship must be controllable by a single parameter, R.

After numerous trials employing a number of different functions, the relationships shown in Fig. 3.11(a) and (b) were chosen as offering a fair compromise of simplicity, viability and conceptual soundness. Recognising similar triangles it follows from Fig. 3.11(a) that

$$E = \frac{S - SZ}{ST - SZ}.PE \quad \ldots\ldots\ldots\



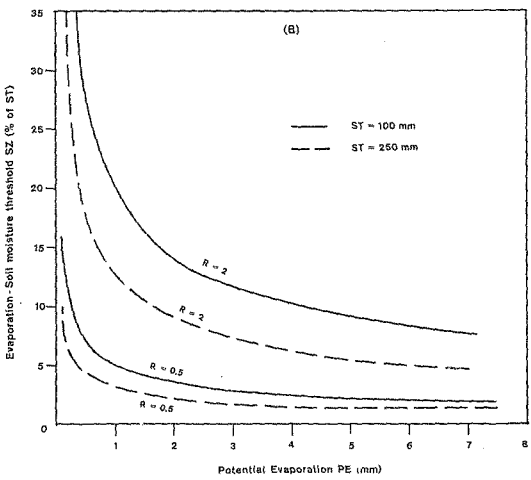


Figure 3.11 Evaporation - soil moisture function

relationship was found to be promising:

$$SZ = R.\ (ST/PE)^{0,5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

Eq. 3.10 links the variability of SZ to the variability in PE, as R and ST are constant parameters of the model. Fig. 3.11(b) illustrates the effect the various elements of equation 3.10 have on the evaporation cessation point SZ. It is important to note that the PE value which is entered in equation 3.9 is the residual potential evaporation not satisfied by either the interception or the depression stores. At this juncture it should be pointed out that the above evaporation-soil moisture relationship needs further testing with data from humid and temperate catchments. Certainly, for semi-arid conditions such as the Ecca catchments and the lower Berg River (Daniel, 1982) it has been found to be reasonable. Present experience indicates that for semi-arid to arid catchments the likely range of R indicates that for semi-arid to arid catchments the likely range of R values is $0 < R < 1$ and for temperate to humid catchments the range is $1 < R < 4$.

3.6.8 Percolation of soil moisture to groundwater storage

The generalized relationship between soil moisture and the rate of percolation to groundwater is depicted in Fig. 3.12.

The Q-S relationship is a simple power curve. It is convenient to express the relationship in terms of the following four parameters:

SL = Soil moisture content below which no percolation occurs (mm)
ST = Total soil moisture capacity (mm)
FT = Percolation at soil moisture equal to ST (mm/day)
POW = Power of Q-S curve

The equation is of the form $Q = A\ (S - SL)^{POW}$ and the constant A is determined by substituting $Q = FT$ at $S = ST$

relationship was found to be promising:

$$SZ = R.\ (ST/PE)^{0,5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

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POW = Power of Q-S curve

The equation is of the form $Q = A\ (S - SL)^{POW}$ and the constant A is determined by substituting $Q = FT$ at $S = ST$

therefore $A = \frac{FT}{(ST - SL)^{POW}}$

and $Q = FT \cdot [(S - SL)/(ST - SL)]^{POW}$ .....(3.11)

When the soil moisture capacity, ST, is exceeded (variable SPILL), a function that divides this excess into interflow and groundwater additions comes into action:

$$DIVB = DIVG/(DIVG + SPILL) \quad .....(3.12)$$

where SPILL = spillage or excess from soil moisture store (mm)
DIVB = proportion of SPILL that becomes groundwater (mm/h)
DIVG = model parameter controlling the groundwater/interflow split

Equation 3.12 is based on the assumption that low rates of soil moisture excess would generate a high proportion of the slow responding groundwater and, conversely, that high rates of excess would yield a high proportion of the faster responding interflow. This function is of course identical to equation 3.8, the interflow/surface flow function, but controlled by a different model parameter, DIVG.

3.6.9 Groundwater discharge

Numerous trials by Pitman (1976) revealed that adoption of a single recession constant was not satisfactory and that a variable recession constant, related to the groundwater storage state, led to more accurate results. The tests indicated the relationship depicted in Fig. 3.13 to be the most satisfactory for the catchments studied.

The above relationship assumes the recession constant Kr to be proportional to the square root of groundwater storage, i.e. that $Kr \propto (GWS)^{0.5}$. The position of the curve is fixed by the parameter GW, which is the recession constant when GWS is equal to a fixed value. For convenience this fixed value is taken to be equal to

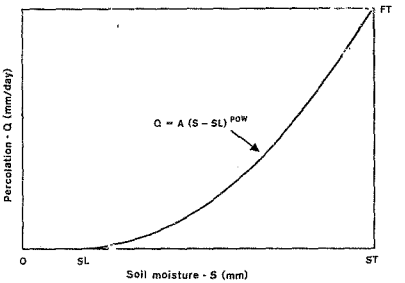


Figure 3.12 Soil moisture percolation function
(after Pitman, 1976)

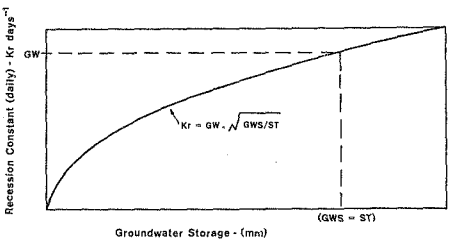


Figure 3.13 Groundwater recession function
(after Pitman, 1976)

the soil moisture capacity ST. The equation to the curve in Fig. 3.13 is thus:-

$$Kr = GW.GWS/ST$$

Groundwater outflow over a one-day period, GWF, is given by:-

$$GWF = Kr.GWS$$

Substituting for Kr:-

$$GWF = GW.GWS^{1.5}/ST \quad \ldots\ldots\ldots\

zero. The surface flow computed for hour N is then assumed to appear at the catchment outlet at hour (N + LAG). Attenuation of surface flow is accomplished by application of the well-known Muskingum routing equation with the weighting factor, x, set to zero for reservoir type storage attenuation. This equation takes the following form:

$$RSURF_2 = RSURF_1 + CF1\ (TSURF_1 - RS\ \ ) + CF2\ (TSURF_2 - TSURF_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.14)$$

in which $$CF1 = \frac{1}{TL + 0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.15)$$

and $$CF2 = \frac{CF1}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.16)$$

The variables in these equations have the following meaning:

$RSURF_1$, $RSURF_2$ = surface flow at catchment outlet for present and previous hours respectively (mm)

$TSURF_1$, $TSURF_2$ = surface flow as channel inflow for present and previous hours respectively (mm)

TL = storage factor (model parameter) (hours)

(b) Interflow: Parameter LAG is also used for interflow lagging. Since interflow rates change more slowly than surface flow rates it is assumed that routing through a simple linear storage adequately attenuates inter-flow. "Storage" of interflow at the beginning and end of any hour is represented by SINT1 and SINT2, respectively, and the release from "storage" over the hour (FINT) is computed by the equation:

$$FINT = \frac{RECI.(SINT1 + SINT2)}{2} \quad \text{.....(3.17)}$$

where RECI = recession constant of interflow decay and is related to model parameter TLI (routing constant for interflow) according to the equation:

$$RECI = 1 - (2.TLI - 1)/(2.TLI + 1) \quad \text{.....(3.18)}$$

Interflow "storage" at the end of the hour (SINT2) is calculated through an iterative procedure by:

$$SINT2 = SINT1 - RECI.\frac{(SINT1+SINT2)}{2} + DIVA\ ADDSI + (SPILL-DIVB.SPILL) \quad \text{.....(3.19)}$$

3.6.11 Initial storage states

At the start of simulation initial values for the various storages states of the model are an obvious necessity. By utilizing observed flow rates at the catchment outlet just prior to calibration, rough estimates can be made of the initial contents of the soil moisture store and groundwater store, as well as input values to the surface flow and interflow routing functions. By applying a simple form of "hydrograph separation" (Pitman, 1976) to the observed hydrograph for a day or two before the start of simulation, estimates of quickflow and baseflow can be made. The baseflow estimate, QOBS, for the hour prior to simulation start becomes an input initial value from which the model calculates approximate storage states from equations 3.11 and 3.13. The average quickflow estimate, DGF, for LAG number of hours prior to simulation state also serves as an input initial value and is divided equally between interflow and surface flow. Over the first LAG number of hours the value DGF/2 serves as input and/or output value to both surface flow and interflow routing functions.

3.6.12 Model parameter definitions

For the convenience of the reader the parameters of PITH and PITR are listed alphabetically below, in categories according to their effective influence on model outputs and operation, i.e. runoff volume control; hydrograph shape, attenuation and timing control; initial or starting values and output option.

Parameters that control runoff volumes:

AREA - Catchment area (km^2)
AI - Fraction of catchment area regarded as impervious and that is effectively connected to the channel network - $0 \leq AI < 1$
FT - oil moisture percolation rate to groundwater
PI - M... interception storage (mm)
POW - Power of soil moisture storage - percolation curve
R - Coefficient of evaporation - soil moisture relationship - $0 < R < 4$
SL - Soil moisture storage below which no percolation occurs (mm)
ST - Maximum soil moisture capacity (mm)
SU - Maximum depression storage (mm)
ZMAXN - Nominal maximum infiltration rate when soil moisture storage = ST (mm/h)
ZMINN - Nominal minimum infiltration rate when soil moisture storage = ST (mm/h)

Parameters that control hydrograph shape indirectly:

DIV - Maximum expected interflow rate; controls division of potential surface runoff into surface flow and interflow (mm/h)
DIVG - Maximum groundwater recharge rate when soil moisture capacity ST is exceeded; controls division of excess soil moisture between interflow and groundwater (mm/h)

Parameters that control hydrograph attenuation and timing:

GL - 1/Recession constant for groundwater depletion when groundwater storage = ST (day)
LAG - Time delay of channel outflow (h)
TL - Muskingum routing coefficient for surface flow (h)
TLI - Linear-storage routing coefficient for interflow (h)

Initial values and control option

DGF - Observed average quickflow rate during LAG no. of hours prior to start of simulation ($10^{-3}.m^3/s$)
QOBS - Observed baseflow in hour prior to start of simulation ($10^{-3}.m^3/s$)
THRES - Daily average flow above which hourly outputs are required; daily average flow in $10^{-3}.m^3/s$ and a monthly summary are always output ($10^{-3}.m^3/s$).

CHAPTER 4

DESCRIPTION OF MODELS USED IN THE ECCA STUDY

The conceptual rainfall-runoff models referred to in this document comprise sets of mathematical algorithms representing catchment and channel processes, coded in standard Fortran IV for use in digital computers. Since all the models under consideration have been described in detail elsewhere in easily obtainable reports, this chapter does not offer much in-depth information about the mathematical aspects of the models. Instead, attention is rather focused on the conceptual underpinnings of each model and, in the case of daily and hourly models, the level of physical representativeness of each model; from the latter, conclusions are drawn regarding the possibility of a priori determination of model parameter values on the basis of catchment information. Computer listings of all model programs appear in Appendix B.

4.1 DESCRIPTION OF HOURLY MODEL FORD

Model FORD constitutes a version of the Stanford Watershed Model IV (Crawford and Linsley, 1966; Hydrocomp Inc., 1969) modified by Anderson (Parmele, 1972) of the U.S. Weather Bureau. The Anderson version is set up for simulation at a single flowpoint as opposed to the multi-flowpoint Stanford Model; it differs further from the original in that it uses a much enhanced infiltration function (at the cost of an additional parameter) and is coded in Fortran instead of Algol. Roberts (1978) further modified the Anderson version by basing the channel routing subroutine on a time delay histogram of quarter-hour (instead of multi-hour) increments - a necessity for small catchments. Apart from the original two reports on the Stanford Model (Crawford and Linsley 1966; Hydrocomp Inc., 1969), a valuable description of the model which he named, FORD, is offered by Roberts (1978), including presentation of some of the important functions in graphical form.

The general input requirements for FORD are quarter-hourly, hourly, or six-hourly rainfall totals, daily or average monthly pan

evaporation, twelve monthly pan to free water surface conversion factors and hourly or six-hourly flow data where the flow data are required for model calibration and verification. Irrespective of the selected time interval for rainfall input data, the model operates on quarter-hourly iterations for processing rainfall data while evaporation from the three non-groundwater storages are calculated on an hourly and, from groundwater storage, on a daily basis.

4.1.1 Conceptual design

Fig. 4.1 shows a flow diagram of model FORD while the model parameters are described in Table 4.1. It can be seen that the model is structured around a vertical arrangement of four conceptual storages, each representing a zone in the land surface vertical profile in which explicit moisture accounting takes place. Crawford and Linsley (1966) saw the conceptual role of the interconnected system of storages that make up FORD as follows: "The upper and lower zone storages, together with the groundwater storage, combine to represent variable soil moisture profiles and groundwater conditions. The upper- and lower-zone storages control overland flow, infiltration, and inflow to the groundwater storage. The upper zone control watershed response to major storms by controlling longer term infiltration rates. Groundwater storage supplies the baseflow to stream channels. Evaporation and transpiration may occur from all of the storages."

The interception storage, the first process to act on rainfall inputs to the model, is of finite size while the upper zone, lower zone and groundwater stores have infinite sizes. Deep groundwater percolation losses from the catchment can be seen as a fifth inactive moisture store, also of infinite capacity. The calibration parameters associated with the upper and lower zone storages UZSN and LZSN (see Table 4.1) represent specific, functionally-important moisture-holding states of these two infinite stores which have a dictating influence on the behaviour of the infiltration function, the upper zone function (i.e. increments to overland flow detention and interflow detention), the lower zone function (i.e. increments to active and inactive groundwater) and the percolation function (i.e.

Table 4.1

Parameters used in model FORD

Variable name	Parameter	Possible a priori source
	Volume control parameters	
K1	Rainfall scaling factor (usually inactive)	
IMPV	Impervious area (fraction)	maps, aer. phot
EPXM	Interception storage (inches)	maps, field surveys
UZSN	Nominal upper zone soil moisture storage (inches)	
LZSN	Nominal lower zone soil moisture storage (inches)	
POWER	Exponent of infiltration curve equation	
CB	Infiltration index	
CC	Interflow index	maps, aer. phot.
K3	Areal cover of deep-root vegetation (lower zone evapotranspiration parameter) (fraction)	
K24	Seepage to inactive groundwater (fraction)	
K24EL	Fraction of catchment where evapotranspiration occurs at potential rate from groundwater	
	Timing control parameters	
L	Length of overland flow (feet)	maps, aer. phot.
SS	Overland flow slope (fraction)	maps, aer. phot.
NN	Manning's roughness coefficient for overland flow	hydraulics texts
IRC	Daily interflow recession rate (fraction)	
KK24	Daily groundwater recession rate (fraction)	obs. hydrographs
KS1	Channel storage routing parameter (fraction)	obs. hydrographs
KV	Groundwater recession variable rate (fraction)	

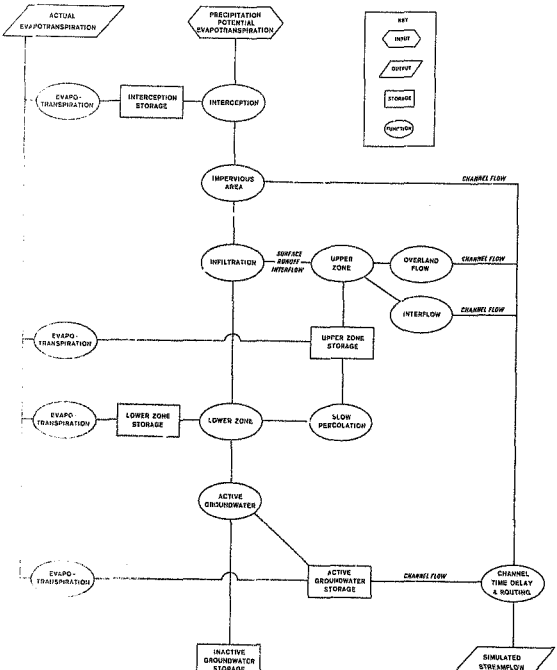


Figure 4.1 Flow diagram : model FORD
(after Roberts, 1978)

moisture movement from upper to lower stores).

The interconnected system of storages that make up the central structure of FORD merely serves to calculate the inflow into a river channel during any specific time interval. This channel inflow has to be translated to the catchment exit or the channel point of interest to the simulation. Such translation constitutes two phases: time delay (or catchment lag") and channel storage attenuation. Time delay 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 channel. 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 the channel travel times but not channel storage attenuation. Such attenuation is achieved by routing the lagged hydrograph through a pseudo-linear storage

4.1.2 Physical representativeness

Though the alignment of components and the interaction between storages of FORD may be a rational and sound conceptualization of the way moisture distribution occurs during the catchment phase of the hydrological cycle, it does not imply that the whole model can be regarded as being physically realistic. In fact, the model is "an assemblage of empirical functions linked together into a system which conforms to our understanding of the real-world system .... The equations are empirical but the model as a whole is a physical description of the hydrological cycle" (Linsley, 1976). However, certain parts of the model are more physically-realistic than others. The most realistic component of the model is its overland flow function.

The overland flow function is based on the hydraulic principles governing unsteady flow over a plane and requires the formulation of an imaginary plane (representing the catchment surface) whose characteristics can be input to the model as parameters L (length), SS (slope) and NN (Manning's roughness coefficient). Though none of the

Stanford Model descriptions mentioned earlier gives much guidance on how this imaginary plane should be inferred from catchment information, experimentation with Ecca data showed that good results can be achieved if the following procedure is followed. Plane length L can be taken as the mean slope length (in feet) from the channels of the main tributaries (and from the main channel) to the applicable interfluves. Plane slope SS can be based on the mean catchment slope calculated as (total contour length. contour interval)/catchment area (see Table 2.14). For semi-arid catchments Manning's roughness coefficient (NN) can be expected to be between 0,30 and 0,40.

For the above deviations of L and SS one would naturally rely on maps or aerial photographs of suitable scale. This process by which certain model parameters are determined from catchment information prior to overall model calibration is known as a priori calibration. Models with physically-realistic components, such as FORD's overland flow function above, hold the promise of easier calibration through a priori parameter estimates and inspire greater confidence in their output. However, though their functions may not be physically-realistic, certain parameters have enough physical meaning to allow their a priori estimation as well. In the case of FORD the following parameters belong to this category: IMPV, EPXM, K3, K24EL, L, SS, NN, KK24, KS1. Sources of a priori information on these parameters are indicated in Table 4.1.

4.1.3 Footnote on Roberts's (1978) description and application of FORD

The description of FORD by Roberts (1978) is recommended to a potential user as valuable in terms of good a priori understanding of the internal workings of the model. However, the reader is cautioned that certain errors exist in Roberts (1978) which may jeopardize understanding or successful application of the model. In Roberts's section 3.2, the description of FORD, the following errors were found. Firstly, the flow diagram of FORD (Fig. 17) shows no link between the groundwater function and the active groundwater storage. Secondly, equations 4 and 5, representing the excess precipitation after infiltration loss, are based on a variable D3FV, an index of the mean hourly infiltration rate. However, because the model operates on

quarter-hourly iterations, the variable D3FV in Roberts's equations 4 and 5 should be replaced by D3FV/4. In fact, Roberts's graphical representation of the infiltration function (Fig. 18) does not make sense without the above amendments.

Two serious errors exist in the computer listing of model FORD in Roberts's Appendix A. The errors occur in subroutine "CHANNEL" which effects channel delay and routing computations. These cause a more than 50% "loss" of channel inflow during routing in all months except the first month modelled. Roberts's version of FORD consequently operated with a corrupted moisture accounting system. This was confirmed by inspection of the original computer printouts of Roberts's applications of FORD to the Ecca catchments. A possible reason why Roberts did not detect the error may reside in the fact that the flow total of the first month simulated by him, March 1976, completely dominated the flow pattern during his whole simulation period, March 1976 to May 1977 - and the nature of the errors is such that the first month simulation is not affected by them. Further minor errors also exist in Roberts's computer listing in the main program and subroutine "READER" which cause problems during the printing of model outputs. All the foregoing errors were corrected and the computer listing of FORD appearing in this document in Appendix B should replace that in Roberts (1978).

4.2 DESCRIPTION OF HOURLY MODELS PITH AND PITR

Models PITH and PITR are modified versions of an hourly model developed by Pitman (1977; Pitman and Basson, 1979) as a flood-forecasting tool. Chapter 3 discusses apparent shortcomings in Pitman's original model and describes in detail the nature of the modifications that led to the final versions called PITH and PITR. Chapter 3 (section 3.6) also contains algebraic and graphical representations of all the model functions and a listing of all parameters.

4.2.1 Conceptual design

Figs. 3.7 and 3.8 provide flow charts of the two models under

consideration. Like FORD, these two models are structured around four vertically aligned moisture storages. As can be seen, the difference between PITH and PITR is that the contents of the depression storage are "re-infiltrated" in PITR whereas this is not the case in PITH. An important difference between these two models and FORD is that two of their soil zone stores have finite capacities (SU and ST) while FORD's equivalent storages are infinite. The relevance of this difference to likely hydrological response differences between the two types of models is that a finite size to, especially, soil zone stores causes discontinuities in model behaviour during periods of store capacity exceedence (Johnston and Pilgrim, 1973). During such events the otherwise smoothly non-linear response of the model with finite stores would display sudden increases. Such response changes would be much attenuated in models with infinite stores. (The presence of a finite soil moisture store in the various versions of PITR investigated in Chapter 3, may explain why it was concluded "re-infiltration" would make the infiltration process too dominant a part of the model, whereas this is not the case for FORD which also uses a form of "re-infiltration": the higher amounts of moisture entering the soil moisture store caused exceedence of ST too early and too often, leading to the aforementioned discontinuities in hydrological response).

PITH and PITR produce three flow phases: a quickflow phase surface flow, an intermediate phase, interflow, and a delayed flow phase, groundwater. Surface flow originates as spillage from depression storage, whereas interflow originates both as depression store spillage and as soil moisture exceedence runoff.

4.2.2 Physical representativeness

Though less complex than FORD, it is unlikely that PITH and PITR can be regarded as less physically-based - except for the overland flow function. Nevertheless, the individual functions that constitute these two models are empirical and are far from physically-realistic in the true sense of the word. Still, as with FORD, certain parameters have sufficient physical or conceptual meaning to allow their a priori estimation. Table 4.2 lists the relevant parameters and their likely a priori sources.

Table 4.2

A priori type parameters used by PITH and PITR

Variable name	Parameter	Possible a priori source
AI	Impervious fraction of catchment area	maps, aer. phot.
PI	Interception storage (mm)	maps, field surveys
TL	Muskingum routing coefficient for surface flow (h)	obs. hydrographs, Bauer and Midgley (1974)
DIV	Maximum expected interflow rate (mm/h)	obs. hydrographs

4.3 DESCRIPTION OF DAILY MODEL PITD

Model PITD is a slightly modified version of a daily model developed by Pitman (1976) at a level of complexity commensurate with the requirements of water resources engineering practice in South Africa and with the disparate availability of reasonable quality hydrometeorological data in various parts of the country. Modifications to Pitman's original model are threefold and are discussed in subsection 4.3.2. The general input requirements for PITD are daily rainfall and daily pan evaporation data and twelve monthly pan to free water surface conversion factors. Infiltration into and evaporation from soil are processed on an hourly or sub-daily basis on raindays and a daily basis on non-raindays. The groundwater and channel lag-routing functions always operate on daily iterations.

4.3.1 Conceptual design

Fig. 4.2 depicts a flow chart of model PITD. The model is structured around three vertically aligned moisture storages of which the upper two, interception and soil moisture storage, are finite and the lower storage, groundwater, is infinite. PITD produces only two flow phases: a quickflow phase, surface runoff, and a delayed flow phase, groundwater outflow. Surface runoff can originate both as infiltration excess runoff or soil moisture exceedence runoff. PITD displays more or less the same discontinuous hydrological response as PITH and PITR during soil store saturation, due to the finite nature of the soil moisture store. Channel inflows are lagged directly in terms of one or more days to represent time delay while channel storage attenuation is effected by means of the Muskingum routing approach.

4.3.2 Modifications to the original daily model

(a) Rainfall disaggregation function: Pitman (1976) disaggregates daily rainfall inputs into hourly distributions of specific duration by means of a simple linear regression relationship between duration in hours and daily rainfall in mm. Instead of the

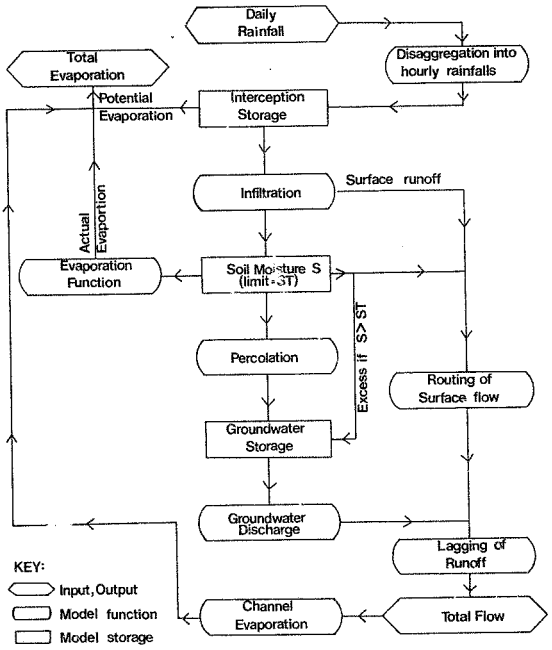


Figure 4.2 Flow diagram : model PITD

single relationship offered by Pitman, two seasonal relationships were developed for the Ecca catchments from autographic rainfall data. The relationships are:

summer duration of storms (h) = 3,17 + 0,23. daily fall (mm)
.....(4.1)

winter duration of storms (h) = 7.5 + 0,2. daily fall (mm)
.....(4 2)

Summer is defined as the months October to March and winter as the months April to September. Each of the two equations above was developed using data from 50 Ecca storms. This seasonal hourly disaggregation of daily rainfall produced modelling results far superior to Pitman's original function.

(b) Evaporation - soil moisture relationship: Pitman (1976) designed his original daily model to accept only twelve longterm monthly mean Symons pan values as evaporation inputs and devised an evaporation-soil moisture relationship at a level of simplicity commensurate with the level of evaporation inputs. To operate with actual daily pan readings as input, the evaporation-soil moisture relationship had to be modified. Modifications identical to those used in PITH and PITR, and described in subsection 3.6.7, were incorporated.

(c) Channel evaporation function: Inspection of Pitman (1976) discloses that the catchments on which Pitman developed and tested his original model all lie in temperate to humid climatic zones. A characteristic of such zones is the presence of sustained baseflow during dry months. The groundwater function Pitman devised is well suited to such catchments as it causes unceasing outflow from the groundwater storage. However, in semi-arid catchments long recessions are rare phenomena due to small soil moisture storage capacities and extremely high channel evap[illegible] seepage losses. Consequently, as the applications of PIT[illegible] a semi-arid data in Chapter 6 show, the model overpredict[illegible] low for many days, even months,

after a major storm. To remedy this baseflow problem a channel evaporation function was added to PITD.

The channel evaporation function is based on the assumption that most of the losses from semi-arid river channels are due to evapotranspiration at a near-potential rate. These losses are a function of the total free water surface area in the main and tributary channels and the near-saturated area in the proximity of any free water surfaces. As such, the function utilizes the level of lag-routed potential channel discharge to calculate the total free water surface area. Near-saturated areas are assumed to increase the total evaporative surface by about 10%, while deeprooted riparian vegetation is assumed to have a permanent evaporative effect equivalent to a discharge level at 10% of the bankfull capacity. After experimentation with many different functions, it was found that a modified quadratic relationship best describes the increase in channel free water surface area with increase in the level of discharge (at least in terms of Ecca data). The resulting channel evaporation function is

$$CLOS_i = FRAC_i \cdot AREAC \cdot 1{,}1 \cdot PE_i \qquad \ldots\ldots(4.3)$$

where $CLOS_i$ = channel loss for day i, in mm,
PE_i = potential evaporation for day i, in mm,
AREAC = ratio of free water surface area at estimated bankfull discharge level to total catchment area,
and $FRAC_i$ = ratio of free water surface area at mean discharge level of day i to free water surface area at bankfull discharge.

In equation 4.3 the following holds:

$$FRAC_i = 0.1 + 2(RAT_i)^{0,5} - RAT_i \qquad \ldots\ldots(4.4)$$

where $RAT_i = DOUT_i/QBANK$

.....(4.5)

and $DOUT_i$ = mean discharge level for day i, in mm
QBANK = estimated bankfull discharge level, in mm,
and AREAC = TRIB.CHAN/AREA.1000

..... (4.6)

where TRIB = total tributary length, in km
CHAN = average width of flow at bankfull discharge, in mm
AREA = total catchment area in km^2.

The channel evaporation function has created three additional parameters for PITD i.e. TRIB, CHAN and QBANK, but they are physical in nature and can therefore be estimated prior to calibration: TRIB through planimetering suitably scaled maps, CHAN from aerial photographs or a field visit and QBANK through a field visit or even approximated as the maximum discharge. It was found that the channel evaporation function considerably improved the ability of PITD to model the overall flow pattern in the Ecca catchments, both on a daily and a monthly basis. Daily peaks were hardly affected but recession fits were much improved, both in terms of daily and monthly totals. Monthly and daily standard deviation errors were also reduced

The reader should note that the channel evaporation function was introduced to PITD only after all computations up to and including Chapter 6 had been completed. Improvements owing to the incorporation of equation 4.3 have thus a bearing only on Chapters 7 and 8.

4.3.3 Physical representativeness

As is the case with PITH and ..., the essential structure of PITD contains no truly physically realistic functions, but certain parameters have sufficient conceptual meaning to allow their a priori estimation. Table 4.3 lists all PITD parameters and likely a priori sources where applicable.

4.4 DESCRIPTION OF DAILY MODEL DALT

Model DALT is a version of an extremely simple single-storage

Table 4.3

Parameters used in model PITD

Variable name	Parameter	Possible *a priori* source
	Volume control parameters	
AI	Impervious fraction of catchment area connected to stream network	maps, aer. phot.
FT	Maximum soil moisture percolation rate to groundwat r (mm/day)	
PI	Maximum interception storage (mm)	maps, field surveys
POW	Power of soil moisture storage-percolation curve	
R	Coefficient of evaporation-soil moisture relationship	
SL	Soil moisture storage below which no evaporation occurs (mm)	
ST	Maximum soil moisture capacity (mm)	
ZMAXN	Nominal maximum infiltration rate when soil moisture storage = ST (mm/h)	
ZMINN	Nominal minimum infiltration rate when soil moisture storage = ST (mm/h)	
QBANK	Estimated bankfull discharge or maximum expected discharge (m^3/s)	obs. hydrograph field survey
TRIB	Total tributary length (km)	maps, aer. phot.
CHAN	Estimated width of flow at bankfull discharge (m)	aer. phot , field survey
	Timing control parameters	
DIV	Proportion of soil capacity excess moisture routed to groundwater	
TL	Muskingum routing coefficient for surface flow (day)	obs. hydrographs
GL	1/Recession constant for groundwater depletion when groundwater storage = ST (day)	
LAG	Time delay of channel outflow (day)	

model by Diskin, Buras and Zamir (1973), modified and extensively improved by Roberts (1978). The objective with the development of DALT was to "provide a model that could produce output at an acceptable level of accuracy with the least possible complexity of model structure". (Roberts,1978). In modifying the original model Roberts imposed restraints such 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." The model input requirements are daily rainfall totals, daily pan evaporation totals or long term mean monthly pan evaporation values and monthly pan to free water surface conversion factors.

4.4. Conceptual design

Fig. 4.3 comprises a flow chart of DALT, showing its single (linear or non-linear) moisture storage of finite capacity (SSM) which represents the maximum soil moisture deficiency averaged over the catchment. No interception, depression storage or infiltration processes are recognized and the soil moisture level is increased by addition of daily rainfall and depleted by daily evaporation according to a modified quadratic function of soil moisture storage level. Runoff occurs either as soil moisture excess (storage level > SSM) which represents a quickflow phase or as baseflow (when storage level > threshold SSB) which is a delayed flow phase.

A novel aspect of model DALT is its flexibility: it is in fact a series of four models built into the same program, where each "model" is a bit more complex than its predecessor in the series. Roberts (1978) refers to the models run by program DALT as:

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

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

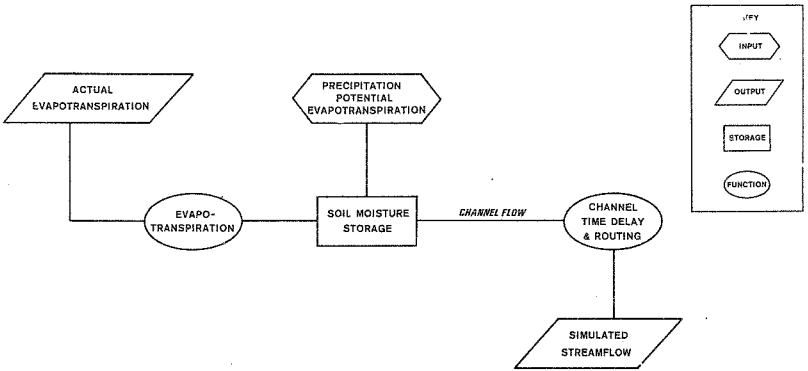


Figure 4.3 Flow diagram : models DALT and DALM
(from Roberts, 1978)

"(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,

"(4) DALT4 is model DALT3 with the *non*-linear depth response function being restricted to storage values below the base flow threshold". 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. The non-linearity of the single store is a special feature of DALT; Fig. 4.4 shows the variety of "container" shapes that are possible. Roberts (1978) found that from its level 2 upwards, DALT performance was equal to or progressively better than that of certain other much more complex models tested on 15 months of Ecca data. Considering this fact and that at its most complex (DALT4) DALT has only seven parameters to calibrate, Roberts achieved quite a feat in the development of this model.

4.4.2 Physical representativeness

Table 4.4 lists all the parameters used in DALT. Though Roberts attempted to maintain a reasonable level of physical relevance in the parameters of DALT, none of them can actually be estimated by a priori means. The model ignores many of the traditional concepts underlying well-known rainfall-runoff models such as the Stanford Model and Pitman's models (see earlier sections) and which give rise to multi-storage structures and large numbers of parameters - and as such it may seem physically less representative. However, Roberts (1978) himself cautions that "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".

4.5 DESCRIPTION OF MONTHLY MODEL PITM

Model PITM is a slightly modified version of a monthly model

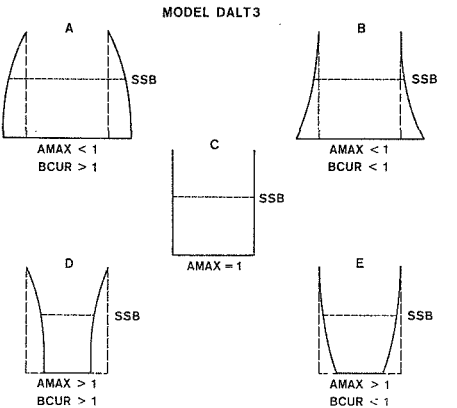


Figure 4.4 Possible shapes of moisture stores (from Roberts, 1978)

Table 4.4

Parameters used in models DALT and DALM

Variable name	Parameter
	Volume control parameters
SSM	Maximum capacity of storage (mm)
SSB	Storage level at which base flow begins (mm)
POWER	Power of base flow function
BCUR	Power of non-linear storage depth function
AMAX	Maximum value of storage depth factor
PERC	Maximum fraction moisture to deep percolation
	Timing control parameter
LAG	Time delay (days or months)

developed by Pitman (1973), which has already enjoyed widespread use in South Africa. Amongst others, it was a major aid in the recently completed national survey of South Africa's surface water resources (Hydrological Research Unit, 1981-1982). General input requirements for PITM are monthly rainfall totals, monthly pan evaporation totals and twelve monthly pan to free water surface conversion factors.

4.5.1 Conceptual design

A flow chart of PITM is presented in Fig. 4.5. The model is structured around two vertically aligned moisture storages, both of finite capacity. Two flow phases are produced: quickflow is generated either by infiltration excess or by a form of "interflow" runoff from the soil moisture store; delayed flow is produced by limited percolation from the soil moisture store. The two flow phases are Muskingum-routed separately to allow for channel attenuation.

As the original Pitman monthly model was designed to accept longterm mean monthly evaporations, PITM had to be modified to operate on observed monthly pan evaporation totals. Specifically, the soil moisture storage - evaporation relationship had to be changed. To this end, modifications identical to those used in PITH and PITR and described in subsection 3.6.8, were incorporated.

4.5.2 Parameter estimates

Table 4.5 lists all the parameters used in PITM. The only parameter that lends itself to direct a priori estimation is AI, the fraction of total catchment area which is impervious and directly linked to the channel network. However, a novel feature of PITM which has as yet not been equalled anywhere in the western world at the same scale is that regional values of the parameters have been determined for the whole of South Africa by the Hydrological Research Unit (1981-1982) of the University of the Witwatersrand. This was a necessary component of the national surface water resources survey by that Research Unit. In essence, the existence of proven regional parameters for PITM means that a priori estimates of all parameters are possible for application in any catchments, gauged or ungauged.

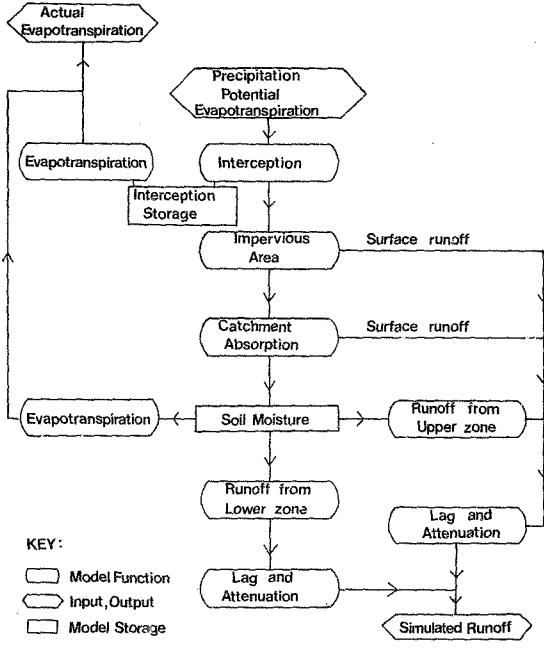


Figure 4.5 Flow diagram : model PITM

Table 4.5

Parameters used in model PITM

Variable name	Parameter
	Volume control parameters
AI	Impervious fraction of catchment area connected to stream network
FT	Maximum soil moisture percolation rate to groundwater (mm/month)
PI	Maximum interception storage (mm)
POW	Power of soil moisture storage-percolation curve
R	Coefficient of evaporation-soil moisture relationship
SL	Soil moisture storage below which no evaporation occurs (mm)
ST	Maximum soil moisture capacity (mm)
ZMAX	Maximum catchment absorbtion rate (mm/month)
ZMIN	Minimum catchment absorbtion rate (mm/month)
GW	Maximum groundwater discharge rate (mm/month)
	Timing control parameters
TL	Muskingum routing coefficient for surface flow (month)
GL	Muskingum routing coefficient for groundwater flow (month)

4.6 DESCRIPTION OF MONTHLY MODEL DALM

Model DALM is a monthly-input version of daily model DALT described earlier, developed by Hughes (1982) for a monthly model parameter transfer study in catchments of the Southern Cape coastal lakes area. The model input requirements are monthly rainfall totals, monthly pan evaporation totals and twelve monthly pan to free water surface conversion factors. Because he used the model in forested catchments, Hughes (1982) added an interception storage function to DALM and this function is retained in the model program included in Appendix B. However, for application to the Ecca catchments, this function was bypassed so that DALM, like DALT, operated as a single-storage model. Consequently, Fig. 4.3 also represents the structure of model DALM while Table 4.4 also describes the DALM parameters.

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CHAPTER 5

A ROBUST AND RELIABLE APPROACH TO MODEL CALIBRATION

5.1 INTRODUCTION

Essentially, estimation of parameters, or calibration, of conceptual rainfall-runoff models can be pursued in three ways.

(a) Model parameters can be inferred from measurable catchment characteristics. This is termed an a priori approach by Chapman (1975) and can be regarded as being reasonably objective. This approach obviously presupposes that the model in question is sufficiently deterministic or at least physically realistic to such an extent that field and/or laboratory measurements of catchment characteristics and processes become meaningful prerequisites for successful operation of the model.

(b) Model parameters can be inferred by curve-fitting or goodness-of-fit procedures, i e. finding parameters that will ensure close correspondence between specific characteristics of one or more simulated hydrologic time series and their equivalent observed time series, such as runoff, soil moisture storage and groundwater storage. Exactly how closely the simulated and observed time series correspond is measured by one or more statistical procedures or goodness-of-fit criteria. The term objective function is now widely used to describe any specific fitting criterion employed in the parameter estimation process. Obviously, the nature of the objective function used, will dictate the outcome of the calibration process (Diskin and Simon, 1977). Consequently, a purely curve-fitting or goodness-of-fit approach to parameter estimation is usually accompanied by uncertainty as to whether or not the inferred parameters are "artifacts of the fitting process" (Chapman, 1975), and to what extent they can be related to the "true" values which they claim to represent. This approach can range from being completely objective, achieved by using automatic optimization routines (Ibbitt and O'Donnell, 1971b), to being pragmatically subjective - trial-and-error fitting by manual perturbation of model parameters and relying strongly on visual

impressions of the correspondence between the simulated and observed time series (Pitman, 1976).

(c) Model parameters can be inferred by a mixed approach employing both a priori and curve-fitting methods. Exactly what "mix" of the two methods be employed in a specific situation will depend on which, and how many, of the model components are physically-based to an extent that warrants a priori parameter estimates; also, on whether the objectives of the model application and available time and facilities justify the effort and cost that a priori estimates may entail. In practice the proportion (claimed by the authors) of a priori determinable parameters in often-used "mixed" conceptual models is found to vary through a wide range spanning 4 out of 13 parameters in a daily-input model by Pitman (1976), 5 out of 19 parameters in the Stanford Watershed Model (Crawford and Linsley, 1966), the majority of the 12 (Body and Goodspeed, 1979) or all 19 (Black and Aitken, 1977) parameters of the Australian Representative Basins Model, the majority of the ±50 parameters of the USDAHL-74 revised model (Holtan, et al., 1975) and 14 out of 17 parameters of the hourly-input model, HYSIM, by Manley (1975, 1977, 1978). Important to note in the foregoing type of application is that the a priori component of the mixed calibration approach often does not comprise more than merely basing initial estimates of so-called physically-realistic parameters on catchment data. These initial estimates are then further "hardened" by subsequent curve-fitting calibration methods (Manley, 1978; Body and Goodspeed, 1979).

Fully deterministic, spatially-distributed, multi-dimensional rainfall-runoff models have been shown to be theoretically workable by Smith and Woolhiser (1971a and b), Freeze (1972a and b), Beven (1975) and Beven, et al. (1980), and probably represent the only type of conceptual models for which a priori measurement of catchment characteristics can legitimately be claimed to be crucial. In a comprehensive review of this modelling approach Freeze (1978) concludes that, inter alia, the astronomical a priori parameter estimation requirements involved will for many years to come restrict the use of these models to "the examination of flow mechanisms on hypothetical hillslopes or on small instrumented research watersheds".

It is no wonder that recent years have seen several attempts at the development of much simpler a priori physical models than the "Freeze generation" of models (Bultot and Dupriez, 1976; Beven and Kirkby, 1979; Jayawardena and White, 1979). The most promising amongst these must be the attempt by Beven and Kirkby (1979) to devise "a model for humid temperate areas that attempts to combine the advantages of simple lumped parameter models with the important distributed effects of variable contributing areas and flow routing through the channel network, while retaining the possibility of deriving parameters by direct measurement within the basin under study". The above model simulated the outflow from an 8km^2 catchment, subdivided into 23 segments, fairly well without any recourse to calibration Nevertheless, even at this small basin size the authors found the task of deriving the parameters of all 23 segments directly by field measurement very daunting. "Wherever a hydrological process is to be modelled from strictly physical considerations, the spectre of spatial variability appears", is Moore and Clarke's (1981) apt formulation of this dilemma. It does seem therefore as if the outlook for operational application of the latest generation of simpler a priori physical models in the short term is fairly bleak.

The aforementioned situation leaves the practising hydrologist with little choice but to accept the inevitability of a certain amount of "curve-fitting" when using conceptual rainfall-runoff models in an applied or operational situation. Fortunately, some of the pitfalls of curve-fitting/goodness-of-fit methods can be redressed in two ways. Firstly, there is the a priori estimation of at least some parameters (outlined earlier) - even if only as initial values in the fitting process to ensure that the calibration starts in a realistic parameter environment, or as physically realistic boundaries for specific parameters to which they may be constrained during calibration. Very useful for this limited form of a priori parameter estimates would be compendia of physical characteristics of catchments, such as the paper by Jones (1976) who collated physical catchment data typically needed by conceptual models from published surveys spread over several disciplines. Employing initial parameter values derived from very small typical plots (7m^2 area) representing hydrological zones in small agricultural catchments is a further promising technique used by

the USDAHL modellers (Comer and Holtan, 1976). In Australia much research is being done on actual field observation and mapping at small to medium catchment scale of hydrologically significant physical catchment characteristics (Bell and Vorst, 1981; Laut et al., 1982).

In South Africa, mapping of a different variety is being employed to assist a priori parameter estimates (Hydrological Research Unit, 1981-1982): in this case the primary parameters of a specific model, i.e. Pitman's (1973) monthly model, have been mapped on a regional scale in association with regional maps of rainfall, vegetation, geology, soils and land use. A priori estimation of model parameters by multiple regression with physical catchment characteristics, valid for a specific region, has been used fairly successfully by James (1972) and Magette et al. (1976) in applications of the Kentucky Watershed Model in five southern states in the U.S.A., and by Betson et al. (1980) in applications of model TVA-HYSIM under the auspices of the Tennessee Valley Authority.

The second way of redressing curve-fitting shortcomings is to use other observed hydrological time series such as soil moisture or groundwater storage additional to streamflow records in model calibration, i.e. to fit both the model output and an internal state variable of the model to the correspondiong observed records. In this way the amount of information utilized in the calibration is much expanded and confidence in the fitting method per se is enhanced. This multiple-time series calibration was first tentatively used by Johnston and Pilgrim (1973) and later strongly advocated by Chapman (1975), but reported results to date seem fairly inconclusive. Douglas et al. (1976) using monthly soil moisture readings and 6-hourly streamflow data in two catchments found that calibration was little improved by the soil moisture information. They ascribed this disappointing result to sparseness of soil moisture information. Similarly, Jackson et al. (1980) reported only partial success in using observed soil moisture additionally in the calibration of the USDAHL model. Kuczera (1982), on the other hand, reported much improved parameter estimates by incorporating 2-monthly groundwater depth readings, additional to streamflow, in the calibration of his simple catchment model by automatic optimization.

Undoubtedly, much research can still be expected on parameter estimation as a limited *a priori* process, as well as on the use of multiple observed time series in model calibration by curve-fitting/goodness-of-fit methods. Unfortunately, both these avenues towards more reliable model calibration are of little help in the modelling studies reported in this document. The only *a priori* estimates that can be attempted in this study are related to those parameters which can be read off or calculated from maps, aerial photographs and hydrographs of instantaneous discharge - a minor help for all models included in the study. Furthermore, additional observed time series of catchment storage variables such as soil moisture and groundwater are also unavailable for enhanced calibration. For the foregoing reasons and by reason of the sizeable number of models selected for application to the Ecca catchments, as well as the multiple objectives of this study, it was deemed essential that the establishment of a robust but reliable curve-fitting/goodness-of-fit approach to model calibration should precede any other developments. Moreover, during the early stages of the research reported in Chapter 3 it was already clear that the manual trial-and-error calibration approach was proving to be of only limited usefulness and that some form of automatic search or optimization procedure was going to be indispensable - for three principal reasons. Firstly, the envisaged modelling studies implied many tens of thousands of model calibration runs, sometimes with large input data sets. Manual procedures as the only calibration approach would have been immensely costly in man-hours. Secondly, the manual approach necessitates an intimate understanding of the workings of a model for rapid convergence on an optimal set of parameters. Though this may commonly be regarded as a fruitful pursuit in its own right, the equitableness of the planned model intercomparison (Chapter 7) might have been compromised by extensive experience the writer had had of two of the selected models, i.e. the daily- and monthly-input models developed by Pitman (1973; 1976). Thirdly, notwithstanding the fact that calibration by one person only should limit spurious subjectivity in the model intercomparison phase (as would be the case if each model was calibrated by a different person), it was felt that rational use of automatic optimization procedures would facilitate minimization of

the general subjectivity that is usually present in calibration by goodness-of-fit criteria (Moore and Clarke, 1981).

It follows that rational decisions about items such as the exact techniques and theoretical considerations that the parameter estimation approach in the Ecca study should encompass could be made only on the basis of a sound appreciation of the state-of-the-art regarding parameter optimization for rainfall-runoff models. In what follows, the discussion of the state-of-the-art in optimization leads in the rest of the chapter. After discussion of relevant theory and problems, the choice of a suitable automatic optimization procedure is described. The influence of a large and varied set of objective functions on the optimization procedure is explored and suitable functions identified, using Ecca research data. This is followed by an investigation into the robustness of the chosen objective function/automatic optimization combination. A discussion of parameter sensitivity considerations leads on from the robustness tests. A synthesis of the findings into a rational calibration procedure concludes the chapter. At this point it must be stressed that no attention is given in this chapter to the specific problem of the optimal length of the calibration sample. The role of calibration period length is analysed in Chapter 6 as a separate study because of its importance.

5.2 STATE-OF-THE-ART IN PARAMETER OPTIMIZATION FOR RAINFALL-RUNOFF MODELS

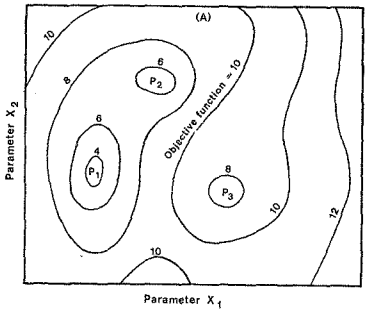
5.2.1 Optimization procedures used in catchment modelling

Automatic optimization procedures have attracted increasing interest in the field of conceptual catchment modelling since Dawdy and O'Donnell (1965) showed in the mid-sixties that this type of model can be calibrated automatically. Automatic optimization procedures are mathematical search algorithms (computer-coded) which seek to minimize differences between selected features of modelled and observed streamflows by systematic trial alterations in the values of the model parameters. These trial alterations are called

"iterations". The objective function, i.e. the quantitative measure of the fit of the modelled runoff to the observed runoff, is calculated after each parameter iteration. Successful iterations are those which cause a reduction in the value of the objective function. During the search only the parameter set associated with the current least objective function value is retained, which, at the end of the search is regarded as the optimal parameter set. The end of a search can be decided by a convergence test of the rate of reduction of the objective function value, by a predetermined number of iterations, or by a computer run-time limitation.

For two-parameter models, the distribution of the objective function values produced by different pairs of parameter values can be plotted on two-dimensional diagrams as contours of equal values, as shown in Fig. 5.1. This distribution of objective function values in the two-parameter plane is known as a response surface. For a multi-parameter model the same concepts will hold: if there are N parameters and these are represented by N of the coordinates of an M-dimensional coordinate system (where M = N+1), and the remaining coordinate represents the objective function, then this function forms a surface in the M-dimensional space known as a response surface (Johnston and Pilgrim, 1973). For N>2 this surface obviously cannot be represented visually. The optimum parameter set is defined by the lowest point on the surface in the case of a minimizing objective function. This lowest point is known as the global optimum and discovery of the optimum is known as convergence. There may be other points on the surface which are lower than all others in their immediate vicinity, but not lower than the global optimum. Such points are known as local optima. Fig. 5.1(a) illustrates the aforementioned phenomena.

The response surface is a most useful concept: the optimizing procedure may be portrayed as a search on and across the response surface for its lowest point. Most search algorithms conduct a line-search, i.e. the objective function values at various points along a search direction are determined. When the line-optimum in that direction has been found, a new search direction is defined and a new search cycle starts. How the search directions are defined, how each subsequent search step is generated, how each line is searched and



P_1 = Global optimum

P_2, P_3 = Local optima

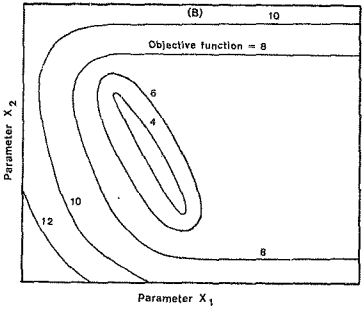


Figure 5.1 Two-dimensional response surface (hypothetical)

which assumptions are made about the form of the response surface give rise to the different optimization algorithms reported in the literature.

Outlines of a number of different optimization procedures have been given by Ibbitt and O'Donnell (1971b), Clarke (1973a), Wood (1975) and Johnston and Pilgrim (1973), while Pickup (1977) recommended the work by Himmelblau (1972) as a primary source of information. The different procedures can be categorized as either deterministic or stochastic, with the former being much more common. The deterministic category can in turn be subdivided into direct search, steepest descent (also known as "hill-climbing") and least squares search methods.

(a) Direct search procedures: These methods merely require the ability to make simple comparisons of values of the objective function at different points along a directional search, using no information about the shape of the response surface.

(b) Steepest descent procedures: In contrast with direct search procedures, the descent methods make use of additional information about the surface being searched. Many of these methods require the slope of the surface in each coordinate direction, i.e. the partial derivative of the objective function with respect to each parameter, at each iteration. Additionally, some methods assume that close to the optimum the surface may be approximated by a positive quadratic shape.

(c) Least squares procedures: This approach assumes that the objective function is quadratic for all parameter sets. It finds the optimum by solving analytically for those parameter sets that will define a direction along which the partial derivatives of the objective function will tend to zero.

Comparisons of the fitting ability of different automatic optimization procedures using conceptual rainfall-runoff models have been reported by Ibbitt and O'Donnell (1971b) who tested nine different techniques, Johnston and Pilgrim (1973) who investigated four algorithms in depth, Wood (1975) who compared three techniques, Pickup (1977) who tested four different algorithms and Manley (1978)

who compared two techniques. From the aforementioned and other studies it can safely be concluded that, in general, direct search procedures perform better than steepest descent in that they are less susceptible to irregularity of the response surface such as local optima and discontinuities and that they converge more rapidly in the earlier stages of optimization. A second conclusion is possible further progress in the search from a point where convergence seems to cease is often possible by switching to another type of optimization Ibbitt and O'Donnell (1971b) achieved unexpected progress beyond the apparent optimum by switching from a direct search to a stochastic search algorithm, Johnston and Pilgrim (1973) from direct search to steepest descent and Porter and McMahon (1975) also from direct search to steepest descent. A third conclusion stems from the second: a set of parameter values should not be accepted as an optimum until a number of attempts to make further improvements have been made. Apart from employing a different optimization algorithm, the complete optimization should be repeated from different initial parameter sets (spanning the uncertainties in the a priori estimates); in other words, starting from different points on the response surface.

5.2.2 Problems common to optimization procedures and catchment modelling

The effects of the unique problems encountered with optimization methods in conceptual rainfall-runoff modelling have been studied by a number of researchers: O'Connell, Nash and Farrel (1970); Ibbitt and O'Donnell (1971a, b); Plinston (1971); Johnston and Pilgrim (1973, 1976); Pickup (1977); Mein and Brown (1978); Sorooshian and Dracup (1980); Kuczera (1982). These effects are that different sets of "optimum" values are derived from different sets of initial values of the parameters and that quite different sets of parameter values often give very similar values of the same objective function and of the computed runoff, which also agree with the observed runoffs with acceptable accuracy. Reasons for these difficulties as summarised by Pilgrim (1975) and Moore and Clarke (1981) include the following points.

(i) Interdependence between model parameters, by which a large

number of combinations of parameter values will give similarly low values of the objective function - a change in one parameter may be compensated by changes in one or more of the other parameters. For a two parameter model, a long flat-bottomed valley results in the response surface, as shown in Fig. 5.1(b). Optimization methods make only slow or no progress along the floor of such a valley towards its lowest point. It could be argued, of course, that this interdependence is not a problem, since any of the pairs of values in the valley is almost an optimum and the resulting output sequence is none the worse for the interdependence. However, if any meaning is to be attached to individual parameter values - if, say, parameter values are to be correlated with catchment characteristics - the values obtained from such an optimization would be meaningless.

(ii) Indifference of the objective function to parameter values such that appreciable changes in the value of one parameter may cause little or no change in the objective function. Plateau areas will result on the response surface, as shown in Fig. 5.1(b) for high values of X_1, and it may not be possible for search methods to make progress in such areas, leading to a declaration of a false optimum.

(iii) Discontinuities, or points on the response surface at which the objective function, while still continuous, is nondifferentiable.

(iv) Local optima, as shown in Fig. 5.1(a) - also leading to premature declaration of convergence.

(v) Scaling of parameters - the particular scales used for different parameters may result in unfavourable configurations of the response surface for search progress.

Possible solutions to these problems include the following measures. Problems (i) can be partially redressed by optimizing interdependent parameters individually in separate searches. Problem (ii) can be avoided by setting indifferent parameters to constant values or by starting more than one search from different points on the response surface. Problem (iii) affects only steepest descent

algorithms and cannot be solved except by multiple searches from different points on the response surface. Problem (iv) can often be overcome by direct search methods or by switching optimization algorithms when the search slows down. Point (v) is less of a problem in direct search than in steepest descent methods and can be redressed by either scaling parameters to the same order of magnitude or weighting the search steps for individual parameters according to parameter scale.

A measure that is often used to cope with more than one of the above difficulties is to constrain the values of certain parameters to a "likely range" during optimization, i.e. to prevent "impossible" values from being chosen by the search routine or for the routine to wander into one of the difficulty-prone areas of the response surface. Pilgrim (1975) argues that this procedure is unjustifiable because a parameter value might pass through an impossible region during the search but then return to a realistic level. Imposition of limits also implies that the model structure and the parameters are indeed physically realistic and that the data contain no serious errors. Chapman (1975) argues conversely, i.e. that modellers should consciously strive to make their models more physically-based; then crucial parameters must be constrained to known physical limits commensurate with each catchment situation.

The choice and the role of the objective function are aspects of optimization which also offer serious difficulties to the modeller. Because of their importance, these aspects are discussed under a separate heading in the next subsection.

5.2.3 The importance of the objective function

It is axiomatic that the optimal set of parameters arrived at by optimization is in fact optimal only in the context of the objective function used during the process. A substantially different objective function may converge on a substantially different optimum parameter set, though all other conditions of optimization remain unchanged (Diskin and Simon, 1977; Pilgrim, 1975). Perusal of the scores of modelling studies published since the mid-sixties discloses that in

the majority of cases calibration (manual or automatic) occurred, at least partially, by minimization of the sum of the squared deviations between modelled and simulated streamflows, or of a function based on the sum of squared deviations. These least squares-type objective functions can be said to have a general form:

$$\text{objective function} = f\left(\sum_{j=1}^{n} W_j \left|QOBS_j^m - QSIM_j^m\right|^k\right) \qquad \ldots\ldots\ldots\ldots(5.1)$$

where f(.) signifies some function of the entity in brackets,

$QOBS_j$ is the observed streamflow (or some characteristic of the hydrograph such as the peak) in time period j,

$QSIM_j$ is the simulated streamflow in time period j,

n is the number of time periods being modelled,

m is the power transformation of the streamflows,

k is a power to which the deviation for each time period is raised,

W_j is a weight applicable to each time period (usually related to $QOBS_j$).

By algebraic analysis of two moisture stores typical of those in most explicit-soil-moisture-accounting models, Johnston and Pilgrim (1973) investigated the merits of different configurations of the exponents, m and k, in equation 5.1, while keeping the weight w constant at one. This work resulted in five important findings:

(i) changing the values of the exponent k did not affect the optimum values of the parameters

(ii) leading on from (i) changing exponent k had no effect on the reproduction by the model of small or large events. This finding disproves the traditional assertion that changing the value of k varies the relative weighting given to small and large flow events

(iii) the shape of the response surface was altered by changes in exponent k, affecting the ease or difficulty of optimization. The value of k=2, i.e. the simple least squares function (Clarke, 1973b), was found to produce the most favourable shape - a parabolic shape

(iv) *changing the values of exponent m, i.e.* transforming the streamflows, before calculation of deviations did affect the optimum parameter values considerably

(v) setting m=2 favoured the reproduction of the large events while m=0,5 favoured the reproduction of small events.

One suspects that often the main reasons for the popularity of the least squares criterion must be familiarity and computational simplicity, because notably few of the many authors of modelling reports referred to earlier bother to motivate employment of least squares-type objective functions or to *explore the implications their* use and the use of specific weights and exponents (w, m and k in equation 5.1) might have for reliability of parameter estimates. Still, all modellers desire exactly that - estimators of reliable model parameters. This need for reliable parameter estimators is one of the main themes in Clarke's (1973b) benchmark review of the calibration and use of mathematical models in hydrology. Clarke points out that parameters estimated by analysis of the stochastic nature of model residuals through application of maximum likelihood theory must be regarded as the "most acceptable" parameters, because statistically sound (significance) statements about how "good" the estimates are may then be possible (also because such estimates are unbiased, have minimal variance and have computable confidence regions that converge as the number of observed data used in the calibration becomes large). A least squares objective function according to Clarke can lead to a maximum likelihood estimate only if four assumptions about the probability distribution of the model residuals, i.e. the deviations $QOBS_j - QSIM_j$, are valid: that the residuals are *normally distributed, have a zero mean and* constant variance, are uncorrelated and produce a response surface of quadratic form (for all parameters) near the optimum. Clarke then goes on to show the numerous ways in which reported runoff model residuals invalidate one or more of these assumptions. Inevitably, the conclusion must be that more often than not the parameter estimates achieved by least squares objective functions are not of a maximum likelihood nature, are in fact of unknown statistical significance and may be mere artifacts of

the minimization process, thereby complicating attempts to attribute physical or conceptual meaning to them.

Clarke's (1973b) advocacy of the importance of model residual analysis in calibration can now be linked to two of the findings by Johnston and Pilgrim (1973) discussed earlier. Firstly, the finding that k=2 in equation 5.1 produces a parabolic response surface on which it is easiest to find the optimum validates one of Clarke's four assumptions for maximum likelihood estimates by a least squares objective function, i.e. quadracity of the response surface near the optimum. Secondly, awarding values to exponent m in equation 5.1 such that m≠1 changes the statistical characteristics of the model residuals and is analogous to transformation techniques used to try to achieve homogeneity of residual variance in linear regression applications. (Nonhomogeneous residual variance or heteroscedasticity typically arises in conceptual modelling when, due to measurement errors, the residual variance increases as discharge increases - a consequence of the concavity of the typical stage/discharge relationship. The result is that higher-stage errors translate into larger deviations in discharge than lower-stage errors; Sorooshian and Dracup, 1980). Choosing a value for m(m≠1, k=2) that stabilizes nonhomogeneous variance will validate another of Clarke's four assumptions. Unfortunately, selecting values for m has in the past been done rather arbitrarily by conceptual modellers and usually there is no certainty of achieving a stabilized residual variance situation.

Computing proper weights, w_j in equation 5.1, for individual deviations can be fraught with uncertainty. An example of the rule-of-thumb approach often used is the weighted least squares objective function in the parameter estimation routine of the flood hydrograph package (HEC-1) of the U.S. Army Corps of Engineers (1973). Here the weights are assigned according to the rule

$$w_j = (QOBS_j + \overline{QOBS})/2\overline{QOBS} \qquad \ldots\ldots(5.2)$$

where $\overline{QOBS}$ is the average of the historical discharge values. Although this weighting will accentuate peak flows in the minimization process,

it is likely that the derived parameters are not transferable in time or space. Sorooshian and Dracup (1980) show that rule-of-thumb weighting is in direct conflict with the principles of maximum likelihood theory and that the only legitimate form of weighting is one in which weights are derived during the optimization process by analysis of residuals.

The inadequacy of least squares-type objective functions (m=1, k=2 in equation 5.1) for parameter estimation in the presence of input data errors is explored by Kuczera (1982) (uncorrelated and homoscedastic errors) and for the case of streamflow data errors by Sorooshian and Dracup (1980) and Sorooshian (1981) (correlated and heteroscedastic errors). All three studies demonstrate that careful attention to the stochastic structure of model residuals during the optimization process can lead to substantial gains in accuracy of parameter estimation in comparison with blind minimization of a simple or a weighted least squares objective function.

Despite increasing recognition in the past ten years that great uncertainty surrounds the physical or conceptual significance of model parameters derived by minimization of one or more objective functions without support by stochastic analysis of model residuals, this practice continues among water resources engineers and consulting hydrologists. In most cases, it is granted, the "feel" which the modeller has for his model and for the particular catchment he is modelling may dictate the final parameter choice. This "feel" of the modeller for a catchment, incorporating as it does the intangibles of his/her professional experience, may be a pragmatic way to evade the problems of parameter uncertainty analysis - an undertaking beyond the mathematical and computational resources of the average consulting engineer/hydrologist, as inspection of the attempts by Wood (1976), Douglas, Clarke and Newton (1976), Mein and Brown (1978) and Sorooshian and Dracup (1980) very quickly reveals. It must be expected therefore that model calibration practice comprising this blend of subjective experience and objective optimization, which has gradually developed in engineering-oriented modelling applications, will persist for many years to come - at least until model residual analysis and maximum likelihood estimation techniques can be

streamlined, packaged and "sold" to engineers, both as ideas and as products.

Recognising the need for pragmatism in water resources engineering practice, hydrologists such as Aitken (1973), Pitman (1977) and Weeks and Hebbert (1980) have continued research into reducing the subjectivity of objective function selection for common modelling applications. Pilgrim (1975) stresses that, without losing sight of the foregoing findings on parameter uncertainty, the choice of an objective function must be related to the aims of the modelling application, e.g. catchment yield studies, flood peak estimation for frequency analysis, low flow studies, land use effects on yield or on the whole hydrograph. This theme is echoed by Diskin and Simon (1977) in a comprehensive study of the problem of selection of objective functions in terms of specific engineering modelling applications. They analysed a configuration consisting of twelve different objective functions and six different engineering applications by optimizing two different models on data from three different catchments. Individual objective functions were not necessarily based on all observed flow data, but often on a specified subset of data. The subset used in any given case was such that the objective function became orientated towards a certain engineering application, e.g. only peaks or only low flows. In some cases the objective functions were calculated not from computed and observed values but from statistical parameters derived from these, such as variance, skewness and kurtosis.

The central aim of the Diskin and Simon (1977) study was "to investigate the effects of the objective function selection and to arrive if possible at some recommendations or guidelines for this selection which will reduce the apparent subjectivity involved". They demonstrate that a systematic procedure (albeit elaborate) for selection of objective functions is possible, that greatly improved results can be obtained if the objective function is formulated according to the engineering application for which modelling results will be used that it is desirable to use more than one objective function in the optimization procedure for a given model and a given engineering application. It is of interest to note that as an integrated result over the catchments, models and applications

considered in this study an objective function based on the sum of absolute deviations proved to be the most robust, with a simple least squares function second best. The worst two performances belonged to functions based on power-transformed observed and simulated values.

5.2.4 Summary of perspectives on optimization/objective function difficulties

Perspectives on the role of objective functions in parameter estimation are currently still separable into two groups. On the one hand there are the practising engineers/hydrologists who are often hard-pressed to operate against a background of non-existent, inadequate or incomplete hydrometeorological records and having financial constraints and limited time to produce reasonable "answers". In this context the operation of conceptual rainfall-runoff models is regarded as completely deterministic and, consequently, model residual analysis is largely ignored in parameter estimation. However, uncertainty in derived model parameters is often indirectly acknowledged by steering model calibration towards simultaneous optimization of a group of objective functions, each measuring a different aspect of the goodness-of-fit (Aitken, 1973; Hydrological Research Unit, 1981-1982; Cundy and Brooks, 1981). Subjective but conservative judgement tempered by experience usually completes the optimization process.

The other group of perspectives is exemplified by the ideas of Clarke (1973b), namely that the operation of a conceptual model should be regarded as a stochastic process. Due to model structure inadequacies and data errors the true parameters of a model can be merely estimated and this parameter uncertainty must be defined via the stochastic structure of the model residuals. In other words, the objective function should be of a type that integrates the information in the statistical properties of model residuals to ensure appropriate minimization of uncertainty in model parameters and to make possible confidence statements about simulated streamflows. Although other workers are also making progress in this field, as shown above, Clarke has been developing his approach fairly consistently during the past ten years: Clarke (1973b); Douglas, Clarke and Newton (1976); O'Connell and Clarke (1981); Moore and Clarke (1981).

Perspectives on the general complexities of the calibration process, cited in subsection 5.2.2, and the possible solutions that are at hand vary from cautiously hopeful (Manley, 1978; Mein and Brown, 1978) to almost pessimistic (Moore and Clarke, 1981). There does seem to be consensus that the available measures by which the typical optimization problems of 5.2.2 can be redressed still do not guarantee convergence on the global optimum, so that the spectre of "false" optimum parameter sets or dubiously subjective parameter choices often cannot be escaped. A good example is the long and detailed searches for optimum parameters of the Boughton (1966) model conducted in three different instances by Johnston and Pilgrim (1976), Moore and Mein (1976), Mein and Brown (1978) and Pickup (1977) (in the case of Johnston and Pilgrim over two years of full-time work concentrated on one watershed). In none of these instances could the modellers claim to have found a truly optimum parameter set for the 13-parameter Boughton model, which is a typical example of the class of models under discussion. Indeed, the aforecited complexities are so fundamental that they have led a prominent hydrologist such as R.T. Clarke to remark that "difficulties of the kind encountered by Johnston and Pilgrim (1973) and Pickup (1977), ... appear to have led to a decreasing emphasis on the use of conceptual models where it is necessary to forecast future runoff in real time ..... instead, forecasters have turned to more empirical models in which there has been little or no attempt to use the principle of continuity that is embodied in all ESMA (explicit-soil-moisture-accounting) models" (Tucci and Clarke, 1980).

Undoubtedly much research on the difficulties of optimizing conceptual models by objective functions can still be expected. However, it may be that the root cause of these difficulties should be sought in the complexity of the rainfall-runoff models containing anything from 6 to 30 parameters to be optimized and not in the objective functions or the optimization methods - whether they be automatic or trial-and-error. Moore and Clarke (1981) deliver a powerful verdict on existing rainfall-runoff models saying that because of model complexity

"the objective function cannot in practice be written down explicitly; even if it could be written, it would contain points in the parameter space at which derivatives were undefined. The result is that the existence of multiple optima cannot be satisfactorily explored in a systematic manner, and we are forced to use relatively slow direct search methods for the calculation of optima instead of a method using gradients, such as Newton-Raphson with quadratic convergence. Because the objective function cannot be written down, the hydrologist must have blind faith in the computer that he is using and in the program that he has written; his attention is so much occupied by the problems of optimization that he rarely gets to a full study of the residuals given by the model, which will indicate how it is unsatisfactory. He can acquire no feel for the statistical properties of these residuals, and therefore he cannot use existing statistical methods for testing hypotheses about the model, for making confidence statements about estimated streamflows, for making use of prior information about parameters, and for using additional measurements recorded within the basin that he is modelling."

Against the background of this rather destructive criticism, Moore and Clarke propose a new conceptual rainfall-runoff modelling approach in which the traditional few moisture stores are replaced by a statistical population of stores, while

"bearing in mind that the aim should be the development of models that are parsimonious of parameters (so that rationalization becomes more straightforward), with objective functions that are differentiable everywhere in the parameter space (so that faster optimization procedures may be used) and such that the relation between streamflow, rainfall, and potential evaporation can be written down explicity (so that standard errors of estimated streamflows can be calculated easily)" (Moore and Clarke, 1981).

The first few preliminary tests of this modelling approach produced promising results, but a general purpose model along the aforesaid lines is still only a remote possibility.

5.2.5 Implications for the Ecca modelling studies

The group of models selected for application in the Ecca research catchments constitutes a fairly representative sample of the category of models affected by the formidable complexities of reliable parameter estimation. The implications for the Ecca study of the foregoing discussions are therefore that difficulties in defining unique parameters for each of the model/catchment combinations were to be expected from the outset and that the calibration procedure had to be designed to forestall the effects of these difficulties. A very important implication was the fact that a purely objective automatic optimization was not necessarily safer than a manual trial-and-error procedure and that rational manual intervention in the course of an automatic search was often essential to overcome complexities in the response surface geometry. Lastly, a calibration approach based on analysis of the stochastic nature of model residuals could not be employed in the Ecca study, as it would have been excessively costly in terms of man-hours and computer time owing to the complex computational and stringent mathematical demands involved; in addition, by treating the operation of the model as a deterministic process, results from such a study could be expected to be much more accessible to the engineering fraternity.

5.3 SELECTION OF AN OPTIMIZATION ALGORITHM

Among the optimization algorithms that have been tested for catchment modelling purposes (discussed in the previous section), the direct search methods of Rosenbrock (1960) and Nelder and Mead (1965) (simplex method) and the steepest descent method known as the Davidon method (Fletcher and Powell, 1963) feature prominently. In general, it seems as if the former two algorithms may be better than the Davidon method (Ibbitt and O'Donnell, 1971b; Wood, 1975; Pickup, 1977) but that there is little to choose between the Rosenbrock and Nelder/Mead algorithms (Pickup, 1977; Manley, 1978). Computer programs of all three algorithms are available in various published sources, eg. Rosenbrock in Kuester and Mize (1973) and Douglas (1974), and the other two in Himmelblau (1972).

5.3.1 The Rosenbrock optimization algorithm

On the strength of its reported robustness, the Rosenbrock algorithm was selected as the automatic optimization technique that would be employed in the Ecca modelling studies. For this purpose a modified version of the optimizer computer program developed by Ibbitt (Ibbitt and O'Donnell, 1971b) was obtained and tested. A printout of this program is included in Appendix B. The Rosenbrock algorithm is well suited to the catchment model problem, since the particular class of problems for which the method was developed is one in which, firstly, the parameters are restricted by physical considerations and must fall within specific limits. Secondly, the objective function dependent on those parameters is such that partial derivatives of the objective function with respect to the various parameters cannot be stated analytically in usable forms (Dawdy and O'Donnell, 1965).

The Rosenbrock algorithm uses a so-called rotating coordinate search procedure, consisting of search cycles or orthogonalizations. The technique is illustrated for the 2-parameter case for three orthogonalizations in Fig. 5.2. In the first cycle it changes one parameter at a time until the line-optimum for that parameter is found. Each line-search is conducted in a series of steps, parallel to one of the coordinate axes. A step of arbitrary length, e, is attempted first. This is treated as successful if the resulting new value of the objective function presents an improvement of, or is equal to, the previous value. If a success, the step is allowed, and e is multiplied by $\alpha > 1$; if a failure, the step is not allowed and e is multiplied by $-\beta$, in which $0 < \beta < 1$. A new attempt is then made. These attempts are terminated as soon as at least one successful attempt, followed by one failed attempt, has been achieved in each parameter line-search. After the first cycle, however, changes are no longer made separately in each of the parameter directions; instead, orthogonal linear combinations of the parameters are changed. From its experience in the first cycle, the program defines the best direction of search as a line joining the starting point to the point reached at the end of the cycle. It uses this direction as the first axis of search in the second cycle, subsequent axes being defined

orthogonally to this. At the end of each orthogonalization, this re-orientation of axes is made, so that the search is always made in the most likely direction (see Fig. 5.2).

5.3.2 Testing the Rosenbrock algorithm

Before any serious modelling studies were undertaken with its aid, some tentative testing of the Rosenbrock algorithm was done to gain familiarity with its behaviour and also to probe the nature of any convergence difficulties that may arise. For this purpose the daily-input conceptual rainfall-runoff model developed by Pitman (1976) was used. This model, called PITD, is described in Chapter 4. In addition, it was decided to use the full five years of data available for Ecca catchment A at the time (1976-1980) as the test data set. It was deemed important that the tests should be done on typical data used in the project and that a model of at least moderate complexity be used to gauge the power of the optimization technique fully, to probe for typical response surface complexities and to assess optimal cumputer run-time requirements in terms of adequate convergence. The objective functions, which were arbitrarily selected, were of a least squares nature, viz. functions of the coefficients of efficiency calculated on monthly flow values, MCE, and daily flow values, DCE -these are defined in Appendix A along with other objective functions and goodness-of-fit criteria used in this study. The objective functions were used in the form $(1\text{-MCE})^{0,5}$ and $(1\text{-DCE})^{0,5}$; subtraction from one allows minimization towards zero while the square root increases the sensitivity of the function to very small changes in MCE or DCE.

Model PITD was roughly calibrated by manual trial-and-error procedure at the start of the tests to establish a reference set of parameters, whereafter 56 individual searches were executed with the optimizer. The following phenomena were explored: sensitivity of individual parameters, response surface geometry for pairs of parameters, interdependence among parameters, occurrence of local optima, influence on the search of sequence of parameter changes relative to each other, influence on the search of different search starting points (initial parameter sets) on the response surface the

effect of constraining certain parameter values during the search, typical convergence time requirements for different-sized parameter perturbations around the reference parameter set, the potential benefit or otherwise of manual intervention during the search, and the advantage or otherwise of minimizing combined objective functions instead of single objective functions.

Figs. 5.3 and 5.4 illustrate some of the typical results for the three most sensitive parameters of PITD, (optimizing on monthly streamflows): the soil moisture store capacity ST, the nominal maximum infiltration rate ZMAXN, and the nominal minimum infiltration rate ZMINN. Fig. 5.3 shows that the optimizer could converge on the optimum in three out of four cases, starting from very distant points on the response surface, in a fraction of the preset maximum number of onthogonalizations. It is interesting to note that if the search happened to enter the broad, flat valley surrounding the optimum at one of the valley ends progress towards the optimum was much slower than when the search entered the valley diagonally, where the gradient was steeper. The horizontal nature of the valley implies no interdependence between ST and ZMAXN, but the flatness of the valley spells trouble for a search containing more than two parameters. Fig. 5.4 illustrates severe interdependence of parameters ZMINN and ZMAXN and a response surface with a narrow but flat valley. As with the previous surface, the optimizer converges rapidly across the contours but progress is laborious from the flat end of the valley.

Fig. 5.5 depicts the response surfaces of the above two pairs of parameters in the case where the search is conducted according to both the daily and the monthly fits, using the coefficients of efficiency, DCE and MCE, in a combined objective function. This combination was devised when it became clear that optimization in terms of DCE alone often did not converge on a parameter set that could restrict errors in MAR and monthly standard deviation (SD) to reasonable levels. Comparison with Figs. 5.3 and 5.4 reveals fairly similar response surface geometry. As can be expected from the flatness of the valleys, the optimizer often had difficulty converging lengthwise down the valley. The response surfaces produced by another combined objective function are shown in Fig. 5.6. In this equation the

$(1\text{-DCE})^{0,5}$ value is "penalised" or weighted by a function of the percentage difference between the MAR and SD and some acceptable percentage error limit in each case. Error limits of $\pm 5\%$ for MAR and $\pm 10\%$ for SD are shown in Fig. 5.6. If the MAR and SD errors are inside the preset limits, the weights revert to zero. It is clear that this function creates steep gradients on the response surface; but, more importantly, once the MAR and SD errors are within the specified limits, the search remains trapped inside a narrow valley commensurate with those limits. This valley, which also contains the optimum, is much narrower than the equivalent surface feature in the case of optimization against $(1\text{-DCE})^{0,5}$ unweighted. Convergence is also faster with the weighted objective function shown than in the unweighted case.

Apart from the results shown in the aforesaid diagrams, other important findings common to the model/objective function combinations used, were as follows. The volume parameters of the model (see Chapter 4) were much more sensitive, i.e. caused much bigger objective function value changes, proportionately speaking, than the delay and routing parameters; small amounts of interdependence existed between certain parameters, but of a lower order compared with the ZMINN/ZMAXN interdependence shown; local optima were absent in all the instances where pairs of parameters were investigated together, except for a trivial case shown in Fig. 5.6 (though they may exist for parameter combinations larger than pairs); some evidence of plateaus (parameter-indifference zones) were found in the regions of high volume parameter value combinations; the sequence in which parameters were changed made little difference to the ultimate outcome of the search, though certain sequences always seemed to produce a faster convergence (i.e. ZMAXN before ZMINN); optimization of more than five parameters simultaneously produced some "wandering" by the less sensitive parameters; different starting points have a crucial outcome on the success of the search (see Fig. 5.4); constraining parameter values to a reach inside which the optimum was suspected to lie accelerated the search noticeably (but how to know beforehand in a new situation?); in most searches where the optimum was found, it was in less than 15 orthogonalizations (see Fig. 5.3) which is equivalent to between 150 and 250 iterations (depending on the number of parameters optimized);

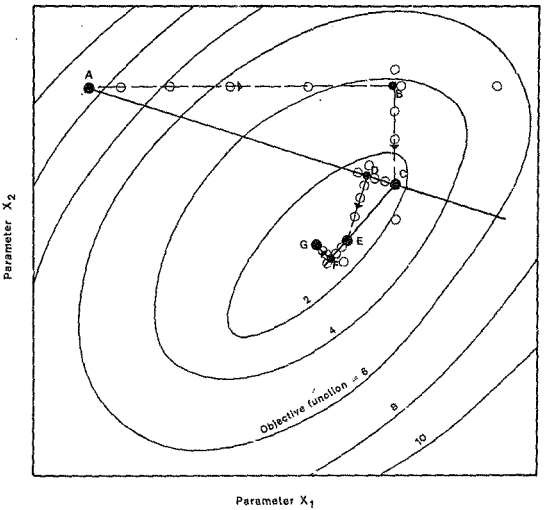


Figure 5.2 Typical search pattern according to the Rosenbrock algorithm

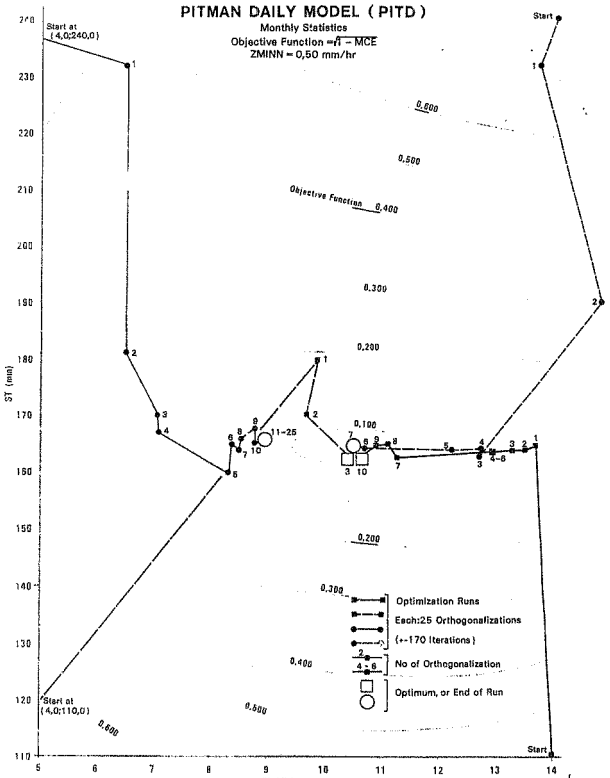


Figure 5.3 Four different optimization searches : model PITD

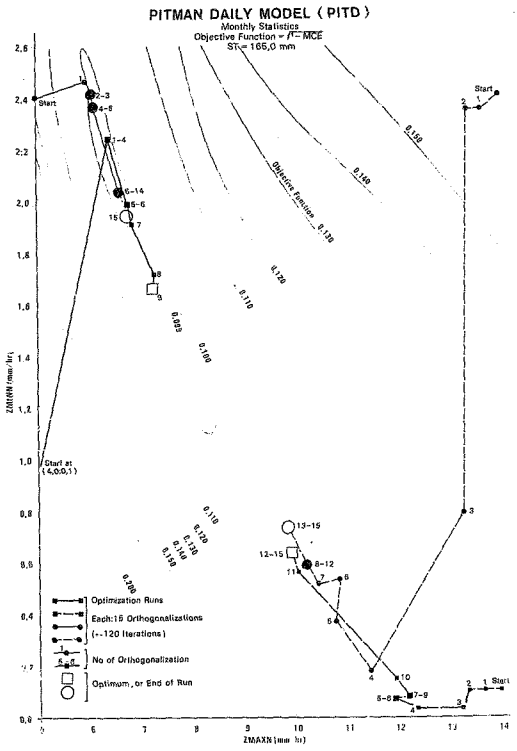
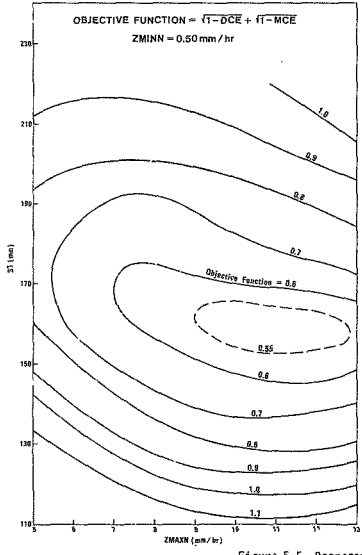


Figure 5.4 Four different optimization searches : model PITD



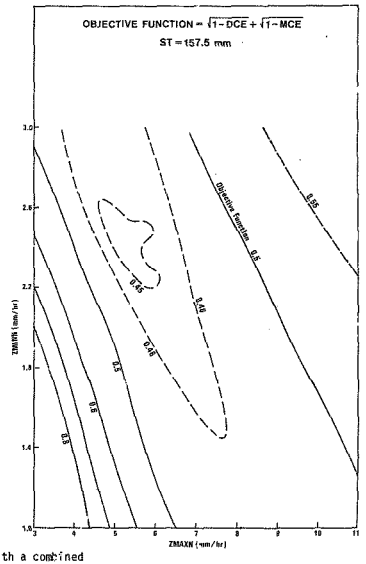
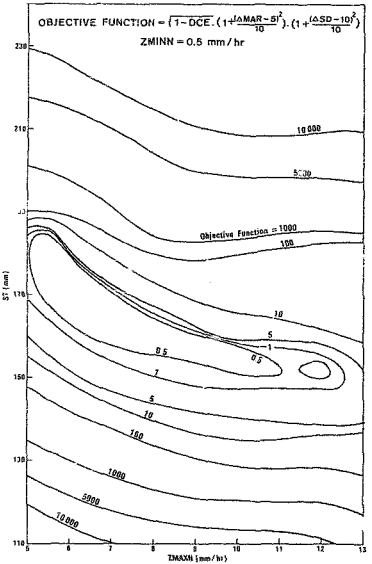


Figure 5.5 Response surfaces with a combined objective function : model PITD



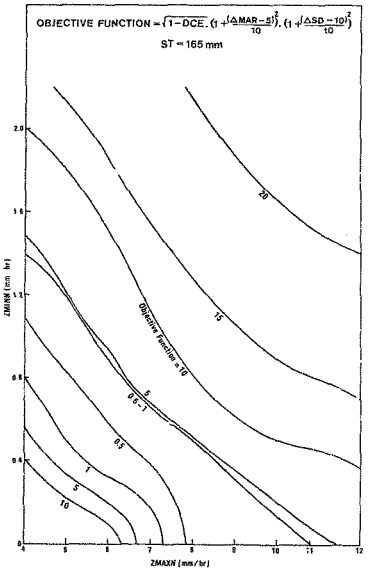


Figure 5.6 Response surfaces with a weighted objective function : model PITD

manual intervention during the search proved to be highly beneficial in cases where progress in the search slowed down a ter just a few orthogonalizations: by manually adjusting two or three of the sensitive parameters by about 5% of their current value and continuing the optimization, the search path can perhaps be nudged over the edge of a plateau or out of a flat valley up its side-slopes from where the direction of the optimum is easier to find.

These tests indicated that the Rosenbrock algorithm would be a viable and often powerful calibration aid in the Ecca modelling studies as long as sight is not lost of the typical complexities associated with automatic search techniques. At this point a word of caution may be necessary: the reader should not be misled by the relative simplicity of the response surface, shown in Fig. 3.3 to 3.6 for a 2-parameter space. For example, a 3-parameter "valley", though hard to visualize, could be very difficult for an optimizer to traverse. After selection of and familiarisation with the Rosenbrock algorithm, selection of a robust objective function to use in the algorithm was necessary.

5.4 SELECTION OF OBJECTIVE FUNCTIONS

5.4.1 Procedure of selection

Since appraisal of models used in the Ecca study was to take place on the basis of the goodness-of-fit both of monthly and of daily flows, objective functions for both had to be selected from the many reported in the literature. It was decided to base this selection on the objective function/Rosenbrock optimizer combination that managed to produce the best overall fit on five years (1976-1980) of Ecca catchment A streamflow, employing model PITD, Pitman's (1976) daily-input model. This overall fit would be measured by a range of goodness-of-fit criteria The steps leading to objective function selection can be summarized as follows:

Step 1: Select two groups of objective functions suitable for the monthly and daily cases, respectively. These are defined and discussed in the next subsection.

Step 2: Select those parameters of the model that are clearly more sensitive than the rest, based on the optimizer tests reported earlier. For the monthly case ST, ZMAXN, ZMINN (all defined earlier) and DIV, a parameter that divides excess soil moisture between groundwater storage and quickflow, were chosen. For the daily case parameters, ST, ZMAXN, ZMINN and TL, the channel routing parameter were the most sensitive.

Step 3: Perturb each of the eight parameters by an arbitrary amount larger than 30% away from the manually derived values mentioned earlier. This forms the initial parameter set at the start of each optimization.

Step 4: Using the starting parameter sets, optimize the model with each selected objective function for a preset maximum of 25 orthogonalizations in each case.

Step 5: Devise a meaningful set of performance or goodness-of-fit criteria to measure various aspects of the correspondence of simulated and observed flows. (Most of the objective functions are of course goodness-of-fit criteria in their own right).

Step 6: Run the model (without optimizer) with each "optimal" parameter set determined in step 4 and determine the overall goodness of-fit by means of the set of criteria assembled as step 5.

Step 7: Rank the performance of each objective function for each goodness-of-fit criterion and determine the best performance by summing the rankings.

5.4.2 Description of objective functions

The mathematical definition of all functions mentioned can be found in Appendix A.

(a) The monthly case

(i) Sum of squared residuals (SSRES): a dimensional measure of one-to-one fit and the most common version of equation 5.1 with w_j=1, m=1 and k=2.

(ii) Sum of squared residuals (logarithms) (SSRESL): a measure of one-to-one fit biased towards low flows.

(iii) Coefficient of efficiency (MCE): a dimensionless measure of one-to-one fit sensitive to systematic error and first proposed by Nash and Sutcliffe (1970); here it is used in a slightly modified form though, namely the form suggested by Garrick, Cunnane and Nash (1978) where the model residuals are based on individual calendar month means instead of the overall monthly mean flow to allow for any seasonal effect; to allow minimization towards zero and to make the search more sensitive to small changes in objective function value, the term $(1-MCE)^{0,5}$ was used in this study.

(iv) Relative sum of absolute errors (RAE): a dimensionless measure of one-to-one fit used in the WMO (1975) international conceptual model intercomparison as a goodness-of-fit criterion.

(v) Maximum equivalent constant error (MECE): a dimensionless measure of one-to-one fit used in the WMO (1975) model intercomparison as a so-called coefficient of variation of residuals; here it is used in modified form suggested by Weeks and Hebbert (1980) where the overall fit is expressed as an equivalent constant error in each value; it is a trivial matter to show that MECE, the traditional "standard error of estimate" and the "coefficient of variation of residuals" are all based on $(SSRES)^{0,5}$ and that all three produce identical response surfaces.

(vi) Residual mass curve coefficient (RMCC): a dimensionless measure of systematic error in the simulated time series; first proposed by Aitken (1973); accually measures the one-to-one fit of the cumulative observed and simulated residual time series; to allow minimization towards zero the function was used in the form (1-RMCC) in this study.

(vii) Coefficient of persistence (CP): a dimensional measure of

systematic error (persistence in residual errors); first proposed by Wallis and Todini (1975) and used in the WMO (1975) project; accentuates the continuous runs of differences between observed and simulated time series, i.e. the areas between the curves that are being fitted.

(viii) Relative mean persistence (RMP): a dimensionless measure of systematic error (persistence in residual errors); developed by the author and represents an improvement on the CP (see (vi) above, and also section 5.7) which was found to be inconsistent during early tests on Ecca data.

(ix) Proportional error of estimate (PEE): a dimensionless measure of one-to-one fit with each residual weighted by the inverse of the observed flow ($w_j = (1/QOBS_j)^2$ in equation 5.1) thereby giving weight to equal proportional errors (instead of the equal weight to equal absolute errors by a sum of squares function); it was used by Manley (1978) to bias the fit in favour of medium to low flows.

(x) Sum of squared ratios of simulated to observed flows (SSRAT): a dimensionless measure of the one-to-one fit that is reasonably unaffected by the order of magnitude of the flows - suggested by Pitman (pers. comm., 1981).

(xi) Sum of squared ratios of logarithms of simulated to logarithms of observed flows (SSRATL): a dimensionless measure of one-to-one fit that is unaffected by the order of magnitude of the flows likely to favour medium to low flows.

(xii) Combined MCE and RMCC (COM1): a dimensionless measure of the combined one-to-one fit of both the observed and simulated flow series and the observed and simulated cumulative residual time series - an attempt to control systematic error while improving one-to-one fit; to allow minimization towards zero COM1 was used in the form (1-MCE) + (1-RMCC).

(b) The daily case

(i) Coefficient of efficiency (DCE): a dimensionless measure of one-to-one fit used in the form $(1\text{-DCE})^{0,5}$ (see (a) above).

(ii) Relative sum of absolute errors (RAE): a dimensionless measure of one-to-one fit (see (a) above).

(iii) Maximum equivalent constant error (MECE): a dimensionless measure of one-to-one fit (see (a) above).

(iv) Sum of squared residuals of logarithms (SSRESL): a dimensional measure of one-to-one fit, biased towards low to medium flows.

(v) Proportional error of estimate (PEE): a dimensionless measure of one-to-one fit, biased towards low to medium flows (see (a) above).

(vi) Sum of mean ratio and standard deviation of ratios (SMRAT): a dimensionless measure of one-to-one fit based on the mean and the standard deviation of the ratios formed by each simulated value divided by the equivalent observed value, thereby preventing a bias in fit in favour of high flows - first suggested by Cundy and Brooks (1981).

(vii) Coefficient of efficiency of flow duration curves (CEFDC): a measure of the model's ability to reproduce the frequency distribution of daily flows, regardless of the one-to-one fit of individual flow values - used in the form $(1\text{-CEFDC})^{0,5}$.

(viii) Combined DCE and RMCC (monthly flows) (COM2): a combined measure of the frequency distribution of daily one-to-one fit and monthly systematic error - used in the form (1-DCE) + (1-RMCC).

(ix) Combined CEFDC and MCE (COM3): a combined measure of the frequency distribution of daily flows and the monthly one-to-one fit - used in the form (1-CEFDC) + (1-MCE)

(x) Combined DCE and MCE (COM4): a combined measure of the one-to-one fit of both daily flows and monthly flows - used in the form

(1-DCE) + (1-MCE).

(xi) Weighted DCE (WDCE): a measure of one-to-one fit that brings the error in MAR and in monthly standard deviation into play during optimization (Manley, 1978); in this study a maximum acceptable error in MAR of $\pm$5% and in standard deviation of $\pm$10% was adopted, because if these error limits are set wider the constraint has little benefit and if set narrower then too many trials that improve the unweighted objective function are rejected because of contravention of the limits, thus slowing the optimization procedure -in this study the weighting was applied to the (1-DCE) form of the function.

5.4.3 Description of goodness-of-fit criteria

The ability of each objective function to lead the optimization search to an optimal parameter set was assessed by the following goodness-of-fit criteria (many of the objective functions previously described double up as goodness-of-fit criteria). The criteria were selected to focus on a variety of flow record characteristics that are of typical interest to engineering hydrology.

(a) Monthly case

(i) Percentage error in the MAR (ΔMAR)

(ii) Percentage error in the monthly variance (ΔVAR)

(iii) Coefficient of efficiency (MCE) - the Garrick, Cunnane and Nash (1978) version

(iv) Maximum equivalent constant error (MECE)

(v) Residual mass curve coefficient (RMCC)

(vi) Coefficient of persistence (CP)

(vii) Relative mean persistence (RMP).

(viii) Percentage error in the range of the residual mass curve (ΔR_s): a typical measure relating to storage requirements for long-term flow regulation (Aitken, 1973).

(ix) Percentage error in the index of seasonal variability (ΔI_s): a typical measure relating to storage requirements for seasonal flow regulation (Hydrological Research Unit, 1981-1982).

(b) Daily case

The goodness-of-fit criteria for the daily case are divided into four categories: the fit of the monthly values, the overall fit of daily values, the fit of the maximum daily flow per month (annual peaks are meaningless on 5 years of data), and the fit of low flows.

Overall monthly fit

(i) to (vii) Identical to the monthly goodness-of-fit criteria (i) to (iii), (v) and (vi), (viii) and (ix) above (the need for the RMP was not appreciated at the time of these model runs).

(ix) Percentage error in the average deficient flow period (ΔADFP): a low flow index based on continuous periods of monthly totals less than the mean monthly flow.

(x) Percentage error in the maximum deficient flow period (ΔMDFP): a low flow index equal to the maximum continuous period of flow less than the monthly mean.

Overall daily fit

(xi) Percentage error in the daily variance (ΔVAR).

(xii) Coefficient of efficiency (DCE) - the Garrick, Cunnane and Nash version (1978).

(xiii) Coefficient of efficiency of logarithms of daily flows (DCEL).

(xiv) Coefficient of efficiency of daily flow duration curves (CEFDC).

(xv) Relative sum of absolute errors (RAE).

Peak daily flow/month for months with peaks > mean daily flows:

(xvi) Percentage error in mean peak daily flow/month (Δ MPF).

(xvii) Coefficient of efficiency (CE).

(xviii) Relative sum of absolute errors (RAE).

Low flow (all daily flows < mean daily flow):

(xix) Percentage error in mean of low flows (Δ MLF).

(xx) Coefficient of efficiency of low flows (CE).

(xxi) Relative sums of absolute errors (RAE).

After the foregoing goodness-of-fit criteria had been selected, statistical subroutines AFIT for monthly data and BFIT for daily data were developed to perform the actual calculations to evaluate the criteria, using model outputs of monthly and daily flows and inputs of the relevant observed time series. FORTRAN listings of the two subroutines appear in Appendix B.

5.4.4 Comparison of monthly objective functions

The optimal parameter sets defined by each of the 12 monthly objective functions after 25 orthogonalizations (±350 iterations)

are listed in Table 5.1 along with other relevant information. Notable from these results are the following points:

(a) The three functions of which the sum of squared residuals is a major component - SSRES, MCE and MECE - produced almost identical optima, which were not too different from the RAE and COM1 optima.

(b) The objective functions based on proportions, PEE, SSRAT and SSRATL, converged on highly different parameter sets relative to each other and also to the aforesaid group of five residual-based functions.

(c) Both in terms of the overall degree of minimization in objective function value (Final OF/Start OF") and the speed of convergence (column: "Convergence ortho's") PEE, SSRAT and SSRATL performed more poorly than SSRES, MCE and MECE.

(d) The functions based on minimization of systematic errors, [illegible] and RMP converged on widely divergent parameter sets.

(e) The two functions using log-transformed data - SSRESL and SSRATL - produced parameters very different from those of their counterparts that used untransformed data.

(f) The column "Final OF/Start OF" reveals a surprising range in the degree of minimization achieved by the 12 functions over the same number of orthogonalizations, i.e. from a 99,2% reduction in MECE to a 37,9% reduction in SSRATL; this may be indicative of the complexity of the response surface or merely of whether or not a fortuitous starting point on the surface was chosen.

(g) Reasonably small errors in both MAR and SD were achieved by many of the objective functions, but for a range of parameter sets.

The performances of the monthly objective functions are compared

in Table 5.2. Because their optimal parameters came out almost identical, the group SSRES, MCE and MECE was treated as a single objective function using the MCE parameters. The performances of the 12 objective functions were ranked in terms of the proximity of the goodness-of-fit criteria values to their individual optimum values. The rankings confirm the pattern of performance discernible in Table 5.1. The MCE function performed best (lowest total ranking) followed closely by COM1 and RAE. The poorest performances were by SSRAT, SSRESL, PEE and SSRATL, in that order.

The search problem used in the objective function comparison was not regarded as very difficult, as inspection of the starting values in Table 5.1 will reveal; but even so, objective functions based on proportional or log-transformed versions of the flow sequences failed to find acceptable near-optimal parameters. In recognition that the above results could be fortuitous, the whole exercise was repeated for a different set of starting values, representing a more difficult search. The derived optimal parameters of this search revealed a pattern almost identical to that of Table 5.1. Unfortunately, the parameter sets cannot be compared with those of Table 5.1, because a different 24-hour rainfall distribution function (see Chapter 4) was accidentally used. This error should not cause any increase or reduction of complexity of response surfaces associated with objective functions on a monthly basis and therefore the observed pattern is accepted as genuine. Calculation of goodness-of-fit criteria based on parameters derived in the second comparison was not attempted as it was felt that evidence was already strong enough to prove that the objective functions based on simple or squared sums of residuals were more robust than any others tested, given a model of medium complexity and the specific data set used. Specifically, the monthly coefficient of efficiency MCE was selected as a suitably robust objective function for use in the Ecca modelling study whenever optimization on a monthly basis was required.

5.4.5 Comparison of daily objective functions

The comparison of daily objective functions was also in two

Table 5.1

Comparison of optima derived by different objective functions : monthly flow series

Objective function (OF)	Parameter values*1				Final OF value	Final OF/ Start OF	Δ MAR (%)	Δ SD (%)	Convergence ortho's*2
	ST	ZMAXN	ZMINN	DIV					
SSRES ($10^6.m^6$)	163,3	5,0	0,9	0,8	139355	0,028	1,9	2,4	5
SSRESL	134,6	14,6	1,3	[illegible]	1982	0.109	7,4	23	24
MCE	163,8	5,0	0,9	0,7	0,073	0,167	1,8	2,2	6
RAE	161,6	5,3	0,8	0,8	0,122	0,338	2,2	2,2	10
MECE	163,8	5,0	0,9	0,7	0,138	0,008	1,8	2,2	8
RMCC	164,6	4,4	1,3	0,5	0,001	0,167	3,1	2,2	6
CP ($10^6.m^6$)	186,7	7,4	0,1	1,0	1,05	0,440	-5.6	-13	10
RMP	159,6	11,3	0,7	0,6	0,010	0,568	-8,9	5,0	4
PEE	131,9	14,9	1,4	0,4	2,725	0,309	4,9	25	16
SSRAT	87,5	6.4	0,3	0,9	15,83	0,593	86	66	25
SSRATL	153,6	3,0	1,0	0,5	858,1	0,621	35	20	25
COM1	164,0	4,6	1,1	0,7	0,006	0,021	0,8	2,2	14
Starting values	201,0	11,2	0,7	0,5	.	.	-34	-17	.

*1 All other parameters held constant at approximately optimal values.

*2 Number of orthogonalizations after which convergence slowed down significantly; a [illegible] of 25 orthogonalizations was used in all cases.

Table 5.2

Comparison of objective function performance : monthly flow series used

Criterion	SSRES MCE MECE	SSRESL	RAE	RMCC	CP	RMP	PEE	SSRAT	SSRATL	COM1
ΔMAR(%)	1,9	7,4	2,2	3,1	-5,6	-8,6	4,9	86	35	0,8
ΔVAR(%)	4,6	50,0	7,4	4,7	-13	10,3	57,0	179	28	4,7
MCE	0,994	0,899	0,994	0,994	0,929	0,980	0,874	0,169	0,920	0,994
MECE	0,005	0,023	0,006	0,005	0,025	0,012	0,025	0,065	0,020	0,005
RMCC	0,999	0,884	0,999	0,999	0,958	0,972	0,844	0,754	0,966	0,999
CP	0,91	1,18	0,44	1,20	1,05	1,18	1,02	1,25	1,33	0,99
RMP	0,003	0,021	0,003	0,004	0,013	0,009	0,021	0,042	0,019	0,004
ΔR_a(%)	-0,5	20,1	1,0	-1,0	-17,0	2,8	22,5	53,5	6,2	-0,6
ΔI_S(%)	-1,0	24,4	0,1	5,2	-15,4	18,6	23,7	-16,0	-22	2,4
				Ranking per goodness-of-fit criterion						
ΔMAR	2	7	3	4	6	8	5	10	9	1
ΔVAR	1	8	4	2	6	5	9	10	7	2
MCE	1	8	1	1	6	4	9	10	7	1
MECE	1	7	4	1	8	5	8	10	6	1
RMCC	1	8	1	1	7	5	8	10	6	1
CP	2	6	1	8	5	6	4	9	10	3
RMP	1	8	1	3	6	5	8	10	7	3
ΔR_a	1	8	3	3	7	5	9	10	6	1
ΔI_S	2	10	1	4	5	7	9	6	8	3
Total ranking	12	70	19	26	56	50	69	85	66	16

phases. In the first, all 11 selected daily objective functions were compared, while in the second phase only the five "best" performers from the first phase were compared. The first phase search was less difficult than the second phase, as the starting values in Table 5.3 illustrate. For daily optimizations the more sensitive TL (channel routing constant) replaced the less sensitive DIV. Table 5.3 also lists the optima derived by the objective functions in both phases. Tables 5.4(a) and (b) provide a comparison of performances of the objective functions during the first phase and Table 5.5 compares the second phase results. The following points about the first phase results can be noted.

(a) The objective functions based on simple or squared sums of residuals OCE, RAE, MECE, COM2, COM3, COM4 and WDCE converged on fairly similar parameter values.

(b) The average degree of minimization achieved by the various functions, as expressed in the proportion of the final value after 25 orthogonalizations to the starting value, is much smaller than in the monthly optimization case; partly due to the fact that the objective function is now based on a 30-fold larger number of values, thus providing more opportunity for different configurations of errors to produce the same result.

(c) The increasingly laborious nature of the search (implied under (b)) is also clear from the last column in Table 5.3 which shows that most functions needed many more orthogonalizations before the search slowed down significantly than in the monthly case.

(d) The low number of orthogonalizations required by CEFDC is a measure of the function's lack of sensitivity (perhaps a very flat response surface) rather than its power - attributed partly to the fact that it is based on only 44 points on a flow duration curve (distributed logarithmically).

(e) The performance of the functions OCE, MECE, RAE, PEE, COM4 and WDCE was overall notably better than any other, while SMRAT was notably poorer, overall.

(f) However, low flows were best simulated by parameters derived

by SMRAT and PEE, the two "proportional" functions.

(g) Peak flows were best simulated by parameters derived by the group of functions based on sums of simple or squared residuals.

(h) Functions WDCE and DCE were superior in the "all daily flows" category.

The second phase comparison was aimed at further exploration of the differences among the five best performers mentioned above. It was felt that the poor performers SMRAT, CEFDC, SSRESL AND COM3, did not need further testing, while the combined function COM4 was rejected on the grounds of uncertainty about the response surface of a combined objective function. The following observations are of interest:

(a) Final objective function values are higher than the first phase values in all cases except DCE AND PEE, implying that the first phase parameter sets derived by DCE and PEE were not optimal: this may mean that PEE's good performance in the first phase (2nd best) may have been coincidental.

(b) PEE converged on very different parameter values in the second search compared with the first, leading to the poorest overall performance in terms of goodness-of-fit values.

(c) DCE, RAE, MECE and WDCE converged on values fairly similar to those for the first phase, with RAE performing the best, followed closely by MCE in the overall rankings.

(d) PEE was again the best performer in terms of low flows, with DCE, RAE and MECE best in terms of peak flows.

On the grounds of the foregoing results it was decided that the daily coefficient of efficiency, DCE, would be a suitably robust

Table 5.3

Comparison of optima derived by different objective functions : daily flow series used

Objective function (OF)	Parameter values*1				Final OF value	Final OF/ Start OF	Δ MAR (%)	Δ SD (%)	Convergence ortho's*2
	ST	ZMAXN	ZMINN	TL					
					First phase				
DCE	165,5	5,6	0,7	0,9	0,300	0,584	1,7	1,3	15
RAE	162,2	5.7	0,9	0,7	0.334	0,672	1,0	3,5	15
MECE	165,2	5,4	0,8	0,9	0,999	0,582	0,2	1,5	21
SSRESL	118,8	4,3	2,2	3,5	10202	0,676	22	34	25
PEE	165,0	4,5	1,1	1,1	15,21	0,161	0,8	1,8	16
SMRAT	198.3	15,0	0,5	1,6	1,209	0,925	33	15	7
CEFDC	172,3	11,2	0,7	0.6	0,001	0,576	17	2.5	3
COM2	163,6	5,9	0,5	0.8	0,330	0,390	5,2	2,5	23
COM3	164,1	5,6	0,6	1,2	0,063	0,158	4,7	2,2	6
COM4	164,0	5.7	0,6	0,8	0,370	0,408	3,4	2,3	21
WDCE	166,3	6,0	0.6	0,8	0,304	0,592	1,2	0,7	23
Starting values	201,0	11,2	0,7	0,5	.	.	-34	-17	.
					Second phase				
DCE	165,6	6,0	0.5	0,8	0,091	0,113	4,9	1,1	18
RAE	165,5	6,3	0,4	0,7	0,382	0,208	3,8	1,2	20
MECE	166,8	6,0	0,4	0,8	1,014	0,337	5,3	0,4	20
PEE	195,3	10,9	0,8	1,4	0,861	0,029	31	14	16
WDCE	169,4	6,5	0,3	0,8	0,308	0,342	4,8	-1,4	17
Starting values	82,0	3,0	0,3	1,6	.	.	164	76	.

*1 All other parameters held constant at approximately optimal values.

*2 Number of orthogonalizations after which convergence slowed down significantly; a limit of 25 orthogonalizations was used in all cases.

Table 5.4(a)

Comparison of objective function performance : daily flow series used (first phase)

Criterion	DCE MECE	BAE	SSRESL	PEE	SMRAT	CEFDC	COM2	COM3	COM4	WDCE
					All monthly flows					
ΔMAR(%)	0,6	-0,5	22,8	-0,1	-32,8	-16,5	5,9	5,4	4,0	1,7
ΔVAR(%)	2,6	6,6	79,9	3,2	-28,1	-5,3	4,6	3,9	4,1	1,7
MCE	0,994	0,994	0,911	0,995	0,810	0,961	0,994	0,994	0,994	0,993
RMCC	0,999	0,999	0,844	0,999	0,945	0,989	0,999	0,999	0,999	0,999
CP	0,80	1,20	1,20	0,94	1,99	1,54	1,06	0,98	0,94	0,94
ΔR_8(%)	-1,5	0,7	31,4	-1,3	-24,3	-6,1	-0,5	-0,9	-0,7	-2,3
ΔI_5(%)	0,1	4,3	12,6	1,3	15,0	16,8	-5,0	-4,8	-3,0	-1,8
ΔADFP(%)	0,0	35,7	35,7	0,0	107	35,7	0,0	0,0	0,0	0,0
ΔMDFP(%)	4,2	62,5	62,5	4,2	75	62,5	4,2	4,2	4,2	4,2
					All daily flows					
ΔVAR(%)	-17,8	-14,4	-13,2	-19,2	-59,8	-42,4	-16,5	-25,8	-16,0	-11,7
DCE	0,904	0,900	0,582	0,894	0,572	0,772	0,903	0,879	0,904	0,907
DCEL	0,225	0,250	0,386	0,318	0,246	0,253	0,109	0,117	0,158	0,148
CEFDC	0,996	0,973	0,903	0,994	0,867	0,882	0,977	0,953	0,995	0,998
RAE	0,345	0,353	0,798	0,348	0,610	0,525	0,377	0,423	0,362	0,364
					Peak daily flow/month					
ΔM2F(%)	-15,4	-16,3	-43,3	-19,2	-61,7	-43,9	-12,3	-20,7	-12,8	-12,8
CE	0,921	0,935	0,732	0,900	0,599	0,814	0,924	0,878	0,926	0,948
RAE	0,229	0,216	0,447	0,241	0,618	0,441	0,236	0.301	0,232	0,210
					Low flows (< daily mean flow)					
ΔMLF(%)	-4,1	-17,2	-6,4	-18,9	-37,3	-36,7	30,4	40,1	16,1	30,9
CE	-2,45	-1,72	-0,85	-0,81	0,21	-0,27	-6,50	-4,53	-4,87	-4,90
RAE	0,983	0,967	0,987	0,824	0,713	0,861	1,27	1,23	1,16	1,19

Table 5.4(b)

Rankings of objective furction performance : daily flow series used (first phase)

Criterion	DCE MECE	RAE	SSRESL	PEE	SMRAT	CEFDC	COM2	COM3	COM4	WDCE
				All monthly flows						
ΔMAR	3	2	9	1	10	8	7	6	5	4
ΔVAR	2	8	10	3	9	7	6	4	5	1
MCE	2	2	9	1	10	8	2	2	2	7
RMCC	1	1	10	1	9	8	1	1	1	1
CP	1	7	7	2	10	9	6	5	2	2
ΔR_a	6	2	10	5	9	8	1	4	2	7
ΔI_S	1	5	8	2	9	10	7	6	4	3
ΔADFP	1	7	7	1	10	7	1	1	1	1
ΔMDFP	1	7	7	1	10	7	1	1	1	1
				All daily flows						
ΔVAR	6	3	2	7	10	9	5	8	4	1
DCE	2	5	9	6	10	8	4	7	2	1
DCEL	6	4	1	2	5	3	10	9	7	8
CEFDC	2	6	8	4	10	9	5	7	3	1
RAE	1	3	10	2	9	8	6	7	4	5
				Peak daily flow/month						
ΔMPF	4	5	8	6	10	9	1	7	2	2
CE	5	2	9	6	10	8	4	7	3	1
RAE	3	2	9	6	10	8	5	7	4	1
				Low flows (< daily mean flow)						
ΔMLF	1	4	2	5	9	8	6	10	3	7
CE	6	5	4	3	1	2	10	7	8	9
RAE	5	4	6	2	1	3	10	9	7	8
Total ranking	59	84	145	66	172		98	115	70	71

Table 5.5

Comparison and ranking of objective function performance : daily flow series used (second phase)

Criterion	Comparison					Ranking				
	DCE	RAE	MECE	PEE	WDCE	DCE	RAE	MECE	PEE	WDCE
					All monthly flows					
ΔMAR(%)	5,5	4,5	6,0	-30,5	5,7	2	1	4	5	3
ΔVAR(%)	2,5	2,6	0,9	-26,4	-2,6	2	3	1	5	3
MCE	0,993	0,993	0,992	0,849	0,989	1	1	3	5	4
RMCC	0,998	0,999	0,997	0,955	0,955	2	1	3	5	4
CP	0,95	0,84	0,94	1,98	0,92	4	1	3	5	2
ΔR_a(%)	-2,0	-1,9	-2,8	-22,2	-4,8	2	1	3	5	4
ΔI_s(%)	-5,6	-4,5	-7,3	15,5	-9,4	2	1	4	5	3
ΔADFP(%)	0,0	0,0	-21,5	35,7	-35,7	1	1	3	4	4
ΔMDFP(%)	4,2	4,2	-25,0	62,5	-33,3	1	1	3	5	4
					All daily flows					
ΔVAR(%)	-12,5	-10,9	-13,1	-54,4	-16,3	2	1	3	5	4
DCE	0,908	0,905	0,908	0,662	0,905	1	3	1	5	3
DCEL	0,084	0,076	0,048	0,292	-0,04	2	3	4	1	5
CEFDC	0,972	0,979	0,951	0,864	0,903	2	1	3	5	4
RAE	0,389	0,384	0,401	0,543	0,423	1	1	3	5	4
					Peak daily flow/month					
ΔMPF(%)	-10,8	-11,0	-10,2	-56,1	-12,5	2	3	1	5	4
CE	0,944	0,953	0,944	0,669	0,937	2	1	2	5	4
RAE	0,226	0,223	0,231	0,569	0,244	2	1	3	5	4
					Low flows (< daily mean flow)					
ΔMLF(%)	33,3	29,6	42,3	-44,7	70,3	2	1	3	4	5
CE	-7,2	-7,4	-8,5	0,39	-8,7	2	3	4	1	5
RAE	1,27	1,29	1,34	0,68	1,47	2	3	4	1	5
Total ranking						37	32	58	86	78

objective function to use in the Ecca modelling study whenever optimization on a daily basis was required. Because experimentation revealed that the DCE did not always ensure convergence in terms of acceptable MAR and SD errors, this decision was amended: viz. when the last-mentioned problems arose, the weighted coefficient of efficiency, WDCE, would be used to ensure parameter values that would restrict the MAR and SD errors while providing a reasonable one-to-one fit. Although WDCE was ranked only fourth in both searches, Tables 5.4(a) and 5.5 show that the actual differences in goodness-of-fit criteria values for DCE and WDCE are minimal.

5.5 ROBUSTNESS OF SELECTED OPTIMIZER/OBJECTIVE FUNCTION COMBINATION

A shortcoming of the optimizer/objective function tests described in 5.4 is that the true optimal parameter values were unknown and the comparisons had to be based on a group of goodness-of-fit criteria measuring the correspondence of observed flows and flows generated by the so-called optimal parameters. This section will obviate this shortcoming in that it comprises a description of a most stringent test of exactly how robust the selected combination of Rosenbrock optimizer/MCE-DCE-objective function is. The test consists of the following steps.

Step 1: Select a set of parameters for PITD, accept these as "true" and generate a monthly or daily flow sequence, using the same five years of Ecca rainfall and evaporation data as before.

Step 2: Using the generated flow series now as an "observed" series, optimize the model for the same four parameters as before, three times over, each time with a different configuration of initial values. Clearly, if sufficiently robust, the optimizing routine should converge on parameter values very close to if not identical with the "true" values.

Step 3: Again employing the generated flow series of step 1, as an "observed" series, optimize the model for seven parameters this time, comprising four volume control parameters and three delay and routing parameters. This optimization is done in two different ways: "staged" optimization in which the four volume parameters are

optimized separately from the three timing parameters in alternating searches; and "blunt" optimization where the seven parameters are optimized simultaneously. Again, a robust procedure should derive parameter values very close to the "true" values.

§ 5.1 The monthly case

Table 5.6 lists the outcome of the 4-parameter and 7-parameter searches described above, for the case of optimization on monthly values using the MCE objective function. The "observed" monthly flow sequence used in this case was generated by the optimal parameters derived by MCE in the monthly objective function intercomparison (Table 5.1). It is interesting to see that in the 4-parameter searches after 15 orthogonalizations (±210 iterations) the most sensitive parameters, ST, ZMAXN and ZMINN were close to their true values. The proximity of the final MCE value to its perfect fit-status, i.e. MCE=1,0, implies that progress in the convergence must have been exceedingly slow by this stage. Interdependence of ZMAXN and ZMINN (see Fig. 5.4) would also retard the search at this stage. On a monthly basis parameter TL is obviously too insensitive to be optimized efficiently.

The 7-parameter search was terminated after about 900 iterations in each case. It is clear from Table 5.6 that at this point the staged optimization had made notably superior progress in the important parameters, ZMAXN and ZMINN, and had achieved a higher MCE value. To assess the status of the blunt search at the termination point, this search was continued for a further 20 orthogonalizations (400 iterations), the outcome of which is also shown in Table 5.6. Suprisingly enough, much further improvement in a number of parameters was achieved without appreciable improvement in MCE value: notable is the fact that parameters ST, GL (groundwater recession constant) and FT (max. percolation rate to groundwater) had arrived at their true values.

The following conclusions are possible in the light of these results. With the selected optimization procedure, a monthly optimization restricted to four or fewer parameters has a good chance

of converging to the proximity of sound parameter values in the case of parameters that affect monthly flow totals meaningfully -within a modest number of iterations such as 50-60 iterations per parameter. Optimization in terms of larger numbers of parameters may require a staged approach where volume parameters are estimated independently of delay or routing parameters - especially if only a restricted number of iterations is possible. If optimization time is not a serious problem, it is likely that there will be little to choose between the staged and the blunt approaches.

5.5.2 The daily case

The outcomes of the 4-parameter and 7-parameter searches for the case of optimization on daily values using the DCE objective function are listed in Table 5.7. The "observed" daily flow series used was generated with the optimal parameters derived by DCE in the daily objective function intercomparison (Table 5.3). In the 4-parameter searches the optimization procedure proved extremely accurate after 15 orthogonalizations (±245 iterations) despite the known interdependence of ZMAXH and ZMINH. Estimates for ST and TL were near perfect.

The 7-parameter search was terminated after about 840 iterations in each case. The parameter values in Table 5.7 show that at this point the blunt search approach had progressed to a position very close to the true parameter set, while the staged optimization had been much less successful. It appears that interaction between the parameters ST and FT may have been compensating the effects on the DCE value of changes in each others values. Pitman (1973) recommends that FT be set close to zero when the model is used in semi-arid to arid catchments; the ST/FT interdependence should therefore not affect the Ecca study. An additional 20 orthogonalizations using the blunt approach progressed fractionally closer to a perfect fit in all parameter values.

The following conclusions are possible regarding optimization by the Rosenbrock/DCE procedure. An optimization in terms of four to

Table 5.6

Ability of selected optimizer/objective function combination to converge on true parameters : monthly flow series

Item	Parameters							Objective function value
	ST	ZMAXN	ZMINN	TL	GL	FT	DIV	(MCE)
True parameter values	163,8	5,0	0,89	0 5	1,5	0,001	0,71	
				4-Parameter search				
Test no.*1								
1:start	81,9	2,	0,45	0,25	1,5	0,001	0,71	-0,3197
1:final	164,4	4,33	1,17	0,07	.	.	.	0,9998
2:start	81,9	7,5	1,8	2,5	1,5	0,001	0,71	0,1597
2:final	163,5	4,28	1,15	1,32	.	.	.	0,9993
3:start	81,9	3,0	2,7	2,5	1,5	0,001	0,71	0,1468
3:final	163,7	4,19	1,18	1,84	.	.	.	0,9993
				7-Parameter search				
Starting values	81,9	2,5	0,45	0,25	0,5	0,25	0,35	-0,4876
Staged*2	166,2	4,64	0,98	2,22	1,68	0,053	0,24	0,9988
Blunt*2	165,8	7,07	0,09	1,56	0,61	0,016	0,83	0,9957
Blunt*3 (extra)	163,8	6,51	0,24	0,15	1,46	0,002	0,48	0,9981

*1 Each test : 15 orthogonalizations (±210 parameter iterations)

*2 State of convergence after approximately 900 parameter iterations in each case.

*3 State of convergence after an additional 400 iterations.

Table 5.7

Ability of selected optimizer/objective function combination to converge on true parameters : daily flow series

Item	Parameters							Objective function value (OCE)
	ST	ZMAXN	ZMINN	TL	GL	FT	DIV	
True parameter value	165,6	5,97	0,47	0,84	1,5	0,001	0,53	
	4-Parameter search							
Test no.*1								
1:start	81,9	2,5	0,25	0,25	1,5	0,001	0,53	-2,6042
1:final	165,9	6,22	0,30	0,84	.	.	.	0,9997
2:start	81,9	7,5	1,8	2,5	1,5	0,001	0,53	0,3210
2:final	165,2	5,88	0,51	0,84	.	.	.	0,9999
3:start	81,9	3,0	2,7	2,5	1,5	0,001	0,53	0,3623
3:final	165,1	5,55	0,69	0,85	.	.	.	0,9994
	7-Parameter search							
Starting values	81,9	2,5	0,3	0,42	0,75	0,25	0,25	-1,6965
Staged*2	187,8	5,66	0,39	0,81	0,43	0,417	0,30	0,9693
Blunt*2	165,8	6,01	0,42	0,83	1,37	0,063	0,52	0,9997
Blunt*3 (extra)	165,7	5,99	0,44	0,84	1,40	0,054	0,52	0,9998

*1 Each test : 15 orthogonalizations (±245 iterations)

*2 State of convergence after ±840 parameter iterations in each case

*3 State of convergence after an additional 388 iterations

seven parameters and based on daily flows has a very good chance of converging on sound parameter values if between 60 and 120 iterations per parameter can be allowed. If serious interdependence among volume parameters exists then a blunt optimization may be preferable to a staged approach.

5.6 SENSITIVITY OF PARAMETERS

Optimization procedures rely implicitly for their success upon the relative significance each model parameter plays in the performance of the whole model. This "relative significance" is what is meant by "sensitivity" of parameters. When Dawdy and O'Donnell (1965) introduced the use of optimization algorithms for model fitting, they also presented a simple method to examine the sensitivity of the model performance to any given parameter. This was done by first determining the optimum parameter set by minimization of an objective function and then computing increases in the objective function value for perturbations of 1%, 5% and 10% in each of the parameters about their optimum values.

Despite its attractiveness owing to its "common sense" nature, the Dawdy-O'Donnell sensitivity concept soon proved inadequate in terms of making statistically meaningful statements about the parameter sensitivity; only relative statements such as "X is more sensitive than Y" were possible. As Nash and Sutcliffe (1970) pointed out ".... if it is hoped eventually to use the model for basins without records by establishing relations between the model parameters and basin characteristics, it is essential to obtain some guide to the relative significance of model parts and the accuracy of parametric values. Methods of measuring significance and accuracy of determination must be found which are applicable to complex non-linear models". From this position various research strains developed aimed at establishing modelling approaches that would make statistical significance or analytically pure statements possible about model outputs, model state variables, model residuals and, relevant to this point, optimization-derived parameter values. In general there are the developments by R.T. Clarke discussed earlier in this chapter but,

regarding parameter sensitivity specifically, the following two themes developed: firstly, sensitivity analysis by analytical or statistical examination of the shape of the response surface in the region surrounding the optimum: Plinston (1971), Douglas (1974) and Mein and Brown (1978), and secondly, sensitivity analysis of the sampling variance of each model parameter: McCuen (1973), Douglas, Clarke and Newton (1976) and Machado and O'Donnell (1977).

In the Ecca modelling studies the less ambitious Dawdy-O'Donnell approach to sensitivity analysis is preferred for the following reason. The use of an optimizing routine with its concomitant restrictions on the number of parameters simultaneously optimized, requires identification of the most sensitive parameters of each model. For this purpose only relative measures of sensitivity would be sufficient. However, instead of relying on changes in a single objective function for information about parameter sensitivity as Dawdy and O'Donnell (1965) did, the approach by Pickup (1977) is preferred. Here, a number of characteristics of the generated flow sequence are simultaneously monitored [illegible] parameter values are being perturbed. In the case of each m[illegible] in the Ecca study, a sensitivity analysis was performed acc[illegible] to the following steps.

Step 1: Estimate the most likely set of parameters for the Ecca catchments; for this any source of a priori information may have to be used, including some rough manual trial-and-error "calibration".

Step 2: Using a subset of Ecca data that includes a variety of runoff events, i.e. the 1976-1978 record, generate a flow sequence by means of the estimated parameters.

Step 3: Regard the generated flow sequence as an "observed" sequence and run the model repeatedly with each parameter in turn changed by +10%, +50%, -10% and -50% while keeping all others constant at the original values, each time calculating a set of goodness-of-fit criteria (see section 5.4) based on the newly generated and the "observed" flow series.

Step 4: Rank the changes in each parameter for each goodness-of-

fit criterion and sum the rankings to identify the more sensitive parameters.

The advantage of the above step-wise procedure over the Dawdy-O'Donnell approach is that the sensitivity of the parameters is determined in terms of a range of desired flow characteristics (instead of just one), and against a background of error-free "data"; hopefully, this simple procedure makes an unbiased interpretation of parameter sensitivity possible.

For reasons of space economy not all the results of the sensitivity analysis will be reported here. Instead, three examples from three different models will be given to illustrate the procedure. The models in question are Pitman's daily model PITD, Pitman's monthly model PITM and the Stanford model FORD (descriptions in Chapter 4). Tables 5.8 and 5.9 show some results for models FORD and PITD respectively, while Fig. 5.7 depicts some results for model PITM. As can be seen from the rankings in the two tables, sensitivity tests based on any single criterion could be highly deceptive. In general terms, the technique illustrated provides the modeller with a wealth of information about the behaviour of the model apart from identifying relative sensitivity among parameters.

5.7 FOOTNOTE ON MEASUREMENT OF PERSISTENCE IN MODEL RESIDUAL ERRORS

Aitken (1973) brought to the field of rainfall-runoff modelling an awareness that measurement of the persistence in residual errors (also known as systematic errors) should be an essential component of assessing the goodness-of-fit of a calibrated model, especially if the model is to be used in water resources analysis and planning. Three useful measures of persistence were suggested by Aitken: firstly, a difference between the coefficient of efficiency and the coefficient of determination (correlation coefficient squared) indicates systematic error; secondly, a Chi-square test of the randomness (or lack thereof) of the number of positive and negative residual runs (also known as the "sign" test); thirdly, the residual mass curve coefficient (RMCC). Aitken (1973) accentuates the usefulness of the RMCC in that "it measures the relationship between the sequence of flows and not simply the relationship between individual flow events."

Table 5.8

Sensitivity test on Stanford Model (FORD) parameter change = +10%

Item	Parameters*1									
	EPXM	UZSN	LZSN	POWER	CB	CC	K3	K24L	IRC	KK24
True values	0,15	0,92	9,0	1,7	0,003	1,7	0,34	0,5	0,75	0,9
					All monthly flows					
ΔMAR(%)	-4,4	-27,4	-3,7	-7,8	-3,2	9,0	-4,9	-1,3	0,2	-3,8
ΔVAR(%)	-8,2	-55,1	-8,4	-18,3	-8,2	18,2	-9,6	-1,0	-10,3	-7,8
ΔI_5(%)	0,1	-3,8	-0,5	-1,0	-0,8	0,3	-0,2	0,5	1,4	-0,6
MCE	0,997	0,805	0,996	0,979	0,997	0,986	0,995	1,0	0,981	0,995
Ranking		1		2		3	5		4	
					All daily flows					
ΔVAR(%)	-10,4	-62,7	-11,3	-28,2	-13,5	10,7	-13,6	-0,6	-18,7	-4,4
DCE	0,996	0,799	0,995	0,954	0,992	0,990	0,992	1,0	0,973	0,999
CEFDC	0,998	0,968	0,998	0,995	0,998	0,994	0,997	0,998	0,974	0,992
Ranking		1		2		4	5		3	
					Daily peak flow/month					
ΔMPF(%)	-6,6	-40,4	-7,4	-21,6	-9,2	2,5	-8,7	-0,3	-10,9	-2,5
CE	0,992	0,631	0,988	0,886	0,979	0,996	0,991	1,0	0,981	1,0
Ranking		1		2		3	5		4	
					Daily low flows					
ΔMLF(%)	-7,4	-10,6	-3,7	5,5	-0,2	3,1	-6,2	-8,5	23,9	-26,3
CE	0,985	0,951	0,990	0,974	0,990	0,977	0,987	0,986	0,429	0,812
Ranking	5	3		4				5	1	2

Table 5.9

Sensitivity test on Pitman's daily model (PITD) : parameter change = +50%

Item	Parameters*1						
	POW	ST	ZMAXN	ZMINN	PI	GL	TL
True values	2,0	165,6	5,97	0,47	2,5	1,5	0,84
				All monthly flows			
ΔMAR(%)	-0,3	-26,6	-55,9	-26,1	-14,6	0,0	0,0
ΔVAR(%)	0	-56,1	-79,9	-30,0	-30,9	0,0	-1,3
ΔI_S(%)	0,3	-7,1	0,6	9,9	-1,7	0,0	-0,0
MCE	1,0	0,818	0,503	0,943	0,953	1,0	0,996
Ranking		2	1	3	4		
				All daily flows			
ΔVAR(%)	0	-54,9	-80,0	-28,5	-24,8	0,0	-23,2
DCE	1,0	0,882	0,679	0,968	0,980	1,0	0,952
CEFDC	1,0	0,981	0,745	0,887	0,979	1,0	0,943
Ranking		2	1	3			4
				Daily peak flow/month			
ΔMPF(%)	0	-27,1	-56,3	-23,7	-11,9	0,0	-11,2
CE	1,0	0,828	0,529	0,953	0,974	1,0	0,975
Ranking		2	1	3	4		
				Daily low flows			
ΔMLF(%)	-1,8	-8,3	-56,5	-60,8	-29,4	-1,0	91,9
CE	0,996	0,907	0,321	0,177	0,726	0,997	-4,67
Ranking			3	2	4		1

*1 Only selected parameters are included (descriptions in Chapter 4)

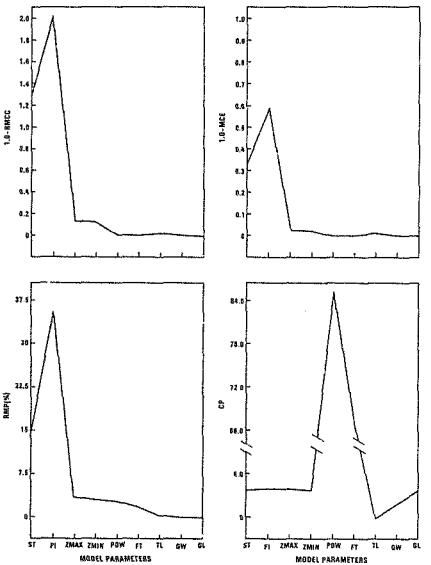


Figure 5.7 Results of parameter sensitivity test : model PITM

Wallis and Todini (1975) respond to Aitken's suggestions by showing several conditions under which the RMCC is incapable of detecting the correct degree of persistence in a time series. They recommend a "totally new approach to measuring persistence" by the statistic known as the coefficient of persistence (CP) in the WMO (1975) international model intercomparison. The CP accentuates the areas between the fitted and observed hydrographs. A further measure of persistence is suggested by Sorooshian and Dracup (1980) in the form of the Durban-Watson d-test, a statistical test sensitive to correlated residuals in time series analysis, i.e. to persistence in the residuals.

As can be seen in foregoing sections and will be seen later, most of the above measures of persistence were employed in the Ecca modelling study. However, it was often noticed that the coefficient of persistence was producing inconsistent results, when compared with the other measures. The following three examples will serve to illustrate this point. Firstly, in the parameter sensitivity study CP was identifying completely different parameters as highly sensitive in comparison with other goodness-of-fit criteria. Fig. 5.7 illustrates this point well for the case of model PITM. The diagrams represent changes in each criterion's value with a 50% change in each parameter's value while all other parameters are held constant.

Secondly, in the monthly objective function intercomparison, CP converged on a parameter set very different to that of RMCC, the other persistence measure, in both searches attempted. RMCC's parameters, however, compared favourably with those derived by MCE, the "best" objective function (see subsection 5.4.4).

Thirdly, in the investigation into optimal calibration period lengths for the fitting of monthly- and daily-input models described in Chapter 6, CP provided goodness-of-fit information contrary to that provided by RMCC or MCE. Fig. 5.8 illustrates this point clearly. The dots on the diagrams represent goodness-of-fit values for each of 50 verification runs by model PITM on 101 years of a synthetic flow

sequence after 10 calibrations on each of the five lengths of calibration period shown. The curves shown connect the average values for each calibration period. It is clear from Fig. 5.8 that whereas RMCC and MCE registered greatly improved goodness-of-fit with increased calibration sample size, CP showed an opposite pattern.

With programming errors eliminated, an analysis of the structure of the CP equation, as suggested by Wallis and Todini (1975), revealed a possible cause of the inconsistencies. The equation is as follows:

$$CP = \Sigma A_k^2 / SSRES \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

where A_k represents the area between the observed and simulated hydrographs for positive or negative run, k, and SSRES is the sum of squared residuals as defined before.

Wallis and Todini (1975) show tests of equation 5.3 on short "well-behaved" flow series only. However, if the following points are considered, it may be that weighting the persistence term ΣA_k^2 by a goodness-of-fit measure was a judgemental error on their part.

It is conceivable that CP may be used on two time series that are a very close fit, but with one consistently smaller than the other by a small amount. Under these conditions SSRES could be much smaller than ΣA_k^2, especially with long time series. This would lead to large values of CP, thereby providing false information about the goodness-of-fit or about the severity of the systematic error. Fig. 5.7 is an exact case in point: the 50% changes to the above two inactive parameters of PITM, POW and FT caused a minute but systematic shift of the generated flow away from the "observed" flows, leading to large CP values. Moreover, when CP is used as an objective function (subsection 5.4.4), the conflicting roles of ΣA_k^2 and SSRES could easily lead to CP changes that would deceive the optimizer about the progress of the search. Lastly, the fact that CP is not dimensionless may also restrict its value in intercomparison of models on different catchments.

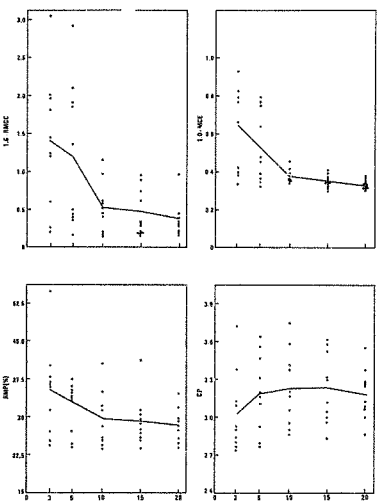


Figure 5.8 Effect of choice of calibration period on simulation

The term ΣA_k^2 is an obvious powerful indicator of persistence, but has the disadvantage of being dimensional. To utilize this term, but to avoid the pitfalls of equation 5.3, the author devised the concept of "relative mean persistence" (RMP) referred to in subsection 5.4.2:

$$RMP = (\Sigma A_k^2/N)^{0.5}/(\overline{QOBS})^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.4)$$

where A_k is as before,

N is the total number of negative or positive runs, and

$\overline{QOBS}$ is the mean observed flow.

The RMP is dimensionless, "standardized" by the squared mean flow, and usually lies in a convenient range of 0-1.0. Figs. 5.7 and 5.8 show that RMP provides information on goodness-of-fit that is in harmony with that provided by RMCC and MCE.

5.8 SUMMARY OF CALIBRATION PROCEDURE

In the modelling studies reported in the next few chapters, the following general calibration procedure was used. A priori estimates of all parameters of a specific model were made according to the best information possible. This sometimes included rough "calibration" by manual trial-and-error approach. By means of a flow sequence generated by the a priori parameters a sensitivity analysis by the procedures of section 5.6 was performed and the most sensitive parameters identified. This was followed by automatic optimization of the model based on the selected parameters and using the Rosenbrock algorithm combined with MCE for monthly flows, or DCE/WDCE for daily flows. Automatic optimization was by the "staged" approach in the case of hourly models and by the "blunt" approach in the case of daily and monthly models. For the studies of Chapter 7 invariably more than one configuration of starting values was used and manual intervention to redirect the automatic search was often attempted - usually with success. Calibration was sometimes concluded with minor manual adjustment of parameters. Decisions on final convergence were always taken on the basis of the DCE and/or MCE values, the percentage error in MAR and monthly SD and a visual comparison of observed and computed flow sequences.

CHAPTER 6

EFFECT OF CHOICE OF CALIBRATION PERIOD ON RELIABILITY OF MODEL CALIBRATION

6.1 INTRODUCTION

A primary uncertainty associated with the use of lumped-parameter conceptual rainfall-runoff models that was not explored in Chapter 5 is the effect of choice of calibration data sample on reliability of the model parameter estimates. It follows axiomatically that the shorter the period of observed data used for model calibration the less likely the calibration sample will contain a broad enough range of rainfall and runoff events to ensure activation of all flow paths in a model or to reveal particular model deficiencies - such as inability to model extreme events. Parameters obtained from such a sample are subject to uncertainty as to how they relate to "true" parameters for the catchment under consideration; in other words, short sample calibrations produce parameters of suspect reliability. There is a distinct danger that estimated parameters may be mere artifacts not only of an unreliable fitting procedure (see Chapter 5) but also of an unrepresentative calibration period.

In both applied and research situations the question has to be faced: how many years of calibration data does the chosen model require for the establishment of representative or at least stable parameter values? Phrased differently, how does the accuracy of model predictions improve if the calibration period is increased from N to M years, and is this improvement worth the extra effort involved in data collection and preparation, as well as extra computer charges? Often the modeller uses whatever length of concurrent hydrometeorological records are available, generally in a split-record approach: the model is calibrated on one part of the record and verified (tested) on an independent part of the record. The split-record procedure imparts increased intuitive confidence in the reliability of the model fitting than if all the records are used in the fitting process without verification; and if the verification succeeds the above questions are presumed to have been adequately answered. However, if

verification fails, in other words, if the error variance of the verification period is greatly in excess of the error variance of the fitting period (known as "model divergence" - Sorooshian and Dracup, 1980), the question again looms: is it the model that is inadequate or is it merely the calibration or the verification period that was unrepresentative (ignoring for a moment data errors)? Moreover, available records are in practice sometimes so short that there can be no question of split-record testing and the modeller has to face an unquantified risk that his parameter estimates are not reliable. This state of affairs is aptly described by O'Donnell and Canedo (1980): "Practising modellers have little quantitative guidance on how much reliability they can place on their modelling results. Much more attention has been given to the development of models for specific hydrological purposes, or to the improvement of parameter optimization techniques. The impression given is that a single split-record procedure giving satisfactory results is a sufficient, not merely a necessary, condition. If that hurdle is successfully cleared, it is implied that one can proceed to use a model with confidence; there is no mention of confidence limits" (my underlining).

The above issues reflect directly on the Ecca modelling studies reported in chapters preceding and following this one: on the one hand, intuition would lead to the expectation that because of their semi-arid nature, the Ecca catchments would require "fairly long" records for reliable calibration - at least, longer records than, say, catchments in temperate to humid areas. On the other hand, the whole data base for the Ecca comprises only six years (1976-1981) of concurrent rainfall, runoff and evaporation records. Many questions arise: How representative of the longterm flow regime is this data base? Is a split-record approach feasible with such short records? How much reliability should typically be placed on the estimated parameters in this study? Are model comparisons valid when based on such relatively short hydrometeorological records? Can parameter transfers reasonably be expected to yield meaningful results under these conditions?

With Ecca data used in various ways, an attempt is made in this chapter to throw some light on these questions, both for the general

case of streamflow generation in semi-arid catchments and for the Ecca modelling studies specifically. Firstly, Pitman's models PITM, PITD and PITH (see Chapters 3 and 4) are used to explore how serious the variations in parameter values are for "typical" models covering a range of complexities, when each model is calibrated for different calibration samples extracted from the full six years of Ecca records. This is followed by the main study comprising the calibration of models PITM and PITD (regarded as "typical" models) for each of 159 calibration samples of variable lengths, drawn from a synthetic 101-year streamflow series. The ability of each model to reproduce the original 101 years of streamflows for each of the calibrations was subsequently examined against a set of statistics of annual and daily and/or monthly flows. The variabilities of important model parameters for different calibration samples of the same length, as well as between lengths, were also investigated. The chapter is closed with some general conclusions and with a resumé of the implications for the Ecca modelling studies.

6.2 VARIATION IN PARAMETERS ESTIMATED FROM DIFFERENT ECCA RECORD PERIODS

The relationship between parameter stability (i.e. that different calibration periods produce near-identical parameter values) and differing degrees of model complexity does not seem to have been examined extensively in the literature. Therefore, apart from being an essential preliminary for meaningful model comparisons using Ecca data, such a study would have value in its own right.

It was decided to use the full six years of available data for Ecca catchment A as the population from which three individual calibration samples were extracted, covering the periods 1976-1980 (sample 1), 1976-1978 + 1981 (sample 2) and 1976-1978 (sample 3) respectively. These periods have the following special attributes: sample 1, containing as it does the very extreme events of 1979 and the severe drought of 1980 (see Chapter 2), as well as a range of other events, represents the "best" calibration period available if split-record testing is considered. Sample 2 excludes these two years and represents a broad range of small to medium runoff events. Sample

3 represents a typical "short-sample" situation. Further to allowing for the influence of model complexity, it was thought wise to allow for possible effects of objective function choice by basing the optimization of the daily and hourly models PITD and PITH on minimization of both DCE and MCE (see Chapter 5) in the case of each model. In total, therefore, 15 optimizations were executed, the results of which are listed in Table 6.1. Optimization was by the Rosenbrock algorithm (see Chapter 5) using the same set of starting parameter values in all runs with the same model, viz. parameter values determined by manual calibration earlier (see Chapter 7), and the same number of orthogonalizations in the case of each model.

Perusal of Table 6.1 reveals that parameter instability is present in the case of all three models but that the degree of variability in parameter values is different for each model. It must be conceded that some of the variability may be the result of an incomplete optimization search (due to response surface complexities) but, in the face of the regular pattern of the parameter value differences between calibration samples 1, 2 and 3, it is highly likely that imperfect calibration played a minor role. If this suggestion is accepted the following conclusions follow:

(a) Parameter instability is not so much dependent on calibration sample length as on whether or not the sample includes major runoff events: in the case of all three models and both objective functions only minor differences exist between optimal values for most primary (volume) parameters derived from sample 2 and 3, but either or both these parameter sets show notable differences with the values derived by sample 1 - the calibration period containing the extreme events of 1979.

(b) The more complex the model, the more relevant parameter instability seems to be: model PITH's "optimal" parameters seem much more variable than those of PITM, with PITD somewhere inbetween; this trend corresponds with similar findings by Pickup (1977), Mein and Brown (1978) and Moore and Clarke (1981), and can partially be explained in terms of the greater number of degrees of freedom in the

Table 6.1
Variation in parameter estimates for models PITM, PITD and PITH associated with different calibration periods.

Calibration sample no.*1	Parameter values								Objective function
				Model PITM					
	ST	ZMAX	ZMIN	GW	TL	GL			MCE
1	126,9	400	0,1	0,1	0,1	0,24			0,982
2	137,0	476	0,7	0,1	0,0	0,36			0,836
3	137,0	500	0,0	0,1	0,0	0,27			0,841
				Model PITD					
	ST	ZMAXN	ZMINN	DIV	TL	GL			DCE
1	167,7	5,2	0,81	0,3	0,9	1,8			0,909
2	117,9	8,5	0,60	0,2	1,5	2,1			0,788
3	118,9	5,7	1,28	0,2	1,5	2,2			0,793
	ST	ZMAXN	ZMINN	DIV	TL	GL			MCE
1	161,2	5,4	0,75	0,5	2,2	3,0			0,998
2	120,5	7,0	0,77	0,0	0,2	2,7			0,932
3	120,6	7,1	0,71	0,2	2,7	2,1			0,940
				Model PITH*2					
	ST	ZMAXN	ZMINN	SU	TL	GL	TLI	DIV	DCE
1	140,6	8,2	0,01	4,1	14	1,5	18	2,6	0,874
2	121,3	12,0	0,03	2,4	6,2	1,4	33	6,4	0,748
3	123,3	12,2	0,36	2,2	3,1	0,7	13	2,4	0,827
	ST	ZMAXN	ZMINN	SU	TL	GL	TLI	DIV	MCE
1	159,9	10,2	0,36	1,7	0,2	2,0	43	5,0	0,965
2	126,7	11,2	0,22	2,6	20	1,3	48	14	0,858
3	126,8	11,9	0,22	2,2	14	1,5	69	14	0,841

*1 1976-1980: sample 1
1976-1978 + 1981: sample 2
1976-1978: sample 3

*2 Pitman's original hourly model (Pitman and Hasson, 1979) more complex models.

(c) Parameter instability cannot be contained by using a "coarser" objective function, such as MCE instead of DCE: for both the daily and hourly models, more or less the same degree of parameter variability due to variation of calibration sample seems to exist in the case of both objective functions.

The tentative investigation described above shows clearly that the choice of a suitable calibration period for model testing and comparison from the available Ecca data set is not as straightforward as it may seem, and may have a crucial bearing on the performance of individual models. In addition, the results signal a need to quantify just how adequate the Ecca data set is in terms of the general calibration period length requirements that may exist for confident use of the type of model under investigation in a semi-arid environment. The rest of this chapter is devoted to such a general investigation of calibration reliability. The original idea for the study was gleaned from a paper by O'Donnell and Canedo (1980) on model reliability.

6.3 RELIABILITY OF CALIBRATION OF A MONTHLY AND A DAILY MODEL USING SEMI-ARID DATA

6.3.1 A synthetic semi-arid test data set

(a) Requirements of the data set

An investigation into the reliability of calibration of a rainfall-runoff model employed for water resources appraisal should focus on the calibrated model's ability to reproduce the characteristics of very long flow records, from which the calibration samples are drawn. To achieve this in the face of non-availability of such records in a semi-arid part of South Africa, it was decided to synthesize a long semi-arid flow "record" using a modified version of the Stanford Watershed Model, as set up and calibrated for the Ecca catchment A. (The calibration of the Stanford model is described in Chapter 7.) The calibrated Stanford model may be regarded - for the purposes of this study - as a "semi-arid catchment prototype".

The Stanford Watershed Model (here called FORD) was chosen for prototype flow sequence generation for the following reasons:

* It has achieved high credibility through many successful applications in many parts of the world.
* In the intercomparison with the three Pitman models described in Chapter 7 using seven years of data from the Ecca catchments, the Stanford model produced somewhat superior results and proved that it is competent to generate typical semi-arid flow sequences.
* It differs sufficiently from the models chosen for this study, PITM and PITD, as the simple comparison in Table 6.2 may help to illustrate, to ensure that the results of the study are not dictated by crucial similarities between the models.

(b) Development of the test data set

A fundamental requirement for the study was the establishment of a long observed daily rainfall record from which the long synthetic

6.3 RELIABILITY OF CALIBRATION OF A MONTHLY AND A DAILY MODEL USING SEMI-ARID DATA

6.3.1 A synthetic semi-arid test data set

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Table 6.2

Comparison of characteristics of models PITM, PITD and FORD

Model	No. of conceptual model storages	No. of parameters	Input/ output	Iteration interval	Execution time*1 seconds
PITM	2	12	1 month	0,25 month	7
PITD	3	13	1 day	1 hour (raindays)	41
				1 day (non-raindays)	
FORD	4	19	1 hour	0,25 hour	204

*1 CPU time on ICL 1904 computer for a 6-year calibration run

flow record could be generated. After consideration of a number of Eastern Cape rainfall station records held by the Weather Bureau in Pretoria, the choice fell on Alicedale, 35km from the Ecca area: Weather Bureau station no. 56/139. Apart from being geographically close to the Ecca River, this station revealed for an overlapping period of five years a monthly rainfall distribution similar to that of the Ecca catchment, mean annual precipitation and monthly standard deviation figures within 12 percent of those of the Ecca and a daily rainfall frequency curve almost identical above the 2mm total. The total Alicedale record of 102 years - 1880 to 1981 - was consequently regarded as suitably representative of the Eastern Cape semi-arid climate. Statistical tests (split-sample t-tests) could not detect any non-stationarity over the 102 years. The 40 months that had one or more missing daily values were "patched" by substitution from the Granamstown Weather Bureau record (station 57/048), after correction for mean and variance. The resulting record has a MAP of 411mm and a monthly standard deviation of 33mm.

As the Stanford model requires hourly rainfall input, a way had to be found to express the 102 years of daily totals as representative

24-hour distributions. This was done by selecting 80 one-day storm prototypes from the Ecca autographic data, 40 each for winter and summer. Each group of 40 storms was further divided into 5 categories of 8 storms each, based on magnitude. Table 6.3 provides information on the storms used for this purpose. As each daily rainfall was input to the model it was categorized according to season and magnitude, and was assigned a 24-hour distribution equivalent to one of the 8 Ecca distributions in that category, selected by a pseudo-random number between 1 and 8.

Daily A-pan evaporation values required by the Stanford model were chosen from the Ecca records as well. The complete set of daily values for 1978, being an "average" year, was chosen for this purpose, and re-used for each of the 102 years of flow generation. The only random variability between years allowed for in this case was that on all winter days with rainfall higher than 1mm the daily pan evaporation was set 1mm. This was done to prevent high 1978 winter Ecca daily evaporations from obscuring "simultaneous" modest winter daily rainfalls in any of the 102 years.

Finally, 101 years of hourly and daily flow totals were generated by the Stanford Model, calibrated for the Ecca catchment A as described in Chapter 7, with the aforementioned rainfall and evaporation records as inputs. Rainfall for the first year, 1880, was used as a "warm-up" year for the model. Monthly flow totals were summed from the generated daily values to provide a hypothetical but typical semi-arid monthly streamflow time series 101 years long. Equivalent monthly rainfall totals were then calculated from the 102 years of daily falls. Table 6.4 lists the synthetic monthly flows and comparison with the Ecca flow data reported in Chapter 2 reveals the typical semi-arid nature of the synthetic flow series. The statistical characteristics of this flow series are provided in Table 6.5, along with a comparison of observed Ecca statistics.

The foregoing technique for developing a hypothetical prototype catchment (with concomitant inputs and outputs) holds some notable advantages for specific investigations related to rainfall-runoff

Table 6.3

Ecca storms used for 24-hourly disaggregation of daily rainfalls (date and daily total in mm).

Summer (October to March)

Category 1 0-5mm		Category 2 5-10mm		Category 3 10-18mm		Category 4 18-27mm		Category 5 >27mm	
20/1/76	3,5	9/1/76	7,9	5/12/75	14,1	22/12/75	20,3	21/3/76	54,0
13/10/76	3,2	9/2/76	6,4	29/2/76	15,4	6/2/76	23,3	27/2/77	30,8
4/11/77	1,4	11/1/77	5,3	12/2/77	17,7	28/2/77	25,8	26/11/77	34,1
12/1/78	1,2	31/3/78	8,5	6/10/78	16,3	29/12/77	18,8	30/12/77	46,8
22/12/78	2,7	15/10/79	6,6	1/1/79	12,0	3/2/78	22,4	21/2/79	30,6
6/2/79	4,8	27/2/80	9,4	21/3/80	13,1	5/10/78	25,7	29/11/80	31,8
5/3/80	3,1	1/3/81	9,6	25/11/80	10,2	27/2/79	26,9	22/10/81	39,0
12/12/81	4,2	11/12/81	7,8	2/3/81	14,4	26/3/81	25,1	23/12/81	35,1

Winter (April to September)

Category 1 0-5mm		Category 2 5-10mm		Category 3 10-15mm		Category 4 15-27mm		Category 5 >27mm	
30/8/75	4,4	18/9/75	8,0	31/8/75	13,1	1/9/75	17,7	8/6/75	37,5
2/5/76	4,8	20/6/76	8,8	4/5/76	11,6	2/9/75	16,4	7/5/77	53,9
18/7/76	2,9	10/8/77	5,2	9/7/76	11,6	23/4/77	26,4	20/4/78	35,2
13/6/77	1,3	7/4/78	7,4	19/7/76	13,0	22/5/79	16,7	21/4/78	36,3
26/9/77	3,8	26/5/79	7,1	18/9/77	12,4	12/6/79	19,6	20/7/79	44,0
13/6/78	3,3	21/6/80	5,7	21/8/79	14,6	15/9/79	21,2	21/7/79	106,1
15/6/80	1,7	27/5/81	9,6	9/4/80	10,7	30/5/81	23,7	24/7/79	27,4
30/8/81	2,5	31/8/81	6,5	21/8/81	14,6	28/8/81	22,4	20/8/79	70,4

Table 6.4 Synthetic monthly flows generated for hypothetical semi-arid catchment
(see following pages)

Table 6.4 (Continued)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1881	0.0	0.0	9.4	5.7	6.8	10.9	122.8	27.7	7.4	0.4	0.0	0.0
1882	0.0	0.2	0.0	11.1	3.7	0.6	0.0	4.3	0.2	4.5	1.1	1.5
1883	0.8	0.0	2.0	0.7	4.3	4.4	0.0	6.2	0.0	0.0	0.0	0.0
1884	0.2	15.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.0
1885	0.0	0.0	1.8	1.7	76.1	1.4	0.0	0.0	3.7	1.0	0.0	0.0
1886	0.2	4.3	11.5	16.9	65.6	0.0	4155.5	9.0	0.2	91.6	3.8	38.3
1887	8.6	0.0	0.0	4.2	3.7	0.0	0.0	18.8	3.4	0.0	6.5	0.0
1888	0.0	0.0	18.3	13.7	152.1	1.1	0.0	0.5	31.3	0.6	0.0	0.0
1889	175.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	2.6
1890	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.6
1891	0.0	0.0	0.0	0.0	26.6	11.6	1.6	4.3	0.2	0.2	59.6	2.9
1892	0.0	0.0	0.0	23.4	10.2	2.4	0.0	0.0	552.8	18.0	0.0	0.0
1893	0.0	5.0	0.4	0.2	0.0	0.0	0.0	0.0	0.5	1.6	518.4	31.8
1894	8.0	0.2	13.4	5.6	4.6	0.0	0.0	0.0	0.0	0.7	2.9	0.0
1895	1.1	123.2	23.5	3.3	0.0	0.0	0.0	0.0	4.2	0.0	0.0	0.0
1896	0.0	0.0	0.0	0.0	0.0	1.3	0.4	0.0	0.0	2.1	204.2	5.8
1897	0.0	0.0	0.0	0.4	13.3	9.2	0.0	0.0	227.9	2.8	0.0	0.0
1898	7.1	1.1	0.0	0.8	0.4	0.0	0.0	0.0	0.0	14.3	0.0	0.0
1899	0.0	0.0	0.0	2.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.2
1900	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9
1901	0.2	0.0	0.2	0.0	0.0	5.6	0.0	0.0	14.6	6.9	6.1	0.0
1902	0.0	0.0	20.9	2.8	0.0	3.5	0.0	0.0	3.8	0.0	89.1	0.2
1903	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	9.5	0.0
1904	0.0	0.0	2.2	3.5	0.0	0.0	0.0	0.0	0.2	1.2	0.2	0.0
1905	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	223.5	1237.6	1.5	0.0
1906	0.0	0.6	2.4	7.3	3.8	2.1	1.1	0.3	2.1	1.7	27.0	170.2
1907	0.0	0.0	0.0	17.7	1.6	0.6	0.0	0.0	0.0	0.0	0.0	1.2
1908	0.0	0.0	0.0	12.9	0.0	4.0	0.0	0.0	0.9	4.3	4.2	0.2
1909	0.0	0.2	0.0	1.2	2.3	0.0	0.0	0.0	1.1	0.0	0.0	0.6
1910	105.4	825.1	16.7	0.3	3317.8	151.3	0.0	0.0	0.0	2.8	9.5	4.9
1911	7.9	0.0	0.8	3.6	3.9	4.9	1.4	0.0	0.2	6.6	1.6	0.0
1912	1.4	0.5	0.0	2.8	0.0	9.2	1.0	2.9	0.0	1.4	0.0	0.0
1913	0.2	10.4	4.7	4.5	0.0	0.0	0.0	0.8	11.4	10.1	0.0	0.0
1914	2.6	8.7	0.0	1.5	17.8	50.8	2.1	4.6	0.3	0.0	43.1	0.5
1915	0.0	0.0	0.0	1.2	0.6	0.0	5.8	0.0	0.0	0.0	0.0	0.3
1916	0.4	0.0	0.9	0.0	42.5	9.0	0.0	0.0	0.0	0.0	0.0	8.1
1917	0.0	0.0	0.7	1.6	0.0	3.2	1.7	6.2	3.5	0.2	3.0	2.8
1918	8.1	0.0	67.3	4.8	1.2	3.0	0.2	0.0	4.1	10.0	0.0	0.0
1919	0.0	3.9	0.6	0.0	1.2	0.0	0.0	0.0	0.0	0.6	0.2	0.0
1920	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	10.1
1921	0.0	0.4	1.4	11.7	0.0	0.0	0.0	0.0	0.0	0.0	61.0	2.1
1922	0.8	0.0	0.0	0.2	3.5	53.8	15.9	2.1	0.0	0.0	191.0	1.9
1923	0.2	0.0	0.0	0.0	0.0	0.0	9.7	0.0	0.0	0.4	0.0	0.0
1924	0.0	8.4	4.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5
1925	0.0	0.4	0.2	0.4	0.4	1.5	1.7	1.0	0.0	2.1	0.6	1.4
1926	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	5.9	5.3	6.4
1927	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.6	0.0	0.3	0.0	0.0
1928	0.0	0.0	0.2	0.4	0.0	0.0	0.0	0.0	10.7	8.3	0.0	0.0
1929	0.0	3.9	0.6	0.0	0.0	0.0	0.4	0.0	12.7	5.6	0.5	0.9
1930	1.7	15.5	1.3	0.8	0.0	1.2	0.0	0.6	0.0	16.5	0.0	0.0
1931	8.8	0.0	0.0	31.0	1.5	0.0	8.9	0.0	0.6	11.2	0.0	124.8
1932	13.8	0.0	0.0	0.0	0.0	0.0	2.9	0.0	22.1	4.7	0.8	0.0
1933	0.0	4.2	1.1	9.3	0.0	0.0	0.0	9.5	16.5	0.3	0.5	0.0
1934	2.3	1.4	28.9	0.0	0.0	0.0	6.3	1.2	0.0	69.1	0.4	0.0
1935	0.0	0.0	0.0	8.8	1480.3	32.3	0.0	10.7	19.9	0.0	10.4	0.4

Table 6.4 (Continued)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1936	0.0	0.5	12.1	1.6	2.6	0.0	1.9	0.0	0.0	5.7	18.6	0.0
1937	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	18.1
1938	5.8	53.2	15.4	11.7	0.0	0.0	0.0	0.0	0.0	1.3	30.9	0.2
1939	0.0	6.6	2.8	0.0	0.4	0.0	5.2	4.4	3.6	12.2	9.7	0.0
1940	0.0	0.0	133.9	14.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1941	0.0	3.2	0.0	14.1	0.0	0.0	0.0	0.0	0.0	104.9	266.2	1.8
1942	2.0	2.0	1.5	0.0	0.6	1.4	0.0	0.0	0.4	25.6	5.4	0.0
1943	6.2	0.0	1.3	0.0	0.0	55.2	5.6	1.4	0.0	0.0	10.9	3.8
1944	0.4	0.8	22.3	0.2	492	7.5	364.8	14.5	0.0	2.5	0.0	0.0
1945	0.0	5.6	0.0	0.6	2.0	1.1	0.0	0.0	0.0	0.9	0.0	0.0
1946	0.0	0.0	1.7	0.9	0.0	0.0	0.0	0.0	0.0	0.8	0.0	1.1
1947	0.0	0.0	0.2	0.0	0.0	0.0	1.2	0.0	0.2	4.3	1.9	0.0
1948	0.6	3.2	1.8	34.1	3.6	0.0	4.0	0.0	0.0	0.0	0.0	0.0
1949	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1950	0.0	0.0	0.2	0.0	0.8	0.0	0.0	0.0	0.0	32.5	7.3	1.0
1951	67.7	0.2	0.0	0.0	0.0	0.0	3.1	1.7	0.0	2463.9	0.0	0.0
1952	0.0	317.7	28.7	0.0	3.3	0.0	0.0	0.2	21.7	100.7	0.0	0.0
1953	0.0	2.8	0.0	0.0	0.0	0.0	0.0	46.0	151.9	4489.2	214.8	4.9
1954	0.0	0.0	3.9	3.3	3.8	0.4	1.3	0.9	1.6	0.4	1.5	0.0
1955	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	52.6
1956	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	69.4	9.8	3.8	4.5
1957	0.0	106.8	19.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1958	1.0	0.2	0.0	0.0	23.8	1.5	0.0	0.0	0.0	0.0	0.0	0.0
1959	7.5	0.0	1.1	2.8	4.4	0.0	37.1	5.5	2.2	0.0	0.0	0.0
1960	0.0	0.0	5.6	2.7	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1961	3.0	5.0	2.0	0.8	1.7	0.0	0.0	4.1	4.1	0.0	0.0	0.0
1962	0.0	0.2	10.9	2.2	1.8	0.0	0.0	0.0	0.0	0.3	9.1	0.0
1963	3.1	0.2	261.0	394.0	2.5	0.0	0.3	1.1	0.0	0.0	0.0	1.7
1964	0.0	79.0	0.0	0.0	0.0	21.5	0.6	5.0	10.8	0.0	10.7	0.4
1965	0.0	0.2	0.0	0.8	0.3	6.9	62.8	0.5	6.6	34.0	616.4	0.0
1966	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	5.2	0.0
1967	0.0	0.0	8.1	0.4	479.0	154.2	25.6	0.0	0.0	0.0	0.0	0.0
1968	0.0	0.0	0.0	3.8	0.0	91.0	1.5	0.0	2535.4	0.2	0.0	0.0
1969	0.0	0.0	21.8	3.2	0.0	3.5	0.4	0.4	0.0	0.0	0.0	0.0
1970	0.0	0.0	0.0	0.0	0.0	0.2	0.0	66.5	45.9	1.2	12.4	3143.0
1971	0.7	0.0	3.4	42.7	4.8	0.0	0.7	1035.4	21.1	0.0	0.0	0.8
1972	0.0	3.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0
1973	0.0	0.0	18.7	3.0	2.7	0.0	0.0	0.8	0.0	0.0	2.4	1.6
1974	7.0	17.8	259.7	6.1	90.5	0.0	1.4	751.9	243.4	0.0	0.0	0.0
1975	0.0	1.1	15.9	0.0	0.0	4.9	0.0	3.0	11.9	0.2	0.0	0.0
1976	0.0	2.4	136.1	11.8	2.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0
1977	0.2	5.8	19.0	2.7	47.4	0.0	0.0	0.2	0.0	0.0	2.9	17.5
1978	63.2	1.2	0.0	161.0	61.5	2.8	0.0	0.0	0.0	6.2	0.6	0.6
1979	0.2	2.8	16.4	0.0	0.4	1.5	3951.6	2775.6	196.1	2.6	0.0	0.0
1980	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	75.4
1981	0.6	0.0	54.9	18.4	2.0	4.3	0.0	1.2	4.0	18.8	3.4	6.2

Table 6.5

Statistics of 101-year synthetic flow series compared with 6-year Ecca observed flow record.

Statistic	Synthetic series	Ecca record	Dimensions
Mean annual precipitation	411	487	mm
(Range)	207-735	347-649	mm
Longterm runoff coefficient	1,87	4,59	%
Annual flow totals			
Mean annual runoff	562,5	1690,8	10^3m^3
(Range)	0-6447	30-8563	
Standard deviation	1266	3375	10^3m^3
Skewness coefficient	2,91	-	
Mean annual runoff (logarithms)	4,32	5,97	
Skewness coefficient (logarithms)	0,20	-	
Monthly flow totals			
Standard deviation	343,3	662,2	10^3m^3
Range of residual mass curve	14098	8027	10^3m^3
Index of seasonal variability	20,8	61,4	%
Maximum monthly total	4928	4417	10^3m^3
Mean deficient flow period	19	17	months
Maximum deficient flow period	78	28	months
Daily flow totals			
Standard deviation	0,53	0,66	m^3/s
Maximum daily peak flow	52,3	21,1	m^3/s
Second highest peak flow	37,8	12,5	m^3/s

modelling. Firstly, the synthetic streamflow sequence representing the output from the hypothetical catchment is free of the effects of landuse or upstream diversions. Secondly, the rainfall and potential evaporation inputs to a model that is being investigated with the aid of the synthetic flow-sequence are 100 percent accurate estimates of the hypothetical catchment inputs and conditions - a situation impossible to achieve in real catchments. Thirdly, as with rainfall, there are no measurement inaccuracies in the streamflow "record" - always a serious problem in practice. Fourthly, known non-stationarities, trends, gaps in both rainfall and flow records and other inaccuracies can be super-imposed on the inputs and outputs of the hypothetical catchment and their implications for rainfall-runoff modelling assessed.

6.3.2 Experimental procedure

(a) Model calibrations

Models PITM and PITD were selected for this study as exemplifying the type of model for which quantified guidance on parameter stability and optimal calibration period length is required, both for the general case of semi-arid catchment modelling and for the specific case of the Ecca modelling investigations. In the case of the monthly model, PITM, the study was based on calibration periods of 3, 6, 10, 15 and 20-year lengths, respectively, with 10 samples per calibration period. For a 101-year flow series, this meant the 3,6 and 10-year samples could be chosen to be independent, but that overlaps of 33% and 50% between successive calibration periods had to be accepted in the case of the 15 and 20-year samples respectively.

The investigation of parameter variability in the daily model was executed in two phases. In the first phase parameter estimates were based on reproduction of the monthly flow series; in the second phase the reproduction of the daily flow series dictated the parameter estimates. Optimizing a daily model such as PITD mainly on monthly flow reproduction as in the first phase enables comparison to be made of its reliability of calibration with that of a monthly model such as PITM. If data availability and computer run-time are not serious constraints, such a comparison may offer useful guidance on the preferability of either type of model in water resources apprais l

studies where the focus usually is on monthly flow series.

For the first phase, calibration period lengths of 3, 5, 7, 10, 15, 25, 33 and 50 years were chosen, while the second phase samples were 3, 5, 10 and 13 years in length. (Computer run-time limitations necessitated a smaller sample length in the fifth category of the second phase). Smaller increments between the five calibration categories were used in the case of PITD than for PITM because it was expected that PITD might very well turn out to have an optimal calibration length shorter than 10 years. Ten samples per calibration period were used in all cases except the 25, 33 and 50-year lengths; in these three cases only non-overlapping samples were used.

The semi-automatic calibration procedure set out at the end of Chapter 5 was pursued for the 50 and 109 individual calibrations of PITM and PITD respectively. For PITM the Rosenbrock algorithm was combined with objective function MCE and the calibration achieved by maximizing the one-to-one fit (MCE) of monthly "observed" and simulated values, while minimizing the errors in simulated MAR and monthly SD. Only the seven most sensitive parameters of the model were optimized, and in all cases the optimizer was set to allow a maximum of 300 parameter iterations. The most acceptable combination of one-to-one fit and minimal errors in MAR and monthly SD was always achieved before optimizer run termination. Table 6.6 depicts the optimum status of the three calibration criteria for each calibration. It can be seen that monthly SD often had to be "sacrificed" in exchange for more acceptable values in the other two criteria and sometimes reasonable one-to-one fits without systematic error were not possible at all, as some of small the coefficient of efficiency (MCE) values indicate. The consistent negative errors in SD are due to the fact that the model in most cases overpredicted baseflow.

For PITD the Rosenbrock algorithm was combined with objective function MCE in the first phase and with WDCE in the second phase. The unweighted function DCE was attempted in the second phase but converged on reasonable MAR and monthly SD errors in none of the 15 calibration runs tried, as Table 6.7 clearly illustrates. Only the six most sensitive parameters were optimized and in all cases the

optimizer was set to terminate the search after 250 parameter iterations. In the first phase convergence was decided not only in terms of maximum MCE value and minimum MAR and monthly SD error, but also in terms of the highest DCE value that corresponds with a good combination of the other three criteria. In this way, it was hoped, some allowance for reasonable daily fits could be made. In the second phase convergence was declared in the vicinity of the best WDCE value achieved, which automatically implied relatively low errors in MAR and monthly SD and a fairly high MCE; however, more than one search from different starting parameter sets were often required to ensure that convergence was not declared prematurely. Tables 6.8 and 6.9 depict the optimum status of the four calibration criteria for each calibration in the first and second phases respectively. As with PITM, the monthly SD often had to be sacrificed in exchange for more acceptable values in the other two criteria. More important, however, is the fact that high DCE values were only infrequently achieved; even in the second phase study where a weighted DCE was the objective function. This was mainly due to the fact that PITD consistently overpredicted daily baseflows, causing a systematic error which no amount of legitimate parameter "juggling" could amend. Possible reasons for the apparently poor daily fit achieved in this instance, are explored in section 6.6 where the overall results for model PITD are discussed.

(b) Model verification

Utilizing the parameter sets associated with each triplet of criteria in Table 6.6, the full 101 years of monthly streamflow totals were regenerated with model PITM, using the 102 years of monthly rainfalls, the 1978 monthly A pan totals for the Ecca and a warm-up year at the start. A similar procedure was followed with model PITD, employing the relevant daily input time series and outputting both daily and monthly flows. The equivalence of each of the 159 reconstructed flow series to the original synthetic flow series was measured by means of the array of fitting criteria and statistical tests contained in statistical subroutines AFIT (monthly) and BFIT

Table 6.6

Optimum values of fitting criteria for optimization runs, using calibration samples of varying length : model PITM

Calibration period in years		Calibration run number 1	2	3	4	5	6	7	8	9	10	Mean
3:	MCE	0,775	0,194	0,225	0,715	0,982	0,388	0,440	-0,19	0,120	0,876	0,453
	ΔMAR	0,7	-8,1	-6,1	12,1	7,4	0,5	-6,4	10,9	-8,5	4,7	0,7
	ΔSD	-13,2	-30,4	-28,1	-25,0	-0,7	-33,0	-16,7	-65,1	-39,5	-2,1	-25,4
6:	MCE	0,983	0,207	0,252	0,659	0,998	0,270	0,980	0,430	0,846	0,896	0,652
	ΔMAR	3,2	7,3	2,5	2,0	2,3	-0,3	11,8	7,8	5,9	1,0	4,4
	ΔSD	-2,5	-41,3	-26,3	-16,2	-0,2	-37,6	-4,2	-29,4	-10,4	-2,2	-17,0
10:	MCE	0,984	0,827	0,556	0,393	0,997	0,117	0,919	0,872	0,503	0,793	0,696
	ΔMAR	2,5	4,1	2,8	0,9	2,7	0,9	5,2	-6,8	5,9	-0,3	1,8
	ΔSD	-2,4	-8,4	-10,8	-35,7	-0,2	-56,3	2,5	-10,9	-71,9	-7,2	-15,1
15:	MCE	0,911	0,754	0,573	0,326	0,994	0,290	0,917	0,790	0,511	0,689	0,676
	ΔMAR	3,7	3,1	5,3	4,8	2,8	7,3	2,0	3,8	1,4	3,0	3,7
	ΔSD	-13,5	-12,1	-7,0	-32,3	0,0	-38,3	1,7	0,3	-27,9	-14,5	-14,5
20:	MCE	0,908	0,905	0,343	0,390	0,296	0,668	0,842	0,849	0,759	0,635	0,660
	ΔMAR	2,1	2,8	-0,7	2,6	3,0	-4,5	-1,8	0,8	0,1	0,8	0,3
	ΔSD	-13,6	-10,1	-31,9	-37,3	-40,1	-20,3	-4,4	-2,8	-17,3	-15,9	-19,4

Table 6.7

Optimum values of fitting criteria for optimization runs, using calibration samples of varying length and daily coef. of efficiency (DCE) as objective function : model PITD*1.

Calibration period in years	Calibration run number 1	2	3	4	5	Mean
5: DCE	0,98	0,94	0,77	0,87	0,59	0,83
MCE	0,78	0,75	0,52	0,78	0,80	0,73
ΔMAR	81	64	34	44	-9,2	42,8
ΔSD	4,8	9,7	-1,3	0,0	-3,1	-3,6
10: DCE	0,70	0,92	0,63	0,59	0,48	0,66
MCE	0,85	0,78	0,65	0,77	0,61	0,73
ΔMAR	30	40	60	-6,4	-23	20,1
ΔSD	-9,0	3,9	-23	-39	-37	-20,8
15: DCE	0,63	0,83	0,61	0,55	0,53	0,63
MCE	0,74	0,96	0,62	0,70	0,69	0,74
ΔMAR	47	-31	126	-21	-29	18,4
ΔSD	-9,4	-16	-9,5	-4,8	-37	-24,0

*1 Note that the large MAR and monthly SD errors associated with convergence by DCE in the optimization routine, caused this objective function to be abandoned in favour of WDCE (see Table 6.9).

Table 6.8

Optimum values of fitting criteria for optimization runs, using calibration samples of varying length : model PITD (monthly fit).

Calibration period in years		Calibration run number 1	2	3	4	5	6	7	8	9	10	Mean
3:	MCE	0,94	0,80	0,90	0,93	0,99	0,77	0,61	0,92	0,82	0,98	0,87
	DCE	-3,5	0,69	0,90	-1,0	0,19	0,76	0,64	0,87	0,58	0,47	0,06
	ΔMAR	1,3	-0,2	9,3	-9,6	-3,8	4,8	10	-7,5	4,4	9,7	1,84
	ΔSD	-3,9	-9,7	-0,8	-0,7	-5,1	-6,1	-13	0,6	-3,1	-8,5	-5,03
5:	MCE	0,79	0,98	0,99	0,91	0,99	0,55	0,99	0,90	0,90	0,95	0,90
	DCE	0,69	0,98	0,92	0,92	0,34	0,59	0,54	0,66	0,27	0,39	0,62
	ΔMAR	-0,5	-1,9	2,4	-3,8	-2,8	8,5	2,0	-1,5	3,1	3,6	1,16
	ΔSD	-19	-1,5	-1,0	-3,5	-3,0	-21	0,3	-10	-19	-12	-8,97
7:	MCE	0,97	0,93	0,97	0,80	0,99	0,99	0,99	0,98	0,99	0,77	0,94
	DCE	0,24	0,43	0,69	0,86	0,39	0,53	0,36	0,53	0,33	0,34	0,47
	ΔMAR	-3,5	-7,2	-7,4	8,0	2,7	3,4	-2,4	6,3	-2,0	7,0	0,49
	ΔSD	-16	-19	0,3	-15	2,6	-1,8	1,5	-0,8	-4,9	3,9	-0,49
10:	MCE	0,97	0,99	0,78	0,86	0,99	0,65	0,97	0,93	0,87	0,77	0,88
	DCE	0,25	0,82	0,59	0,91	0,39	0,18	0,31	0,24	0,27	0,22	0,42
	ΔMAR	-0,8	3,8	-3,5	3,6	2,2	4,3	-3,4	-5,4	7,8	6,1	1,47
	ΔSD	-16	-4	-33	-10	4,6	-31	-3,7	-8,7	-16	5,0	-11,3
15:	MCE	0,97	0,79	0,98	0,99	0,99	0,71	0,94	0,87	0,87	0,82	0,89
	DCE	0,26	0,38	0,82	0,83	0,35	0,45	0,25	0,31	0,27	0,37	0,43
	ΔMAR	4,1	0,1	-4,4	5,4	-2,7	7,5	-0,5	-1,9	8,9	6,7	2,32
	ΔSD	-10	-18	-9,8	-1,5	-8,5	-18	-2,2	-20	-17	-2,7	-10,7
25:	MCE	0,97	0,99	0,85	0,82							0,91
	DCE	0,27	0,73	0,26	0,39							0,41
	ΔMAR	3,6	-6,2	2,3	4,1							0,95
	ΔSD	-11	3,5	-18	-2,6							-7,0

Table 6.9

Optimum values of fitting criteria for optimization runs, using calibration samples of varying length : model PITD (daily fit).

Calibration period in years		Calibration run number 1	2	3	4	5	6	7	8	9	10	Mean
3:	DCE	0,57	0,41	0,74	0,16	0,46	0,57	0,25	0,82	0,51	0,50	0,50
	MCE	0,84	0,43	0,62	0,70	0,97	0,27	0,26	0,74	0,57	0,61	0,60
	ΔMAR	5,8	6,8	-0,9	9,4	5,1	1,0	14	-0,1	0,1	4,8	4,6
	ΔSD	-22	-6,2	-12	-28	-9,9	-21	-13	-26	-14	-8,2	-16,0
5:	DCE	0,65	0,65	0,74	0,79	0,40	0,31	0,81	0,70	0,58	0,50	0,61
	MCE	0,72	0,54	0,98	0,85	0,99	0,13	0,98	0,92	0,38	0,65	0,77
	ΔMAR	7,5	4,8	2,3	1,4	4,6	3,8	3,2	-4,9	-4,8	4,6	2,3
	ΔSD	-12	-45	-9,9	-17	-3,0	-28	-10	13	-7,4	-9,2	-12.9
7:	DCE	0,53	0,54	0,37	0,70	0,38	0,50	0,47	0,57	0,41	0,32	0,48
	MCE	0,99	0,71	0,88	0,76	0,99	0,97	0,98	0,97	0,61	0,57	0,84
	ΔMAR	2,7	5,2	8,5	-1,0	-2,3	3,6	-3,7	3,7	4,3	5,2	2,6
	ΔSD	-3,6	-31	-9,9	18	-2,7	-11	-9,4	-9,9	-11	-9,6	-11,6
10:	DCE	0,54	0,61	0,58	0,69	0,28	0,08	0,50	0,62	0,41	0,39	0,47
	MCE	0,99	0,72	0,96	0,69	0,86	0,86	0,94	0,97	0,76	0,57	0,83
	ΔMAR	-4,0	5,1	7,2	15	7,5	8,3	-4,9	5,0	3,8	3,1	4,6
	ΔSD	-9,7	-34	-12	-23	-33	-9,4	-6,3	-9,8	-9,4	-5,1	-15,2
13:	DCE	0,55	0,57	0,56	0,74	0,37	0,36	0,57	0 39	0,48	0,50	0,51
	MCE	0,98	0,67	0,95	0,97	0,98	0,74	0,96	0,84	0,70	0,71	0,85
	ΔMAR	-2,1	5,0	6,2	3,0	3,1	-1,2	3,9	3,0	1,5	5,6	2,8
	ΔSD	-9,2	-38	-13	-13	-10	-37	-6,4	-12	-29	-7,9	-17,5

(daily), included in Appendix B. The most informative results of these verification tests are discussed in the next sections.

6.4 RESULTS AND DISCUSSION : MONTHLY MODEL PITM

6.4.1 Parameter variability

Fig. 6.1 depicts the decrease, with increase in length of calibration period, in variability of the optimum values of two key parameters of semi-arid calibration. ST is the maximum capacity of the soil moisture store and ZMAX is the maximum catchment absorption rate. A third key parameter not shown, ZMIN, the minimum catchment absorption rate, shows a variability pattern similar to that of ZMAX. The other four parameters included in the optimization runs showed much less variability.

It may seem somewhat alarming that the variability in optimum parameter values does not decrease more rapidly with longer calibration periods. However, Table 6.10 provides evidence to suggest that the variability of the streamflow statistics, resulting mostly from the variability of the key parameters, converges much faster with increase in calibration sample length. This convergence is equally pronounced for certain monthly statistics and the one-to-one fit of monthly values. Further investigation showed that because of varying amounts of interdependence among ST, ZMAX and ZMIN alternative configurations of these three parameters can lead to equivalent streamflow statistics. Convergence of variability in these statistics is therefore possible with longer calibration periods while variability of the parameters themselves remains high. It is of course also possible that some of the apparent parameter variability is caused simply by imperfect model calibration.

It is likely that parameter interdependence makes complete parameter stability, i.e. parameter uniqueness, with long calibration periods, an unrealizable ideal. It may also be an unnecessary ideal in

cases where the model is being used only for streamflow time series extension (i.e. no undue significance attached to the physical meaning of parameters), as the rapid convergence of the statistics of reconstructed streamflows indicates. Furthermore, in a parameter transfer study on three monthly models which included Pitman's, Hughes (1982) shows that in practice one is well advised to calibrate monthly conceptual catchment models in a regional context, rather than against a single streamflow record. This should make coping with unavoidable parameter variability a lot easier.

A practical way to reduce the variability of interdependent parameters is to hold one or more of the affected parameters constant while determining optimum values for the remaining parameters (Chapter 5). Only at that point are the held parameters brought back into play. However, this technique brings a level of subjectivity into the optimization procedure which, although very useful in practice, was considered unacceptable in the present study. It was deemed important to keep the parameter search objective to avoid biasing the model performance in any way, either favourably or adversely.

6.4.2 Errors in streamflow statistics

Figs. 6.2(a), (b), (c) and 6.3(a) depict changes in errors of some important reconstructed streamflow statistics with increase in length of calibration period. Notable is the fact that for the three annual statistics in Fig. 6.2 there is little further convergence beyond 15 years and that for MAR and annual SD an arithmetic mean error close to zero is possible at any period longer than 10 years. The consistently positive error in annual C_s can be related to the overprediction of baseflows by the model, thus skewing the frequency distribution of annual flows excessively to the left.

Errors in the range (Aitken, 1973) of the residual mass curve (RMC) calculated from the monthly flow series is of importance if the model is to be used in storage-yield analyses, as range is indicative of the theoretical volume of storage required for complete regulation of flow. Fig. 6.3(a) shows consistent convergence in errors in the RMC range up to the 15-year calibration period, with a bias towards an overprediction of the range for the longer periods.

6.4.3 One-to-one fit

Two different criteria of one-to-one fit were employed. The coefficient of efficiency (MCE) measures the fit of monthly streamflows, whereas the RMC coefficient (RMCC) measures the one-to-one fit of the individual values in the residual mass curves. The RMCC is an important model test in the context of storage-yield analyses (Aitken, 1973). Figs. 6.3(b) and (c) illustrate the steady improvement in both RMCC and MCE achieved with increasing length of calibration period. Again, little improvement is obtained by calibration samples longer than 15 years.

It is worth noting in almost all cases the mean absolute errors in annual and monthly statistics may be reduced by 30 to 50 percent by merely increasing the calibration sample length from 6 to 10 years.

6.4.4 Frequency analysis of annual streamflows

It was found that the logarithms of the "observed" annual streamflows approximated the normal distribution. Consequently, frequency analyses of all 50 regenerated annual flow series were based on the log-normal distribution and plotted on suitable probability paper. Fig. 6.4 depicts the outcome of this undertaking for the 6-, 10-and 15-year cases. Fig. 6.5, based on plots such as in Fig. 6.4, may be more instructive on this point. The latter diagram shows the spread of the reconstructed return periods about the "observed" value for 10-and 100-year return periods. Again, convergence in the spread of estimates is very slow for calibration samples longer than 15 years.

6.4.5 Seasonal distribution of monthly streamflows

The use of a conceptual model in a catchment where streamflow is highly seasonal in character dictates that the model should be able to reproduce the longterm seasonal distribution of streamflow fairly

Table 6.10

Variability of key model parameters (expressed as coefficient of variation*1) and consequent variability of some annual generated streamflow statistics.

Calibration period	ST	ZMAX	ZMIN	Mean	MAX	SD	Cs	Mean
6 year	36.0	51.3	38.8	42.0	52.8	46.8	25.0	41.5
10 year	24.1	37.8	27.0	29.6	28.7	22.7	19.2	23.5
15 year	23.9	42.6	22.0	29.5	16.9	18.3	7.2	14.1

*1 Coefficient of variation = (standard deviation/mean) x 100 (%)

Table 6.10

Variability of key model parameters (expressed as coefficient of variation*1) and consequent variability of some annual generated streamflow statistics.

Calibration period	ST	ZMAX	ZMIN	Mean	MAR	SD	Cs	Mean
6 year	36.0	51.3	38.8	42.0	52.8	46.8	25.0	41.5
10 year	24.1	37.8	27.0	29.6	28.7	22.7	19.2	23.5
15 year	23.9	42.6	22.0	29.5	16.9	18.3	7.2	14.1

*1 Coefficient of variation = (standard deviation/mean) x 100 (%)

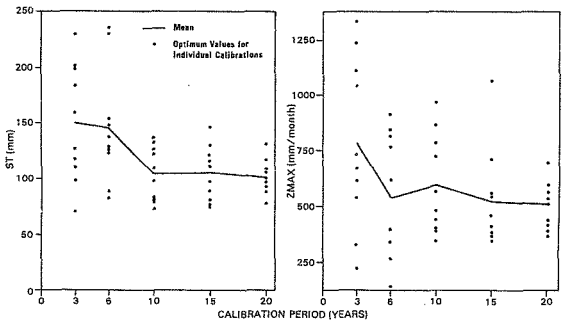


Figure 6.1 Variation in key model parameters : model PITM

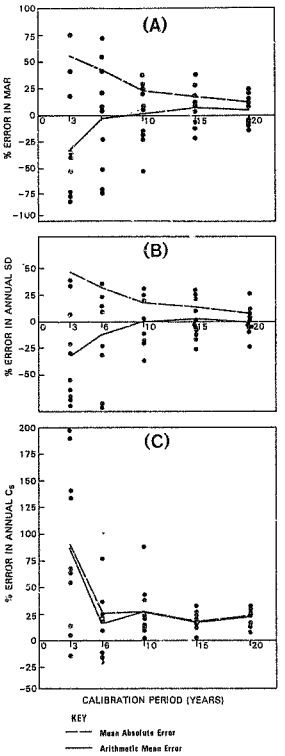


Figure 6.2 Effect of choice of calibration period on annual flows : model PITM

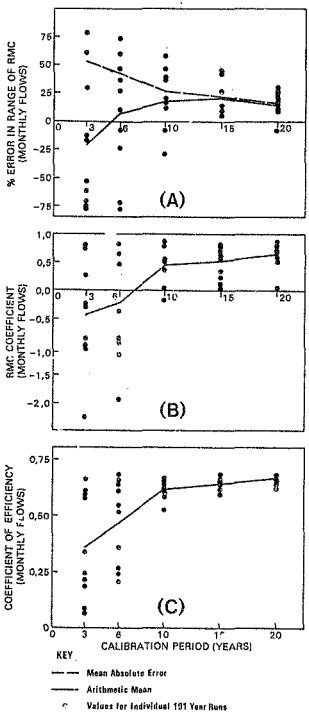


Figure 6.3 Effect of choice of calibration period on on goodness-of-fit : model PITM

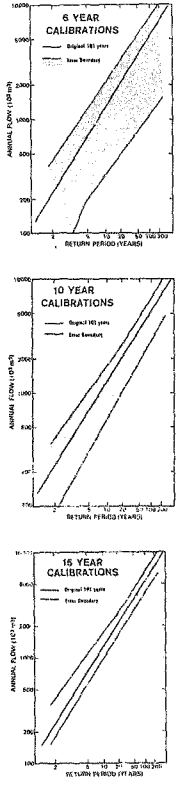
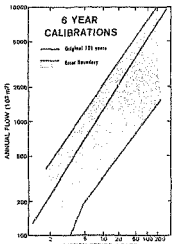
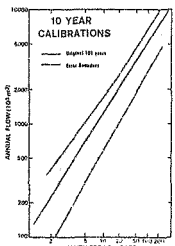


Figure 6.4 Frequency analysis of simulated annual flows : model PITM





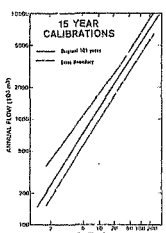


Figure 6.4 Frequency analysis of simulated annual flows : model PITM

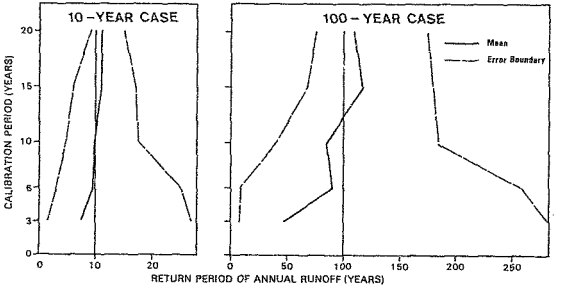


Figure 6.5 Variability of return periods of simulated annual flows : model PITM

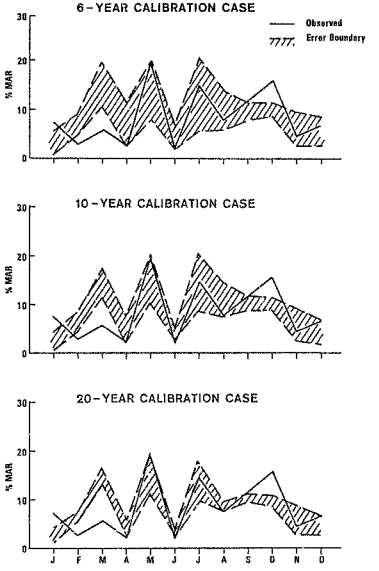


Figure 6.6 Seasonal distribution of simulated flows : model PITM

well. In the Eastern Cape, eg. the hypothetical catchment used in this study, the seasonality of streamflow is not well-defined because of the 65:35 division of rainfall between summer and winter, on the average. Nevertheless, it was thought worthwhile to investigate the improvements, if any, in prediction of the longterm monthly distribution of flow that can be associated with longer calibration periods. Fig. 6.6 illustrates that there is a consistent though diminishing improvement of the error boundaries of the predicted flow distributions with increases in calibration lengths. A safe conclusion would be that increases in calibration period up to at least 15 years would benefit predicted seasonal distributions most of the time.

6.4 RESULTS AND DISCUSSION : DAILY MODEL (PITD) CALIBRATED ON MONTHLY GOODNESS-OF-FIT (MCE) (first phase)

6.4.1 Parameter variability

The variability of the six optimized parameters due to different calibration periods is shown in Fig. 6.7, where each dot is associated with a specific calibration period. It is gratifying to see that two key parameters, ST and ZMAXN, converge strongly with longer calibration periods. Other parameters such as ZMINN and TL are probably too insensitive in terms of monthly flow totals to allow proper optimization by an automatic routine. On the whole, it is clear that longer calibration periods do not eradicate parameter variability completely. Table 6.11 lists the coefficients of variation of the key parameters against those of the annual streamflow statistics. In contrast with the case of PITM (Table 6.10) the parameter variability converges at about the same rate as the variability of the annual flow statistics. The variability of PITD values in Table 6.11 for the 15-year calibration period is lower, in general, than the variability of equivalent PITM values in Table 6.10. This may imply greater stability of key parameters in model PITD than in model PITM for longer calibration periods.

6.5.2 Errors in streamflow statistics and one-to-one fit

Errors in streamflow statistics and improvements in the one-to-one fit associated with increased calibration period lengths are plotted in Figs. 6.8 and 6.9 (note that the RMCC axis is demarcated by two different scales). There is a useful convergence both in errors and in fitting statistics from the 10 to the 15-year cases, but very little difference among the 5, 7 and 10-year cases. This may be a fortuitous result caused by combinations of parameter interdependence and imperfect calibration; however, taken at face value, this may imply that in situations where the user is "unhappy" with an existing calibration sample that is seven years or shorter in length, he could expect to effect meaningful improvement in model reliability only if he could more than double the calibration period. Fig. 6.10, depicting the reproduction of the seasonal distribution of flows, provides further evidence regarding this point.

Inspection of the results for the longer calibration samples in Figs. 6.8 and 6.9 leads to the conclusion that a calibration sample size of approximately 15 years represents a point of "diminishing returns" in terms of improvement in regenerated flow statistics and reduction of errors. The range of values for the non-overlapping samples of 25 years and 33 years is not much smaller than that for the overlapping 15-year samples. The two 50-year samples produced very similar results (and almost identical parameter sets).

A strong bias towards overprediction of annual statistics and the range of the residual mass curve is evident from the plots in Figs. 6.8 and 6.9. This may be related to sometimes excessive overprediction of baseflows by model PITD - a fact confirmed by visual inspection of the regenerated monthly flow series. Fig. 6.9 reveals that the mean coefficient of determination and the mean coefficient of efficiency converge with longer calibration periods; this implies a decreasing systematic error with larger calibration samples.

6.5.3 Comparison of models PITD and PITM

As stated in section 6.3 it may be useful to compare relative

Table 6.11

Variability of key model parameters (expressed as coefficients of variation in %) and consequent variability of some annual generated streamflow statistics : model PITD (first phase)

Calibration period	ST	ZMAXN	ZMINN	Mean	MAR	SD	C_s	Mean
3 ye.	51,3	36,2	[illegible],3	36,0	53,3	50,0	34,4	45,9
5 year	24,9	24,1	26,6	25,2	[illegible]	[illegible]	14,7	19,1
7 year	19,7	23,0	29,9	24,2	43,9	40,4	21,3	35,2
10 year	18,6	22,9	27,4	23,0	37,9	28,6	18,6	28,4
15 year	10,6	11,5	24,5	15,5	14,4	13,4	7,7	11,8

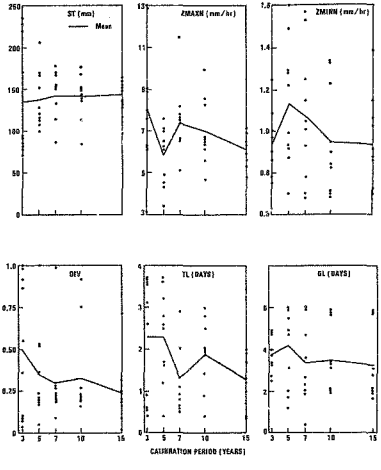


Figure 6.7 Variability of model parameters : model PITO (monthly calibration)

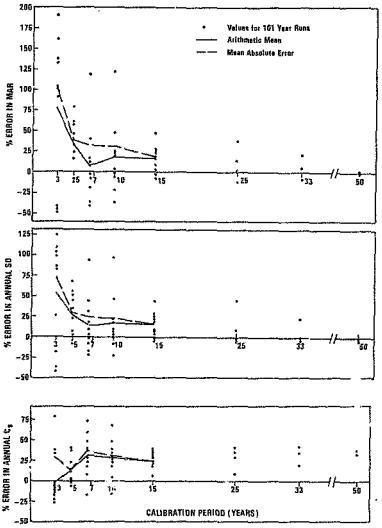


Figure 6.8 Effect of choice of calibration period on annual flows : model PITD

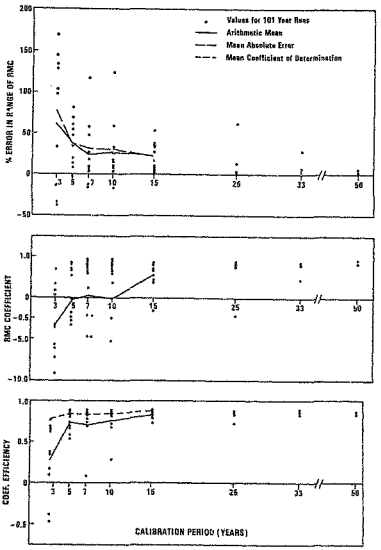


Figure 6.9 Effect of choice of calibration period on goodness-of-fit : model PITD

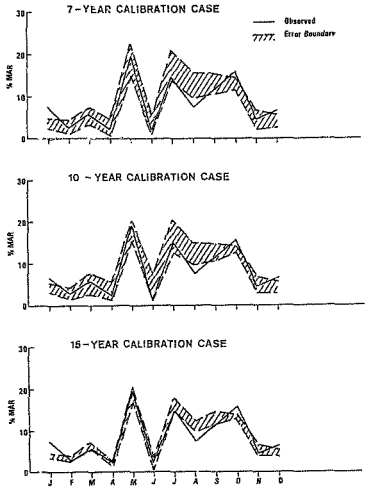


Figure 6.10 Seasonal distribution of monthly flows : model PITD

differences in calibration reliability between models PITD and PITM in terms of their potential as "tools" for water resources appraisal. The first notable point is that the expected difference in the optimum calibration length did not materialise. Both models seem to need a calibration period length of about 15 years for optimal reduction in regenerated flow series errors and errors in one-to-one fit. Secondly, comparison of coefficients of variation listed in Tables 6.10 and 6.11 discloses that at least for the three parameters most important for the use of each model in semi-arid catchments, model PITD seems more stable than PITM. Thirdly, PITD seems to be slightly superior to PITM in terms of reproduction of seasonal flow distribution and achieving one-to-one fits on monthly flows (this may, however, be partially the result of PITD having a structure that is marginally closer than PITM's structure to that of FORD, which generated the synthetic flow series). A fourth point, which is in favour of PITM, is that PITM showed much less bias than PITD in reproduction of annual streamflow statistics, resulting in lower mean errors.

6.6 RESULTS AND DISCUSSION : DAILY MODEL (PITD) CALIBRATED ON DAILY GOODNESS-OF-FIT (WDCE) (second phase)

6.6.1 Variability of parameters

There is little reduction in the variability of all six parameters optimized for calibration lengths greater than 7 years, as Fig. 6.11 clearly illustrates and the overall degree of variability remains fairly high. Table 6.12 provides further evidence of this phenomenon. It is difficult to say whether this variability is the result of imperfect calibration or whether it reflects the inherent instability of model PITD when calibrated on a semi-arid daily flow series. Calibrating PITD during this phase of the study was much more difficult than the first phase calibration on monthly flows. On average, three optimization runs per calibration sample, each with a different starting parameter set had to be attempted before a decision on convergence could be made. The relatively low DCE values in Table 6.9 indicate that convergence often had to be declared even though the fit of daily values was less than good.

Perusal of the annual maximum daily peak flows produced by the model revealed that the model easily reproduced small to medium peaks but that the 15 highest peaks (out of 101) were not matched in a single case. The consistently negative errors in mean annual peak flows (ΔMPF) plotted in Fig. 6.12, mirror this deficiency of the model and/or the calibration procedure. This fact, combined with persistent overprediction of daily baseflows, are probably the main reasons for the low DCE values. The large MAR errors in Table 6.7 provide a clue to the reasons for the last-mentioned fitting-problems. Table 6.7 shows that the only way the optimization procedure could arrive at high DCE values, i.e. match the peaks of large events, was by deriving parameter sets that produced very large hydrographs, thereby causing the large MAR errors. *The reason for the inability of* PITD to reproduce large peaks can be found in the way it calculates the hourly distribution of daily rainfall inputs, i.e. by a simple linear regression equation (see Chapter 4). This equation could attenuate the hourly intensities of an extremely intense rainstorm from which FORD synthesized any specific original flood peak. It *seems therefore that the parameter variability of* PITD could be the result of both imperfect calibration (because the optimizer would be deceived by apparently low DCE values) and of model structure problems (because PITD tended to attenuate extreme rainfall intensities).

6.6.2 Errors in flow statistics

Fig. 6.12 illustrates improvements in selected reconstructed daily flow statistics with increase in calibration period. Although the variabilities do not decrease much there is a general trend of improvement in the daily fit with larger calibration samples, especially in the cases of DCE and ΔMPF. This trend also exists in the case of other daily statistics, to a lesser or greater degree. It does seem, therefore, that in terms of improving the reliability of calibrations based on daily fit, a point of "diminishing returns" does not exist below calibration period 13 years.

The annual and monthly sta which selected values are shown in Fig. 6.13, show a differen however. The errors in

MAR and the relative mean persistence (RMP) show little improvement for calibration sample size increases above seven years; even the MCE and CD values improve on average only slightly (although the variability of these statistics does decrease notably). A possible conclusion from the last-mentioned two figures is that in general a 7-year sample should enable calibration of a daily model to home in on parameters that ensure an approximate annual and monthly water balance, but that for a reasonable daily water balance about double that length of calibration period is required in a semi-arid catchment application. Such a doubling of calibration sample could improve the overall daily fit by over 50%.

6.7 GENERAL CONCLUSIONS

1. In the semi-arid case and for application to water resources analysis it is well worthwhile to increase the calibration sample length when using monthly and daily models such as Pitman's PITM and PITD. At a calibration period of approximately 15 years a point of diminishing returns seems to be reached, in terms of the accompanying reduction in errors in reconstructed streamflow statistics.

2. In the case of monthly model PITM, doubling the length of a calibration period that is initially well below 10 years may decrease the error in most regenerated monthly and annual flow statistics by 30 to 50%. However, the daily model revealed less dramatic equivalent improvements for equivalent calibration sample increases.

3. The daily model PITD, when calibrated in terms of a daily one-to-one fit (as may be required for a run-of-river project), seems to have an optimum calibration length of not much more than seven years if only monthly and annual flow reproduction is considered, but a calibration sample size about double that is required to improve the overall daily fit substantially. Improvements of over 50% in daily fit seem possible with such doubling of the calibration period.

Table 6.12

Changes in variability (expressed as coefficient of variation in %) of key model parameters associated with changes in calibration period length : model PITD (second phase)

Calibration period	ST	ZMAXN	ZMINN	Mean
3 year	12,4	25,3	11,7	16,5
5 year	25,4	16,2	30,8	24,1
7 year	14,8	23,2	29,4	22,5
10 year	12,6	19,1		17,7
13 year	10,3	22,7	18,0	17,0

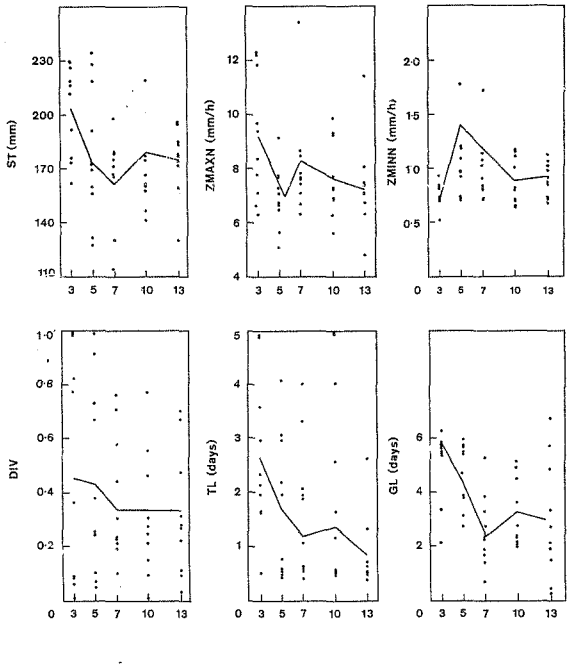


Figure 6.11 Variability of model parameters : model *PITD (daily calibration)*

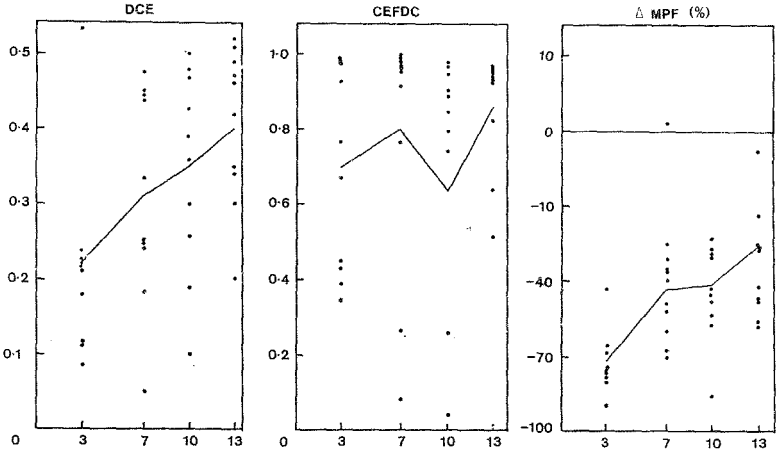


Figure 6.12 Effect of choice of calibration period on daily fit : model PITD

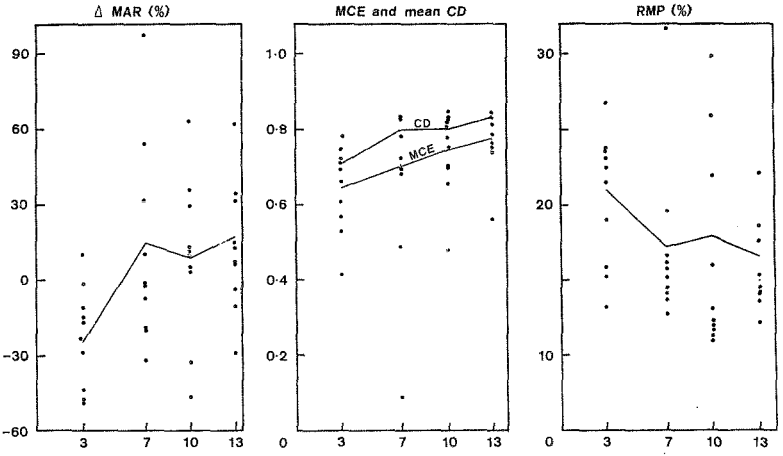


Figure 6.13 Effect of choice of calibration period on monthly and annual fit : model PITD

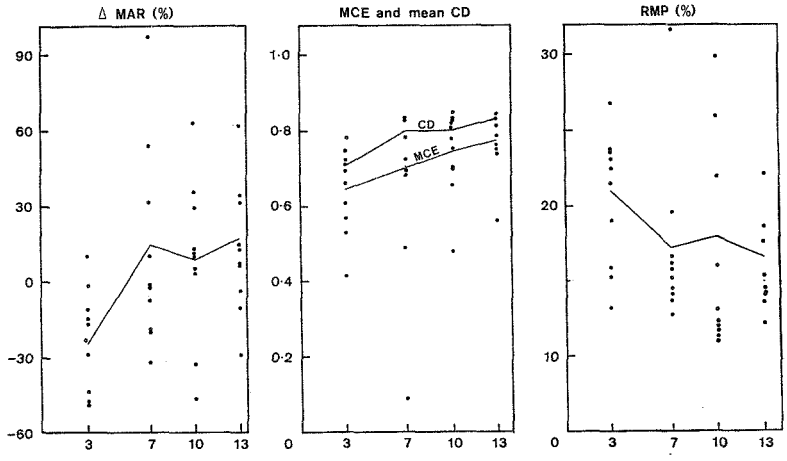


Figure 6.13 Effect of choice of calibration period on monthly and annual fit : model PITD

4. Significant parameter variability in "optimum" parameters seems unavoidable, even at long calibration periods, because of factors such as parameter interdependence, and an unknown degree of imperfection of calibration.

5. The effects of parameter uncertainty were less alarming than expected, as evidenced by an encouraging convergence of regenerated monthly and annual flow statistics with increase in calibration sample length.

6. There is faint evidence that for use in water resources appraisal of semi-arid catchments daily model PITD may be preferable to monthly model PITM. When calibrated on a monthly flow total basis, PITD seems to be slightly more stable in terms of key parameters. When calibrated on a daily basis, it seems to need a shorter calibration period. It also seems to produce better one-to-one fits of monthly totals.

7. The implications of the results of this study for the Ecca modelling studies are twofold. Firstly, the longest possible calibration period should be used for more reliable parameters. As only 6 years of data are available this may mean a calibration sample of 5 years. Secondly, because of the short calibration period (by the standards of the foregoing study), a fair amount of uncertainty in parameter estimates can be expected - this should be borne in mind during model verification assessments.

CHAPTER 7

COMPARISON OF PERFORMANCE OF SELECTED CONCEPTUAL RAINFALL-RUNOFF MODELS

7.1 INTRODUCTION

A comparative assessment of the performance of South African conceptual rainfall-runoff models under semi-arid conditions is a pivotal aspect of the research described in this thesis. Preceding chapters, though geared to specific aims, serve an essential purpose to set the scene for the model comparison study. In Chapter 2 the available data set is described and analysed, with specific reference to its suitability for conceptual model testing. In Chapters 3 and 4 the selected models are described, as well as any modifications thought to be necessary. Chapter 5 comprises a search for a robust and reliable approach to model calibration, specifically focused on the type of data, i.e. semi-arid, to be used in the model intercomparison. Chapter 6 provides [illegible] to "optimal" calibration period lengths that should be [illegible] modelling semi-arid catchments.

The comparison of model performance is intended to provide guidelines to model selection, specific to the semi-arid environment. This is done by determining whether or not models of complex structure and/or fine time-interval requirements for rainfall inputs provide superior output with respect to statistical criteria commonly used in water resources engineering. The complexity of a model, in terms of both structure and input requirements, dictates data preparation time, the time required for adequate calibration and the computer time of each operation of the model. The time involved in and the cost of generating streamflow series at an acceptable level of accuracy are key considerations for the practising engineer or hydrologist. These model users often have to deal with computer facilities of limited sophistication or may be paying commercial rates for computer time.

The research was executed in two phases: an early, exploratory phase during which a limited number of models were manually calibrated

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The research was executed in two phases: an early, exploratory phase during which a limited number of models were manually calibrated

and compared, and later complete investigation involving all the models and calibration according to the semi-automatic procedure described in Chapter 5. In a sense, the questions raised by the first phase study gave rise to much of the work described in Chapters 2 to 6. How could the models tested be improved? How adequate was the manual calibration procedure? How suitable was the calibration period chosen? What statistical criteria should be used to assess model performance? It was felt that answers to these and related questions should be sought before a meaningful model intercomparison could be done. Nevertheless, the exploratory comparison of model performance based on manual calibration is extremely useful in its own right, as the following section will show.

7.2 AN EXPLORATORY MODEL COMPARISON BASED ON MANUAL CALIBRATION

7.2.1 Introduction

It seemed prudent that the format of the exploratory model intercomparison should be designed to meet the information needs of a potential user searching for a time-efficient model to use in semi-arid water resources analyses. In such analyses storage-yield determinations based on monthly runoff data are of prime importance.

The hourly, daily and monthly models developed by Pitman (1973, 1976) (Pitman and Basson, 1979) and the Stanford Watershed Model were chosen for the exploratory study. The Pitman models were only slightly modified to allow use of the particular input data set chosen and are therefore prefixed by "HRU" in this section to distinguish them from the modified versions described in Chapter 4, viz. PITH, PITD and PITM. The complete data set for the Ecca catchments A, B and E, as described in Chapter 2, was used in the study. In terms of the chosen format and models this study can be regarded as an extension of work initiated by Pitman (1977, 1978), who compared his own three models with the Stanford model. He used four years of calibration data from three temperate catchments, but particular inadequacies in instrumentation and data consistency hampered his study. No verification data set was used by Pitman. In the present study the model comparison is done by an independent user, relying only on

published information about the four models, using data of generally higher reliability, consistency and areal representativeness than Pitman's, and employing both calibration and verification data sets. In fact, all four requirements for meaningful model comparisons suggested in section 1.4 are met in this study.

A brief summary of the characteristics or the models used in this study is given in Table 7.1. The range of complexities covered by the four models is well illustrated by the fact that the total amount of computer time needed for the calibration of the Stanford and the HRU hourly models was order of magnitude greater than that needed for calibration of the HRU daily or monthly models.

7.2.2 Model calibration and verification procedures

After some initial experimentation it was decided to follow a "three-stage" calibration/verification strategy in this study. The year 1975, for which no runoff data exist for any of the three Ecca catchments, was used as a "warm-up" year for all four models. Data for the years 1976 to 1980, inclusively, were used as a calibration sample in all cases and the year 1981 as a verification sample. A fair number of runoff events occurred in 1981, which therefore represented a reasonable verification sample on its own. In this way it was hoped that robust model parameters could be ensured by the largest possible calibration sample and that an extraordinary sequence of very high rainfall in 1979 (649mm for catchment A) which included two multiple-day winter rainstorms of large return period, followed by a very dry 1980 (347mm for A) which produced only one runoff event towards December, would especially strengthen the model calibrations.

Calibration of the models was undertaken manually. Manual calibration is deemed the most likely approach by a potential conceptual model user in a non-research environment, because of the computer time costs associated with automatic optimization.

The general manual calibration strategy was to focus on

Table 7.1

Comparison of model characteristics

Model	Number of conceptual storages	Number of parameters	Input/ Output	Execution time*1 (s)	Average no. calibration runs per catchment
HRU monthly	2	12	1 month	7	33
HRU daily	3	13	1 day	41	19
HRU hourly	4	15	1 hour	169	49
Stanford	4	19	1 hour	204	31

*1 CPU time on ICL 1904 computer for a 5 year calibration run.

subjective comparisons of simulated and observed monthly totals and, sometimes individual hydrographs, while all the time attempting to keep certain objective criteria of model performance within an acceptable range of their optimum values. These objective criteria were (see Appendix A for definitions):

(a) % error in mean annual runoff (ΔMAR),
(b) % error in variance of monthly totals (ΔSD),
(c) coefficient of efficiency based on individual monthly means (Garrick, Cunnane and Nash, 1978) (MCE),
(d) residual mass curve coefficient (Aitken, 1978) (RMCC).

The procedure used for each model was to choose initial parameter values for catchment A according to guidance provided in the relevant model documentation. Once an approximate fit was achieved on A, the new parameters were transferred to B and E and approximate model fits on these catchments were sought. Final calibrations on all three catchments were then attempted more or less simultaneously for each model. It was hoped that the above procedure would make maximum use of any possible internal consistency of each model's parameters among such "similar" catchments and that such a "feed-back" loop based on the similitude of the three modelling situations would ensure sound, if not optimum, final parameters.

The verification test was done by running each model with the full seven years of input data using the above final parameters and assessing the models' performance separately for each of the calibration period, the verification period and the total runoff period. In this study a set of eleven statistical criteria that measure the ability of the models to reproduce the observed flow series were utilized, calculated on the basis of simulated and observed monthly totals. These criteria are described in Appendix A and are listed below. All are calculated by statistical subroutine AFIT which is provided in Appendix B.

(i) Percent error in mean annual runoff (ΔMAR)

(ii) Percent error in monthly variance (ΔVAR)

(iii) Two related, but different, criteria of one-to-one fit - the coefficient of efficiency based on individual monthly means (MCE) (Garrick, Cunnane and Nash, 1978) and the maximum equivalent "constant" error, (MECE) (Weeks and Hebbert, 1980).

(iv) Two different criteria to measure persistence in model residual errors - the residual mass curve coefficient (RMCC) (Aitken, 1973) and the coefficient of persistence (CP) suggested by Wallis and Todini (1975).

(v) Two different indexes relating to storage requirements flow regulation - percent error in the range of the residual mass curve (R_R) and percent error in the index of seasonal variability (I_S).

(vi) A simple measure of low flow simulation - percent error in maximum deficient flow duration (ΔMDFD) i.e., the maximum continuous duration of flow smaller than the mean monthly flow.

(vii) Two further measures of the existence of systematic or correlated errors in the simulated time series - the one sample runs test or "sign test"(ST) (Aitken, 1973) and the Durbin-Watson d-statistic (DT) (Sorooshian and Dracup, 1980).

7.2.3 Comparison of model performance

A visual impression of the nature of the observed flow record used for the calibration and verification periods, respectively, as well as the one-to-one fit achieved by the four models, may be gained by inspection of Figs. 7.1 and 7.2. These diagrams show the typically erratic nature of the semi-arid runoff regime and highlight the magnitude of the 1979 winter flows compared to the rest of the available record. All the models seem to fit various parts of the calibration record for catchment A (fig 7.1) with varying degrees of

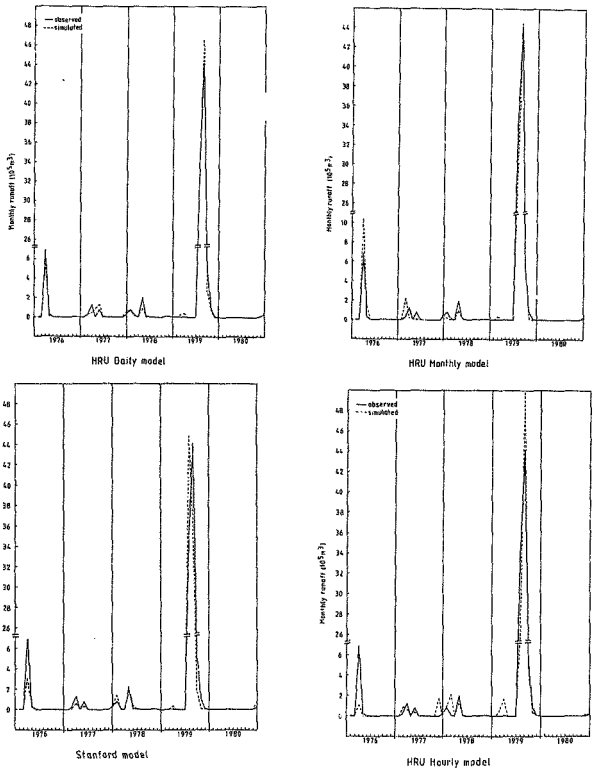


Figure 7.1 Observed and simulated monthly flows : catchment A (calibration period)

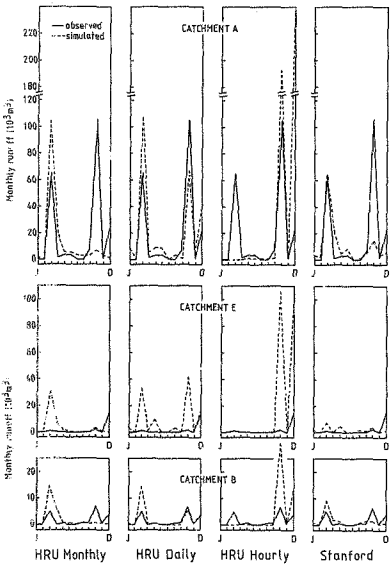


Figure 7.2 Observed and simulated monthly flows : calendar year 1981 (verification period)

success. (This observation also holds for the other two catchments). However, Fig. 7.2 shows distinct differences in the calibrated models' individual abilities to predict runoff for the verification year. Based on visual comparison for all three catchments it may be concluded that for the calendar year 1981 the HRU hourly model (as calibrated) shows the least predictive ability, with the Stanford model performing slightly better that the HRU daily and monthly versions.

The numerical criteria of goodness-of-fit of all the model/catchment combinations for the complete flow record period are shown in Table 7.2. Selected criteria for the verification period are given in Table 7.3. As the relative performance of the models according to the criteria for the calibration period is little different from that for the total flow-record period, only the latter period's criteria are shown for reasons of space economy.

Judging by the mean values in Table 7.2 of the respective criteria for each model, it can be seen that the performance of the Stanford and HRU daily models are more or less equivalent, while the HRU hourly and monthly models are comparable. The numerical goodness-of-fit values for the Stanford and HRU daily models are generally "better" than those for the other two, but the nominal differences between the two sets of values for the two pairs of models are not dramatic. Table 7.2 shows that on average all the models reproduce the overall water balance well enough. However, the HRU monthly model tends to underestimate the monthly variance and the Stanford model exaggerates the monthly variance. The MCE and MECE values indicate a high overall one-to-one correspondence for all the models on catchments A and B but a much lower quality of fit for the HRU hourly and monthly models on catchment E. At this juncture, it should be pointed out that the MCE and MECE values may be disproportionately influenced by the closeness of the one-to-one fit on the high winter flows of 1979, mentioned earlier.

The small persistence in model residual errors suggested by the high RMCC and low CP values in Table 7.2 is deceptive, as the residual mass curve plots in Fig.7.3 show. These diagrams reveal error

Table 7.2

Results of statistical tests*1 on monthly flows for the combined calibration and verification periods.*2

Model	Catch-ment	Δ MAR %	Δ VAR %	MCE	MECE %	RM-CC	CP	ΔR̄a %	ΔIs %	ΔMD-FP %	ST significant at 0.05	DT
	A	-3.5	-9.6	0.98	1.2	0.97	1.71	-7.0	-5.3	0.0	no	no
HRU	B	-1.6	-1.9	0.94	5.9	0.99	1.01	-3.1	-1.8	0.0	yes	no
monthly	E	-7.1	-14.5	0.69	10.1	0.92	1.39	-19.4	-17.3	-28.2	no	no
	mean	-4.1	-8.7	0.87	5.7	0.96	1.37	-9.8	-8.1	-9.4		
	A	-2.2	3.7	0.99	0.7	0.99	1.09	-1.4	5.2	39.3	yes	no
HRU	B	-3.7	7.9	0.95	5.3	0.99	0.86	-3.9	5.8	0.0	yes	no
daily	E	8.8	-3.5	0.86	6.9	0.97	0.36	-13.4	-19.6	-35.9	no	no
	mean	1.0	2.7	0.93	4.3	0.98	0.77	-6.2	-2.9	1.1		
	A	-3.7	-1.6	0.94	1.9	0.97	1.11	-4.8	-1.0	-14.3	yes	no
HRU	B	1.4	5.3	0.86	8.5	0.98	1.07	-1.7	-4.2	0.0	no	no
hourly	E	11.4	-2.7	0.73	9.5	0.92	0.56	-7.9	-27.9	-5.1	no	no
	mean	3.0	0.3	0.84	6.6	0.96	0.91	-4.8	-11.0	-6.5		
Stanford	A	-7.4	0.4	0.92	2.2	0.99	0.61	-3.5	11.2	0.0	no	no
	B	-8.0	14.1	0.91	6.9	0.99	0.83	-5.6	14.9	0.0	yes	no
	E	0.0	12.3	0.97	3.1	0.99	0.71	-1.6	7.5	0.0	yes	no
	mean	-5.1	8.9	0.93	4.1	0.99	0.72	-3.5	11.2	0.0		

*1 See Appendix A for explanation of symbols

*2 1976-1981, inclusive

persistence in at least the HRU hourly and monthly model simulations. All the models consistently underestimate the range ΔR_a of the residual mass curves, but show little consistency and a low success rate in estimating the index of seasonality ΔI_s. The three HRU models all produce one or more serious errors in estimating the maximum deficient flow period MDFP. A presence of systematic errors is indicated by the sign test for at least one catchment in the case of all the models, but the Durban-Watson d-test could not detect any systematic errors.

The apparently poor predictive performance of the models (as calibrated) depicted in Fig. 7.2 is further substantiated by Table 7.3. The three HRU models grossly overestimate total runoff, variance and range of residual mass curve, while the Stanford model shows random variation in errors among the catchments. The best single prediction is achieved by the HRU daily model on catchment A, but the earlier suggestion that the Stanford model shows better predictive ability for 1981, based on overall performance, is further underlined by the values in Table 7.3.

7.2.4 Discussion

In the light of the apparent adequacy of the performance of all the models on most of the catchments suggested by Table 7.2, the generally poor predictions for 1981 are somewhat surprising, if not puzzling. Some or all of the following arguments and counter-arguments will constitute an explanation of the verification results.

(a) The calibration of the models may have been biased towards the reproduction of high runoff events by the presence of the winter 1979 flows in the calibration record, while 1981, the verification year, was a "normal" runoff year: This implies that the calibration sample was too small or too dominated by a few extreme events. The predictive performance of the Stanford model seems to negate this explanation, but perhaps the study reveals that the HRU models need a longer calibration period than the Stanford model for the same quality of optimization on semi-arid data.

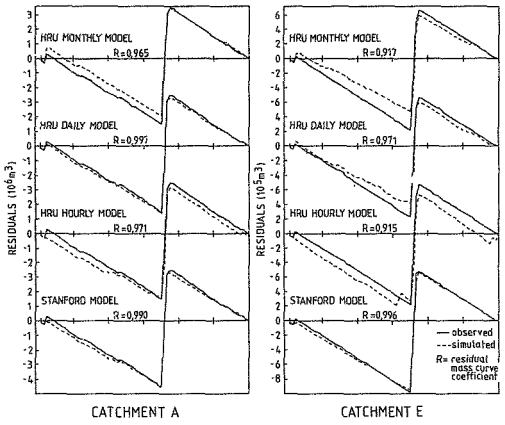


Figure 7.3 Residual mass curves : full data period, 1976 - 1981

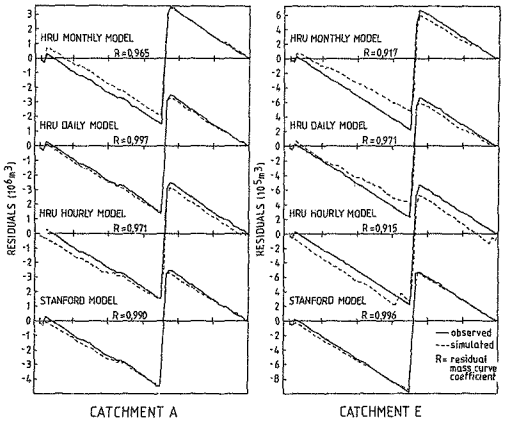


Figure 7.3 Residual mass curves : full data period, 1976 - 1981

Table 7.3

Selected statistics of model performance for the verification period*

Model	Catchment	Δ MAR %	Δ VAR %	MECE %	Δ R_a %
	A	-24.9	-23.9	23.6	7.9
HRU	B	39.4	226.1	134.4	122.0
monthly	E	166.4	333.4	207.7	127.7
	mean	60.3	178.5	121.9	85.9
	A	19.3	-0.7	12.8	8.8
HRU	B	41.6	241.4	100.1	75.1
daily	E	562.3	1021.2	313.8	204.5
	mean	207.7	420.6	142.2	96.1
	A	108.8	536.0	51.1	260.4
HRU	B	159.0	1510.1	273.0	364.7
hourly	E	1204.1	9162.4	820.2	1084.5
	mean	490.6	3736.2	381.4	569.9
	A	-35.9	-72.4	20.2	-30.2
Stanford	B	3.6	18.4	82.4	16.6
	E	32.6	-72.2	97.4	-53.5
	mean	0.1	-42.1	66.7	-22.4

* Calendar year 1981

(b) The calibration itself may have been inexpertly executed, resulting for some catchment/model combinations in non-optimum parameter sets: The verification experience with the Stanford, HRU daily and HRU monthly models on catchment A appears to refute this point. Also, the calibration procedure described in the previous section does seem intuitively sound.

(c) The verification sample may include rainstorm types poorly represented in the calibration sample: Of the bigger runoff events of 1981 the ones earlier in the year were the result of widespread frontal rainfall while the events later in the year were caused by high-intensity convectional thunderstorms. Although these storm types are both well represented in the calibration sample it was noted that localised thunderstorm runoff was poorly simulated by all the models at some points during the calibration period. The verification plots (Fig. 7.2) suggest that the HRU hourly model was calibrated to be hypersensitive and the HRU monthly and the Stanford models to be insensitive to high-intensity rainfall.

(d) The models may inherently be inadequate for the simulation of rainfall-runoff processes in the semi-arid environment: All model/catchment combinations yielded one or more dramatic simulation failures for specific storm events. Also, the three HRU models tended to sustain baseflow for too long while the Stanford model produced too little baseflow.

7.2.5 Conclusions

(i) A comprehensive set of statistical tests on simulated monthly flows for a combined calibration and verification period of six years indicated that there is no great difference in performance of the simpler HRU monthly and daily input models as compared with the more complex HRU hourly and Stanford models. In fact, the HRU daily model along with the Stanford model, can be regarded as yielding the best overall results.

(ii) All the models showed a serious divergence in values of selected goodness-of-fit criteria moving from the calibration to the verification period. For the verification period (calendar year 1981) the Stanford model showed the highest predictive ability, followed by the HRU monthly and daily models.

(iii) The large errors yielded by the verification tests may be attributed to any one or a combination of factors such as calibration sample too small, inadequate calibration causing poor ability to simulate runoff from high-intensity rainstorms, and inherent model inadequacies.

(iv) None of the four models was entirely convincing in simulating the vastly variable range of runoff-generation conditions in semi-arid catchments, and all model/catchment combinations yielded one or more dramatic simulation failures for specific storm events. However, the general performance of the relatively simple HRU daily model is encouraging.

(v) The results provided some evidence that it may not be wise to blindly adopt the most complex available model for a water resources study where, for example, storage-yield determinations are based on monthly flow data.

There was enough uncertainty, however, as to the reasons for the poor performance of the models during the verification period (see (iii)) to warrant suspension of the study until these factors had been investigated in depth. This decision gave rise to much of the work reported in Chapters 3, 5 and 6, at the completion of which the model intercomparison was resumed. The rest of this chapter comprises a description of this final comparison of model performance.

7.3 A COMPLETE MODEL COMPARISON BASED ON AUTOMATIC OPTIMIZATION

7.3.1 Format of the study

The set of seven models outlined in Chapter 4 was employed for a complete intercomparison of performance using the entire Ecca data set as described in Chapter 2. It will be recalled that these models cover a range of complexities, comprising three hourly-input models (FORD, PITH and PITR), two daily-input models (PITD and DALT) and two monthly-input models (PITM and DALM).

The investigation of the effect of the choice of calibration period on reliability of model calibration, described in Chapter 6, led to some findings which are very important for the model intercomparison under consideration. In section 6.2 it is concluded that ".....Parameter instability is not so much dependent on calibration sample length as on whether or not the sample includes *major runoff events*". *The general conclusions* in section 6.7 strongly underline the need for fairly large calibration samples to ensure representative model parameters. Calibration periods upwards of 10 years seem to be necessary for reliable parmete estimation in monthly and daily models.

In the light of these findings and given the fact that the Ecca data set comprises *only six years of concurrent* rainfall and streamflow records it was decided to conduct two separate model intercomparisons:

(i) A study based on the most representative calibration sample possible, i.e. the data for the five-year period 1976-1980,

(ii) *A study based on a calibration in which* the goodness-of-fit of simulation of the most extreme runoff events are ignored but which is nevertheless based on a representative range of small to medium runoff events, i.e. the data for the four years of 1976, 1977, 1978 and 1980. The first study would represent the most complete intercomparison of model performance possible with the available data set. The second study would, it was hoped, provide some insight into

whether or not certain models were more "robust" than others with respect to parameter estimation from "limited" data, i.e. from records that do not contain any extreme runoff events.

7.3.2 Special considerations regarding the models and their calibration

The main characteristics of the seven models used in the intercomparison are given in Table 7.4. It should be noted that in all cases only a portion of the total number of parameters of each model was allowed to change during the calibration. All parameters which had physical meaning (eg. FORD and PITD) or were found to be insensitive during the model sensitivity studies were held at constant values determined at the start of the study. All inactive parameters are identified in Tables 7.5, 7.6 and 7.7.

In the case of models DALT and DALM some initial experimentation with the four complexity levels that are possible with these models (see section 4.4) showed that at least the "DALT2" version of the model was needed for reasonable simulation. At this level the model consists of a single linear storage, an evapotranspiration function, a base flow function and a deep percolation loss function. It was also clear that a higher level version of the model such as DALT4 could provide improvements in model output accuracy but the range of improvement was thought not to justify the extra two paramters required for such a modification (section 4.4). At this level the model has six active parameters which brings it into the range of PITD and PITM, with seven and six active parameters respectively (Table 7.4). In terms of the objectives of the study it seemed prudent to use DALT and DALM at a level of complexity just sufficient to produce reasonable output under semi-arid conditions, i.e. at the "DALT2" level.

A three-stage calibration/verification ("split-sample") strategy was used in both phases of the model intercomparison. The data set was divided into a "warm-up" year, 1975, for which no streamflow information was available, a calibration period of either five years (1976-1980) or four years (1976 to 1978 & 1980) and a one-year

Table 7.4

Comparison of model characteristics

Model	Number of storages	Total no. of parameters	No.of active parameters	Interation interval	Execution time*1 (s)
			Hourly input/output		
FORD	4	19	11	0,25 hour	204
PITH	4	16	11	1 hour	170
PITR	4	16	11	1 hour	171
			Daily input/output		
PITD	3	16	7	1 hour(raindays)	41
				1 day(non-raindays)	
DALT2	1	4	4	1 day	26
			Monthly input/output		
PITM	2	12	6	0,25 month	7
DALM2	1	4	4	0,25 month	4

*1 CPU time on ICL 1904 computer for a 6-year run.

verification period, 1981. Each model was calibrated following the semi-automatic procedure outlined in section 5.8, in which the Rosenbrock optimizing algorithm proved extremely useful.

Some difficulty was experienced, however, with the chosen procedure in the optimization of models FORD, DALT and DALM. The complexity of model FORD often was the cause of slow convergence during the optimization search and necessitated frequent manual interventions to redirect the search. Extreme interdependence of the DALT/ DALM parameters SSR, the moisture storage level at which base flow starts, POWER, the power of the base flow function, and SSM, the maximum moisture storage level, also caused problems. These three parameters compensate very effectively for changes in each other's values, leading to "false" declarations of convergence by the optimizer. This undesirable effect had to be circumvented by optimizing the problem parameters separately.

Statistical criteria of model performance

The comparison of model performances was based on the ability of the models in the respective rainfall input categories to reproduce the observed monthly flow series - all three categories - and the observed daily flow series - the hourly and daily input categories. (A comparative study of the ability of the three hourly models to reproduce the hourly hydrographs of individual stormflow events is described in Chapter 3). The correspondence between observed and simulated flow series was measured by means of statistical criteria selected to focus on a variety of streamflow characteristics that are of typical interest to engineering hydrology, as well as a variety of recognized goodness-of-fit criteria. The criteria are listed below, while their mathematical definitions appear in Appendix A. All are calculated by statistical subroutines AFIT and BFIT provided in Appendix B.

(a) Monthly fit

(i) Percentage error in MAR (ΔMAR).

(ii) Percentage error in monthly variance (ΔVAR).

Table 7.5

Final parameter values : model FORD

Parameter		Catchment		
		A	B	E
*1	K1	1,0	1,0	1,0
*1	IMPV	0,0	0,0	0,0
	EPXM	0,15	0,15	0,20
	UZSN	0,95	0,86	0,93
	LZSN	9,12	8,68	18,54
	CB	0,0025	0,0040	0,0041
	CC	2,71	2,32	1,86
	K3	0,34	0,35	0,40
	K24L	0,51	0,12	0,50
*1	K24EL	0,05	0,05	0,05
*2	L	2500	1800	2200
*2	SS	0,20	0,27	0,17
*2	NN	0,35	0,35	0,35
	IRC	0,91	0,74	0,82
	KK24	0,84	0,22	0,97
*1	KV	0,0	0,0	0,0
	POWER	1,6	2,1	2,1
*1	UZSN WT	0,0	0,0	0,0
	KSI	0,86	0,83	0,76

*1 Regarded as inactive parameters

*2 Physical parameters

Table 7.6

Final parameter values: models PITH and PITR

	Parameter	PITH			PITR		
		Catchment			Catchment		
		A	B	E	A	B	E
*	POW	2,0	2,0	2,0	2,0	2,0	2,0
*	SL	0,0	0,0	0,0	0,0	0,0	0,0
*	AI	0,0	0,0	0,0	0,0	0,0	0,0
*	FT	0,001	0,001	0,001	0,001	0,001	0,001
	ST	154,0	169,0	240,0	157,0	162,9	241,8
	LAG	4	0	0	4	0	0
	DIV	15,9	23,9	20,0	3,8	20,0	23,8
	ZMINH	0,7	0,7	0,3	0,6	1,9	0,6
	ZMAXH	10,7	10,5	10,1	10,6	10,4	6,8
	PI	2,5	2,5	4,0	2,5	2,5	4,0
	GL	3,2	3,7	3,0	2,7	5,7	4,9
	TL	1,1	4,1	5,9	1,6	0,5	2,4
*	R	0,01	0,01	0,01	0,01	0,01	0,01
	SU	1,5	1,5	2,7	1,5	1,5	3,0
	TLI	11,1	13,1	17,3	9,1	8,2	14,9
	DIVG	2,7	5,8	7,2	2,9	5,5	7,0

* Regarded as inactive parameters

Table 7.7

Final parameter values ; models PITD and PITM

Parameter	PITD			Parameter	PITM		
	Catchment				Catchment		
	A	B	E		A	B	E
*1 POW	2,0	2,0	2,0	*1 POW	2,0	2,0	2,0
*1 SL	0,0	0,0	0,0	*1 SL	0,0	0,0	0,0
*1 FT	0,001	0,001	0,001	*1 FT	0,001	0,001	0,001
*1 AI	0,0	0,0	0,0	*1 AI	0,0	0,0	0,0
ST	166,5	160,0	229,9	*1 R	0,01	0,01	0,01
ZMINN	0,6	0,6	0,5	*1 GW	0,001	0,001	0,001
ZMAXN	5,8	6,3	7,3	ST	145	148	184
PI	2,5	2,5	3,5	ZMIN	109	97	117
LAG	0	0	0	ZMAX	334	330	327
DIV	0,45	0,68	0,74	PI	2,5	2,5	4,0
GL	1,5	5,0	4,5	GL	0,25	0,50	0,25
TL	0,8	0,9	0,9	TL	0,09	0,20	0,30
*1 R	0,01	0,01	0,01				
*2 TRIB	317,3	21,2	42,3				
*2 CHAN	6,0	3,0	4,0				
*2 OBANK	21,0	1,7	2,7				

*1 Regarded as inactive parameters

*2 Physical parameters

Table 7.8

Final parameter values : models DALT and DALM

Parameter	DALT			DALM		
	Catchment			Catchment		
	A	B	E	A	B	E
SSM	212,3	216,6	212,6	142,8	185,3	241,1
SSB	61,0	63,8	85,8	36,5	38,0	94,1
POWER	3,33	3,20	2,85	5,11	3,34	2,18
PERC	0,0	0,0	0,05	0,0	0,01	0,0

(iii) Coefficient of efficiency (MCE) - Garrick, Cunnane and Nash (1978) version, replaced by ordinary coefficient of efficiency (CE) (Aitken, 1973) during the verification tests.
(iv) Difference between coefficient of determination and coefficient of efficiency - degree of systematic error (DSE).
(v) Residual mass curve coefficient (RMCC).
(vi) Relative mean persistence (RMP).
(vii) Percentage error in range of residual mass curve (ΔR_a).
(viii) Percentage error in index of seasonal variability (ΔI_s).
(ix) Percentage error in maximum deficient flow period (ΔMDFP).

(b) Overall daily fit

(i) Percentage error in daily variance (ΔVAR).
(ii) Coefficient of efficiency (DCE) (Garrick, Cunnane and Nash, 1978).
(iii) Coefficient of efficiency of logarithms (DCEL).
(iv) Coefficient of efficiency of daily flow duration curves (CEDFC).
(v) Relative sum of absolute errors (RAE).

(c) Peak daily flow/month (for months with peaks > 2.mean daily flow)

(i) Percentage error in mean peak daily flow/month (ΔMPF).
(ii) Coefficient of efficiency (CE).
(iii) Percentage error in maximum daily peak (ΔMDP).

(d) Low flow (all non-zero daily flows < 2.mean daily flow)

(i) Percentage error in mean of low flows (ΔMLF).
(ii) Coefficient of efficiency (CE).
(iii) Percentage error in mean deficient flow period (ΔADFP) - a low flow index based on continuous periods of daily flows less than 2.mean daily flow.

Most of the above criteria were also used in section 5.4 for the selection of the most robust objective functions. The reader should

note, however, that there are important differences in the overall selection of criteria. These changes were thought to be necessary to expand the range of streamflow characteristics under consideration and also to eliminate a small degree of duplication (where two different criteria consistently produced similar rankings).

7.3.4 Presentation of results

The results of the model intercomparison are mostly presented in tabular form and appear as Tables 7.9 to 7.29. For each catchment four performance tests were executed, two based on the calibration on years 1976-1980 and two based on the calibration on years 1976-1978 and 1980. Each pair of tests consists of a series of goodness-of-fit tests on each of the full data period, 1976-1981, and the verification year, 1981. The performances of the full range of models are therefore reported in four tables per catchment, e.g. Tables 7.9, 7.16, 7.20 and 7.24 for catchment A.

For each goodness-of-fit criterion used the performances of the seven models (monthly flows) or the five models (daily flows) are ranked from best to worst on a scale of 1 to 7 or 1 to 5 as the case may be, e.g. Tables 7.12, 7.13, 7.14. By summing the rankings for each model in each of the monthly and daily flow categories as well as the two categories combined, overall performance in each category as well as the total performance of each model can be assessed relative to the other models in the case of each catchment. If these total rankings per catchment are now added together in each category then the combined overall performances over the three catchments can be summarized in the case of each of the four individual performance tests. For example, Table 7.15 summarizes the result of the performance test on the full data period based on the 1976-1980 calibration. The integrated results for all models, all three catchments and all four performance tests are listed in Table 7.29.

A visual impression of the general performance of the models can be gained from selected scattergrams of observed and simulated monthly flows depicted in Figs. 7.4 to 7.10. All values less than 1000 m^3 are plotted as 1000 m^3. The ability of the hourly and daily models to

reproduce the daily flows in catchment A during the two wettest months on record, July and August 1979, can be gauged from the plots in Figs. 7.11 to 7.15. The general ability of the models to reproduce daily flows in catchment A is illustrated in Figs. 7.16 and 7.17 by a variation on the flow duration curve concept. This method of representation was chosen because a conventional flow duration plot does not allow enough distinction between individual curves, as Fig. 7.18 clearly illustrates.

7.4 COMPARISON OF MODEL PERFORMANCE : CALIBRATION PERIOD 1976-1980

7.4.1 General observations

Before proceeding with the actual model intercomparison it is necessary to make a few general observations about the modelling results. The values obtained for the goodness-of-fit criteria in the performance test reported in Tables 7.9 to 7.11 show that over the full data period all models could attain a high level of one-to-one fit on monthly flows on catchment A and B. Furthermore, systematic errors in simulated monthly flows were fairly small for these two catchments. All models produced worse results on catchment E than on the other two catchments. In general, the statistics of daily flows were reproduced fairly well, but there was a clear tendency towards under-prediction of peak flows and over-prediction of low flows. In the latter case the simple model DALT was an exception, with consistent under-estimation of low flows.

As with the manual calibration model tests reported in section 7.2 all models showed a serious divergence in values of goodnes-of-fit criteria moving from the calibration to the verification period - Tables 7.16 to 7.18. Of the verification tests run on the three catchments those on catchment E produced the worst results for all the models. The generally inadequate performance of all the models during the verification period after both a manual calibration (section 7.2) and a semi-automatic calibration provides some evidence of model inadequacy. The two single-storage models DALT and DALM consistently and seriously under-estimated flow, while the five multiple-storage models consistently over-estimated flow during the verification year. The contradicting nature of these errors implies that erroneous data cannot seriously be considered as an explanation for the

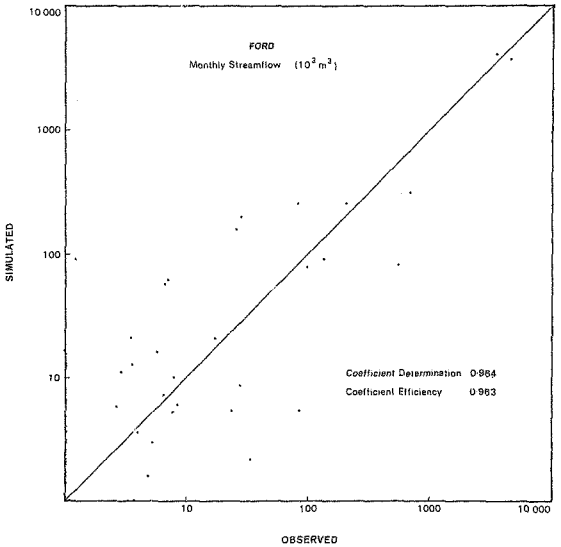


Figure 7.4 Scattergram : model FORD (catchment A)

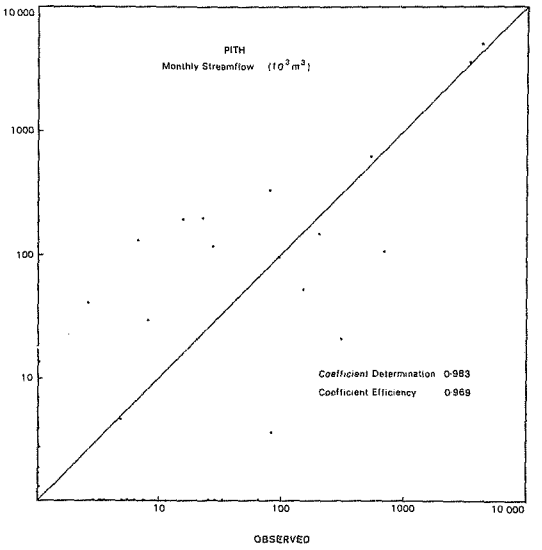


Figure 7.5 Scattergram : model PITH (catchment A)

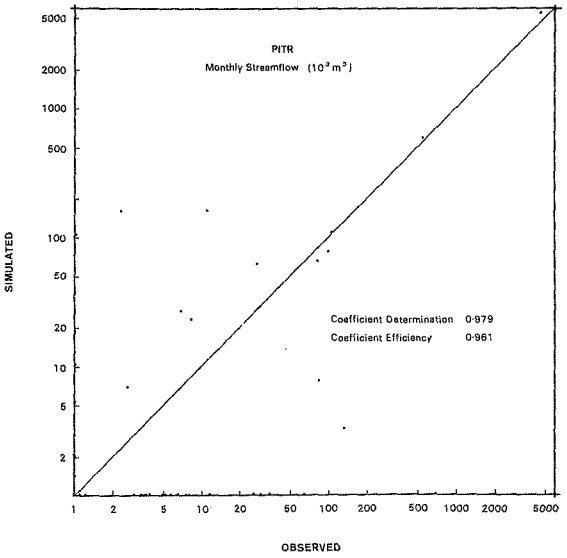


Figure 7.6 Scattergram : model PITR (catchment A)

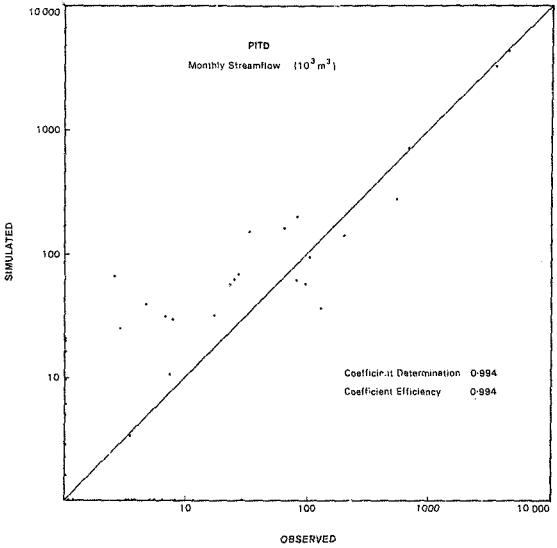


Figure 7.7 Scattergram : model PITD (catchment A)

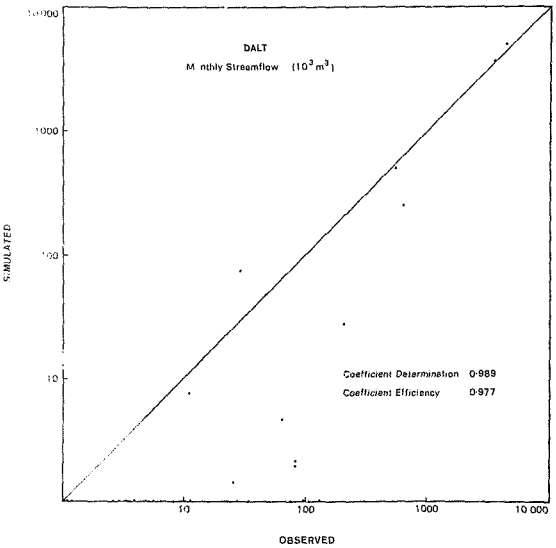


Figure 7.8 Scattergram : model DALT (catchment A)

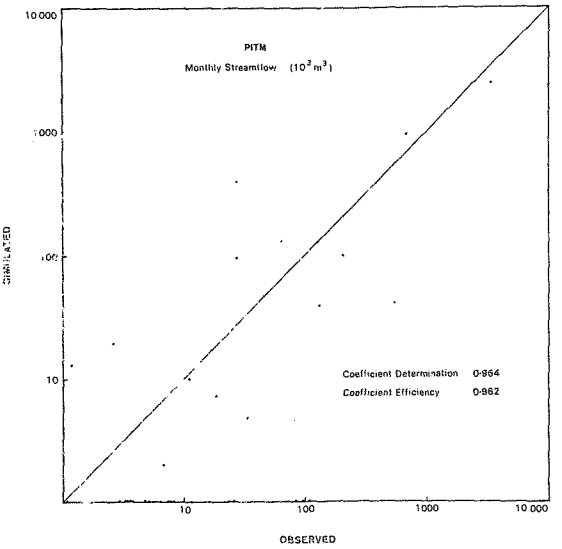


Figure 7.9 Scattergram : model PITM (catchment A)

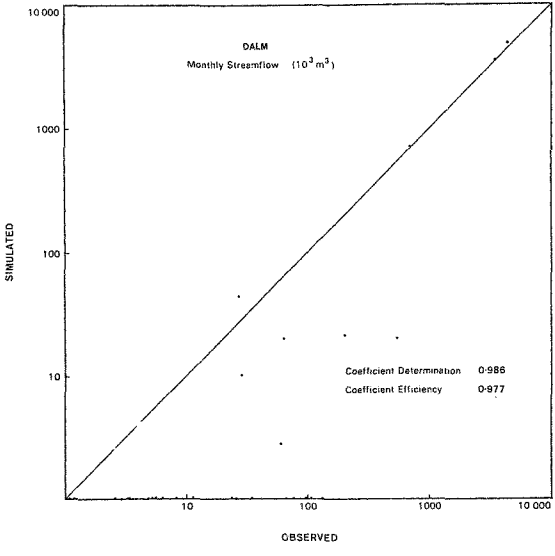


Figure 7.10 Scattergram : model DALM (catchment A)

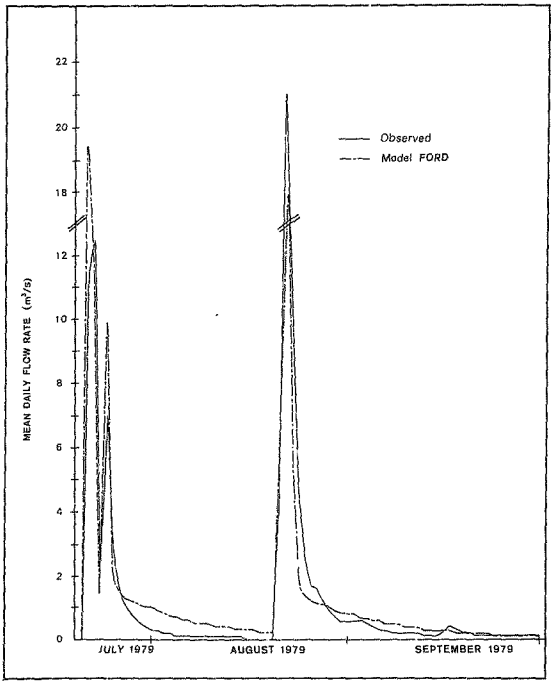


Figure 7.11 Observed and simulated daily flows : model FORD

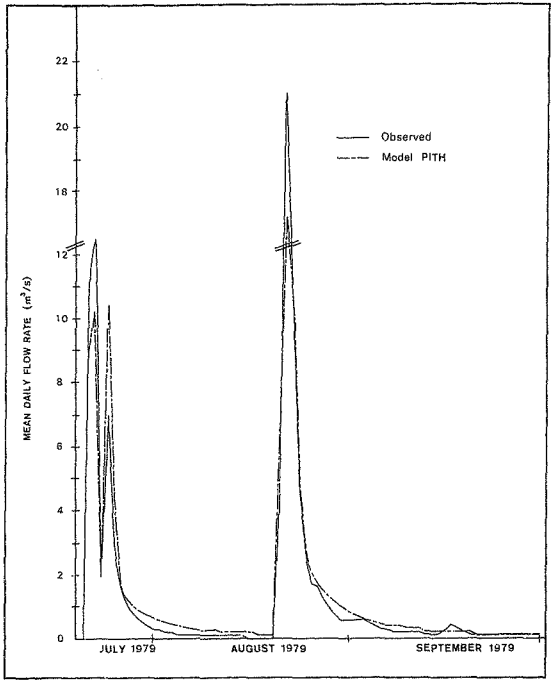


Figure 7.12 Observed and simulated daily flows : *model PITH*

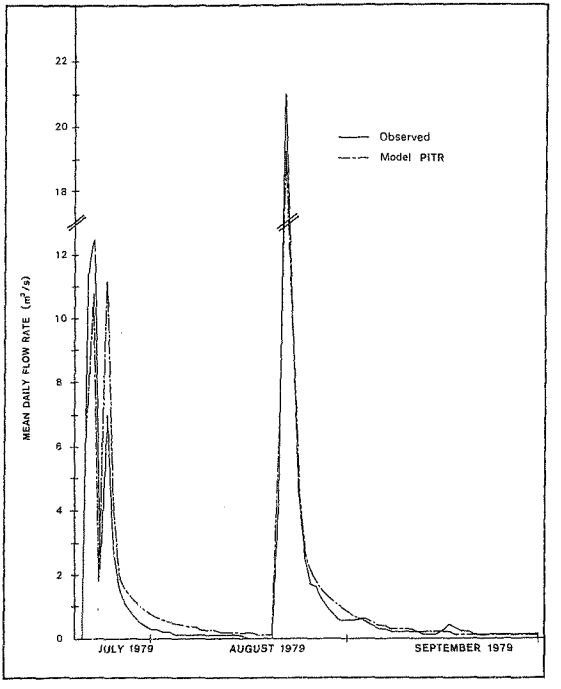


Figure 7.13 Observed and simulated daily flows : model PITR

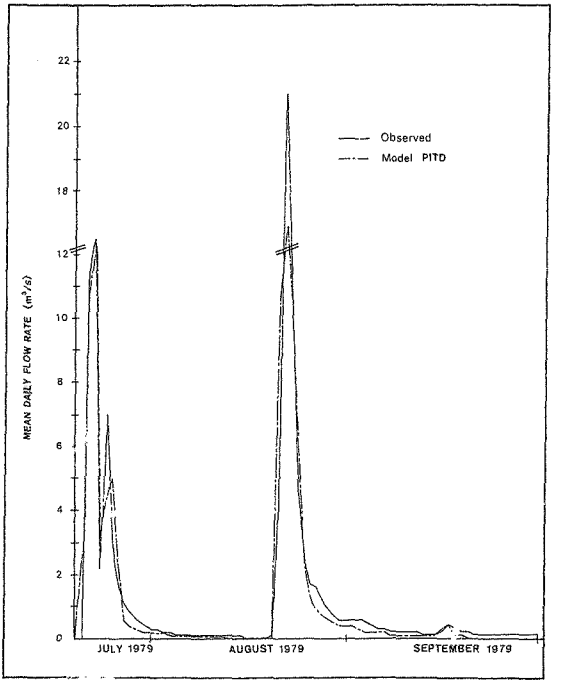


Figure 7.14 *Observed and simulated daily flows :* model PITD

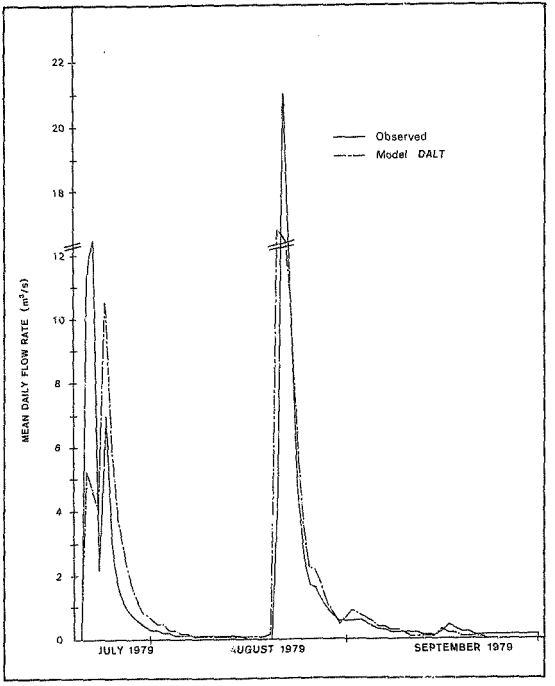


Figure 7.15 Observed and simulated daily flows : model DALT

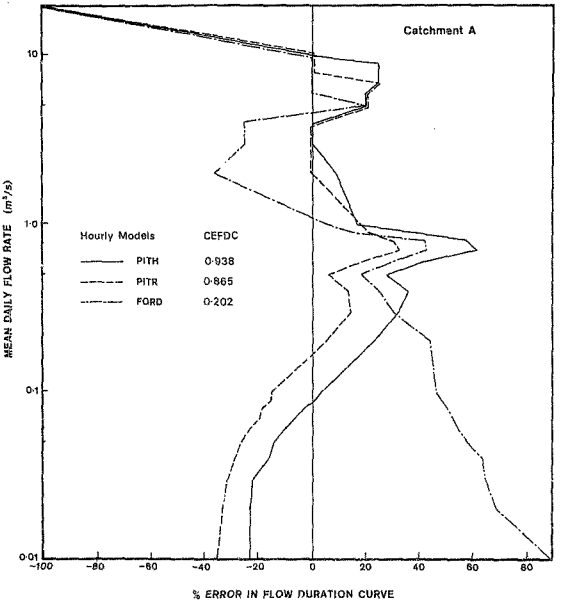


Figure 7.16 Errors in daily flow duration curve : hourly models

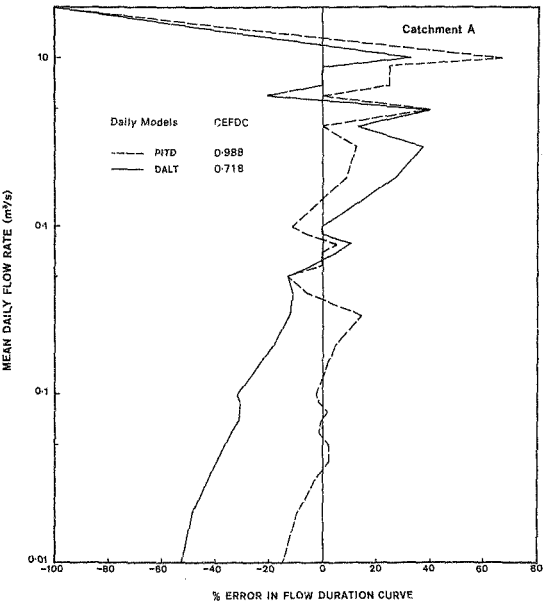


Figure 7.17 Errors in daily flow duration curve : daily models

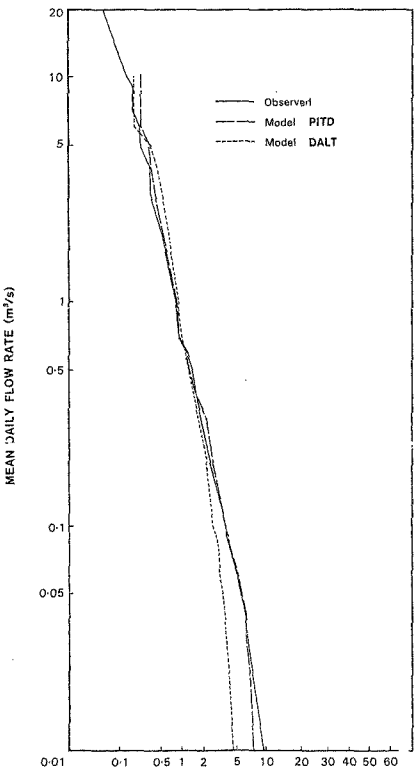


Figure 7.18 Observed and simulated daily flow duration curves : daily models

aforementioned model divergence. It is more likely that the problem lies with a combination of imperfect model structure and "biased" calibration. The major runoff events of July and August 1979 dominated the calibration period to such a extent that a model not calibrated to reproduce flow fairly accurately during these two months had little chance of returning reasonable goodness-of-fit statistics on the full data period. Consequently, simulation of smallish events, such as those of 1981, was inevitably laden with a high degree of uncertainty.

7.4.2 Comparison of the hourly models

The combined results, Tables 7.15 and 7.19, of the two performance tests relevant to this section show that in simulating both monthly and daily flow series FORD consistently gave better results than its hourly counterparts PITH and PITR. Inspection of the values obtained for the goodness-of-fit criteria (Tables 7.9 to 7.11) reveals that the actual difference in performance between PITH and FORD for the full data period simulation was slight. However, the performance of model FORD during the verification period (Tables 7.16 to 7.18) was notably superior to that of PITH and PITR. In general, the superiority of model FORD was more prominent in the reproduction of the monthly flow statistics than in the reproduction of the daily flow statistics. There is little to choose between the general performances of PITH and PITR.

7.4.3 Comparison of the daily models

The rankings listed in Tables 7.15 and 7.19 show that the overall performance of model PITD is far superior to that of its daily counterpart DALT. This is especially the case in catchments A and B. However, model DALT attained much lower overall rankings than PITD in catchment E. In the case of the verification test (Table 7.19) these lower rankings are misleading for the following reasons. Model DALT produced almost zero flow for the twelve month period, as the values in Tables 7.16 to 7.18 clearly show. As -100% is a natural lower limit for negative simulation errors a model producing near-zero flow may produce goodness-of-fit statistics that seem "better" than those

produced by a model that over-predicts flow. This is possible because there is no natural upper limit to positive errors, i.e. errors well in excess of +100% are always possible whereas errors more negative that -100% are impossible. Comparison of model performance based on absolute errors will therefore usually favour the model that produces near-zero flows.

Inspection of the actual values calculated for the goodness-of-fit criteria shown in Tables 7.9 to 7.11 discloses that there are really only small differences between the performances of the two models seen over the whole data period. However, a consistent pattern, even in catchment E, is that daily flows are generally more accurately simulated by model PITD.

7.4.4 Comparison of monthly models

The impression given by the total rankings in Tables 7.15 and 7.19 of the overall performance of monthly models PITM and DALM is that the performance of the simple model is slightly superior to that of its more complex counterpart. This is a misleading impression, as scrutiny of the actual goodness-of-fit values in Tables 7.9 to 7.11 and 7.16 to 7.18 will reveal. During the performance test on the full data period the two models gave comparable results. However, during the verification period model DALM produced near-zero flows in two catchments whereas PITM both under- and over-estimated flows. To a certain extent, the argument offered in the preceding section regarding the performance of model DALT is valid here, namely that the overall statistics favour the model that seriously under-predicts. An objective comparison, while keeping the above arguments in mind, must lead to the conclusion that there is little to choose between the two models in terms of the two performance tests under consideration.

7.4.5 Comparison of daily with hourly models

The combined total rankings listed in Tables 7.15 and 7.19 show that daily model PITD and hourly model FORD produced by far the best overall results of the five models under consideration. No clear pattern of increasing accuracy of simulation with increasing

complexity of model input requirements is discernible, since the two hourly models PITH and PITR gave the worst results. In both performance tests model PITD achieved the best rankings for simulation of daily flows. Unfortunately, no clear evidence was forthcoming that the simple model DALT was definitely competitive with the more complex models in the reproduction of daily flows.

7.4.6 Comparison of monthly with daily and hourly models

In terms of reproduction of monthly flows model FORD was by far superior to the six other models, as the total rankings in Tables 7.15 and 7.19 clearly show. Although the simple model DALM appears to deserve a second place, its low ranking in the verification test is partly due to the effects of near-zero flows in catchments A and E. However, the good performance by DALM during the "full-period" test is encouraging. A representative ranking of the seven models based on general performance (monthly flows) would be : FORD, PITD, PITM, DALM, PITH and PITR. No clear tendency of increasing superiority of performance with increasing complexity of model input requirements is discernible, but the foregoing model ranking suggests some evidence that better performances may be associated with higher structural complexity.

7.5 COMPARISON OF MODEL PERFORMANCE : CALIBRATION PERIOD 1976 to 1978 and 1980

7.5.1 General observations

The calibration sample consisting of data for the years 1976, 1977, 1978 and 1980 covers a range of small to medium flow events caused by a variety of different storm types, but excludes the extreme events of July and August 1979. This exclusion implies a less than optimum calibration procedure but does allow an assessment of model robustness if verification tests are based on a data set that includes such extreme events. Alternatively, if model verification is based on a data set fairly similar to the calibration sample, such as is available for calendar year 1981, it may be possible to explore the reasons for the poor verification performances reported in section 7.4

Table 7.9

Results of goodness-of-fit tests *1 for the combined calibration and verification periods *2 : catchment A

Criterion	FORD	PITH	PITR	PITD	QALT	PITM	QALM
			All monthly flows				
ΔMAR(%)	-7,6	0,4	1,5	1,5	-5,8	-6,7	-7,9
ΔVAR(%)	1,0	21	26	0,0	21	-11	17
MCE	0,957	0,965	0,956	0,965	0,967	0,956	0,974
DSE	0,001	0,014	0,018	0,0	0,012	0,002	0,009
RMCC	0,988	0,929	0,913	0,997	0,967	0,951	0,998
RMP(%)	0,6	1,7	1,6	0,4	0,5	1,0	0,7
ΔR_8(%)	4,3	11	12	-3,7	9,4	-10	2,7
ΔI_8(%)	-7,8	2,1	13	-2,4	21	-3,8	21
ΔMDFP(%)	-29	-10	-7,1	-36	39	0,0	39
			All daily flows				
ΔVAR(%)	-19	-6,9	-6,8	-7,6	-24		
DCE	0,855	0,932	0,902	0,908	0,675		
DCEL	-0,47	-2,0	-2,3	0,56	-0,18		
CEFDC	0,202	0,938	0,865	0,988	0,718		
RAE(%)	57	43	45	40	62		
			Peak daily flow/month				
ΔMPF(%)	-22	-12	-18	-8,3	-41		
CE	0,857	0,953	0,948	0,959	0,825		
Δ[illegible]	-34	-9,6	-8,3	-20	-39		
		Low flows (<2. mean daily flow)					
ΔMLF(%)	246	91	34	3,6	-49		
CE	-9,8	-29	-12	-3,2	-0,5		
ΔADFP(%)	125	33	79	-30	170		

*1 See Appendix A for definitions

*2 1976-1981, inclusive

Table 7.10

Results of goodness-of-fit tests for the combined calibration and verification periods : catchment B.

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-2,1	9,1	2,5	4,5	-6,1	-0,9	-6,9
ΔVAR(%)	17	16	24	11	43	-8,0	30,6
MCE	0,910	0,880	0,887	0,975	0,882	0,927	0,890
DSE	0,013	0,016	0,023	0,004	0,050	0,0	0,031
RMCC	0,990	0,978	0,944	0,993	0,937	0,945	0,994
RMP(%)	13	11	12	5,7	7,6	12	10
ΔR_8(%)	-4,5	2,3	9,1	2,4	11	-9,4	1,9
ΔI_5(%)	8,1	-8,5	7,5	-3,3	30	-11	25
ΔMDFP	0,0	-14	0,0	-11	50	-39	3,6
			All daily flows				
ΔVAR(%)	8,6	-15	-20	-3,4	3,0		
DCE	0,941	0,844	0,809	0,896	0,653		
DCEL	-1,08	-20	-44	0,126	-0,79		
CEFDC	0,866	0,952	0,981	0,933	0,721		
RAE(%)	48	55	58	38	64		
			Peak daily flow/month				
ΔMPF(%)	-16	-3,8	-21	-8,8	-34		
CE	0,970	0,842	0,810	0,990	0,919		
ΔMDP(%)	4,4	-30	-35	-7,8	-19		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	45	143	107	125	-53		
CE	-11	-53	-17	-12	-2,0		
ΔADFP(%)	31	13	112	-1,2	187		

Table 7.11

Results of goodness-of-fit tests for the combined calibration and verification periods : catchment E.

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
▵MAR(%)	9,9	2,2	9,9	9,9	-5,8	-3,8	-5,2
▵VAR(%)	27	-15	-12	-19	15	-25	46
MCE	0,967	0,729	0,538	0,877	0,906	0,825	0,498
DSE	0,018	0,002	0,022	0,002	0,012	0,003	0,137
RMCC	0,988	0,930	0,853	0,983	0,997	0,896	0,986
RMP(%)	14	23	35	13	4,8	19	8,0
ΔR_a(%)	7,8	-13	-13	-9,5	-2,4	-15	-3,3
ΔI_s(%)	-2,4	-23	-29	-25	11	-15	5,1
▵MDFP(%)	-10	-5,1	-5,1	-36	0,0	-2,6	0,0
			All daily flows				
▵VAR(%)	-11	-17	-22	-18	,6		
DCE	0,908	0,684	0,524	0,836	.,694		
DCEL	-6,4	-38	-39	-0,23	-0,06		
CEFDC	0,889	0,974	0,841	0,319	0,864		
RAE(%)	48	71	90	52	48		
			Peak daily flow/month				
▵MPF(%)	-21	-9,1	-13	-3,6	-19		
CE	0,952	0,887	0,704	0,971	0,930		
▵MDP(%)	-8,1	1,2	5,5	-2,4	4,2		
			Low flows (<2. mean daily flow)				
▵MLF(%)	179	518	826	481	-1,0		
CE	-24	-468	-999	-111	-6,3		
▵ADFP(%)	14	-11	-12	-60	61		

Table 7.12

Ranking* of models in terms of performance during the combined calibration and verification periods : catchment A

Criterion	FORD	PITH	PITR	PITO	DALT	PITM	DALM
			All monthly flows				
MAR	5(4)	7(5)	1(1)	1(1)	3(3)	4	6
VAR	2(2)	6(4)	7(5)	1(1)	5(3)	3	4
MCE	5(4)	4(3)	6(5)	1(1)	3(2)	6	2
DSE	2(2)	6(4)	7(5)	1(1)	5(3)	3	4
RMCC	3(2)	6(4)	7(5)	2(1)	4(3)	5	1
RMP	3(3)	7(5)	6(4)	1(1)	2(2)	5	4
R_a	3(2)	6(4)	7(5)	2(1)	4(3)	5	1
I_s	4(3)	1(1)	5(4)	2(2)	6(5)	3	6
MDFP	4(3)	3(2)	2(1)	5(4)	6(5)	1	6
Sub-total	31(25)	46(32)	48(35)	16(13)	38(29)	35	34
			All daily flows				
VAR	4	2	1	3	5		
DCE	4	1	3	2	5		
DCEL	3	4	5	1	2		
CEFDC	5	2	3	1	4		
RAE	4	2	3	1	5		
			Peak daily flow/month				
MPF	4	2	3	1	5		
CE	4	2	3	1	5		
MDP	4	2	1	3	5		
			Low flows (<2. mean daily flow)				
MLF	5	4	2	1	3		
CE	3	5	4	2	1		
ADFP	4	2	3	1	5		
Sub-total	44	28	31	17	45		
TOTAL	69	60	66	30	74		

*Rankings in brackets for hourly and daily models only.

Table 7.13

Ranking* of models in terms of performance during the combined calibration and verification periods : catchment B

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
MAR	2(1)	7(5)	3(2)	4(3)	5(4)	1	6
VAR	4(3)	3(2)	5(4)	2(1)	7(5)	1	6
MCE	3(2)	7(5)	5(3)	1(1)	6(4)	2	4
DSE	3(2)	4(3)	5(4)	2(1)	7(5)	1	6
RMCC	3(2)	4(3)	6(4)	2(1)	7(5)	5	1
RMP	7(5)	4(3)	5(4)	1(1)	2(2)	5	3
P_a	4(3)	2(1)	5(4)	3(2)	7(5)	6	1
I_s	3(3)	4(4)	2(2)	1(1)	7(5)	5	6
MDFP	1(1)	5(4)	1(1)	4(3)	7(5)	6	3
Sub-total	30(22)	40(30)	37(28)	20(14)	55(40)	32	36
			All daily flows				
VAR	3	4	5	2	1		
DCE	1	3	4	2	5		
DCEL	3	4	5	1	2		
CEFDC	4	2	1	3	5		
RAE	2	3	4	1	5		
			Peak daily flow/month				
MPF	3	1	4	2	5		
CE	2	4	5	1	3		
MDP	1	4	5	2	3		
			Low flows (<2. mean daily flow)				
MLF	1	5	3	4	2		
CE	2	5	4	3	1		
ADFP	3	2	4	1	5		
Sub-total	25	37	44	22	37		
TOTAL	47	67	72	36	77		

*Rankings in brackets for hourly and daily models only.

Table 7.14

Ranking* of models in terms of performance during the combined calibration and verification periods : catchment E

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
MAR	5(3)	1(1)	5(3)	5(3)	4(2)	2	3
VAR	7(5)	2(2)	1(1)	4(4)	2(2)	5	7
MCE	1(1)	5(4)	6(5)	3(3)	2(2)	4	7
DSE	5(4)	1(1)	6(5)	1(1)	4(3)	3	7
RMCC	2(2)	5(4)	7(5)	4(3)	1(1)	6	3
RMP	4(3)	6(4)	7(5)	3(2)	1(1)	5	2
R_a	3(2)	5(4)	5(4)	4(3)	1(1)	7	2
I_S	1(1)	5(3)	7(5)	6(4)	3(2)	4	2
MDFP	6(4)	4(2)	4(2)	7(5)	1(1)	3	1
Sub-total	33(25)	34(25)	48(35)	37(28)	19(15)	39	34
			All daily flows				
VAR	2	3	5	4	1		
DCE	1	4	5	2	3		
DCEL	3	4	5	2	1		
CEFDC	2	1	4	5	3		
RAE	1	4	5	3	1		
			Peak daily flow/month				
MPF	5	2	3	1	4		
CE	2	4	5	1	3		
MDP	5	1	4	2	3		
			Low flows (<2. mean daily flow)				
MLF	2	4	5	3	1		
CE	2	4	5	3	1		
ADFP	3	1	2	4	5		
Sub-total	28	32	48	28	26		
TOTAL	53	57	83	56	41		

*Rankings in brackets for hourly and daily models only.

Table 7.14

Ranking* of models in terms of performance during the combined calibration and verification periods : catchment E

Criterion	FOKO	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
MAR	5(3)	1(1)	5(3)	5(3)	4(2)	2	3
VAR	6(5)	2(2)	1(1)	4(4)	2(2)	5	7
MCE	1(1)	5(4)	6(5)	3(3)	2(2)	4	7
DSE	5(4)	1(1)	6(5)	1(1)	4(3)	3	7
RMCC	2(2)	5(4)	7(5)	4(3)	1(1)	6	3
RMP	4(3)	6(4)	7(5)	3(2)	1(1)	5	2
R_a	3(2)	5(4)	5(4)	4(3)	1(1)	7	2
I_s	1(1)	5(3)	7(5)	6(4)	3(2)	4	2
MDFP	6(4)	4(2)	4(2)	7(5)	1(1)	3	1
Sub-total	33(25)	34(25)	48(35)	37(28)	19(15)	39	34
			All daily flows				
VAR	2	3	5	4	1		
DCE	1	4	5	2	3		
DCEL	3	4	5	2	1		
DEFDC	2	1	4	5	3		
RAE	1	4	5	3	1		
			Peak daily flow/month				
MPF	5	2	3	1	4		
CE	2	4	5	1	3		
MDP	5	1	4	2	3		
			Low flows (<2. mean daily flow)				
MLF	2	4	5	3	1		
CE	2	4	[illegible]	3	1		
ADFP	3	1		4	5		
Sub-total	28	32		28	26		
TOTAL	53	57		56	41		

*Rankings in brackets for hourly and daily models only.

Table 7.15

Rankings*1 of overall performance during the combined calibration and verification periods*2 : all three catchments.

		FORD	PITH	PITR	PITD	DALT	PITM	DALM
Monthly	A	31(25)	46(32)	48(35)	16(13)	38(29)	35	34
Sub-totals	B	30(22)	40(30)	37(28)	20(14)	55(40)	32	36
	E	33(25)	34(25)	48(35)	37(28)	19(15)	39	34
Total		94(72)	120(87)	133(98)	73(55)	112(84)	106	104
Daily	A	44	28	31	17	45		
Sub-totals	B	25	37	44	22	37		
	E	28	32	48	28	26		
Total		97	97	123	67	108		
Combined total		169	184	221	122	192		
Monthly rank.		2	6	7	1	5	4	3
Daily rank.		2	2	5	1	4		
Combined rank.		2		5	1	4		

*1 Rankings in brackets for monthly and daily models only.
*2 1976 - 1981, inclusive.

Table 7.16

Results of goodness-of-fit tests for the verification period : catchment A

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	13	72	33	70	-98	-30	-91
ΔVAR(%)	-34	336	167	140	-100	31	-97
CE	-0,42	-2,13	-0,95	-0,01	-0,25	-0,35	-0,12
DSE	0,46	2,46	1,24	0,79	0,44	0,54	0,31
RMCC	-6,0	-20,6	-10,9	-1,50	-0,78	-7,3	-1,1
RMP(%)	17	27	24	3,4	30	25	28
ΔR_a(%)	23	107		68	-95	36	-78
ΔI_s(%)	8,6	73		-5,0	104	93	112
ΔMQFP(%)	50	50	50	0	67	50	67
			All daily flows				
ΔVAR(%)	-84	659	437	128	-100		
DCE	-0,05	-4,55	-2,86	-0,10	-0,08		
DCEL	-3,2	-11,3	-10,7	0,41	-3,3		
CEFD	-1,5	0,543	0,388	0,430	-0,51		
RAE(%)	162	162	124	113	98		
			Peak daily flow/month				
ΔMPF(%)	-84	147	116	49	-99		
ΔMDP(%)	-97	47	30	-19	-100		
		Low flows (<2.	mean daily flow)				
ΔMLF(%)	704	82	-27	-29	-94		
ΔADFP(%)	41	106	1[illegible]	-15	208		

Table 7.17

Results of goodness-of-fit tests for the verification period : catchment B

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	57	203	26	84	-97	53	-63
ΔVAR(%)	98	2061	294	385	-100	596	-37
CE	-0,67	-15,8	-0,78	-1,62	-0,33	-4,8	-0,04
DSE	0,93	16,4	1,42	2,25	0,56	5,0	0,26
RMCC	-9,1	-74	-6,8	-5,6	-1,6	-32	-4,9
RMP(%)	290	535	181	19	215	486	259
ΔR_a(%)	50	447	128	106	-93	208	-18
ΔI_S(%)	-4,7	81	81	12	114	101	120
ΔMDFP(%)	-33	50	50	0,0	67	50	67
			All daily flows				
ΔVAR(%)	-30	1605	273	161	-100		
DCE	-0,11	-17	-3,6	-0,83	-0,05		
DCEL	-4,5	-138	-370	1,68	-4,7		
CEFDC	0,665	-0,453	0,575	0,508	-0,14		
RAE(%)	175	356	194	177	99		
			Peak daily flow/month				
ΔMPF(%)	-44	169	29	9,1	-99		
ΔMDP(%)	-89	407	174	-29	-100		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	221	-99	-100	-46	-100		
ΔADFP(%)	-50	138	139	-14	257		

Table 7.18

Results of goodness-of-fit tests for the verification period : catchment E

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	88	912	1405	471	-100	14	-100
ΔVAR(%)	-79	5605	9999	727	-100	-15	-100
CE	-0,44	-56	-131	-9,3	-0,11	-1,1	-0,11
DSR	0,47	56	132	9,4	0,12	1,1	0,12
RHOC	-3,3	-215	-525	-2,7	-2,7	-9,5	-2,7
RMP(%)	778	4654	7169	1090	25	735	25
ΔR_a(%)	47	820	1268	160	-100	14	-100
ΔI_s(%)	-72	-9,1	-9,1	-54	11	0,5	11
ΔMDFP(%)	-73	-18	-18	-45	-9,1	-18	-9,1
			All daily flows				
ΔVAR(%)	-95	4324	9999	322	-100		
DCE	-0,079	-37	-92	-3,0	-0,06		
DCEL	-20	-462	-511	-6,4	-4,0		
DCEDC	-0,22	-17,8	-20,5	-49,2	-0,49		
RAE(%)	268	918	1412	519	100		
			Peak daily flow/month				
ΔMPF(%)	-92	717	1174	56	-100		
ΔMDP(%)	-98	391	631	-35	-100		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	744	-100	-100	9999	-100		
ΔADFP(%)	-46	-1,1	-1,1	-69	50		

Table 7.19

Rankings*1 of overall performance during the verification period*2 : all three catchments.

		FORD	PITH	PITR	PITD	DALT	PITM	DALM
Monthly	A	22(17)	50(38)	41(30)	25(18)	41(29)	27	37
Sub-totals	B	26(19)	55(41)	30(25)	31(24)	32(24)	46	27
	E	34(22)	47(31)	54(38)	43(27)	18(14)	23	18
	Total	82(58)	152(110)	125(93)	99(69)	91(67)	96	82
Daily	A	26	31	29	16	29		
Sub-totals	B	20	39	32	17	26		
	E	20	30	37	26	18		
	Total	66	100	98	59	73		
Combined total		124	210	191	128	140		
Monthly rank.		1	7	6	5	3	4	1
Daily rank.		2	5	4	1	3		
Combined rank.		1	5	4	2	3		

*1 Rankings in brackets for hourly and daily models only.
*2 Calendar year 1981

50%, if compared with the performance based on the five-year calibration. This finding provides firm evidence that the generally inadequate performance of the models reported in section 7.4 for the verification tests was, at least in the case of the five multi-storage models, due to a calibration biased towards simultation of extreme events.

7.5.2 Comparison of daily with hourly models

It is evident from the combined rankings resulting from the two performance tests under consideration here (Tables 7.23 and 7.28) that models PITD and FORD can be regarded as the most robust of the five general-purpose models tested. Although the total rankings of model DALT are competitive with those of the aforementioned two models, it has to be left out of contention because of artificially low rankings caused by near-zero flow estimation during the verification period in catchment E (Table 7.26). Models PITH and PITR are again the poorest performers, except for two instances : a good performance by PITH in catchment A during the performance test based on the full data period and a fair performance by PITR in catchment B during the verification period. In general, model PITD was again superior in terms of the reproduction of daily flow statistics, with model FORD following in a close second position. Furthermore, there is some evidence that the ability of the simple model DALT to reproduce daily flows is reasonably competitive with that of the more complex models, judged by the actual values of the criteria listed in Tables 7.20, 7,21, 7.22 and 7.25.

7.5.3 Comparison of monthly with daily and hourly models

In terms of simulation of monthly flows the general performances of models FORD, PITD, DALM and DALT are more or less on a par. The overall results achieved by the simple monthly model DALM during the performance test based on the full data period (Tables 7.20 to 7.22) are far superior to those achieved by the other models, all of which are more complex in structure than DALM. Unfortunately, the performance of DALM during the verification period was marred by the prediction of near-zero flows in catchments A and E. The same Table 7.20

50%, if compared with the performance based on the five-year calibration. This finding provides firm evidence that the generally inadequate performance of the models reported in section 7.4 for the verification tests was, at least in the case of the five multi-storage models, due to a calibration biased towards simultation of extreme events.

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In terms of simulation of monthly flows the general performances of models FORD, PITD, DALM and DALT are more or less on a par. The overall results achieved by the simple monthly model DALM during the performance test based on the full data period (Tables 7.20 to 7.22) are far superior to those achieved by the other models, all of which are more complex in structure than DALM. Unfortunately, the performance of DALM during the verification period was marred by the prediction of near-zero flows in catchments A and E. The same Table 7.20

50%, if compared with the performance based on the five-year calibration. This finding provides firm evidence that the generally inadequate performance of the models reported in section 7.4 for the verification tests was, at least in the case of the five multi-storage models, due to a calibration biased towards simultation of extreme events.

7.5.2 Comparison of daily with hourly models

It is evident from the combined rankings resulting from the two performance tests under consideration here (Tables 7.23 and 7.28) that models PITD and FORD can be regarded as the most robust of the five general-purpose models tested. Although the total rankings of model DALT are competitive with those of the aforementioned two models, it has to be left out of contention because of artificially low rankings caused by near-zero flow estimation during the verification period in catchment E (Table 7.26). Models PITH and PITR are again the poorest performers, except for two instances · · good performance by PITH in catchment A during the perfomance · ·ed on the full data period and a fair performance by PITR in c · during the verification period. In general, model PITD wa· ·ain superior in terms of the reproduction of daily flow statistics, with model FORD following in a close second position. Furthermore, there is some evidence that the ability of the simple model DALT to reproduce daily flows is reasonably competitive with that of the more complex models, judged by the actual values of the criteria listed in Tables 7.20, 7,21, 7.22 and 7.25.

7.5.3 Comparison of monthly with daily and hourly models

In terms of simulation of monthly flows the general performances of models FORD, PITD, DALM and DALT are more or less on a par. The overall results achieved by the simple monthly model DALM during the performance test based on the full data period (Tables 7.20 to 7.22) are far superior to those achieved by the other models, all of which are more complex in structure than DALM. Unfortunately, the performance of DALM during the verification period was marred by the prediction of near-zero flows in catchments A and E. The same Table 7.20

Table 7.20

Results of goodness-of-fit tests*1 for the complete period of record*2 - 1979 excluded during calibration : catchment A

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-19	27	18	24	21	-25	6,4
ΔVAR(%)	-19	74	73	85	63	-32	55
MCE	0,855	0,855	0,863	0,755	0,892	0,936	0,912
DSE	0,082	0,110	0,107	0,154	0,082	0,028	0,064
RMCC	0,903	0,903	0,894	0,899	0,924	0,943	0,957
RMP(%)	1,4	2,2	3,2	2,2	1,2	2,4	1,1
ΔR_a(%)	-24	30	32	30	27	-21	20
ΔI_s(%)	6,4	6,4	4,2	12	8,3	7,7	22
ΔMDFP(%)	36	36	36	39	0,0	0,0	39
			All daily flows				
ΔVAR(%)	2,5	20	1,4	48	15		
DCE	0,733	0,897	0,888	0,733	0,659		
DCEL	-0,51	-1,85	-1,62	0,57	-3,1		
CEFDC	0,931	0,981	0,982	0,897	0,968		
RAE(%)	62	50	57	62	63		
			Peak daily flow/month				
ΔMPF(%)	-14	-2,0	-13	-3,7	-21		
CE	0,924	0,957	0,924	0,913	0,918		
ΔMDP(%)	-22	-16	-27	-21	-27		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	76	76	121	-31	38		
CE	-10	-11	-11	-0,7	-5,5		
ΔADFP(%)	71	23	60	25	79		

*1 See Appendix A for definitions

*2 1976 - 1981, inclusive.

Table 7.21

Results of goodness-of-fit tests for the complete period of record - 1979 excluded during calibration : catchment B

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-0,3	27	35	5,2	26	-22	2,3
ΔVAR(%)	26	98	127	20	108	-33	38
MCE	0,867	0,739	0,664	0,950	0,730	0,905	0,869
OSE	0,028	0,187	0,174	0,013	0,211	0,026	0,045
RMCC	0,988	0,882	0,797	0,995	0,860	0,918	0,991
RMP(%)	16	17	20	8,3	12	27	14
ΔR_a(%)	-2,5	30	43	2,5	34	-23	6,1
$\Delta 1_s$(%)	9,1	11	11	1,5	15	1,0	13
ΔMDFP(%)	3,6	-14	0,0	-39	0,0	0,0	0,0
			All daily flows				
ΔVAR(%)	84	34	53	1,2	48		
DCE	0,731	0,785	0,816	0,888	0,714		
DCEL	-1,27	-20	-17	0,051	-1,58		
CEFDC	0,635	0,952	0,253	0,946	0,959		
PAE(%)	63	69	65	42	66		
			Peak daily flow/month				
ΔMPF(%)	22	-6,6	-2,2	-7,6	-19		
CE	0,659	0,907	0,966	0,991	0,973		
ΔMDP(%)	67	-16	14	-7,5	-3,0		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	32	63	96	84	69		
CE	-15	-25	-19	-11	-27		
ΔADFP(%)	15	42	325	-6	41		

Table 7.22

Results of goodness-of-fit tests for the complete period of record - 1979 excluded during calibration : catchment E

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-38	93	92	26	49	-81	-3,8
ΔVAR(%)	-64	271	247	127	178	-95	46
MCE	0,782	-0,09	0,045	0,391	0,297	0,129	0,513
DSE	0,162	0,916	0,801	0,359	0,518	0,297	0,133
RMCC	0,784	0,20	0,269	0,893	0,655	0,110	0,985
RMP(%)	38	35	109	22	19	74	7,9
ΔR_a(%)	-46	79	79	27	54	-85	-2,3
ΔI_s(%)	-4,5	-1,6	-6,2	11	6,9	-22	4,0
ΔMDFP(%)	0,0	-13	0,0	0,0	0,0	-2,6	0,0
			All daily flows				
ΔVAR(%)	-37	334	200	155	134		
DCE	0,793	-0,43	0,28	0,04	0,148		
DCEL	-0,91	-23	-19	0,142	-3,8		
CEFDC	0,510	0,852	0,139	0,793	0,975		
RAE(%)	57	104	98	88	89		
			Peak daily flow/month				
ΔMPF(%)	-18	107	74	25	23		
CE	0,948	-1,47	-0,07	0,04	0,618		
ΔMDP(%)	2,2	74	103	101	65		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	5,5	535	779	101	122		
CE	-5,0	-373	-408	-14	-25		
ΔADFP(%)	-80	0,0	-1,0	-33	60		

Table 7.23

Rankings*1 of overall performance during the complete record period *2 (1979 excluded during calibration) : all three catchments

	FORD	PITH	PITR	PITD	DALT	PITM	DALM
Monthly A	26(15)	41(27)	46(31)	52(38)	28(15)	24	24
Sub-totals B	26(18)	46(33)	51(37)	18(14)	46(30)	28	28
C	23(16)	51(38)	46(33)	27(17)	34(24)	49	11
Total	75(49)	139(98)	143(101)	97(69)	108(69)	101	63
Daily A	33	23	30	30	43		
Sub-totals B	38	38	34	20	35		
C	19	44	44	30	28		
Total	90	105	108	80	106		
Combined total	139	203	209	149	175		
Monthly rank.	2	6	7	3	5	4	1
Daily rank.	2	3	5	1	4		
Combined rank.	1	4	5	2	3		

*1 Rankings in brackets for hourly and daily models only.
*2 1976 - 1981, inclusive.

Table 7.4

Results of goodness-of-fit tests *1 for the verification period *2 (1970 excluded during calibration) : catchment A

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-10	-17	-35	25	-61	-90	-87
ΔVAR(%)	4,9	4,9	-26	53	-74	-98	-95
CE	0,156	-0,07	-0,17	0,31	0,038	-0,13	-0,07
DSE	0,19	0,21	0,29	0,25	0,20	0,31	0,26
RMCC	-4,2	-2,6	-1,3	-2,5	-2,9	-1,1	-1,3
RMP(%)	18	18	18	7,9	18	20	28
ΔR_a(%)	19	41	11	33	-36	-81	-73
Δf_S(%)	33	71	71	6,1	66	92	106
ΔMDFP(%)	0,0	50	50	0,0	50	50	67
			All daily flows				
ΔVAR(%)	-37	63	24	4,9	-89		
DCE	0,14	-0,32	-0,32	0,285	0,036		
DCEL	0,041	-8,7	-9,6	0,616	-14		
CEFDC	0,182	0,571	0,482	0,449	0,739		
RAE(%)	98	107	111	100	95		
			Peak daily flow/month				
ΔMPF(%)	-40	15	-4	-12	-86		
ΔMDP(%)	-85	-35	-62	-58	-100		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	83	67	33	54	118		
ΔADFP(%)	-17	106	106	-16	97		

*1 See Appendix A for definitions

*2 Calendar year 1981

Table 7.25.

Results of goodness-of-fit tests for the verification period (1979 excluded during calibration) : catchment B

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	54	89	-98	100	-31	-28	-17
ΔVAR(%)	178	795	-100	466	40	69	165
CE	-1,0	-4,5	-0,4	-2,2	-0,41	-0,57	-1,1
DSE	1,3	5,1	0,41	2,9	0,59	0,77	1,4
RMCC	-9,4	-22	-1,4	-6,2	-8,5	-10,2	-12
RMP(%)	283	321	260	26	276	322	405
ΔR_a(%)	69	239	-99	122	29	44	69
ΔI_s(%)	9,7	79	-49	11	86	101	102
ΔMDFP(%)	-33	50	-17	0,0	50	50	67
			All daily flows				
ΔVAR(%)	22	449	-100	188	-60		
DCE	-0,28	-5,4	-0,07	-1,0	-0,09		
DCEL	-4,0	-111	-127	-4,4	-18		
CEFDC	0,888	0,039	-0,14	0,173	0,754		
RAE(%)	159	258	102	190	133		
			Peak daily flow/month				
ΔMPF(%)	-30	33	-100	14	-79		
ΔMDP(%)	-89	161	-100	-25	-100		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	169	-97	-99	-35	-94		
ΔADFP(%)	-34	137	630	-14	133		

Table 7.26

Results of goodness-of-fit tests for the verification period (1979 excluded du. calibration) : catchment E

Criterion	FORD	PITH	PITR	PITO	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	112	555	541	98	-99	-86	-100
ΔVAR(%)	-34	2557	2464	9,1	-100	-98	-100
CE	-0,82	-25	-24	-0,73	-0,13	-0,13	-0,13
DSE	0,82	25	24	0,83	0,14	0,14	0,14
RMCC	-5,0	-73	-69	-1,5	-2,7	-3,3	-2,7
RMP(%)	591	2883	2764	289	29	487	25
ΔR_a(%)	-26	495	483	-8,1	-99	-86	-100
ΔI_S(%)	-65	-9,1	-9,1	-54	6,1	0,5	11
ΔMDFP(%)	-73	-18	-18	-45	-9,1	-18	-18
			All daily flows				
ΔVAR(%)	-63	1926	1905	-48	-100		
DCE	-0,17	-17	-16	-0,14	-0,06		
DCEL	-3,7	-380	-410	-9,0	-57		
CEFDC	-8,2	-12	-9,9	-8,8	-0,49		
RAE(%)	271	559	546	237	100		
			Peak daily flow/month				
ΔMPF(%)	-73	441	427	-51	-100		
ΔMDP(%)	-86	81	126	-81	-100		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	3178	-100	-100	4284	-60		
ΔADFP(%)	-75	-1,1	-1,1	-60	-1,4		

Table 7.2/

Comparison of the average goodness-of-fit statistics obtained for the two performance tests on the verification period *: all three catchments and all models

Criterion	5-Year calibration	4-Year calibration
	All monthly flows	
MAR(%)	139	39
VAR(%)	942	290
CE	10,8	-2,91
DSE	11,1	3,11
RMCC	44,9	-11,6
RMP(%)	793	430
R_a(%)	156	50
I_S(%)	40	32
MDFP(%)	19	11
	All daily flows	
VAR(%)	1160	272
DCE	-10,8	-2,7
DCEL	-103	-77
CEFDC	-5,8	-2,3
RAE(%)	325	204
	Peak daily flow/month	
MPF(%)	130	24
MDP(%)	68	-37
	Low flows (<2. mean daily flow)	
MLF(%)	730	493
ADFP(%)	57	66

* Calendar year 1981

Table 7.28

Ranking *1 of overall performance during verification period*2
(1979 excluded during calibration) : all three catchments

		FORD	PITH	PITR	PITD	DALT	PITM	DALM
Monthly	A	19(17)	29(27)	32(28)	22(20)	33(31)	50	50
Sub-totals	B	32(25)	53(41)	24(19)	37(27)	24(22)	33	45
	E	42(28)	54(39)	47(32)	29(19)	20(15)	20	25
Total		93(70)	136(107)	103(94)	88(66)	77(68)	103	120
Daily	A	24	29	28	18	34		
Sub-totals	B	20	38	32	21	23		
	E	25	33	33	21	20		
Total		69	100	93	60	77		
Combined total		139	207	187	126	145		
Monthly rank.		3	7	4	2	1	4	6
Daily rank.		2	5	4	1	3		
Combined rank.		2	5	4	1	3		

*1 Rankings in brackets for hourly and daily models only.
*2 Calender year 1981

Table 7.29

Combined rankings * of overall performance in all four performance tests : all three catchments

		FORD	PITH	PITR	PITD	DALT	PITM	DALM
Monthly	A	115(74)	166(124)	167(124)	115(89)	140(104)	136	145
Sub-totals	B	114(84)	194(145)	142(109)	106(79)	157(116)	139	136
	E	132(91)	186(126)	195(138)	136(91)	91(68)	131	88
Total		361(249)	546(395)	504(371)	357(259)	388(288)	406	369
Daily	A	127	111	118	81	151		
Sub-totals	B	103	152	142	80	121		
	E	92	139	162	106	92		
Total		322	402	422	266	364		
Combined total		571	797	793	525	652		
Monthly rank.		2	7	6	1	4	5	3
Daily rank.		2	4	5	1	3		
Combined rank.		2	5	4	1	3		

* Rankings in brackets for hourly and daily models only.

problem, i.e. near-zero flows in catchment E, makes it difficult to assessthe real merit of the low ranking model DALT attained in the verification period test. Models FORD and PITD produced the most stable performance with both a second and a third place each. As with the performance tests reported in section 7.4 no clear trend of improvement of performance with increasing complexity of model input requirements is discernible in the monthly simulation results discussed in this section.

7.6 SUMMARY OF FINDINGS

The combined rankings of overall model performance in all four performance tests in all three catchments appear in Table 7.29. The final ranking of the models in terms of monthly goodness-of-fit statistics is (from "best" to "worst"): PITH, FORD, DALM, DALT, PITM, PITR and PITH; in terms of daily criteria: PITD, FORD, DALT, PITH and PITR; and in terms of combined monthly and daily statistics: PITD, FORD, DALT, PITR and PITH. It must be stressed that the low rankings of model DALM and, to a certain extent, model DALT are misleading and may be traced to the artificially beneficial effects on goodness-of-fit statistics of near-zero flow estimations in certain catchments during the verification period tests.

In spite of the last-mentioned problem a number of firm conclusions can be drawn from the results reported in this chapter:

(i) Models that require fine time resolutions for input data do not necessarily produce more accurate estimates of daily or monthly flows than models with coarser input requirements. This finding is in accordance with conclusions arrived at by Pitman (1977), Roberts (1978) and Naef (1977,1981).

(ii) With respect to the daily and hourly models used in this study some correspondence was found between increased complexity of model structure and superior performance of the model. This result is contrary to conclusions by Roberts (1978) and Naef (1977,1981) but the sample of models tested in each input category is too small to deduce if this finding can be generalized.

(iii) None of the seven models was entirely convincing in simulating the vastly variable range of runoff-generation conditions in semi-arid

catchments and all model/catchment combinations yielded one or more simulation failures with respect to specific storm events.

(iv) The question of the adequacy of Pitman's three models for flow generation in semi-arid catchments: Pitman's (1978) conclusion that his monthly model could reproduce monthly flow series at a level competitive with that of more complex models requiring input of finer time resolution, was only partially confirmed in this study. The version of Pitman's monthly model used here, PITM, generally performed better than the modified versions of his hourly model, PITH and PITR, but was not competitive with the version of his daily model, PITD, and the Stanford Model (FORD). In fact, PITD must be regarded as the model most capable of simulating semi-arid rainfall-runoff processes of all the models tested here - both in terms of performance relative to other models and in terms of accuracy of actual flow estimates. This finding confirms the tentative conclusion drawn in this regard in the "manual calibration" study. The performance of hourly models PITH and PITR, though good for a few specific catchment/performance test combinations, was generally disappointing. It is likely that these two models would benefit by incorporation of a channel evaporation function such as that used in PITD. An analysis of the behaviour of PITH and PITR during the verification period (1981) suggests that their response to high intensity rainfall is highly exaggerated. This exaggerated response is to a certain extent counteracted by the re-infiltration function in PITR. The basic infiltration function used in these two models is most likely at the root of the problem, which has only partially been solved by addition of the re-infiltration function.

(v) The two models of simple structure DALT and DALM achieved results that were often most encouraging. It is worth nothing that especially in catchment E, the catchment with very high losses and low hydrological response (see Chapter 2), the performances by these two models were among the best in terms of the two performance tests based on the full period of record. As catchment E behaves more like an arid catchment than like a semi-arid one, the implication is that the structure of the DALT/DALM model series may be highly suitable for arid catchment modelling. The fact that the performance of model DALT often was not excessively worse than that of PITD suggests that the "DALT2" level of application may be just not complex enough to ensure

consistently good results in the semi-arid environment. This finding is highly useful in that it provides a clear "lower limit" answer to the question of what level of complexity in model structure is required for a general-purpose model to be used in semi-arid catchments. The tendency of both DALT and DALM to produce near-zero flow during verification period tests provides a clue to changes required in the model structure. These changes involve exaggerating the soil moisture level response to rainfall during dry periods so that the soil moisture level exceeds the "baseflow" threshold more often. This can be achieved by replacing the linear moisture store by a non-linear store such as the "bowl-shaped" container of Fig. 4.4(e), i.e. by switching to Roberts's (1978) version of the model known as DALT3. Unfortunately, such a change involves two additional parameters that have to be estimated during calibration. It must furthermore be stressed that the severe interdependence of the two baseflow parameters SSR and POWER and the soil moisture capacity SSM is a serious shortcoming of the DALT/DALM model series.

(vi) The performance test based on a model calibration procedure which excluded the extreme events of 1979 revealed models FORD, PITD and DALM as being robust. The verification period tests based on the last-mentioned calibration procedure confirmed that the poor verification performance of all the models reported in both section 7.2 (manual calibration) and section 7.4 (semi-automatic calibration on a sample that included the extreme events of 1979) was the result of a calibration biased towards reproduction of extreme runoff events.

CHAPTER 8

TRANSFER OF PARAMETERS VALUES FROM GAUGED TO UNGAUGED CATCHMENTS

8.1 INTRODUCTION

The estimation of runoff from catchments for which no flow records exist ("ungauged" catchments) is one of the major challenges of engineering hydrology. In earlier chapters it was explained that, in theory, conceptual rainfall-runoff modelling constitutes a valuable approach for dealing with the ungauged catchment "problem" - on condition that the model parameter values somehow are estimable for the catchment under consideration. In this situation parameter values can be estimated by three different techniques, if the circumstances allow it.

(a) Parameter values can be inferred by measurable catchment characteristics. This approach presupposes availability of a model that is physically-based to a very high degree. Such models exist, but for practical reasons are out of consideration in a conventional engineering setting (see Chapter 5).

(b) Parameter values can be based on regionalized trends. Some model developers have published regionalized sets of parameter values, based on numerous calibrations of their models in one or more regions (Hydrological Research Unit, 1981-1982; Betson et al., 1980). An obstacle to the full utilization of such publications is that the authors usually omit information on the degree of uncertainty involved in applying such regionalized parameters. Consequently, practising engineers are unable to place confidence limits on runoff estimates based on such regionalized parameters.

(c) Parameters can be estimated by calibrating the model on one or more catchments that are thought to be physically similar to the ungauged one and then assigning those parameters to the problem catchment. this is in fact the first step towards regionalization, but if practising engineers can perform this step themselves, they can at least form an impression of the uncertainties involved in such a

parameter transfer operation.

Intuitively it may be expected that the parameter sets of models that are structurally more complex should display a higher level of transferability that those of simple models - based on the assumption that more complex models simulate rainfall-runoff processes at a higher level of physical representativeness. Similarly, models requiring a finer time resolution of input data may be expected to give better results in a parameter transfer operation, because they incorporate higher levels of input information. To the practising engineer, who is considering a parameter transfer application of a model, the issue of adequate levels of structural and input data complexity is important. He may feel satisfied with the performance of a simple model in a gauged catchment, but may be hesitant to risk such a model in a parameter transfer operation. On the other hand, the costs and time involved in switching to a more complex (and presumably more reliable) model may be unacceptable.

Very little has been reported in hydrological literature on the magnitude of errors involved in and the general feasibility of parameter transfer operations. The research reported in this Chapter is aimed at providing some guidelines to the South African model user on the feasibility of parameter transfer in the semi-arid environment. In the process, the relationships between parameter transferability and complexity of model structure and of model input requirements will be explored.

8.2 EXPERIMENTAL PROCEDURE

The Ecca River research catchments are probably as "similar" in climate, vegetation, lithology and land-use as the practising engineer can ever hope to find in a water resources study that may require a parameter transfer aproach. Also, the quality of data derived from the Ecca River gauging network is probably better that what is available in most practical design situations. Conclusions drawn from a parameter transfer investigation using Ecca River data should therefore be reasonably reliable.

In a succinct discussion of the underlying assumptions of the parameter transfer procedure Roberts (1978) points out that the definition of the "similarity" of two or more catchments is highly problematic. He poses the question whether or not 'similarity' in climate, vegetation and lithology (the usual definition) is in reality commensurate with similarity in hydrological response. Similar hydrological response, according to Linsley (1976) who can be regarded as the "father" of the parameter transfer procedure, is the key to the success of the technique. In section 2.4 a simple analysis of the physical characteristics of the Ecca research catchments is described. It was concluded that "...the balance of the physical evidence points to the likelihood of larger catchment losses and a much more dampened hydrological response in catchment E relative to the other two". This conclusion is followed by a comparison of the observed rainfall-runoff behaviour of the three catchments. The comparison led to the conclusion that catchment E does in fact display a meaningfully different hydrological response from catchment A and B and that "...in general there should be more risk in transferring parameters to E from A or B than between A and B",

The parameter transfer tests were structured to investigate the last-mentioned suggestion and proceeded as follows. For all seven models the parameter sets derived by calibration on the 1976-1980 period of record were chosen for the experiment (see Tables 7.5 to 7.8). This calibration is regarded as the most reliable because it includes the widest range of runoff events. For each model two pairs of parameter transfer tests were executed. Certain parameter values estimated for catchment A were transfered into catchments B and E, followed by a transfer of catchment B values into A and E. In the first case the main catchment, A, can be considered to be the gauged catchment and the sub-catchments, B and E, the "ungauged" ones; similar considerations hold for the second case. Only parameters that affect the overall volume of runoff estimated by the models were transfered while lag, routing and physically-based parameters were kept at the values originally derived in each catchment by calibration (see section 7.3.2). After each transfer a streamflow series for the period 1976-9181 was generated using the rainfall and evaporation records of the catchment "receiving" the parameters. This was

followed by the calculation of a set of goodness-of-fit criteria with the aid of subroutines AFIT and BFIT. The success of each transfer operation was assessed in terms of the deterioration in the value of each criterion compared with the performance test values given in Tables 7.9 to 7.11. These results are listed in Tables 8.1 to 8.4. A negative value signifies a deterioration and a positive value an improvement.

8.3 FEASIBILITY OF PARAMETER TRANSFER

The values in Tables 8.1 and 8.3 suggest that, in general, parameter transfer between catchments A and B is highly feasible in terms of the reproduction of monthly flow statistics and marginally less so in terms of the daily criteria. For most models the deterioration in goodness-of-fit associated with transfered instead of calibrated parameters falls inside tolerance levels acceptable to engineering practice. However, parameter transfer from either catchment A or catchment B into catchment E results for all models in severe errors in estimated streamflow, as Tables 8.2 and 8.4 clearly illustrate.

This result conforms with the prognosis made in section 2.4 and mentioned earlier in this Chapter. The question arises whether or not, on the basis of the analysis of catchment characteristics in section 2.4, relevant model parameters could not have been adjusted before transfer from either catchment A or B to catchment E to accommodate the known differences in vegetation, lithology and crucial physiographic indices (such as mean catchment slope and drainage density). Such adjustments, if possible to make, could enhance confidence in the representativeness of the estimated streamflows. However, in most practical situations such parameter adjustments would be highly subjective. The success thereof would be strongly dependent on the modeller's "feel" for his technique and the thoroughness of his analysis of the catchment characteristics. If parameter adjustments were to have been made in the case of the Ecca parameter transfer study, such adjustments would have focused on three parameter types, i.e. interception storage (small increase), depression storage (small increase) and the principal moisture storage (large increase).

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Table 8.1

Deterioration in statistics due to parameter transfer from catchment A to catchment B

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-12	-10	-9	-2	+1	-6	-2
ΔVAR(%)	-42	-38	-15	-11	-3	+4	-8
MCE	-0,19	-0,03	0	-0,05	0	-0,03	-0,02
DSE	-0,08	-0,06	-0,02	-0,01	-0,01	-0,01	-0,02
RMCC	-0,02	-0,03	-0,01	-0,01	0	+0,03	-0,01
RMP(%)	-5	+1	+2	-7	0	-2	-1
ΔR_a(%)	-6	-13	-5	+2	-2	+1	-4
ΔI_s(%)	+1	+7	+6	+2	0	+6	-8
ΔMDFP(%)	-50	0	-18	-28	0	+39	-35
			All daily flows				
ΔVAR(%)	-74	-28	-3	-27	-4		
DCE	-0,19	-0,03	-0,15	-0,05	0		
DCEL	-1,44	-1,2	0	-0,03	-0,62		
CEFDC	+0,07	+0,02	+0,01	-0,03	+0,01		
RE(%)	-25	-84	0	-12	0		
			Peak daily flow/month				
ΔMPF(%)	-1	-12	+16	+3	+3		
CE	-0,27	-0,02	-0,04	-0,03	+0,01		
ΔMDP(%)	-51	+20	+19	+7	+3		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	-12	+45	-8	+51	+2		
CE	-15	+3	-7	-6	-0,1		
ΔADFP(%)	-24	0	+58	-18	+72		

Table 8.2

Deterioration in statistics due to parameter transfer from catchment A to catchment E

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flow				
ΔMAR(%)	-94	-121	-101	-93	-76	-81	-78
ΔVAR(%)	-234	-255	-224	-185	-226	-157	-211
NCE	-1,04	-0,81	-0,47	-0,65	-0,93	-0,64	-0,63
DSE	-0,88	-0,90	-0,75	-0,62	-0,83	-0,58	-0,76
RNCC	-0,56	-0,65	-0,54	-0,28	-0,56	-0,16	-0,38
RMP(%)	-115	-158	-129	-3	-23	-11	-6
ΔR_a(%)	-69	-66	-64	-49	-75	-32	-62
ΔI_s(%)	-13	+2	+10	+5	+11	-6	+3
ΔMDFP(%)	-36	-33	-10	0	-3	-25	0
			All daily flows				
ΔVAR(%)	-284	-218	-195	-76	-186		
DCE	-1,05	-0,56	-0,34	-0,80	-0,61		
DCEL	-4,2	+18	+24	-0,1	-2,0		
CEFDC	-2,08	-1,51	-1,60	-0,91	-0,01		
RAE(%)	-76	-247	-22	-65	-55		
			Peak daily flow/month				
ΔMPF(%)	-75	-83	-74	-90	-25		
CE	-1,05	-1,10	-0,94	-1,25	-0,43		
ΔMDP(%)	-68	-104	-101	-98	-62		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	-333	-917	-552	-579	-373		
CE	-82	-1089	-1560	-492	-142		
ΔADFP(%)	-20	-28	-16	-7	+1		

Table 8.3

Deterioration in statistics due to parameter transfer from catchment B to catchment A

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	+1	+6	-5	+1	-1	+6	+3
ΔVAR(%)	-27	+16	+24	-9	+2	-11	+1
MCE	0	-0,02	-0,02	0	+0,01	-0,01	-0,01
DSE	-0,02	0,0	+0,02	0	0	-0,01	0
RMCC	+0,01	+0,03	+0,01	0	0	-0,04	0
RMP(%)	0	+1	0	0	0	-1	0
ΔR_8(%)	-6	+10	+6	+2	+1	-2	+2
ΔI_5(%)	-1	-1	+1	-4	0	-15	+7
ΔMDFP(%)	+29	-4	-43	+32	0	-39	0
			All daily flows				
ΔVAR(%)	-40	-29	-39	-22	-2		
DCE	-0,06	-0,11	-0,12	-0,02	0		
DCEL	+0,15	-0,3	-6,5	-0,11	-0,21		
CEFDC	-0,21	-0,03	-0,09	-0,03	-0,01		
RAE(%)	-4	-13	-14	+1	0		
			Peak daily flow/month				
ΔMPF(%)	-26	-21	-23	-13	-2		
CE	-0,12.	-0,13	-0,12	-0,07	-0,02		
ΔMDP(%)	-14	-20	-25	-14	-2		
			Low flows (<2. mean daily flow)				
ΔMLF(%)	+10	+24	-,7	-42	-2		
CE	-1,1	+3,6	+2,8	+1,1	0		
ΔADFP(%)	-91	+10	.0	+13	0		

Table 8.4

Deterioration in statistics due to parameter transfer from catchment B to catchment E

Criterion	FORD	PITH	PITR	PITD	DALT	PITM	DALM
			All monthly flows				
ΔMAR(%)	-75	-92	-78	-87	-74	-94	-81
ΔVAR(%)	-137	-176	-188	-151	-229	-121	-212
MCE	-0,49	-0,47	-0,31	-0,45	-0,90	-0,47	-0,66
DSE	-0,41	-0,60	-0,59	-0,47	-0,78	-0,44	-0,78
RMCC	-0,27	-0,60	-0,48	-0,33	-0,54	-0,21	-0,37
RMP(%)	59	-82	-44	-45	-23	-43	-4
ΔR_a(%)	-46	-48	-58	-51	-73	-30	-61
ΔI_S(%)	-13	+3	+17	+1	+11	-20	0
ΔMDFP(%)	-14	-33	+3	0	-3	-54	0
			All daily flows				
ΔVAR(%)	-115	-88	-73	-111	-175		
DCE	-0,22	-0,14	+0,15	-0,28	-0,57		
DCEL	+3,2	+18	+24	-0,3	-1,6		
CEFDC	-1,24	-1,22	-1,53	-2,2	0		
RAE(%)	-46	-35	-7	-51	-54		
			Peak daily flow/month				
ΔMPF(%)	-17	-26	-21	-57	-21		
CE	-0,28	-0,16	+0,02	-0,43	-0,37		
ΔMDP(%)	-37	-49	-50	-48	-59		
			Low flows (<2. mean daily flow)				
Δ*MLF*(%)	-254	-856	-283	-557	-357		
CE	-62	-1056	+68	-302	-133		
ΔADFP(%)	-14	-32	+10	+3	+1		

8.4 COMPARISON OF MODEL PERFORMANCE

For each criterion in Tables 8.1 to 8.4 the values were ranked from 1 to 7 (monthly flows) or 1 to 5 (daily flows) on a scale representing the least deterioration (or highest improvement) to the worst deterioration. These rankings were summed in the case of each transfer operation and formed the basis for a comparison of overall model performance given in Table 8.5. It must be stressed that in this Chapter "model performance" does not imply goodness-of-fit of simulated flow series, but is defined in terms of "transferability" of parameter values.

8.4.1 Complexity of model structure

The overall rankings listed in Table 8.5 are : for monthly flows, PITD, PITR, PITH/DALM, DALT, PITH, FORD; for daily flows, DALT, PITR, PITD, PITH, FORD; for combined performance, DALT, PITR, PITD, PITH, FORD. In all three categories no correspondence between higher structural complexity and superior transferability of parameter sets is discernible. This finding conforms to a conclusion reached by Roberts (1978). The placing of models PITR and FORD is of interest. Results in Chapter 7 showed that the ability of model PITR to reproduce the observed flows was consistently poor whereas the output for model FORD was consistently good. Hence, if the choice of a model for a water resources study that requires parameter transfer is based merely on highest parameter transferability as expressed in Table 8.5, then an inadequate simulation may still result. If the model cannot produce output of acceptable accuracy in the gauged catchment it is not likely to fare any better with transfered parameters.

The correct criterion would be to compare parameter transferability among the "best" models according to the rankings of Chapter 7 (eg. Table 7.16). In this context models PITD and DALM (monthly flows) and PITD and DALT (combined daily and monthly performance) stand out as the best.

Table 8.5

Ranking* of overall performance during parameter transfer tests (based on least deterioration in goodness-of-fit statistics)

		FORD	PITH	PITR	PITD	DALT	PITM	DALM
Monthly totals	A-B	58(41)	41(29)	31(22)	32(23)	22(17)	21	37
	A-E	54(36)	56(39)	34(22)	21(13)	37(24)	24	24
	B-A	37(28)	23(19)	29(23)	29(25)	28(25)	50	26
	B-E	31(23)	44(35)	29(22)	31(24)	42(31)	32	40
	Total	180(128)	164(122)	123(89)	113(85)	129(97)	127	127
Daily totals	A-B	47	29	27	32	25		
	A-E	38	43	29	35	20		
	B-A	39	34	43	24	22		
	B-E	28	34	19	42	41		
	Total	152	140	118	133	108		
Combined total		280	262	207	218	205		
Monthly rank		7	6	2	1	5	3	3
Daily rank		5	4	2	3	1		
Combined rank		5	4	2	3	1		

*Rankings in brackets for hourly and daily models only.

8.4.2 Time resolution of model input requirements

From the rankings in Table 8.5 no relationship between the time-interval used for input data and the degree of parameter transfer of the models is discernible. Is is noteworthy that Roberts (1978) drew the opposite conclusion. He found that hourly models are more suitable for parameter transfer than daily models and ascribed the phenomenon to the higher level of information contained in the input record of hourly models. However, he speculated that this difference would decrease with increasing length of record for calibration (he used a 15-month record). In the study reported here the two daily models produced results that are convincingly competitive with those of the three hourly models with respect to reliability of parameter transfers.

8.5 SUMMARY OF FINDINGS

By application of a varied set of models the feasibility of transfering parameter values from the gauged to the ungauged catchment has been tested with data from three apparently similar catchments. An analysis of data on the physical characteristics of each catchment, such as vegetation cover, surface geology and a range of physiographic indeces, revealed subtle differences among the catchments (Chapter 2). These differences can be interpreted in terms of differences in hydrological response and are therefore important considerations in the parameter transfer process. The two catchments deduced to be the most "similar" physically allowed highly successful parameter transfer between them. However, very poor transfer results were achieved in the third catchment, deduced to be meaningfully different to the other two in terms of physical characteristics. A point to note here is that the "apparently similar" catchments could be identified as potentially problematic with respect to parameter transfer prior to the exercise by means of data that are within the reach of any practising engineer, i.e. topographical maps, aerial photographs, geological maps and some field observations. An analysis of such data prior to a transfer operation seems indispensable and should enhance the practising engineer's "feel" for his technique considerably.

The parameter transfer study provided no evidence that models with highly complex structure necessarily produce better results in the ungauged catchment than simple models. The very simple daily model, DALT, displayed the highest degree of parameter transferability based on overall goodness-of-fit, while the most complex model, FORD, was the least successful. Furthermore, no correspondence between finer time resolution of model input requirements and superior parameter transferability could be discerned.

CHAPTER 9

CONCLUSIONS AND RESEARCH RECOMMENDATIONS

9.1 CONCLUSIONS

The long term need for guidelines for the selection and application of rainfall-runoff models in semi-arid catchments in South Africa guided the planning and execution of the research project. For this reason the set of models selected for examination and testing with data derived from the semi-arid Ecca River catchments mostly comprised models developed in South Africa. The inclusion of the well-known Pitman models was regarded as especially important in the light of their widespread use in South Africa. It is realized that the data base used, i.e. six years of concurrent rainfall, pan evaporation and streamflow records, is perhaps too limited to allow definitive model tests. However, a wide range of small, medium and extreme runoff events are contained in the data set. By virtue of this fact and because the selected models represent a range of complexities from a very simple monthly-input model to complex hourly-input models, the following firm conclusions are nevertheless possible.

(i) *Data errors:* A simple error analysis of the Ecca River data set disclosed numerous ways in which hydrometeorological data thought to be suitable for research on rainfall-runoff modelling could be contaminated with sizable errors. Operation of the calibrated Stanford Model (model FORD) with contaminated data showed that random errors do not affect the mean annual runoff very much but individual flow events may be substantially affected, even small systematic errors cannot be expected to be neutralized by random errors, simulation errors are much more dependent on systematic errors in rainfall inputs than evaporation inputs and an unfavourable raingauge configuration can affect the simulation of individual events very severely.

(ii) Estimation of parameters - optimization : A direct search optimization algorithm (Rosenbrock) was found to be a powerful aid to

model calibration in a research context if used with circumspection. In automatic optimization the choice of objective function plays a crucial role and a comparison of a number of objective functions revealed that functions based on the sum of squared residuals consistently provided the best results.

(iii) Estimation of parameters - choice of calibration sample : The results of this study suggest that a calibration period length of about 15 years may be optimal for the calibration of monthly- or daily-input models in semi-arid catchments. Vast improvements in the ability of the models to accurately reproduce the long-term characteristics of streamflow can be effected by expanding a calibration sample from, say, a six-year record to a fifteen-year record.

(iv) Comparison of performance - model complexity : Some evidence was found of a correspondence between superiority of model performance and higher structural complexity of the models in the hourly-and daily-input categories. The results indicate a minimum level of model complexity for the generation of daily and monthly flow series of acceptable accuracy.

(v) Comparison of performance - time resolution of input : The results suggest that increased complexity (finer time resolution) of model input requirements does not necessarily lead to improved accuracy of flow estimation. The implication is that for, say, a run-of-river scheme requiring a daily flow duration analysis an hourly-input model need not be more suitable than a daily-input model; equally so, for a water resources appraisal based on monthly flow totals a monthly-input model may be quite adequate. However, there is an important proviso to this finding : that the daily or monthly model selected should meet the minimum structural requirements refered to under (iv) above.

(vi) Parameter transfer - feasibility : In general, parameter transfer between two of the three apparently "similar" catchments was highly successful but between these two and the third produced poor results. This finding can be explained by subtle but measurable

differences in physical characteristics among the catchments. Such physical differences could be signals of crucially different hydrological response characteristics and can be quantified before parameter transfer is embarked upon.

(vii) Parameter transfer - model performance : No evidence was found that either increased structural complexity or more complex input requirements of the models corresponded with superior transferability of parameter values. In terms of general overall performance during both the performance tests and the parameter transfer study the two daily-input models, PITD and DALT, in that order, can be regarded as the most successful of the seven models tested.

(viii) Pitman's models : A modified version of Pitman's hourly-input model, PITH, produced a performance comparable with that of the Stanford Model in a flood simulation mode. In the simulation of daily or monthly flows, however, the Stanford Model was far superior to PITH. A further modification to PITH, i.e. introduction of a re-infiltration function to attenuate model sensitivity to intense rainfall, was only partially successful. In the general model comparison study Pitman's daily-input model produced the best overall results of the seven models tested but his monthly fared less well, being ranked fourth.

(ix) None of the seven models was entirely convincing in simulating the vastly variable range of runoff-generation conditions in semi-arid catchments and all model/catchment combinations yielded one or more serious simulation failures with respect to specific runoff events.

Conceptual modelling emerges as an approach that is viable for semi-arid water resources studies but which requires careful and, often, subtle a priori decision-making. It is hoped that the conclusions outlined above can be employed by the prospective model user as guidelines in the search for an adequate modelling approach.

9.2 RECOMMENDATIONS FOR FURTHER RESEARCH

The encouraging performance of relatively simple models such as

PITD, DALT, DALM and PITM suggests a direction for further research in the Ecca catchments. Comparison of the performance of these conceptual models with that of multiple regression rainfall-runoff models, as well as with stochastic flow-generation models, is a logical extension to the Ecca research programme. Furthermore, the question of adequate calibration periods for statistical streamflow models using data from semi-arid catchments is relatively unresearched and there is a real need for guidelines relating to the reliability of the calibration of statistical models, specific to the semi-arid environment.

In the light of growing concern about the effects of land-use changes on the hydrological regime of a catchment, both in terms of water quality and quantity, much emphasis is currently being placed on the development of distributed-parameter rainfall-runoff models based on "partial and variable source area" concepts (Kirkby, 1978). It is believed that distributed/source area modelling is required to overcome the high degree of empiricism of rainfall-runoff models currently in general use. In order to be useful in catchment studies water quality models require reliable rainfall-runoff models as "carriers". The "signals" of the diffuse effects of land-use changes are usually fairly weak, therefore the rainfall-runoft models used as "carriers" must have a high level of physical representativeness. The exsisting monitoring network and research infrastructure in the Ecca catchments provides a firm basis for the initiation of research into distributed/source area modelling under semi-arid conditions.

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APPENDIX A
DEFINITION OF STATISTICAL CRITERIA

A.1 Notation

A_n	area of positive or negative residual run
B	number of positive or negative residual runs
d	departure from the mean for the residual mass curve
$\bar{d}$	mean of the residual mass curve
F	total number of flood events
H	number of hours in one flood event
I_s	range of the residual mass curve of overall mean monthly flow distribution
i	index of items included in either observed or simulated flow series, or residual mass curve series, or sample of flood events
j	index of calendar month, i.e. j = 1 to 12
N	total number of data in record
n	index of positive or negative residual run
p	peak flow rate for event i
R_a	range of residual mass curve
SD	standard deviation
v_x	variance of observed flow series
v_y	variance of simulated flow series
V	volume of flood event j
x	observed flows
$\bar{x}$	mean of observed flows of a specific category
$\bar{x}_{mj}$	mean of observed flows for calendar month j
y	simulated flows
$\bar{y}$	mean of simulated flows of a specific category

A.2 DEFINITIONS

Notation used in the equations below are detailed in section A.1. The arrangement of the statistical criteria is alphabetical (usually in terms of the abbreviations).

A.2.1 Statistics used in flood modelling (Chapter 3)

(1) Mean peak error = [100.(Py - Px)/Px]/F (%)

(2) Mean volume error = [100.(Wy - Wx)/Wx]/F (%)

(3) Overall HCE $= 1 - \sum^{M} (y - x)^2 / \sum\sum^{FH} (x - \bar{x}_h)^2$

where M $= \sum^{F} H$ and $\bar{x}_h = (\sum^{H} x)/H$

(4) Peak-volume O.F. $= \sum^{F} [(Py - Px)^2 + 25.(\bar{y}_h - \bar{x}_h)^2]$

where $\bar{y}_h = (\sum^{H} y)/H$ and $\bar{x}_h = (\sum^{H} x)/H$

A.2.2 All other statistics

(1) ΔADFP = Error in average deficient flow period (%)
where "deficient flow period" = no. of consecutive monthly or daily flows < mean monthly or daily flow

(2) COM1 = (1 - MCE) + (1 - RMCC) (objective function)

(3) COM2 = (1 - DCE) + (1 - RMCC) (objective function)

(4) COM3 = (1 - CEFDC) + (1 - MCE) (objective function)

(5) COM4 = (1 - DCE) + (1 - MCE) (objective function)

(6) CE = coefficient of efficiency (one-to-one fit)

$$= 1 - \sum^{N} (y - x)^2 / \sum^{N} (x - \bar{x})^2$$

(7) CEFDC = coefficient of efficiency of daily flow duration curve

(8) CD = coefficient of determination (one-to-one fit)
= (correlation coefficient)^2

(9) CP = coefficient of persistence (systematic error)

$$= (\sum^{B} A^2_n)/SSRES$$

(10) DCE = daily coefficient of efficiency based on the mean daily flow for each calendar month (one-to-one fit)

$$= 1 - \sum^{N} (y - x)^2 / \sum^{N} (x - \bar{x}_{mj})^2$$

(11) DCEL = DCE based on logarithms

(12) DSE = difference between coefficient of determination and coefficient of efficiency (systematic error)
= CD - CE

(13) DT = significance of sign test, based on the number of runs of residuals of either positive or negative sign : Chi-square two-tailed test

(14) ΔI_S = error in index of seasonal variation (see A.1) (%)
= 100.(Iy_S - Ix_S)/Ix_S

(15) ΔMAR = error in mean annual runoff (%)
= 100.(MARy - MARx)/MARx

(16) MCE = monthly coefficient of efficiency based on the mean flow for each calendar month (one-to-one fit)

$$= 1 - \sum_{N} (y - x)^2 / \sum_{N} (x - \bar{x}_{mj})^2$$

(17) ΔMDFP = error in maximum deficient flow period (%) where "deficient flow period" = no. of consecutive monthly or daily flows < mean monthly or daily flow

(18) MECE = maximum equivalent constant error (one-to-one fit) which is calculated from

$$Z = MECE.[C_v^2 (N - 1)/N + 1]^{0.25} \text{ where}$$

$$Z = (SSRES/N)^{0.5}/\bar{x} \text{ and}$$

$$C_v = v_x/\bar{x}^2$$

(19) ΔMLF = errors in mean daily "low flow" (%) where "low flow" = all daily flows < *some predetermined threshold*, eg. 2. mean daily flow

$$= 100(\bar{y} - \bar{x})/\bar{x}$$

(20) ΔMPF = error in mean peak daily flow/month (%) for months where the *peak daily flow* > some *predetermined threshold*, eg. 2. mean daily flow

(21) PEE = proportional error of estimate (one-to-one fit of small to medium flows)

$$= (\sum_{N} [(y-x)/x]^2)^{0.5}$$

(22) ΔR_a = error in range of residual mass curve (%)

$$= 100(Ry_a - Rx_a)/Rx_a$$

(23) RAE = relative absolute error (one-to-one fit)

$$= \sum_{N} |y - x| / \bar{x}$$

(24) RMCC = residual mass curve coefficient (*systematic error*)

$$= 1 - \sum^{N}(dy - dx)^2 / \sum^{N}(dx - \bar{dx})^2$$

(25) RMP = relative mean persistence (*systematic error*)

$$= \left(\sum^{B} A^2_n/B\right)^{0,5}/\bar{x}^2$$

(26) ΔSD = error in standard deviation

$$= 100(SDy - SDx)/SDx$$

(27) SMRAT = sum of mean ratio and standard deviation of ratios of simulated to observed daily flows (one-to-one fit)

$$= \bar{z} + SDz$$

where $z = y/x$

(28) SSRAT = sum of *squared ratios of simulated* to observed flows (one-to-one fit)

$$= \sum^{N}(y/x)^2$$

(29) SSRATL = SSRAT calculated on logarithms (one-to-one fit of low to medium flows)

(30) SSRES = *sum of squared residuals* (one-to-one fit)

$$= \sum^{N}(y - x)^2$$

(31) SSRESL = *SSRES calculated on* logarithms (one-to-one fit on low to medium flows)

(32) ST = significance level of Durban-Watson *d-test, based on the auto-correlation* of the series of residuals

where $d = \sum_{i=2}^{N}(e_i - e_{i-1})^2 / \sum_{i=1}^{N} e_i^2$

and $e = y - x$

(33) ΔVAR = error in variance of flows (%)

$= 100.(v_y - v_x)/v_x$

(34) WD$_L$E = weighted daily coefficient of efficiency (one-to-one fit biased by the error in MAR and SD)

$= DCE.(1 + ZMAR).(1 + ZSD)$

where $ZMAR = (\Delta MAR - 5)^2/10$

and $ZSD = (\Delta SD - 10)^2/10$

(33) ΔVAR = error in variance of flows (%)

$= 100.(v_y - v_x)/v_x$

(34) WDCE = weighted daily coefficient of efficiency (one-to-one fit biased by the error in MAR and SD)

$= DCE.(1 + ZMAR).(1 + ZSD)$

where $ZMAR = (\Delta MAR - 5)^2/10$

and $ZSD = (\Delta SD - 10)^2/10$

```
SUBFILE:FORD LC=8200 LENGTH: 179     HRAG


      LIST
      PROGRAM (FORD)
      INPUT 5=CR4
      INPUT 4=CR1
      INPUT 3=CR0
      INPUT 8=CR2
      INPUT 9=CR3
      OUTPUT 6=LP0
      OUTPUT 7=LP0
      COMPRESS INTEGER AND LOGICAL
      TRACE 0
      END
      MASTER FORD
C     STANFORD WATERSHED MODEL  -- WEATHER BUREAU,ANDERSON VERSION
C     THIS VERSION SET UP FOR THE FOLLOWING
C     1 RAINGAUGE
C     1 FLOWPOINT
C     1 POTENTIAL EVAPOTRANSPIRATION STATION
C     10 ELEMENT HISTOGRAMS - 1 HOUR IS THE MINIMUM TIME INTERVAL
C     40 HOURS OF TRANSLATED FLOW ARE RETAINED
C     THAT IS MAXL MUST BE (.LE.48)
C     * * * * * * * * * * * * *
C     THROUGHOUT PROGRAM  0 MEANS NO        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            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 IF YES
C     IFORE                    I5         INPUT DATA IS SET UP FOR FORECASTING
C     POWER                    F5.1       EXPONENT OF THE INFILTRATION CURVE
C     S1XHR                    I5         AVERAGE 6 HR. PRECIPITATION RATE USED
C     ON6HR                    I5         6 HR. PRECIPITATION USED AS INPUT
C     TRSOUT                   I5         TRANSLATED FLOW OUTPUT AT END OF
C     TRSIN                    I5         INPUT TRANSLATED FLOW FOR 1ST MONTH
C     STORE                    I5         STORES CHANNEL INFLOW ON DATA SET
C     ROUTE                    I5         ROUTES ONLY IF YES - CHANNEL INFLOW
C     OSRO                     I5         DAT  UNIT WHERE CHANNEL INFLOW
C     VAREP                    I5         VAR  TIME OF PE IF YES
C     UZSNWF                   F5.2       WT. FACTOR IN EQUATION UZSNTS
C     QUART                    I3           MINUTE PRECIP USED IF YES S1XHR
C     * * * * * * * * * * * * *
C     PEADJ ( )                12F5.3     MONTHLY PE ADJUSTMENT FACTOR
C     * * * * * * * * * * * * *
C     GAGEPE( )                F5.3       RAINGAGE PE ADJUSTMENT FACTOR
C     * * * * * * * * * * * * *
C     AVAPM( )                 12F5.3     AVERAGE MONTHLY PE -- ONLY IF AVEPE=1
C     * * * * * * * * * * * * *
C     SDEP                      F5.2      STANDARD DEVIATION OF PE IN PERCENT
```

```
C      PMBIAS              F5.2      PE BIAS IN PERCENT                IF
C      IXEP                I10       STARTING ODD INTEGER FOR R,N, VAREP=1
C      * * * * * * * * * * * * *
C      RGN( )              5A4       RAINGAGA 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      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      SWSI                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      KSI                 F5.2      CHANNEL ATTENUATION PARAMETER
C      VARK                I5        VARIABLE K IF YES
C      VARL                I5        VARIABLE LAG IF YES
C      RTEINT              I5        ROUTING INTERVAL - HOURS
C      ELEMTS              I5        NO. OF ELEMENTS IN TIME-DELAY
C      * * * * * * * * * * * * *
C      BASEK               F10.0     VAR. K INTERVAL - VARK=1
C      KSIVC( )            10F5.2    VAR. K CURVE
C      * * * * * * * * * * * * *
C      KSIVC( )            10X,10F5.2     REMAINDER OF CURVE
C      * * * * * * * * * * * * *
C      BASEL               F10.0     VAR. LAG,INTERVAL - CFS VARL=2
C      LAG( )              10I5      VAR. LAG, CURVE
C      * * * * * * * * * * * * *
C      CHECK( )            30X,I5    =1 IF OBSERVED SIX HOUR FLOW
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
C      MINFW               F10.0     PRESET BASE FOR OUTPUT OF
C      PLOTMX              F10.0     MAX. ORDINATE MEAN DAILY PLOT
C      PHRMX               F10.0     MAX. ORD HOURLY OR 6 HR. PLOT
C      MSTAT                 I5      OUTPUT MON.FLOWS & DO MON.
C                                    STAT ANAL.:ONLY USABLE ON A
C                                    SET OF COMPLETE 12-MON.YRS
C      * * * * * * * * * * * * *
C      TIMPAK( )           30X,10F5.2  CHANNEL TIME DELAY HISTOGRAM
C      * * * * * * * * * * * * *
C      PHEVFI              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=C
C     ACTFLW( )          INPUT      OBSERVED MEAN DAILY FLOW
C     * * * * * * * * * * * *
C     DISP               I5         ONLY IF ROUTE=0
C     DSN                 I5        DATA SET NUMBER FOR PRECIP IF STORED
C     SKIP               I5         NO. OF RECORDS ON TAPE OR DISK TO
C     * * * * * * * * * * * *
C     PX( )              SWM CARD       PRECIP DATA
C     * * * * * * * * * * * *
C     FLOW1              HOURLY     OBSERVED HOURLY FLOW FOR SELECTED
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     RECORD( )          11F6.X     OBSERVED VALUE
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     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( )           14,1115    OBSERVED PRECIP IN 1/10 MM
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- SELECTE
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        IT                 I3         24 HOUR CLOCK TIME        FOR FLOW
```

```
C          P1              F7.0        FLOW CFS          OTHER THAN THOSE
C          I2              I5          24 HR. CLOCK TIME       MENTION
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,
     1DAYF(7,31),LIRC4,LZSI,KS1,KS1V(20),K24L,SAFX(12)
      COMMON/MCL/EPDIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
     1UZSI,SGW1,GWSI,RESI,SRGX1,SCEPI,REPI,
     2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPF,SET,TIMEAR(10),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,
     9AEP1,MSTAT
C      MAIN,LAND,CHANEL VARIABLES (II)
       INTEGER   PX(31,96),QUART
       INTEGER SIXHR
       REAL A1,QSIM(100),QOBS(100),XSIM(12),XOBS(12)
       COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,
     1QUART,PX
C      INITIALIZE 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
      LX=1
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
      IF(MSTAT.EQ.1)GOTO 1257
C     MONTHLY SUMMARY
      IF (STORE.EQ.0) GO TO 1211
      WRITE (DSKO) 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
      IF(LX.LE.12)GOTO 128
      DAYF(LX-12,IDA)=TEMPFL/35.3147
  128 SSF(MONTH)=SSF(MONTH)+TEMPFL
      QSIM(LX)=SSF(MONTH)*86.4/35.3147
      QOBS(LX)=SAF(MONTH)*86.4/35.3147
      SAF(MONTH)=SAF(MONTH)
C
C       CHECK IF MONTHLY FLOWS AND STATS OUTPUT REQUIRED
C
      IF(MSTAT.EQ.1)GOTO 1301
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(6,951) 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=SAFX(MO)
      INCHES(MO)=TEMPFL/CONV
  815 WYFLOW=WYFLOW+TEMPFL
      WRITE(6,963) (SAFX(MO),MO=10,12),(SAFX(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
      LAFLX=1
```

```
      IF (MONTH.LE.12) GO TO 105
      MONTH=1
      YEAR=YEAR+1
      GO TO 105
  130 CONTINUE
C
C     WRITE MONTHLY FLOWS AND INVOKE AFIT
C
1372  NM=(YR2-YR1+1)*12
      DO 1373 M=13,NM,12
      ME=M+11
      MY=YR1-1+ME/12
      FYC=0.0
      XYC=0.0
      DO 1374 J=M,ME
      K=J-M+1
      XSIM(K)=QSIM(J)
      QSIM(J-12)=QSIM(J)
      XOBS(K)=QOBS(J)
      QOBS(J-12)=QOBS(J)
      XYC=XYC+XOBS(K)
1374  FYC=FYC+XSIM(K)
      WRITE(6,1375)MY,(XSIM(N),N=1,12),FYC
1375  FORMAT(//18,12F8.1,F10.1)
      WRITE(6,1376)(XOBS(N),N=1,12),XYC
1376  FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
1373  CONTINUE
      NM=NM-12
      CALL AFIT(QOBS,QSIM,NM,1)
      LYR=YR1+1
      CALL BFIT(DAYF,NM,1,LYR)
      IF (FIRST.EQ.1) WRITE(7,990)
C     PROGRAM FORMAT STATEMENTS
  900 FORMAT (1H1)
  903 FORMAT (1H ,20X,2044)
  923 FORMAT (////1H1,19HMONTHLY SUMMARY FOR,1X,2044)
  924 FORMAT (1HO,A4,3H 19,I2)
  925 FORMAT (1HO,53X,16HRAINGAGE SUMMARY)
  926 FORMAT (1HO,6X,13HRAINGAGE NAME,10X,8HTOTAL RO,3X,
     11HSURFACE RO,3X,7HINPV 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 (1HO,33HSIMULATED MEAN DAILY FLOW SUMMARY)
  929 FORMAT (1HO,5H DATE,8X,10HFLOW(CFSD))
  930 FORMAT (1H ,15,5X,10F10.1)
  933 FORMAT(1HO,44HSIMULATED AND ACTUAL MEAN DAILY FLOW SUMMARY)
  934 FORMAT(1HO,5H DATE,10X,30HSIMULATED(CFSD)   ACTUAL(CFSD))
  931 FORMAT(1H ,I5,10X,F10.1,6X,F10.1)
  936 FORMAT (1HO,5HTOTAL,10X,F10.1,6X,F10.1)
  935 FORMAT(1HO,5HTOTAL,5X,10F10.1)
  940 FORMAT (1HO,34X,55HRUNOFF, PRECIPITATION AND EVAPOTRANSPIRATION CO
     1MPONENTS)
  941 FORMAT (1HO,52X,18HSTORAGE COMPONENTS)
  942 FORMAT (1HO,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,AF7.2,F10.3)
  945 FORMAT (1HO,43X,29HSIMULATED HOURLY FLOW SUMMARY)
  946 FORMAT (1HO,7A4,10X,41HMINIMUM MEAN DAILY FLOW CAUSING OUTPUT IS,
     1F7.0,4H CFS)
  947 FORMAT (1HO,13,3X,2HAM,6F9.1,4X,6F9.1)
  948 FORMAT (1H ,6X,2HPM,6F9.1,4X,6F9.1,F10.1)
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  952 FORMAT (1H1,19X,26H--WATER YEAR SUMMARY FOR--,7A4)
  953 FORMAT (1HO,37X,13--WATER YEAR 19,I2)
  954 FORMAT (1HO,28HMEAN DAILY DISCHARGE SUMMARY)
  955 FORMAT (1HO,3X,3HDAY,5X,3HOCT,6X,3HNOV,6X,3HDEC,6X,3HJAN,6X,3HFEB,
     14X,5HMARCH,4X,5HAPRIL,4X,3HMAY,5X,4HJUNE,5X,4HJULY,3X,6HAUGUST,5X,
     24HSEPT,7X,6HANNUAL)
  956 FORMAT (1HO)
  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 (1HO,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 (//1HO,5HACT. ,12F9.0,F10.0,5H CFSD)
  980 FORMAT (1HO,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(1215)
  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,LEAPYR,N
      REAL  MINFW,MOCHAR(12),
     1SSF(12),SAF(12),AREA,
     4BASIN(20),RGNAME(5),INFRO(20)
      COMMON/MIN/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 MUCHAR/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,COMHR,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),FIRST,CHECK
C     MAIN,INITL,READER,LAND AND CHANEL VARIABLES
      INTEGER ELE,ELEMTS,
     1RTEINT,AVEPE,VARK,
     2VARL,VAREP
      REAL IMPV,L7SN,K3,K24EL,KV,LKK4,
     1LIRC4,LZSI,KS1V(20),KS1,K24L
      COMMON/MCL/EPDIST(24),EPXM,UZSN,CH,CC,SRC,DEC,
     1UZSI,SWI,GWSI,RESI,SRGSI,SCEPI,REPI,
     2CFSM,PREVEI,TRANST(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPF,SET,TIMEAR(10),PEADJ(12),
     5GAGEPE,POWER,BASEK,BASEL,IMPV,L7SN,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,NSTAT
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
      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(5,994) SOEP,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
      SMC=1020.0*SQRT(SS)/(NN*L)
      DEC=0.0096*((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,
     *MSTAT
      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
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```
      PLOTHK=0
      GO TO 1246
 1246 CKTEST=1
      GO TO 1248
 1247 HRTEST=1
 1248 READ(5,917) (TIMEAR(IE),IE=1,ELE)
      CFSM=28.9*24.0*AREA
      WRITE(6,918) FPNAME,AREA,KS1,RTEINT,COMPAR,CHECK,(TIMEAR(IE),
     1IE=1,ELE)
      IF (VARK.EQ.0) GO TO 1042
      WRITE(6,985) BASEK,(KSIV(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)GOTO 200
      INTR=-1*RTEINT
      KNX=ELEMTS-((ELEMTS/INTR)*INTR)
      ELE=ELEMTS/INTR
      IF(KNX.GT.0)ELE=ELE+1
      GOTO 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 (TKSIM.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) GAMEPE
  900 FORMAT (1H1)
  901 FORMAT (20A4)
  902 FORMAT (1H0,20A4)
  903 FORMAT (1H ,20X,20A4)
  904 FORMAT (1H0,53X,21HBASIC RUN INFORMATION)
  905 FORMAT (715,513)
  906 FORMAT (1H0,10HRUN BEGINS,1X,A4,5H 1,19,12,5X,8HRUN ENDS,1X,A4,1X,
     1I2,3H,19,I2)
  908 FORMAT (1H0,6X,13HRAINGAGE NAME,10X,2HK1,3X,4HIMPV,2X,
     14HEPXM,3X,4HUSN,3X,4HL7SN,4X,2HCB,4X,2HCC,4X,2HK3,4X,4HK24L,2X,
     25HK24EL,4X,4HL,5X,2HSS,5X,2HNN,4X,5HIHC,4X,4HKK24,4X,2HKV)
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  909 FORMAT (1H0,3F5.2,2F5.1,5F5.2)
  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,5HUZS,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,
     14HRINT,2X,7HCOMPARE,2X,5HCHECK,2X,10HHISTOGRAMS)
  915 FORMAT (7A4,2X,F10.2,F5.2,4I5)
  917 FORMAT (3UX,10F5.2)
  918 FORMAT (1H ,6X,7A4,F8.2,F6.2,I5,2I7,5X,9HTIMEDELAY,10F5.2)
  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 (2UX,F5.0,3F5.2,F5.3,F5.2)
  949 FORMAT (2X,F8.0,10F7.0)
  950 FORMAT (31S,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,4I5,3F8.0,I5)
  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=,F6.0,5X,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 (2F5.2,11D)
  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(33),HREW(6),RECEW(4),RECPZ(12)
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 MINEW,MOCHAR(12),SRF(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,MINEW,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),PWRMX,FR TME(7),PLOTMX,
     1ACTFLW(12,31),SIMFLW(12,31),FIRST,CHECK
C     MAIN,INITL,READER,LAND, AND CHANEL VARIABLES
      INTEGER FLE,FLEMTS,RTEINT,AVEPE,VARK,VARL,VAREP
      REAL IMPV,LZSN,K3,K24L,K24EL,KV,LKK4,LIRC4,LZSI,KS1,KS1V(20)
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      COMMON/MCL/EPDIST(24),EPXM,UZSN,CB,CC,SRC,DEC,
     1UZS1,SGWI,GWSI,RES1,SRGX1,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(10),PEADJ(12),
     5GAGEPE,POWER,BASEK,BASF ,IMPV,LZSN,K3,K24L,K24EL,KV,
     6LKK4,LIRC4,LZSI,KS1,K    ,MAXL,MINL,LAG(10),
     7IE,NHR,MOHR1,MOHR2,ELE,LLEMTS,VAREP,SDEP,EPBIAS,IXEP,
     8TEST1,TEST2,RTEINT,AVEPF,MARK,VARL,UZSNWF,AEPI,MSTAT
C     MAIN,LAND,CHANEL VARIABLES (11)
      INTEGER   PX(31,96),QUART
      INTEGER SIXHR
      REAL K1
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,QUART,PX
      IF ((YEAR.EQ.YR1).AND.(MONTH.EQ.MO1)) GO TO 1311
      GO TO 131
 1311 DO 1312 MO=1,12
      SSF(MO)=0.0
      DO 1312 IDA=1,31
 1312 SIMFLW(MO,IDA)=0.0
      WY=YEAR
      GOTO 138
131   IF(MONTH.EQ.1)GOTO 137
C***** NEWWY HAS BEEN CHANGED FROM 1 TO ZERO
      NEWWY=0
      LEAPYR=0
  138 IF ((WY-4*(WY/4)).EQ.0) LEAPYR=1
C**** READ ALL INPUT DATA BY MONTH
C     DAILY POTENTIAL EVAPOTRANSPIRATION
  137 IF (AVEPE.EQ.1) GO TO 1331
      DO 139 I=1,3
      READ(4,931) MO,CN,(RECOBS(II),II=1,11)
      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)
139   CONTINUE
C**** SKIP 3 LINES WITH DAILY RAIN INPUTS ON EVAPS FILE
      READ(4,934)
934   FORMAT(//)
C     ACTUAL MEAN DAILY FLOWS IN THOUSANDTHS OF CUB.MET.
 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 1345 MO=1,12
1345  SAF(MO)=0.0
      READ(8,932)MO,(RECORS(KK),KK=1,33)
      DO 135 IDA=1,31
C**** CHANGE METRIC TO BRITISH
      RECOBS(IDA)=RECOBS(IDA)*0.0353147
      IF(RECOBS(IDA).LE.0.0)GOTO 135
      SAF(MO)=SAF(MO)+RECORS(IDA)
135   ACTFLW(MO,IDA)=RECOBS(IDA)
   25 IF (ROUTE.EQ.0) GO TO 1420
      READ (DSKU) BO
```

```
      PS=0.0
      RUS=0.0
      GO TO 214
  213 PS=0.0
      RUS=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
      PS=0.0
      GO TO 2121
  216 PS=PR-EPX
      SCEP=SCEP+EPX
C     PS IS MAIN REACHING THE GROUND
C     UPPER ZONE CALCULATIONS
      SIMPV=SIMPV+PS*AT
C     PS*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
 2252 UZS=UZS+SHRD-RGX-RX
C UZS IS UPPER ZONE STORAGE VOLUME
C OVERLAND FLOW
      IF (RX.LE.RFS) GO TO 226
      DE=BEC*((RX-RES)**0.6)
C DE IS SURFACE DETENTION AT EQUILIBRIUM
      GO TO 227
226   DE=(RX+PX)/2.0
```

```
      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 (KUHLER.EQ.1) GO TO 204
      IF (AVEPE.EQ.0) GO TO 205
      EP=EVAP(MONTH)
      GO TO 2032
  205 EP=EVAP(MONTH,IDA)*PEADJ(MONTH)/25.4
      GO TO 2032
  204 EP=PE(IDA)*PEADJ(MONTH)/25.4
 2032 IF (VAREP.EQ.0) GO TO 202
      SD=EP*SDEP
      CALL IGAUSS(IX,EP,SD,EP,TV)
      EP=TV+EP*BIAS*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
      ND=(IHR-1)*4
      DO 218 I=1,4
      IN=ND+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 RO=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
```

```
  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 406
      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,I2,12F5.1)
  931 FORMAT (9X,I2,I1,11F6.2)
  932 FORMAT(3X,I3,(11F5.0))
  951 FORMAT (I2)
  970 FORMAT (I2,7X,3I3,2X,4F10.0,I5,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,C8,CC,SRC,DEC,
     1UZSI,SGW1,GWS1,RESI,SRGVI,SCEPI,REPI,
     2CFSM,PREVFI,TRANSI(48),EVAP(12,31),
     5FLOW(744),RO(744),EVAPH(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPE,SET,TIMEAR(10),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,MSTAT
C     MAIN,LAND,CHANEL VARIABLES (II)
      INTEGER   PX(31,96),QUART
      INTEGER SIXHR
      REAL KT
      COMMON/MLCS/KOHLER,PE(31),K1,LAST,IDA,IHR,MONTH,I,SIXHR,QUART,PX
C     LAND INITIAL VALUES
      SNO=0.0
      SNOS=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
```

```
      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(9,922) STATE,YR,MO,DA,CN,(RECPZ(LL),LL=1,12)
      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
C**** CHANGE RAIN INPUT IN MM TO INTEGER IN 1/10 MM
      RECPX(IHR)=IFIX(RECPZ(IHR)*10.0)
  108 PX(DA,NO)=RECPX(IHR)
      GO TO 110
 1081 IF (CNOHR.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,HREW
      IF (STATE.EQ.99) GO TO 401
      BASE=(DA-1)*24+(CN-1)*6
      DO 404 I=1,6
      MHR=BASE+I
```

```
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 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*CR*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
      RU(MHR)=RO
```

```
      SRO=SRO+RU
      IF ((IDA.EQ.LAST).AND.(IHR.EQ.24)) GO TO 246
      IHR=IHR+1
      IF (IHR.LE.24) GO TO 203
 2090 IHR=1
      IDA=IDA+1
      GO TO 203
C END OF HOUR AND DAY LOOP
C LAND CARRY/VER VALUES
246   UZSI=UZS
      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
     1INTEGER 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,PNEVPI,TRANSI(48),EVAP(12,31),
     3FLOW(744),RO(744),EVAPM(12),SRO,SROS,SIMPV,SINTF,
     4SGWF,SRECH,SPR,SPE,SET,TIMEAR(10),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,EPRIAS,IXEP,
     8ESTI,TEST2,RTEINT,AVEPE,VARK,VARL,UZSNWF,
     9AEPI,MSTAT
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
 3009 MOHR1=1
      MOHR2=LAST*24
      IE=MOHR2+48
      DO 3001 I=MOHR1,IE
3001  TRS(I)=0.0
      IF(RTEINT.LT.0)GOTO 100
      HALFR=(RTEINT-1)/2
      IF (VARK.LE.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=OHR+RTEINT*(IE-1)
304   TRS(I)=TRS(I)+RO(MHR)*CFSM*TIMEAR(IE)
      GOTO 305
100   INTR=-1*RTEINT
      KRX=ELEMTS-((ELEMTS/INTR)*INTR)
      DO 110 MHR=MOHR1,MOHR2
      MR=MHR-1
      IM=0
      IX=0
      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)GOTO 120
      IM=IM+1
      I=MR+IM
      TRS(I)=CON+TRS(I)
      CON=0.0
      IX=0
120   CONTINUE
      IF(KRX.GT.0)TRS(I+1)=TRS(I+1)+CON
110   CONTINUE
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 59
      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 PREVFI=PREV
      DO 311 IE=1,MAXL
311   TRANS1(IE)=TRS(MOHR2+IE)
      RETURN
      END
      SUBROUTINE IGAUSS(IX,S,AM,V)
C SUBROUTINE TO COMPUTE NORMAL RANDOM N
C  IX=ODD INTEGER ,LT.9 DIGITS TO BEGIN R.
C  IX=ODD INTEGER ,LT.9 DIGITS TO BEGIN
C  AM=MEAN  V=VALUE OF COMPUTED NORMAL
      DOUBLE PRECISION K,Y,C
      A=0.0
      DO 50 I=1,12
C START RANDU
      IY=IX*65539
      IF (IY) 5,6,6
 5    IY=IY+2483647+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 HOURLY(INFRO,MONTH,YEAR,FLOW)
C SUBROUTINE GENERATES SCALED INPUT FOR AUXILIARY PLOT PROGRAM      B24
      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*4.1
      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
      M2=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(4A4,1H 1Y,I2)
907   FORMAT(20A4)
908   FORMAT(35HBLACK IS OBSERVED--RED IS SIMULATED)
909   FORMAT(16F5.2)
      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 (2HMEAN 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
```

```
SUBFILE:PITH LC=8200 LENGTH:  25     HRAG

      LIST
      PROGRAM(PITE)
      INPUT 4=CR4
      INPUT 5=CR0
      INPUT 7=CR1
      INPUT 8=CR2
      INPUT 9=CR3
      OUTPUT 6=LP0
      CUMPRESS INTEGER AND LOGICAL
      CUMPACT DATA
      TRACE 0
      END
      MASTER PITE
C
C********  PITMAN HOURLY MODEL WITH ONE YEAR WARM-UP PERIOD WHICH
C********  IS NOT INCLUDED IN CALCS OF RUNOFF STATISTICS
C          MODIFIED INTO A CONTINUOUS CATCHMENT MODEL & IMPROVED
C          IN VARIOUS WAYS BY A.GORGENS,H.R.U.,RHODES UNIVERSITY
C                    1981+1982
C
      DIMENSION PE(31),FLOW(100),PERC(12),FIN(12),B(51),
     *DAYF(72,31),XOBS(12),FORS(72),GWF(24),ER(12),C(31),DRN(31)
      DIMENSION DOUT(32),DC(18),HP(24),NT(18),DTE(24),HRP(31,24),
     *RECP(12),HRF(24),TSURF(50),USURF(50),FINT(24)
      READ(9,1) G1,G2,AREA,POW,SL,ST,FT,AI,ZMINN,ZMAXN,PI,TL,LAG,G
     *L,R,SU,DIV,QOBS
      READ(9,209)TLI,THRES,DGF,DIVG
C
C     READ CATCHMENT INFORMATION
C     G1,G2 = GAUGE INDENTIFICATION
C     AREA  = CATCHMENT AREA - SQ.KM
C     POW   = POWER OF SOIL MOISTURE - PERCOLATION CURVE
C     SL    = SOIL MOISTURE STORAGE BELOW WHICH NO PERCOLATION OCCURS -
C     ST    = MAXIMUM SOIL MOISTURE CAPACITY -MM
C     FT    = PERCOLATION AT SOIL MOISTURE = ST -MM/DAY
C     AI    = IMPERVIOUS AREA AS PROPORTION OF TOTAL
C     ZMINN = NOMINAL MINIMUM INFILTRATION RATE (AT S=ST) -MM/HOUR
C     ZMAXN = NOMINAL MAXIMUM INFILTRATION RATE (AT S=ST) -MM/HOUR
C     PI    = INTERCEPTION STORAGE -MM
C     TL    = ROUTING K FOR SURFACE RUNOFF - HOURS
C     LAG   = LAG OF RUNOFF - HOURS
C     GL    = 1/RECESSION CONSTANT OF GROUNDWATER DEPLETION FOR GWS = ST
C             - DAYS
C     R     = COEFFICIENT OF EVAPORATION - SOIL MOISTURE RELATIONSHIP
C     SU    = DEPRESSION STORAGE-MM
C     DIV   = MAX,EXPECTED INTERFLOW RATE,
C             CONTROLS DIVISION OF INTERFLOW AND SURFACE FLOW( >>DIV FOR
C             HIGH INTERFLOW PRODUCTION) - MM/H
C     DIVG  = MAXIMUM GROUNDWATER RECHARGE RATE WHEN ST IS EXCEEDED,
C             CONTROLS DIVISION OF EXCESS BETWEEN INTERFLOW AND
C             GROUNDWATER - MM/H
C     QOBS  = OBSERVED GROUNDWATER DISCHARGE ON DAY PRIOR TO START OF SI
C             MULATION - THOUSANDTHS OF CUMECS
C     TLI   = ROUTING K FOR INTERFLOW(AT S=ST)-HOURS
C     THRES = DAILY AVERAGE FLOW ABOVE WHICH HOURLY OUTPUTS ARE
C             REQUIRED (IN CUMEC*1000)
```

```
C       DGF    = OBSERVED AVERAGE QUICKFLOW RATE DURING LAG+1 HOURS
C                PRIOR TO START OF SIMULATION - MM
C
        RZ=ZMINN/ZMAXN
      1 FORMAT(2A3,F6.0,2F3.0,F5.0,2F5.2,2F4.0,F4.1,F3.0,I2,F4.0,
     *2F3.1,2F5.2)
209     FORMAT(2F4.1,2F5.3)
C
C       READ EVAPORATION PAN MONTHLY COEFFICIENTS
C
        READ(9,86)(FR(I),I=1,12)
     86 FORMAT(12F5.2)
        SUS=0.
        PLS=0.
        DO 471 K=1,12
471     PERC(K)=0.0
        CF1=1./(TL+.5)
        CF2=.5*CF1
        LAG1=LAG+1
        GW=1./(24.*GL)
        DTF=DGF/2.0
C
C       CUMEC=FACTOR TO CHANGE MM TO THOUSANDTHS OF CUMEC
C
        CUMEC=(1-AI)*AREA*1000./3.6
        RI=(2.*TLI-1.0)/(2.0*TLI+1.0)
        REC1=1.0-RI
        TND=0.
        DT=1.0/24.0
C
C       SET TRIANGULAR DISTRIBUTION OF EVAPS OVER 07H00 TO 19H00 HOURS
C
        XK=0.0
        DO 767 L=1,24
        IF(L.LT.8.OR.L.GT.19) GOTO 768
        LX=L-7
        IF(LX.GT.6)LX=12-LX
        XPE=LX/36.0
        DTE(L)=0.5*(XK+XPE)
        XK=XPE
        GOTO 767
 768    DTE(L)=0.0
 767    CONTINUE
  11    M=0
 596    TFLOW=0.
        SINT=0.0
C
C       SET INITIAL CONDITIONS
C
        S1=SL+(ST-SL)*(QOBS/(FT*CUMEC))**(1./POW)
        IF(S1.GT.ST) S1=ST
        GWS=((QOBS*SQRT(ST))/(GW*CUMEC))**.666666
        A=FT/(ST-SL)**POW
        IF(S1-SL)14,14,15
   14   Q1=0.
        GOTO 70
   15   Q1=A*(S1-SL)**POW
   70   WRITE(6,112) Q1,G2
  112   FORMAT('1          AVERAGE HOURLY AND/OR, DAILY FLOWS FOR GAUGE ',
     *2A3,' IN THOUSANDTHS OF CUMECS',//10X,74('*')//,/)
C
```

```
C      READ FIRST AND LAST YEARS OF SIMULATION PERIOD
C
       READ(9,5) LY1,LY2
     5 FORMAT(2I5)
       NY=LY2-LY1+1
       NM=12*NY
       NYN=NY-1
       DO 896 N=1,NYN
       NE=12*N
       NB=NE-11
       READ(8,895)(FOBS(J),J=NB,NE)
895    FORMAT(2X,12F6.1)
896    CONTINUE
C
C      START OF LOOP COMPUTING MONTHLY RUNOFFS
C
       DO 49 J=1,NM
       MY=LY1+(J-1)/12
       M=M+1
       IF(M-12)13,13,12
    12 M=M-12
    13 FLOW(J)=0.
C
C      FILL IN ZERO RAIN HOURS
C
       DO 701 ND=1,31
       DO 701 NH=1,24
   701 HRP(ND,NH)=0.0
C
C      READ DAILY  A PAN DATA - MM
C
       READ(5,20)JY,MON,(DRN(ND),ND=1,31)
    20 FORMAT(2I3,(11F6.2))
       READ(5,21)JY,MON,(PE(ND),ND=1,31)
    21 FORMAT(2I3,(11F6.2))
       DO 81 ND=1,31
       IF(PE(ND))82,81,81
    82 NOFT=ND-1
       OFT=NOFT
       GOTO 83
    81 CONTINUE
       NOFT=31
       OFT=31.
C
C      EXCLUDE WARMUP YEAR FROM STATISTICS
C
    83 IF(JY.EQ.LY1-1900) GOTO 703
       TND=TND+OFT
C
C      READ HOURLY RAIN DATA FOR THIS MONTH
C
703    READ(7,700)IDENT,JY,MMM,ND,NUM,(RECP(I),I=1,12)
700    FORMAT(I2,7X,3I3,I2,12F5.1)
       IF(IDENT.EQ.99)GOTO 27
       DO 702 I=1,12
       NH=(NUM-1)*12+I
702    HRP(ND,NH)=RECP(I)
       GOTO 703
C
C      START OF LOOP COMPUTING DAILY RUNOFFS
C
```

```
   27 DO 48 IT=1,NOFT
      PE(IT)=PE(IT)*ER(MON)
      SZ=R*(ST/PE(IT))**0.5
      B(IT)=PE(IT)/(ST-SZ)
      C(IT)=-PE(IT)*SZ/(ST-SZ)
      DO 711 NH=1,24
711   HP(NH)=HRP(IT,NH)
C
C     START OF LOOP COMPUTING HOURLY RUNOFFS
C
  507 DO 509 K=1,24
      SURF=0.0
C
C     INTERCEPTION
C
501   PIS=PIS+HF(K)-PE(IT)*DTE(K)
      DPI=PE(IT)*DTE(K)
      IF(PIS)515,516,516
515   DPI=PE(IT)*DTE(K)+PIS
      PIS=0.
516   IF(PIS-PI)510,510,511
510   HP(K)=0.
      GOTO 512
511   HP(K)=(PIS-PI)
      PIS=PI
C
C     SURFACE RUNOFF
C
      ZMAX=(ZMAXN*4.)/(2.**(2.*S1/ST))
      ZMIN=RZ+ZMAX
      ZAVE=0.5*(ZMIN+ZMAX)
      IF(HP(K)-ZMIN-.001)200,200,206
  206 IF(HP(K)-ZAVE)202,203,203
202   SURF=2.*(HP(K)-ZMIN)**3/(3.*(ZMAX-ZMIN)**2)
      GOTO 200
203   IF(HP(K)-ZMAX)204,205,205
204   SURF=HP(K)-ZAVE+2.*(ZMAX-HP(K))**3/(3.*(ZMAX-ZMIN)**2)
      GOTO 200
205   SURF=HP(K)-ZAVE
200   HP(K)=HP(K)-SURF
C
C     DEPRESSION STORAGE AND INTERFLOW
C
  512 ADDSI=0.0
      SUS=SUS+SURF-PE(IT)*DTE(K)+DPI
      DSU=PE(IT)*DTE(K)-DPI
      IF(SUS-SU)120,120,121
121   ADDSI=SUS-SU
      SUS=SU
      GOTO 122
120     IF(SUS.GE.0.0)GOTO 122
        DSU=PE(IT)*DTE(K)-DPI+SUS
        SUS=0.0
  122 DIVA=DIV/(ADDSI+DIV)
      FINT(K+LAG1)=DIVA*ADDSI
      ADDS=(1.0-DIVA)*ADDSI
      TSURF(K+LAG1)=ADDS+QIMP
C
C     COMPUTE SOIL MOISTURE , EVAPORATION AND PERCOLATION
C
      IF(PIS-0.0)123,123,35
```

```
123   IF(SUS-0.0)125,125,33
125   IF(DTE(K),EQ,0,0)GOTO 33
      E1=C(IT)+B(IT)*S1-((DSU+DPI)*S1/ST)/DTE(K)
      IF(E1,GT,0,0)GOTO 36
   33 E1=0.
  126 IF(Q1)34,34,35
   34 SLOPE=0.
      GOTO 39
   35 SLOPE=A*POW*(S1-SL)**(POW-1.)
      GO TO 39
   36 IF(Q1)37,37,38
   37 SLOPE=B(IT)
      GOTO 39
   38 SLOPE=B(IT)+A*POW*(S1-SL)**(POW-1.)
   39 QM=(Q1+.5*HP(K)*SLOPE)/(1.+.5*DT*SLOPE)
      EM=E1/(1.0+0.5*DT*SLOPE)
      S2=S1+HP(K)-QM*DT-EM*DTE(K)
      IF(S2-ST)41,41,40
   40 EX=S2-ST
      T1=EX/(EX+ST-SL)
      T2=1.-T1
      QM=.5*(Q1+FT)*T2+FT*T1
      IF(DTE(K),EQ,0.0)GOTO 241
      EM=.5*(E1+PE(IT)-(DPI+DSU)/DTE(K))*T2+(PE(IT)-(DPI+DSU)/DTE(K))*T1
  241 SPILL=S1-ST+HP(K)-(QM)*DT-EM*DTE(K)
      Q1=FT
      S2=ST
C
C     DIVIDE SPILLAGE AND ADJUST INTERFLOW
C
      DIVB=(DIVG)/(SPILL+(DIVG))
      ADDG=DIVB*SPILL
      FINT(K+LAG1)=FINT(K+LAG1)+(SPILL-ADDG)
      FILT=QM*DT+ADDG
      GOTO 47
   41 IF(S2-SL)42,42,43
   42 Q2=0.
      IF(S2,LT,0,0)S2=0.0
      GOTO 44
   43 Q2=A*(S2-SL)**POW
44    FILT=0.5*DT*(Q1+Q2)
      Q1=Q2
   47 S1=S2
C
C     COMPUTE GROUNDWATER STORAGE AND DISCHARGE
C
      GWF(K)=GW*GWS**1.5/SQRT(ST)
      GWS=GWS+FILT-GWF(K)
509   CONTINUE
C
C     LAG AND ROUTE OF SURFACE RUNOFF AND INTERFLOW
C
      IF(J,NE,1,OR,IT,NE,1)GOTO 803
      DO 804 NH=1,LAG1
      TSURF(NH)=DTF
      PSURF(NH)=DGF
803   DO 800 NH=2,25
      RSURF(NH+LAG)=RSURF(NH+LAG-1)+CF1*(TSURF(NH+LAG-1)-RSURF(NH+LAG-1)
     *)+CF2*(TSURF(NH+LAG)-TSURF(NH+LAG-1))
800   IF(RSURF(NH+LAG),LT,0.1E-06)RSURF(NH+LAG)=0.0
      DOUT(IT)=0.0
```

```
123   IF(SUS-0.0)125,125,33
125   IF(DTE(K),EQ.0.0)GOTO 33
      E1=C(IT)+B(IT)*S1-(DSU+DPI)*S1/ST)/DTE(K)
      IF(E1.GT.0.0)GOTO 36
   33 E1=0.
  126 IF(Q1)34,34,35
   34 SLOPE=0.
      GOTO 39
   35 SLOPE=A*POW*(S1-SL)**(POW-1.)
      GO TO 39
   36 IF(Q1)37,37,38
   37 SLOPE=B(IT)
      GOTO 39
   38 SLOPE=B(IT)+A*POW*(S1-SL)**(POW-1.)
   39 QM=(Q1+.5*HP(K)*SLOPE)/(1.+.5*DT*SLOPE)
      EM=E1/(1.0+0.5*DT*SLOPE)
      S2=S1+HP(K)-QM*DT-EM*DTE(K)
      IF(S2-ST)41,41,40
   40 EX=S2-ST
      T1=EX/(EX+ST-SL)
      T2=1.-T1
      QM=.5*(Q1+FT)*T2+FT*T1
      IF(DTE(K),EQ.0.0)GOTO 241
      EM=.5*(E1+PE(IT)-(DPI+DSU)/DTE(K))*T2+(PE(IT)-(DPI+DSU)/DTE(K))*T1
  241 SPILL=S1-ST+HP(K)-(QM)*DT-EM*DTE(K)
      Q1=FT
      S2=ST
C
C     DIVIDE SPILLAGE AND ADJUST INTERFLOW
C
      DIVB=(DIVG)/(SPILL+(DIVG))
      ADDG=DIVB*SPILL
      FINT(K+LAG1)=FINT(K+LAG1)+(SPILL-ADDG)
      FILT=QM*DT+ADDG
      GOTO 47
   41 IF(S2-SL)42,42,43
   42 Q2=0.
      IF(S2.LT.0.0)S2=0.0
      GOTO 44
   43 Q2=A*(S2-SL)**POW
44    FILT=0.5*DT*(Q1+Q2)
      Q1=Q2
   47 ST=S2
C
C     COMPUTE GROUNDWATER STORAGE AND DISCHARGE
C
      GWF(K)=GW*GWS**1.5/SQRT(ST)
      GWS=GWS+FILT-GWF(K)
509   CONTINUE
C
C     LAG AND ROUTE OF SURFACE RUNOFF AND INTERFLOW
C
      IF(J.NE.1.OR.IT.NE.1)GOTO 803
      DO 804 NH=1,LAG1
      TSURF(NH)=DTF
804   RSURF(NH)=DGF
803   DO 800 NH=2,25
      RSURF(NH+LAG)=RSURF(NH+LAG-1)+CF1*(TSURF(NH+LAG-1)-RSURF(NH+LAG-1)
     *)+CF2*(TSURF(NH+LAG)-TSURF(NH+LAG-1))
800   IF(RSURF(NH+LAG).LT.0.1E-06)RSURF(NH+LAG)=0.0
      DOUT(IT)=0.0
```

```
      DO 837 NH=2,25
      RINT=RECI*SINT1
      SINT2=SINT1-RINT+FINT(NH+LAG)
      RINT=RECI*0.5*(SINT1+SINT2)
      SINT2=SINT1-RINT+FINT(NH+LAG)
      FINT(NH+LAG)=RINT
837   SINT1=SINT2
      DO 802 NH=1,24
       HRF(NH)=(GWF(NH)+FINT(NH+1)+RSURF(NH+1))*CUMEC
802   DOUT(IT)=DOUT(IT)+HRF(NH)/24.0
      FLOW(J)=FLOW(J)+DOUT(IT)*0.0864
      IF(MY.EQ.LY1)GOTO 806
      DAYF(J-12,IT)=DOUT(IT)/1000.0
      GUTO 806
      IF(JY.EQ.(LY1-1900))GOTO 806
      IF(DOUT(IT)-THRES)806,805,805
805   WRITE(6,807)IT,MON,MY,(HRF(NH),NH=1,24)
807   FORMAT(2I3,I5,24F5.0)
806   DO 808 NH=1,LA61
      FINT(NH)=FINT(24+NH)
      TSURF(NH)=TSURF(24+NH)
808   RSURF(NH)=RSURF(24+NH)
   48 CONTINUE
      IF(MY.EQ.LY1)GOTO 49
  113 WRITE(6,111) MY,MON,(DOUT(KK),KK=1,NOFT)
  111 FORMAT(I5,I3,11F6.0,//,8X,11F6.0,//,8X,11F6.0)
      TFLOW=TFLOW+FLOW(J)
   49 CONTINUE
      AI=AI*100.
      WRITE(6,61)G1,G2,AREA
   61 FORMAT(///,10X,'SYNTHESIZED RUNOFF AT GAUGE ',2A3,'  CATCHMENT ARE
     *A=',F7.1,'SQ.KM  ',/10X,35('*'),2X,27('*'),/)
      WRITE(6,62)POW,SL,ST,FT,AI,LAG,DIV
   62 FORMAT('   POW=',F4.1,'   SL=',F5.0,'MM   ST=',F5.0,'MM   FT=',
     *F6.3,' MM/DAY   AI=',F4.1,' %    LAG=',I1,' HRS   DIV= ',F4.2,//)
      WRITE(6,78)ZMINN,ZMAXN,PI,GL,TL
   78 FORMAT('    ZMINN=',F5.2,' MM/HOUR    ZMAXN=',F5.2,' MM/HOUR
     *PI=',F4.1,' MM   GL=',F4.1,' DAYS   TL=',F4.1,' HRS',/)
      WRITE(6,517)R,SU,TLI,DGF,THRES,DIVG
517   FORMAT('    R=',F4.2,'SU = ',F4.1,' TLI=',F4.1,'HOURS   DGF=',F5.3,
     *'MM   THRES = ',F6.1,' CUMEC/1000   DIVG = ',F6.3,' MM/H'//)
      DO 74 M=13,NM,12
      ME=M+11
      MY=LY1-1+ME/12
      FYC=0.0
      XYC=0.0
      DO 53 J=M,ME
      K=J-M+1
      XOBS(K)=FOBS(J-12)
      FIN(K)=FLOW(J)
   73 PERC(K)=PERC(K)+FIN(K)
      XYC=XYC+XOBS(K)
      FLOW(J-12)=FLOW(J)
   53 FYC=FYC+FIN(K)
   54 WRITE(6,55)MY,(FIN(N),N=1,12),FYC
   55 FORMAT(//18,12F8.1,F10.1)
      WRITE(6,491)(XOBS(N),N=1,12),XYC
491   FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
74    CONTINUE
      NM=NM-12
      CALL APLT(FOBS,FLOW,NM,1)
```

```
      DO 837 NH=2,25
      RINT=RECI*SINT1
      SINT2=SINT1-RINT+FINT(NH+LAG)
      RINT=RECI*0.5*(SINT1+SINT2)
      SINT2=SINT1-RINT+FINT(NH+LAG)
      FINT(NH+LAG)=RINT
837   SINT1=SINT2
      DO 802 NH=1,24
       HRF(NH)=(GWF(NH)+FINT(NH+1)+RSURF(NH+1))*CUMEC
802   DOUT(IT)=DOUT(IT)+HRF(NH)/24.0
      FLOW(J)=FLOW(J)+DOUT(IT)*0.0864
      IF(MY.EQ.LY1)GOTO 806
      DAYF(J-12,IT)=DOUT(IT)/1000.0
      GOTO 806
      IF(JY.EQ.(LY1-1900))GOTO 806
      IF(DOUT(IT)-THRES)806,805,805
805   WRITE(6,807)IT,MON,MY,(HRF(NH),NH=1,24)
807   FORMAT(213,I5,24F5.0)
806   DO 808 NH=1,LAG1
      FINT(NH)=FINT(24+NH)
      TSURF(NH)=TSURF(24+NH)
808   RSURF(NH)=RSURF(24+NH)
   48 CONTINUE
      IF(MY.EQ.LY1)GOTO 49
  113 WRITE(6,111) MY,MON,(DOUT(KK),KK=1,NOFT)
  111 FORMAT(I5,I3,11F6.0,/,8X,11F6.0,/,8X,11F6.0)
      TFLOW=TFLOW+FLOW(J)
   49 CONTINUE
      AI=AI*100.
      WRITE(6,61)G1,G2,AREA
   61 FORMAT(///,10X,'SYNTHESIZED RUNOFF AT GAUGE ',2A3,'  CATCHMENT ARE
     *A=',F7.1,'SQ.KM  ',/,10X,35('*'),2X,27('*'),/)
      WRITE(6,62)POW,SL,ST,FT,AI,LAG,DIV
   62 FORMAT('   POW=',F4.1,'   SL=',F5.0,'MM   ST=',F5.0,'MM   FT=',
     *F6.3,' MM/DAY   AI=',F4.1,' %     LAG=',I1,' HRS   DIV= ',F4.2,/)
      WRITE(6,78)ZMINN,ZMAXN,PI,GL,TL
   78 FORMAT('   ZMINN=',F5.2,' MM/HOUR    ZMAXN=',F5.2,' MM/HOUR
     *PI=',F4.1,' MM   GL=',F4.1,' DAYS   TL=',F4.1,' HRS',/)
      WRITE(6,517)R,SU,TLI,DGF,THRES,DIVG
517   FORMAT('    R=',F4.2,'SU = ',F4.1,' TLI=',F4.1,'HOURS   DGF=',F5.3,
     *'MM   THRES = ',F6.1,' CUMEC/1000   DIVG = ',F6.3,' MM/H'//)
      DO 74 M=13,NM,12
      ME=M+11
      MY=LY1-1+ME/12
      FYC=0.0
      XYC=0.0
      DO 53 J=M,ME
      K=J-M+1
      XOBS(K)=FOBS(J-12)
      FIN(K)=FLOW(J)
   73 PERC(K)=PERC(K)+FIN(K)
      XYC=XYC+XOBS(K)
      FLOW(J-12)=FLOW(J)
   53 FYC=FYC+FIN(K)
   54 WRITE(6,55)MY,(FIN(N),N=1,12),FYC
   55 FORMAT(//18,12F8.1,F10.1)
      WRITE(6,491)(XOBS(N),N=1,12),XYC
491   FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
74    CONTINUE
      NM=NM-12
      CALL AFIT(FOBS,FLOW,NM,1)
```

```
LY9=LY7+1
CALL BFIT(DAYF,NM,1,LY9)
STOP
END
```

```
SUBFILE:PITH LC=8200 LENGTH=  84     HRAG


      LIST
      PROGRAM(PITE)
      INPUT 4=CR4
      INPUT 5=CR0
      INPUT 7=CR1
      INPUT 8=CR2
      INPUT 9=CR3
      OUTPUT 6=LP0
      COMPRESS INTEGER AND LOGICAL
      COMPACT DATA
      TRACE 0
      END
      MASTER PITE
C
C********  PITMAN HOURLY MODEL WITH ONE YEAR WARM-UP PERIOD WHICH
C********  IS NOT INCLUDED IN CALCS OF RUNOFF STATISTICS
C          MODIFIED INTO A CONTINUOUS CATCHMENT MODEL & IMPROVED
C          IN VARIOUS WAYS BY A.GORGENS,H.R.U.,RHODES UNIVERSITY
C                1981+1982
C              +++++ RE-INFILTRATION INCLUDED +++++
C
      DIMENSION PE(31),FLOW(100),PERC(12),FIN(12),R(31),
     *DAYF(72,31),XOBS(12),FOBS(72),GWF(24),ER(12),C(31),DRN(31)
      DIMENSION DOUT(32),DC(18),HP(24),NT(18),DTE(24),HRP(31,24),
     *RECP(12),HRF(24),TSURF(50),PSURF(50),FINT(24)
      READ(9,1) G1,G2,AREA,POW,SL,ST,FT,AI,ZMINN,ZMAXN,PI,TL,LAG,G
     *L,R,SU,DIV,QOBS
      READ(9,209)TLI,THRES,DGF,DIVG
C
C     READ CATCHMENT INFORMATION
C     G1,G2 = GAUGE INDENTIFICATION
C     AREA  = CATCHMENT AREA - SQ.KM
C     POW   = POWER OF SOIL MOISTURE - PERCOLATION CURVE
C     SL    = SOIL MOISTURE STORAGE BELOW WHICH NO PERCOLATION OCCURS -
C     ST    = MAXIMUM SOIL MOISTURE CAPACITY -MM
C     FT    = PERCOLATION AT SOIL MOISTURE = ST -MM/DAY
C     AI    = IMPERVIOUS AREA AS PROPORTION OF TOTAL
C     ZMINN = NOMINAL MINIMUM INFILTRATION RATE (AT S=ST) -MM/HOUR
C     ZMAXN = NOMINAL MAXIMUM INFILTRATION RATE (AT S=ST) -MM/HOUR
C     PI    = INTERCEPTION STORAGE -MM
C     TL    = ROUTING K FOR SURFACE RUNOFF - HOURS
C     LAG   = LAG OF RUNOFF - HOURS
C     GL    = 1/RECESSION CONSTANT OF GROUNDWATER DEPLETION FOR GWS = ST
C             - DAYS
C     R     = COEFFICIENT OF EVAPORATION - SOIL MOISTURE RELATIONSHIP
C     SU    = DEPRESSION STORAGE-MM
C     DIV   = MAX.EXPECTED INTERFLOW RATE,
C             CONTROLS DIVISION OF INTERFLOW AND SURFACE FLOW( >>DIV FOR
C             HIGH INTERFLOW PRODUCTION) - MM/H
C     DIVG  = MAXIMUM GROUNDWATER RECHARGE RATE WHEN ST IS EXCEEDED,
C             CONTROLS DIVISION OF EXCESS BETWEEN INTERFLOW AND
C             GROUNDWATER - MM/H
C     QOBS  = OBSERVED GROUNDWATER DISCHARGE ON DAY PRIOR TO START OF SI
C             MULATION - THOUSANDTHS OF CUMECS
C     TLI   = ROUTING K FOR INTERFLOW(AT S=ST)-HOURS
C     THRES = DAILY AVERAGE FLOW ABOVE WHICH HOURLY OUTPUTS ARE
```

```
C                REQUIRED (IN CUMEC*1000)
C       DGF    = OBSERVED AVERAGE QUICKFLOW RATE DURING LAG+1 HOURS
C                PRIOR TO START OF SIMULATION - MM
C
      RZ=ZMINN/ZMAXN
    1 FORMAT(2A3,F6.0,2F3.0,F5.0,2F5.2,2F4.0,F4.1,F3.0,I2,F4.0,
     *2F3.1,2F5.2)
209   FORMAT(2F4.1,2F5.3)
C
C     READ EVAPORATION PAN MONTHLY COEFFICIENTS
C
      READ(9,86)(ER(I),I=1,12)
   86 FORMAT(12F5.2)
      SUS=0.
      PIS=0.
      DO 471 K=1,12
471   PERC(K)=0.0
      CF1=1./(TL+.5)
      CF2=.5*CF1
      LAG1=LAG+1
      GW=1./(24.*GL)
      DTF=DGF/2.0
C
C     CUMEC=FACTOR TO CHANGE MM TO THOUSANDTHS OF CUMEC
C
      CUMEC=(1-AI)*AREA*1000./3.6
      RI=(2.*TLI-1.0)/(2.0*TLI+1.0)
      RECI=1.0-RI
      TMD=0.
      DT=1.0/24.0
C
C     SET TRIANGULAR DISTRIBUTION OF EVAPS OVER 07H00 TO 19H00 HOURS
C
      XK=0.0
      DO 767 L=1,24
      IF(L.LT.8.OR.L.GT.19) GOTO 768
      LX=L-7
      IF(LX.GT.6)LX=12-LX
      XPE=LX/36.0
      DIE(L)=0.5*(XK+XPE)
      XK=XPE
      GOTO 767
 768  DIE(L)=0.0
 767  CONTINUE
  11  M=0
 596  TFLOW=0.
      SINT=0.0
      WRITE(6,7744)
7744  FORMAT(///8X,'PITMAN'S HOURLY MODEL PITR '
     *'(RE-INFILTRATION INCLUDED)'///)
C
C     SET INITIAL CONDITIONS
C
      S1=SL+(ST-SL)*(400BS/(FT*CUMEC))**(1./POW)
      IF(S1.GT.ST) S1=ST
      GWS=(((400BS*SQRT(ST))/(GW*CUMEC))**.6666667
      A=FT/(ST-SL)**POW
      IF(S1-SL)14,14,15
   14 Q1=0.
      GOTO 70
   15 Q1=A*(S1-SL)**POW
```

```
   70 WRITE(6,112) 61,62
  112 FORMAT('1',          AVERAGE HOURLY AND(OR) DAILY FLOWS FOR GAUGE ',
     *2A3,' IN THOUSANDTHS OF CUMECS',//,10X,74('*')//)
C
C     READ FIRST AND LAST YEARS OF SIMULATION PERIOD
C
      READ(9,5) LY1,LY2
    5 FORMAT(2I5)
      NY=LY2-LY1+1
      NM=12*NY
      NYN=NY-1
      DO 896 N=1,NYN
      NE=12*N
      NB=NE-11
      READ(8,895)(FOBS(J),J=NB,NE)
895   FORMAT(2X,12F6.1)
896   CONTINUE
C
C     START OF LOOP COMPUTING MONTHLY RUNOFFS
C
      DO 49 J=1,NM
      MY=LY1+(J-1)/12
      M=M+1
      IF(M-12)13,13,12
   12 M=M-12
   13 FLOW(J)=0.
C
C     FILL IN ZERO RAIN HOURS
C
      DO 701 ND=1,31
      DO 701 NH=1,24
  701 HRP(ND,NH)=0.0
C
C     READ DAILY  A PAN DATA - MM
C
      READ(5,20)JY,MON,(DRN(ND),ND=1,31)
   20 FORMAT(213,(11F6.2))
      READ(5,21)JY,MON,(PE(ND),ND=1,31)
   21 FORMAT(213,(11F6.2))
      DO 81 ND=1,31
      IF(PE(ND))82,81,81
   82 NOFT=ND-1
      OFT=NOFT
      GOTO 83
   81 CONTINUE
      NOFT=31
      OFT=31.
C
C     EXCLUDE WARMUP YEAR FROM STATISTICS
C
   83 IF(JY.EQ.LY1-1900) GOTO 703
      TND=TND+OFT
C
C     READ HOURLY RAIN DATA FOR THIS MONTH
C
703   READ(7,700)IDENT,JY,MMM,ND,NUM,(RECP(I),I=1,12)
700   FORMAT(I2,7X,3I3,I2,12F5.1)
      IF(IDENT.EQ.99)GOTO 27
      DO 702 I=1,12
      NH=(NUM-1)*12+I
702   HRP(ND,NH)=RECP(I)
```

```
      GOTO 703
C
C     START OF LOOP COMPUTING DAILY RUNOFFS
C
   27 DO 48 IT=1,NOFT
      PE(IT)=PE(IT)*ER(MON)
      SZ=R*(ST/PE(IT))**0.5
      B(IT)=PE(IT)/(ST-SZ)
      C(IT)=-PE(IT)*SZ/(ST-SZ)
      DO 711 NH=1,24
711   HP(NH)=HRP(IT,NH)
C
C     START OF LOOP COMPUTING HOURLY RUNOFFS
C
  507 DO 509 K=1,
      SURF=0.0
C
C     INTERCEPTION
C
501   PIS=PIS+HP(K)-PE(IT)*DTE(K)
      DPI=PE(IT)*DT
      IF(PIS)515,516,
515   DPI=PE(IT)*DTE(K)+PIS
      PIS=0.
516   IF(PIS-PI)510,510,511
510   HP(K)=0.
      GOTO 512
511   HP(K)=(PIS-PI)
      PIS=PI
C
C     SURFACE RUNOFF
C
      ZMAX=(ZMAXN+4.)/(2.**(2.*S1/ST))
      ZMIN=HZ+ZMAX
      ZAVE=0.5*(ZMIN+ZMAX)
      IF(HP(K)-ZMIN-.001)200,200,206
  206 IF(HP(K)-ZAVE)202,203,203
202   SURF=2.*(HP(K)-ZMIN)**3/(3.*(ZMAX-ZMIN)**2)
      GOTO 200
203   IF(HP(K)-ZMAX)204,205,205
204   SURF=HP(K)-ZAVE+2.*(ZMAX-HP(K))**3/(3.*(ZMAX-ZMIN)**2)
      GOTO 200
205   SURF=HP(K)-ZAVE
200   HP(K)=HP(K)-SURF
C
C     REINFILTRATION,DEPRESSION STORAGE & INTERFLOW
C
  512 ADDSI=0.0
      LCOUNT=0
      SUS2=SUS
  228 HP2=0.5*(SUS+SUS2)
      SURF2=0.0
      LCOUNT=LCOUNT+1
      IF(HP2-ZMIN-0.001)220,220,226
226   IF(HP2-ZAVE)222,223,223
222   SURF2=2.0*(HP2-ZMIN)**3.0/(3.0*(ZMAX-ZMIN)**2.0)
      GOTO 220
223   IF(HP2-ZMAX)224,225,225
224   SURF2=HP2-ZAVE+2.0*(ZMAX-HP2)**3.0/(3.0*(ZMAX-ZMIN)**2.0)
      GOTO 220
225   SURF2=HP2-ZAVE
```

```
220     DEPINF=HP2-SURF2
        SUS=SUS2+SURF-PE(IT)*DTE(K)+DPI-DEPINF
        DSU=PE(IT)*DTE(K)-DPI
        IF(SUS-SU)120,120,121
121     ADDSI=SUS-SU
        SUS=SU
        GOTO 122
120       IF(SUS,GE,0,0)GOTO 122
          DSU=PE(IT)*DTE(K)-DPI+SUS
          SUS=0,0
122       IF(LCOUNT,EQ,1)GOTO 228
          DIVA=DIV/(ADDSI+DIV)
        FINT(K+LAG1)=DIVA*ADDSI
        ADDS=(1,0-DIVA)*ADDSI
        TSURF(K+LAG1)=ADDS+QIMP
C
C       COMPUTE SOIL MOISTURE , EVAPORATION AND PERCOLATION
C
        IF(PIS-0,0)123,123,33
123     IF(SUS-0,0)125,125,33
125     IF(DTE(K),EQ,0,0)GOTO 33
        E1=C(IT)*B(IT)*S1-(DSU+DPI)*S1/ST),DTE(K)
        IF(E1,GT,U,0)GOTO 36
     33 E1=0,
    126 IF(Q1)34,34,35
     34 SLOPE=0,
        GOTO 39
     35 SLOPE=A*POW*(S1-SL)**(POW-1,)
        GO TO 39
     36 IF(Q1)37,37,38
     37 SLOPE=B(IT)
        GOTO 39
     38 SLOPE=B(IT)+A*POW*(S1-SL)**(POW-1,)
     39 QM=(Q1+,5*HP(K)*SLOPE)/(1,+,5*DT*SLOPE)
        EM=E1/(1,U+0,5*DT*SLOPE)
        S2=S1+HP(K)-QM*DT-EM*DTE(K)+DEPINF
        IF(S2-ST)41,41,40
     40 EX=S2-ST
        T1=EX/(EX+ST-SL)
        T2=1,-T1
        QM=,5*(Q1+FT)*T2+FT*T1
        IF(DTE(K),EQ,U,0)GOTO 241
        EM=,5*(E1+PE(IT)-(DPI+DSU)/DTE(K))*T2+(PE(IT)-(DPI+DSU)/DTE(K))*T1
    241 SPILL=S1-ST+HP(K)-(QM)*DT-EM*DTE(K)+DEPINF
        Q1=FT
        S2=ST
C
C       DIVIDE SPILLAGE AND ADJUST INTERFLOW
C
        DIVB=(DIVG)/(SPILL+(DIVG))
        ADDG=DIVB*SPILL
        FINT(K+LAG1)=FINT(K+LAG1)+(SPILL-ADDG)
        FILT=UM*DT+ADDG
        GOTO 47
     41 IF(S2-SL)42,42,43
     42 Q2=0,
        IF(S2,LT,0,0)S2=0,0
        GOTO 44
     43 Q2=A*(S2-SL)**POW
44      FILT=U,5*DT*(Q1+Q2)
        Q1=Q2
```

```
   47 S1=S2
C
C     COMPUTE GROUNDWATER STORAGE AND DISCHARGE
C
      GWF(K)=GW*GWS**1.5/SQRT(ST)
      GWS=GWS+FILT-GWF(K)
509   CONTINUE
C
C     LAG AND ROUTE OF SURFACE RUNOFF AND INTERFLOW
C
      IF(J.NE.1.OR.IT.NE.1)GOTO 803
      DO 804 NH=1,LAG1
      TSURF(NH)=DTF
804   RSURF(NH)=DGF
803   DO 800 NH=2,25
      RSURF(NH+LAG)=RSURF(NH+LAG-1)+CF1*(TSURF(NH+LAG-1)-RSURF(NH+LAG-1)
     *)+CF2*(TSURF(NH+LAG)-TSURF(NH+LAG-1))
800   IF(RSURF(NH+LAG).LT.0.1E-06)RSURF(NH+LAG)=0.0
      DOUT(IT)=0.0
      DO 837 NH=2,25
      RINT=REC1*SINT1
      SINT2=SINT1-RINT+FINT(NH+LAG)
      RINT=REC1*0.5*(SINT1+SINT2)
      SINT2=SINT1-RINT+FINT(NH+LAG)
      FINT(NH+LAG)=RINT
837   SINT1=SINT2
      DO 802 NH=1,24
       HRF(NH)=(GWF(NH)+FINT(NH+1)+RSURF(NH+1))*CUMEC
802   DOUT(IT)=DOUT(IT)+HRF(NH)/24.0
      FLOW(J)=FLOW(J)+DOUT(IT)*0.0864
      IF(MY.EQ.LY1)GOTO 806
      DAYF(M-12,IT)=DOUT(IT)/1000.0
      GOTO 806
      IF(JY.EQ.(LY1-1900))GOTO 806
      IF(DOUT(IT)-THRES)806,805,805
805   WRITE(6,807)IT,MON,MY,(HRF(NH),NH=1,24)
807   FORMAT(213,15,24F5.0)
806   DO 808 NH=1,LAG1
      FINT(NH)=FINT(24+NH)
      TSURF(NH)=TSURF(24+NH)
808   RSURF(NH)=RSURF(24+NH)
   48 CONTINUE
      IF(MY.EQ.LY1)GOTO 49
  113 WRITE(6,111) MY,MON,(DOUT(KK),KK=1,NOFT)
  111 FORMAT(15,I3,11F6.0,/,8X,11F6.0,/,8X,11F6.0)
      TFLOW=TFLOW+FLOW(J)
   49 CONTINUE
      AI=AI*100.
      WRITE(6,61)G1,G2,AREA
   61 FORMAT(///,10X,'SYNTHESIZED RUNOFF AT GAUGE ',2A3,'  CATCHMENT ARE
     *A=',F7.1,'SQ.KM  ',/1UX,35('*'),2X,27('*'),/)
      WRITE(6,62)POW,SL,ST,FT,AI,LAG,DIV
   62 FORMAT('   POW=',F4.1,'   SL=',F5.0,'MM   ST=',F5.0,'MM   FT=',
     *F6.3,' MM/DAY   AI=',F4.1,' %      LAG=',I1,' HRS   DIV= ',F4.2,/)
      WRITE(6,78)ZMINN,ZMAXN,DT,GL,L
   78 FORMAT('    ZMINN=',F5.2,' MM/HOUR    ZMAXN=',F5.2,' MM/HOUR
     *PI=',F4.1,' MM   GL=',F4.1,' DAYS   YL=',F4.1,' HRS',/)
      WRITE(6,517)R,SU,TLI,DGF,THRES,DIVG
517   FORMAT('    R=',F4.2,'SU = ',F4.1,' TLI=',F4.1,'HOURS   DGF=',F5.3,
     *'MM   THRES = ',F6.1,' CUMEC/1000   DIVG = ',F6.3,' MM/H'//)
      DO 74 N=13,NM,12
```

```
      ME=M+11
      MY=LY1-1+ME/12
      FYC=0.0
      XYC=0.0
      DO 53 J=M,ME
      K=J-M+1
      XOBS(K)=FOBS(J-12)
      FIN(K)=FLOW(J)
   73 PERC(K)=PERC(K)+FIN(K)
      XYC=XYC+XOBS(K)
      FLOW(J-12)=FLOW(J)
   53 FYC=FYC+FIN(K)
   54 WRITE(6,55)MY,(FIN(N),N=1,12),FYC
   55 FORMAT(//I8,12F8.1,F10.1)
      WRITE(6,491)(XOBS(N),N=1,12),XYC
491   FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
74    CONTINUE
      NM=NM-12
      CALL AFIT(FOBS,FLOW,NM,1)
      LY9=LY1 1
      CALL BFIT(DAYF,NM,1,LY9)
      STOP
      END
C ##########################################################
C SUBROUTINE AFIT BY P.J.T.ROBERTS***EXTENDED AND MODIFIED
C BY A.M.M.VORGENS,DURING 1980+1981+1982*****
C      X IS THE ARRAY OF OBSERVED MONTHLY DISCHARGE
C      Y IS THE ARRAY OF SIMULATED MONTHLY DISCHARGE
C      NMON IS THE LENGTH OF RECORD IN MONTHS
C      M1 IS THE FIRST MONTH OF RECORD (I.E. 1 FOR CALENDER
C      YEARS AND 10 FOR HYDROLOGICAL YEARS)
C ##########################################################
      SUBROUTINE AFIT(X,Y,NMON,M1)
      DIMENSION X(100),LRUN(200),Y(100),RESX(200),RESY(200)
      DIMENSION DIFRES(200),FDCX(60),FDCY(60),FLEV(60)
      DIMENSION AUTOX(200),AUTOY(200),JM(12),SMONX(12),SMO' '(12)
      INTEGER TEMP1,TEMP2,TEMP3,TEMP4
      TN=FLOAT(NMON)
      YEAR=FLOAT(NMON/12)
      TOTX=0.0
      TOTY=0.0
      N1=0
      N2=0
      NRUN=0
      NPOS=0
      NNN=0
      NPP=0
C  ===========================================================
C    SIGN TEST
C  ===========================================================
      DO 10 I=1,NMON
      SIG=Y(I)-X(I)
      IF (SIG.NE.0.0) GOTO 13
      NNN=0
      NPP=0
      GOTO 12
   13 IF (SIG.LT.0.0) GOTO 11
      IF (NPP.EQ.0) NPOS=NPOS+1
      NPP=NPP+1
      N1=N1+1
      NNN=0
```

```
SUBFILE:PITD LC=8200 LENGTH:  83    HRAG


      LIST
      PROGRAM(PITE)
      INPUT 5=CR0
      INPUT 7=CR1
      INPUT 8=CR2
      INPUT 9=CR3
      OUTPUT 6=LP0
      COMPRESS INTEGER AND LOGICAL
      COMPACT DATA
      TRACE 0
      END
      MASTER PITE
C********  PITMAN DAILY MODEL WITH ONE YEAR WARM-UP PERIOD WHICH
C********  IS NOT INCLUDED IN CALCS OF RUNOFF STATISTICS
C           MODIFIED BY A.GORGENS,M.R.U.,RHODES UNIV.,1981-1982
C                  +++ CHANNEL EVAPORATION INCLUDED +++
      DIMENSION  P(100),PE(31),FLOW(100),PERC(12),FIN(12),B(31),
     *SCLOS(100),DR(31),GWF(100),ER(12),C(31)
      DIMENSION DING(32),DINT(40),DOUTG(32),DOUTT(32),DOUT(32),
     *DAYF(72,31),MP(24),CARRY(8),FOBS(100),XOBS(100)
      READ(8,1) G1,G2,AREA,POW,SL,ST,FT,AI,ZMINN,ZMAXN,PI,TL,LAG,G
     *L,R,DIV,QOBS
C
C     READ CATCHMENT INFORMATION
C     G1,G2 = GAUGE INDENTIFICATION
C     AREA  = CATCHMENT AREA - SQ.KM
C     POW   = POWER OF SOIL MOISTURE - PERCOLATION CURVE
C     SL    = SOIL MOISTURE STORAGE BELOW WHITCH NO PERCOLATION OCCURS -
C             MM
C     ST    = MAXIMUM SOIL MOISTURE CAPACITY -MM
C     FT    = PERCOLATION AT SOIL MOISTURE = ST -MM/DAY
C     AI    = IMPERVIOUS AREA AS PROPORTION OF TOTAL
C     ZMINN = NOMINAL MINIMUM INFILTRATION RATE (AT S=ST) -MM/HOUR
C     ZMAXN = NOMINAL MAXIMUM INFILTRATION RATE (AT S=ST) -MM/HOUR
C     PI    = INTERCEPTION STORAGE -MM
C     TL    = ROUTING K FOR SURFACE RUNOFF - DAY
C     LAG   = LAG OF RUNOFF - DAYS
C     GL    = 1/RECESSION CONSTANT OF GROUNDWATER DEPLETION FOR GWS = ST
C             DAYS
C     R     = COEFFICENT OF EVAPORATION - SOIL MOISTURE RELATIONSHIP
C     DIV   = PROPORTION OF 'SPILL' INTO GROUNDWATER STORAGE
C     QOBS  = OBSERVED GROUNDWATER DISCHARGE ON DAY PRIOR TO START OF SI
C             MULATION - CUMECS
C     TRIB  = TOTAL TRIBUTARY LENGTH - KM
C     CHAN  = AVERAGE WIDTH OF FLOW AT BANKFULL DISCHARGE - M
C     QBANK = ESTIMATED BANKFULL DISCHARGE LEVEL(MEAN DAILY)
C             = CUMEC
C
      RZ=ZMINN/ZMAXN
    1 FORMAT(2A3,F6.0,2F3.0,F5.0,2F5.2,2F4.0,F4.1,F3.0,12,F4.0,
     *F3.1,2F5.2)
      READ(8,7722)TRIB,CHAN,QBANK
7722  FORMAT(3F5.3)
C
C     SUMMER STORM DURATION = AA + BB * DAILY RAINFALL(MM) - HOURS
C     WINTER STORM DURATION = CC + DD * DAILY RAINFALL(MM) - HOURS
```

```
C
      READ(6,2)AA,BB,CC,DD
    2 FORMAT(4F4.2)
C
C     READ EVAPORATION PAN MONTHLY COEFFICIENTS
C
      READ(6,86)(ER(I),I=1,12)
   86 FORMAT(12F5.2)
      SUR=0.0
      GROU=0.0
      AREAC=TRIB*CHAN/(AREA*1000.0)
      QBANK=QBANK*24.0*360      *1000.0*AREA)
      PIS=0.
      CF1=1./(TL+.5)
      CF2=.5*CF1
      LAG1=LAG+1
      GW=1./GL
      CUMEC=AREA*1000./86.4
C
C      UNDERFLOW BOUNDARY TO PREVENT ERROR MESSAGE
C     DURING ROUTING:  ZONK=1 CUMECDAY/10000 =8.64 M**3
C
       ZONK=8.64/(AREA*1000)
   11 M=0
      TFLOW=0.
      S1=SL+(ST-SL)*(QOBS/(FT*CUMEC))**(1./POW)
      IF(S1.GT.ST) S1=ST
      GWS=((QOBS*SQRT(ST))/(GW*CUMEC))**.666667
      A=FT/(ST-SL)**POW
      IF(S1-SL)14,14,15
   14 Q1=0.
      GOTO 70
   15 Q1=A*(S1-SL)**POW
   70 WRITE(6,112) Q1,G2
  112 FORMAT('1          AVERAGE DAILY FLOWS FOR GAUGE ',2A3,' IN THOUSAN
     *DTHS OF CUMECS',//,10X,81('*'),/,/)
C
C     READ FIRST AND LAST YEARS OF SIMULATION PERIOD
C
      READ(6,5) LY1,LY2
    5 FORMAT(2I5)
      NY=LY2-LY1+1
      NM=12*NY
      NYN=NY-1
C
C
C     READ MONTHLY RECORDED FLOWS
C
      DO 896 N=1,NYN
      NE=12*N
      NB=NE-11
      READ (7,895)(FOBS(J),J=NB,NE)
895   FORMAT(2X,12F6.1)
896   CONTINUE
C
C     START OF LOOP COMPUTING MONTHLY RUNOFFS
C
      DO 49 J=1,NM
      M=M+1
      IF(M-12) 3,13,12
   12 M=M-12
```

```
   13 FLOW(J)=0.
      GWF(J)=0.
      SCLOS(J)=0.0
C
C     READ DAILY RAINFALL AND A PAN DATA - MM
C
      READ(5,20)JY,MON,(DR(ND),ND=1,31)
   20 FORMAT(213,(11F6.2))
      READ(5,21)(PE(ND),ND=1,31)
   21 FORMAT(6X,(11F6.2))
      DO 81 ND=1,31
      IF(DR(ND))82,81,81
   82 NOFT=ND-1
      OFT=NOFT
      GOTO 27
   81 CONTINUE
      NOFT=31
      OFT=31.
C
C     START OF LOOP COMPUTING DAILY RUNOFFS
C
   27 DO 48 IT=1,NOFT
      PE(IT)=PE(IT)*ER(MON)
    9 SZ=R*(ST/PE(IT))**0.5
      B(IT)=PE(IT)/(ST-SZ)
   10 C(IT)=-PE(IT)*SZ/(ST-SZ)
      FILT=0.
      TSURF=0.
      DINT(IT+LAG1)=0.
      DING(IT+1)=0.
      IF(DR(IT))498,498,499
498   NHRS=0
      DURS=0.
      GOTO 507
C
C     DISAGGREGATION OF DAILY RAINFALL INTO HOURLY FALLS
C
499   NHRS=AA+BB*DR(IT)+0.5
      IF(MON.GT.3.AND.MON.LT.10)NHRS=CC + DD*DR(IT)+0.5
      DURS=NHRS
      IF(NHRS-23)503,503,500
500   NHRS=25
      DURS=25.
      GOTO 506
503   IF(NHRS-2)504,505,506
504   HP(1)=DR(IT)
      GO TO 507
505   HP(1)=0.2*DR(IT)
      HP(2)=0.8*DR(IT)
      GOTO 507
506   SP1=0.
      DO 508 K=1,NHRS
      SUMT=K
      SP2=DR(IT)*SUMT**2/(SUMT**2+(DURS-SUMT)**2)
      HP(K)=SP2-SP1
508   SP1=SP2
507   NHRS=NHRS+1
      HP(NHRS)=0.
C
C     START OF LOOP COMPUTING HOURLY RUNOFFS
C
```

```
      DO 509 K=1,NHRS
      IF(K-NHRS)513,514,514
514   DT=(24.-DURS)/24.
      GO TO 501
513   DT=1./24.
C
C     INTERCEPTION
C
501   PIS=PIS+PP(K)-PE(IT)*DT
      DPI=PE(IT)*DT
      IF(PIS)515,516,516
515   DPI=PE(IT)*DT+PIS
      PIS=0.
516   IF(PIS-PI)510,510,511
510   HP(K)=0.
      GOTO 512
511   HP(K)=(PIS-PI)
      PIS=PI
C
C     SURFACE RUNOFF
C
      TSURF=TSURF+HP(K)*AI
      ZMAX=(ZMAXM*4.)/(2.**(2.*S1/ST))
      ZMIN=RZ*ZMAX
      ZAVE=.5*(ZMIN+ZMAX)
      IF(ZMAX-ZMIN-.001)201,201,206
201   S
      C
  206 IF(HP(K)-ZAVE)202,203,203
202   SURF=2.*(HP(K)-ZMIN)**3/(3.*(ZMAX-ZMIN)**2)
      GOTO 200
203   IF(HP(K)-ZMAX)204,205,205
204   SURF=HP(K)-ZAVE+2.*(ZMAX-HP(K))**3/(3.*(ZMAX-ZMIN)**2)
      GOTO 200
205   SURF=HP(K)-ZAVE
200   HP(K)=HP(K)-SURF
      TSURF=TSURF+SURF
C
C     COMPUTE SOIL MOISTURE , EVAPORATION AND PERCOLATION
C
512   E1=C(IT)+B(IT)*S1-DPI*S1/ST
      IF(E1)33,33,36
   33 E1=0.
      IF(Q1)34,34,35
   34 SLOPE=0.
      GOTO 39
   35 SLOPE=A*POW*(S1-SL)**(POW-1.)
      GO TO 39
   36 IF(Q1)37,37,38
   37 SLOPE=B(IT)
      GOTO 39
   38 SLOPE=B(IT)+A*POW*(S1-SL)**(POW-1.)
   39 Q1=E1+Q1
      QM=(Q1+.5*HP(K)*SLOPE)/(1.+.5*DT*SLOPE)
      S2=S1+HP(K)-QM*DT
      IF(S2-ST)41,41,40
   40 EX=S2-ST
      T1=EX/(EX+ST-S1)
      T2=1.-T1
      QM=.5*(Q1+FT)*T2+FT*T1
      EM=.5*(L1+PE(IT)-DPI)*T2+(PE(IT)-DPI)*T1
```

```
      SPILL=S1-ST+HP(K)-(QM+EM)*DT
      FILT=FILT+QM*DT+SPILL*DIV
      TSURF=TSURF+SPILL*(1.-DIV)
      Q1=FT
      S2=ST
      GOTO 47
   41 IF(S2-SL)42,42,43
   42 Q2=0.
      IF(S2.LT.0.0)S2=0.0
      GOTO 44
   43 Q2=A*(S2-SL)**POW
44    FILT=FILT+.5*DT*(Q1+Q2)
      Q1=Q2
   47 S1=S2
509   CONTINUE
C
C     COMPUTE GROUNDWATER STORAGE AND DISCHARGE
C
      DINT(IT+LAG1)=DINT(IT+LAG1)+TSURF
      GF1=GW*GWS**1.5/SQRT(ST)
      SLOPE=1.5*GW*SQRT(GWS/ST)
      DING(IT+1)=(GF1+.5*FILT*SLOPE)/(1.+.5*SLOPE)
      GWS=GWS+FILT-DING(IT+1)
   48 CONTINUE
C
C     ROUTING OF SURFACE RUNOFF AND LAG OF ALL RUNOFF
C
      IF(J-1)107,107,108
  107 DO 600 KL=1,LAG1
      DOUTT(KL)=0.
  600 DINT(KL)=0.
      DOUTG(1)=DING(2)
      DING(1)=DING(2)
      NROUT=NOFT+1
      GOTO 109
  108 DOUTT(1)=DOUTT(NROUT)
      DOUTG(1)=DOUTG(NROUT)
      DINT(1)=STARTT
      DING(1)=STARTG
      IF(LAG)109,109,603
  603 DO 601 KL=1,LAG
  601 DINT(KL+1)=CARRY(KL)
  109 NCALC=NOFT+1
      DO 110 IROUT=2,NCALC
       IF(DINT(IROUT).LT.ZONK) DINT(IROUT)=0.0
       IF(DOUTT(IROUT-1).LT.ZONK) DOUTT(IROUT-1)=0.0
      DOUTG(IROUT)=DING(IROUT)
      DOUTT(IROUT)=DOUTT(IROUT-1)+CF1*(DINT(IROUT-1)-DOUTT(IROUT-1))+CF2
     **(DINT(IROUT)-DINT(IROUT-1))
      FLOW(J)=FLOW(J)+DOUTT(IROUT)
      GWF(J)=GWF(J)+DOUTG(IROUT)
      DOUT(IROUT)=(DOUTG(IROUT)+DOUTT(IROUT))
      RAT=DOUT(IROUT)/QBANK
      RAT=0.142.0*RAT**0.5-RAT
      CLOS=1.1*RAT*AREAC*PE(IROUT-1)
      RESF=DOUT(IROUT)-CLOS
      IF(RESF.LT.0.0)RESF=0.0
      SCLOS(J)=SCLOS(J)+(DOUT(IROUT)-RESF)
      DOUT(IROUT)=RESF*CUMEC
      IF(JY.EQ.LY1-1900)GOTO 110
      DAYF(J-12,IROUT-1)=DOUT(IROUT)/1000.0
```

```
  110 CONTINUE
      NROUT=NCALC
      STARTT=DINT(NROUT)
      IF(LAG)604,604,605
  605 DO 602 KL=1,LAG
  602 CARRY(KL)=DINT(NROUT+KL)
  604 STARTG=DING(NROUT)
      MY=LY1+(J-1)/12
      IF(JY.EQ.LY1-1900)GOTO 49
      MS=M
      IF(MS-12)113,113,114
  114 MS=MS-12
      MY=MY+1
  113 WRITE(6,111) MY,MS,(DOUT(KK),KK=2,NCALC)
  111 FORMAT(I5,I3,11F6.0,/,8X,11F6.0,/,8X,11F6.0)
      TFLOW=TFLOW+FLOW(J)+GWF(J)
      SUR =SUR+FLOW(J)
   49 CONTINUE
      SUR=100.0*(SUR/TFLOW)
      GROU=100.0-SUR
      AI=AI*100.
      WRITE(6,61)G1,G2,AREA
   61 FORMAT(///,10X,'SYNTHESIZED RUNOFF AT GAUGE ',2A3,'  CATCHMENT ARE
     *A=',F7.1,'SQ.KM  ',/1UX,35('*'),2X,27('*'),/)
      WRITE(6,62)POW,SL,ST,FT,AI,LAG,DIV
   62 FORMAT('   POW=',F4.1,'   SL=',F5.1,'MM   ST=',F6.2,'MM   FT=',
     *F7.4,' MM/DAY   AI=',F4.1,' %     LAG=',I1,' DAYS   DIV= ',F4.2,/)
      WRITE(6,78)ZMINN,ZMAXN,PI,GL,TL,R
   78 FORMAT('   ZMINN=',F5.2,' MM/HOUR   ZMAXN=',F5.2,' MM/HOUR
     *PI=',F4.1,' MM   GL=',F4.2,' DAYS   TL=',F4.2,' DAYS',
     *'       R= ',F5.2//)
      QBANK=QBANK*1000.0*AREA/(24.0*3600.0)
      WRITE(6,7733)TRIB,CHAN,QBANK
7733  FORMAT(/2X,'TRIB = ',F6.1,'KM  CHAN = ',F6.1,'M  QBANK = ',
     *F6.2,'CUMEC'//)
      WRITE(6,517)AA,BB
  517 FORMAT('   SUMMER DURATION OF RAIN(HOURS) =',F6.3,' + ',F6.3,
     *' * DAILY FALL(MM)',/,/)
      WRITE(6,467)CC,DD
  467 FORMAT('   WINTER DURATION OF RAIN(HOURS) =',F6.3,' + ',F6.3,
     *' * DAILY FALL(MM)',/,/)
      WRITE(6,520)TFLOW,SUR,GROU
  520 FORMAT(///1X,30('+')//1X,'TOTAL SIMULATED RUNOFF(MM)=',F10.3,
     */1X,'QUICKFLOW PART OF TOTAL RUNOFF(%)=',F5.1,/1X,'DELAYED',
     *' FLOW PART OF TOTAL RUNOFF(%)=',F5.1//1X,30('+')///)
      DO 74 M=13,NM,12
      ME=M+11
      MY=LY1-1+ME/12
      FYC=0.
      XYC=0.0
      DO 53 J=M,ME
      FLOW(J)=FLOW(J)*AREA
      GWF(J)=GWF(J)*AREA
      SCLOS(J)=SCLOS(J)*AREA
      K=J-M+1
      XOBS(K)=FOBS(J-12)
      FIN(K)=FLOW(J)+GWF(J)-SCLOS(J)
   73 PERC(K)=PERC(K)+FIN(K)
      XYC=XYC+XOBS(K)
      FLOW(J-12)=FIN(K)
   53 FYC=FYC+FIN(K)
```

```
   54 WRITE(6,55)MY,(FIN(N),N=1,12),FYC
   55 FORMAT(//18,12F8.1,F10.1)
      WRITE(6,491)(XOBS(N),N=1,12),XYC
491   FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
74    CONTINUE
      NM=NM-12
      CALL AFIT(FOBS,FLOW,NM,1)
      LY9=LY1+1
      CALL BFIT(DAYF,NM,1,LY9)
      STOP
      END
C ##########################################################
C SUBROUTINE AFIT BY P.J.T.ROBERTS***EXTENDED AND MODIFIED
C BY A.H.M.GORGENS,DURING 1980-1981-1982******
C     X IS THE ARRAY OF OBSERVED MONTHLY DISCHARGE
C     Y IS THE ARRAY OF SIMULATED MONTHLY DISCHARGE
C     NMON IS THE LENGTH OF RECORD IN MONTHS
C     M1 IS THE FIRST MONTH OF RECORD (I.E. 1 FOR CALENDER
C     YEARS AND 10 FOR HYDROLOGICAL YEARS)
C ##########################################################
      SUBROUTINE AFIT(X,Y,NMON,M1)
      DIMENSION X(100),LRUN(200),Y(100),RESX(200),RESY(200)
      DIMENSION DIFRES(200),FDCX(60),FDCY(60),FLEV(60)
      DIMENSION AUTOX(200),AUTOY(200),JM(12),SMONX(12),SMONY(12)
      INTEGER TEMP1,TEMP2,TEMP3,TEMP4
      TN=FLOAT(NMON)
      YEAR=FLOAT(NMON/12)
      TOTX=0.0
      TOTY=0.0
      N1=0
      N2=0
      NRUN=0
      NPOS=0
      NNN=0
      NPP=0
C     ================================================================
C       SIGN TEST
C     ================================================================
      DO 10 I=1,NMON
      SIG=Y(I)-X(I)
      IF (SIG.NE.0.0) GOTO 13
      NNN=0
      NPP=0
      GOTO 12
   13 IF (SIG.LT.0.0) GOTO 11
      IF (NPP.EQ.0) NPOS=NPOS+1
      NPP=NPP+1
      N1=N1+1
      NNN=0
      GOTO 12
   11 NPP=0
      IF (NNN.EQ.0) NRUN=NRUN+1
      NNN=NNN+1
      N2=N2+1
   12 TOTX=TOTX+X(I)
   10 TOTY=TOTY+Y(I)
      PIOT=((TOTY-TOTX)/TOTX)*100
      XMM=TOTX/TN
      YMM=TOTY/TN
      PMM=((YMM-XMM)/XMM)*100
      XMAM=TOTX/YEAR
```

```
SUBFILE:DALT LC=B200 LENGTH:  81    HRAG

      LIST
      PROGRAM(DALT)
      INPUT 5=CR0
      INPUT 7=CR1
      INPUT 3=CR2
      INPUT 4=CR3
      OUTPUT 6=LP0
      TRACE 0
      END
      MASTER DALT
C     ##########################################################
C     THIS PROGRAM GENERATES DAILY RUNOFF IN THOUSANDTHS OF CUMEC
C     FROM DAILY RAINFALL (MM) AND DAILY A- CLASS 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     DEVELOPED BY P.ROBERTS,H.R.U.,RHODES U.,1974-78
C     MODIFIED BY A.GORGENS,H.R.U.,RHODES U.,1982
C     ONE WARM-UP YEAR ALLOWED,EXCLUDED IN STATS. CALCS.
C     ##########################################################
      DIMENSION RAIN(31),EVAP(31),FLOW(31),RFLO(31),TRANS(20),LAST(12)
      DIMENSION DAYF(72,31),XOBS(12),FIN(12),PEADJ(12),DL(31),PL(31),
     *OBFL(84),QFL(31),FSIM(84),EVAP(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.),FIRST AND LAST YEARS
C     OF INPUT DATA USED FOR STMULATION, AND ALL FLAG SETTINGS
C     ************************************************************
      READ (5,2) AREA,IYR1,IYR2,LINE,ILIM,MVAP
    2 FURMAT (F8.2,5I5)
C     ************************************************************
C     READ IN INITIAL LEVEL AND ALL PARAMETERS
C     ALL 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     NB:FLAG SETTINGS FOR THE DALT RANGE OF MODELS ::
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 (5,3) SSL,SSM,SSB,POWER,BCUR,AMAX,PERC
    3 FORMAT (7F6.2)
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 EVAP(MM)
C       JAN-DEC,ONLY IF MVAP=1
C
        IF(MVAP.EQ.2)GOTO 799
        READ(5,766)(EVMO(NX),NX=1,12)
766     FORMAT(12F6.1)
799     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 (8F5 MONTH----ONLY IF LAG IS REQUIRED
C       ***************************************************************
C       READ IN PAN TO FREE WATER SURFACE EVAPORATION CONS ANTS
C       12 VALUES  JAN. TO DEC.
C       ***************************************************************
    9 READ (5,6) (PEADJ(K),K=1,12)
    6 FORMAT (12F5.3)
      NMON=IYR2-IYR1+1
      NMON=NMON*12
C
C       READ IN OBSERVED MONTHLY RUNOFF TOTALS
C
      KMON=NMON-12
      READ(4,782)(OBFL(K),K=1,KMON)
782   FORMAT(2X,12F6.2)
      ICON=0
      RTOT=0.
      AMENX=0.0
      AMENY=0.0
      COF=0.0
      TTEST=0.0
      RECO=0.0
      BASE=0.0
      SDEVY=0.0
      NOD=0
      TOVF=0.0
      TOTMM=0.0
      PSL=SSL
      RRA=SSB/SSM
      WRITE(6,1112)H1,H2,H3,H4
1112  FORMAT(1X,'SIMULATED RUNOFF AT ',4A8,//,
     *1X,'DAILY FLOWS IN THOUSANDTHS OF CUMEC;'/,
     *' MONTHLY FLOWS IN 10**3 MM**3'///)
      WRITE (6,7) SSL,SSM,SSB,POWFR,BCUR,AMAX,PERC,LAG
    7 FORMAT (1H1,1X,21HPARAMETER VALUES USED,//,6X,5HSSL,6X,3HSSM,
     *6X,3HSSB,4X,5HPOWER,5X,4HBCUR,5X,4HAMAX,5X,4HPERC,6X,3HLAG,/,
     *7(1X,F8.2),4X,I5)
      WRITE(6,111)AREA,NMON,LINE,ILIM,MVAP
111   FORMAT(/1X,37HAREA AND PROGRAM CONTROL FLAGS SET AS,//,
     *5X,4HAREA,5X,4HNMON,4X,4HLINE,5X,4HILIM,5X,4HMVAP,/,1X,
     *F8.2,4(1X,I8))
      DO 46 JK=1,31
46    OFL(JK)=0.0
C     ---------------------------------------------------------------
C       START OF THE MONTHLY LOOP
C     ---------------------------------------------------------------
      KQ=0.0
```

```
      DO 100 M=1,NMON
      KW=KQ+1
      IF(KQ.GT.12)KQ=1
      SPR=0.
      SPE=0.
      SET=0.
      SROS=0.0
      SGWF=0.0
      FSUM=0.
      TFLO=0.
      TPER=0.0
      OTFLO=0.0
C     ****************************************************************
C     READ IN ONE MONTH RAINFALL AND EVAPORATION DATA AS FOLLOWS
C     RAINFALL RECORD PRECEDES EVAP RECORD FOR EACH MONTH
C     ****************************************************************
      READ(7,10)NYR,NM,(RAIN(ND),ND=1,31)
   10 FORMAT(2I3,(11F6.2))
      NEND=LAST(NM)
      IF ((NYR-4*(NYR/4)).EQ.0).AND.(NM.EQ.2)) NEND=NEND+1
      IF(MVAP.EQ.2)GOTO 790
      DO 781 IZ=1,NEND
      EVAP(IZ)=EVMO(NM)/FLOAT(NEND)
781   CONTINUE
  790 READ(7,11)(EVAP(ND),ND=1,31)
   11 FORMAT(6X,(11F6.2))
C     ----------------------------------------------------------------
C     START OF THE DAY LOOP
C     ----------------------------------------------------------------
      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**0.5+RAT**0.5-RAT
      EP=EP*PRE
      PLE=SSL+PR
      IF(PLE.LE.EP)GOTO 200
      SET=SET+EP
      PLE=PLE-EP
      GOTO 210
200   SET=SET+PLE
      PLE=0.0
210   OVF=PLE-SSM
      DL(IDA)=PLE
      IF(OVF.GT.0.0)GOTO 220
      SSL=PLE
      FLOW(IDA)=0.0
      OVF=0.0
      GOTO 230
220   FLOW(IDA)=OVF*AREA
      SROS=SROS+OVF
      FSUM=FSUM+OVF
      SSL=SSM
C
C     THE NON-LINEAR STORAGE 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)GOTO 240
      BF=0.0
      GOTO 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.0.0)SSL=0.0
      PSL=PSL-BF*FAT
      FLOW(IDA)=FLOW(IDA)+(BF*AREA)
      FSUM=FSUM+BF
250   IF(LAG.GT.0.0)GOTO 50
      TFLO=TFLO+FLOW(IDA)
50    CONTINUE
      TOVF=TOVF+SROS
C     ------------------------------------------------------------------
C     END OF DAY LOOP AND START OF TIME DELAY SECTION
C     ------------------------------------------------------------------
      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)/(24.0*3.6)
      GO TO 93
   94 I=I+1
      TRANS(I)=FLOW(J)
   93 CONTINUE
      DO 95 NJ=1,NEND
      TFLO=TFLO+RFLO(NJ)
      RFLO(NJ)=RFLO(NJ)*1000.
      IF(NYR.EQ.IYR1-1900)GOTO 95
      DAYF(M-12,NJ)=RFLO(NJ)/1000.0
```

```
   95 CONTINUE
      FSIM(M)=TFLO
      GOTO 1113
      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//,
     3 13HTOTAL FLOW = ,F8.2//1X,19H DEEP PERCOLATION = ,F8.2)
 1113   IF(NYR.EQ.IYR1-1900)GOTO 100
  113 WRITE(6,1111) NYR,KQ,(RFLO(KK),KK=1,NEND)
 1111 FORMAT(I5,13,11F6.0,//,8X,11F6.0,//,8X,11F6.0)
      TOTMM=TOTMM+FSUM
  100 CONTINUE
C
C     END OF MONTH LOOP
C
      IF(TOTMM.LE.0.0)GOTO 919
      SUR=100.0*(TOVF/TOTMM)
      GROU=100.0-SUR
919   WRITE(6,520)TOTMM,SUR,GROU
520   FORMAT(///1X,30('+')//1X,'TOTAL SIMULATED RUNOFF(MM)=',F10.3,
     */1X,'QUICKFLOW PART OF TOTAL RUNOFF(%)=',F5.1,/1X,'DELAYED',
     *' FLOW PART OF TOTAL RUNOFF(%)=',F5.1//1X,30('+')//)
      DO 74 M=13,NMON,12
      ME=M+11
      MY=IYR1-1+ME/12
      FYC=0.
      XYC=0.0
      DO 53 J=M,ME
      K=J-M+1
      XOBS(K)=OBFL(J-12)
      FIN(K)=FSIM(J)
      XYC=XYC+XOBS(K)
      FSIM(J-12)=FIN(K)
   53 FYC=FYC+FIN(K)
   54 WRITE(6,55)MY,(FIN(N),N=1,12),FYC
   55 FORMAT(//I8,12F8.1,F10.1)
      WRITE(6,491)(XOBS(N),N=1,12),XYC
491   FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
74    CONTINUE
      NMON=NMON-12
      CALL AFIT(OBFL,FSIM,NMON,1)
      LY9=IYR1+1
      CALL BFIT(DAYF,NMON,1,LY9)
      STOP
      END
C ##################################################################
C SUBROUTINE AFIT BY P.J.T.ROBERTS***EXTENDED AND MODIFIED
C BY A.M.M.GORGENS,DURING 1980-1981-1982******
C     X IS THE ARRAY OF OBSERVED MONTHLY DISCHARGE
C     Y IS THE ARRAY OF SIMULATED MONTHLY DISCHARGE
C     NMON IS THE LENGTH OF RECORD IN MONTHS
C     M1 IS THE FIRST MONTH OF RECORD (I.E. 1 FOR CALENDER
C     YEARS AND 10 FOR HYDROLOGICAL YEARS)
C ##################################################################
      SUBROUTINE AFIT(X,Y,NMON,M1)
      DIMENSION X(100),LRUN(200),Y(100),RESX(200),RESY(200)
      DIMENSION DIFRES(200),FDCX(60),FDCY(60),FLEV(60)
```

```
SUBFILE:PITM LC=8300 LENGTH=  58     HRAG


      LIST
      PROGRAM (BILL)
      INPUT 5=CR0
      OUTPUT 6=LP0
      INPUT 8=CR2
      INPUT 7=CR1
      COMPRESS INTEGER AND LOGICAL
      TRACE 0
      END
      MASTER BILL
C     ==========*=========*=========*=
```

```
   60 READ(5,5) LY1,LY2
    5 FURMAT(215)
      NY=LY2-LY1+1
      NM=12*NY
C     ***************************************************************
C     READ MONTHLY CATCHMENT RAINFALLS,PAN EVAPS AND OBSERVED FLOWS
C     ***************************************************************
      DO 6 N=1,NY
      NEND=12*N
      NBEG=NEND-11
      READ(5,7) IYC,(P(J),J=NBEG,NEND)
      READ(8,7) IYC,(PE(J),J=NBEG,NEND)
    7 FURMAT(I2,12F6.2)
    6 CONTINUE
      NYN=NY-1
      DO 707 N=1,NYN
      NE=12*N
      NB=NE-11
      READ(7,708)IYC,(FOBS(J),J=NB,NE)
708     FORMAT(I2,12F6.1)
707   CONTINUE
C     ---------------------------------------------------------------
C     COMPUTE COEFFICIENTS RELATING EVAPORATION TO STORAGE
C     ---------------------------------------------------------------
      MON=0
      DO 10 J=1,NM
      MON=MON+1
      IF(MON.GT.12)MON=1
      PE(J)=PE(J)*ER(MON)
      SZ=R*(ST/PE(J))**0.50
      B(J)=PE(J)/(ST-SZ)
10    C(J)=-PE(J)*SZ/(ST-SZ)
      M=0
C     ---------------------------------------------------------------
C     INITIALISE STORAGE AND COMPUTE INITIAL CATCHMENT RUNOFF
C     ---------------------------------------------------------------
      TFLOW=0.
      S1=.2U*ST
      AY=FT/(ST-SL)**POW
      IF(S1-SL)14,14,15
   14 Q1=0.
      FG1=0.
      FI1=0.
      GOTO 70
   15 Q1=AY*(S1-SL)**POW
      IF(Q1-GW)83,82,82
   83 FG1=Q1
      FI1=0.
      GOTO 70
   82 FG1=GW
      FI1=Q1-GW
C     ---------------------------------------------------------------
C     START OF LOOP CALCULATING MONTHLY RUNOFFS
C     ---------------------------------------------------------------
   70 DO 49 J=1,NM
   13 FLOW(J)=AI*P(J)
      GWF(J)=0.
      IF(P(J))90,90,91
   90 DE=0.
      GOTO 92
   91 DE=X*(1.-EXP(Y*P(J)))
```

```
   92 E1=C(J)+B(J)*S1-DE*S1/ST
      IF(E1)17,18,18
   17 E1=0.
   18 QT=QT+E1
      IF(NIT)19,19,30
C     ***************************************************************
C     READ DAILY RAINFALL DATA (MM)
C     ***************************************************************
   19 READ(5,20)JY,MON,(DR(ND),ND=1,31)
   20 FORMAT(213,(16F4.1))
      DPI=PI
C     ---------------------------------------------------------------
C     COMPARE MONTHLY RAINFALL TOTALS AT DAILY GAUGE WITH THAT OF
C     CATCHMENT MEAN AND ADJUST DAILY RAINFALL TOTALS ACCORDINGLY
C     ---------------------------------------------------------------
      SDR=0.
      DO 22 ND=1,31
      IF(DR(ND))22,22,21
   21 SDR=SDR+DR(ND)
   22 CONTINUE
      IF(P(J))23,23,24
   23 SDR=1.
      GOTO 25
   24 IF(SDR)29,29,25
   25 DO 28 ND=1,31
      IF(DR(ND))26,26,27
   26 NOFT=ND-1
      OFT=NOFT
      DI=1./OFT
      GOTO 32
   27 DR(ND)=DR(ND)*P(J)/SDR
   28 CONTINUE
      NOFT=31
      DI=1./31.
      GOTO 32
   29 NOFT=30
      DI=1./30.
   30 IF(P(J))57,57,56
C     ---------------------------------------------------------------
C     COMPUTE COEFFICIENTS(W,EN) FOR SYNTHESIZING MASS CURVE OF RAINFALL
C     ---------------------------------------------------------------
   56 W=-2.1.3732*(P(J)+1.6)**.8
      W=W/P(J)
      EN=1.28/(1.02-W)**1.49
      IF(EN-120.)65,65,64
   64 EN=120.
C     ---------------------------------------------------------------
C     COMPUTE INCREMENTAL RAINFALLS FROM SYNTHETIC MASS CURVE
C     ---------------------------------------------------------------
   65 SP1=0.
      SUMT=0.
      DO 31 IT=1,NOFT
      SUMT=SUMT+DT
      SP2=P(J)*SUMT**EN/(SUMT**EN+(1.-SUMT)**EN)
      DR(IT)=SP2-SP1
   31 SP1=SP2
      GOTO 32
   57 DO 58 IT=1,NOFT
   58 DR(IT)=0.
   32 DZMIN=ZMIN*DT
      DZMAX=ZMAX*DT
```

```
      DZAVE=.5*(DZMIN+DZMAX)
C     ------------------------------------------------------------------
C     START OF LOOP CALCULATING RUNOFF FOR EACH TIME STEP
C     ------------------------------------------------------------------
      DO 48 IT=1,NOFT
      SURF=0.
      IF(P(J))100,100,101
  100 DPI=0.
      GOTO 102
  101 DPI=DE*DR(IT)/P(J)
  102 DR(IT)=(1.-AI)*(DR(IT)+DPI)
      IF(DR(IT))84,85,85
   84 DR(IT)=0.
C     ------------------------------------------------------------------
C     COMPUTE SURFACE RUNOFF
C     ------------------------------------------------------------------
   85 IF(DR(IT)-DZMIN-.0001)200,200,201
  201 IF(DR(IT)-DZAVE)202,203,203
  202 SURF=2.*(DR(IT)-DZMIN)**3/(3.*(DZMAX-DZMIN)**2)
      GOTO 200
  203 IF(DR(IT)-DZMAX)204,205,205
  204 SURF=DR(IT)-DZAVE+2.*(DZMAX-DR(IT))**3/(3.*(DZMAX-DZMIN)**2)
      GOTO 200
  205 SURF=DR(IT)-DZAVE
  200 DR(IT)=DR(IT)-SURF
C     ------------------------------------------------------------------
C     COMPUTE SOIL MOISTURE AT END OF TIME INTERVAL
C     ------------------------------------------------------------------
      IF(E1)33,33,36
   33 IF(Q1)34,34,35
   34 SLOPE=0.
      GOTO 39
   35 SLOPE=AY*POW*(S1-SL)**(POW-1.)
      GOTO 39
   36 IF(Q1)37,37,38
   37 SLOPE=B(J)
      GOTO 39
   38 SLOPE=B(J)+AY*POW*(S1-SL)**(POW-1.)
   39 DM=(Q1+.5*DR(IT)*SLOPE)/(1.+.5*DT*SLOPE)
      S2=S1+DR(IT)-DM*DT
      IF(S2-ST)41,41,40
C     ------------------------------------------------------------------
C     COMPUTE SURFACE RUNOFF DUE TO EXCEEDENCE OF SOIL MOISTURE CAPACITY
C     ------------------------------------------------------------------
   40 EX=S2-ST
      T1=EX/(EX+ST-S1)
      T2=1.-T1
      DM=.5*(S1+ST)*T2+FT*T1
      EM=.5*(E1+PE(J)-DE)*T2+(PE(J)-DF)*T1
      SPILL=S1-ST+DR(IT)-DT*(DM+EM)
      DFLOW=SPILL+DT*(DM-GW)
      GFLOW=DT*GW
      E1=PE(J)
      Q1=FT
      Q1=E1+Q1
      S2=ST
      GOTO 47
C     ------------------------------------------------------------------
C     COMPUTE RUNOFF RELATED TO SOIL MOISTURE CONTENT
C     ------------------------------------------------------------------
   41 IF(S2-SL)42,42,43
```

```
   42 QZ=0.
      FG2=0.
      FI2=0.
      GOTO 44
   43 QZ=AY*(S2-SL)**POW
      IF(Q2-GW)16,94,94
   16 FG2=QZ
      FI2=0.
      GOTO 44
   94 FG2=GW
      FI2=Q2-GW
   44 DFLOW=.5*DT*(FI1+FI2)
      GFLOW=.5*DT*(FG1+FG2)
      FG1=FG2
      Q1=Q2
      FI1=FI2
      E1=C(J)+B(J)*S2-DE*S2/ST
      IF(E1)45,46,46
   45 E1=0.
   46 Q1=Q1+E1
   47 S1=S2
      GWF(J)=GWF(J)+GFLOW
   48 FLOW(J)=FLOW(J)+DFLOW*SURF
   49 TFLOW=TFLOW+FLOW(J)+GWF(J)
      AI=AI*100.
C     ------------------------------------------------------------------
C     WRITE HEADINGS
C     ------------------------------------------------------------------
      WRITE(6,61)G1,G2,AREA
   61 FORMAT(1H1,11X,28HSYNTHESIZED RUNOFF AT GAUGE ,2A5,'CATCHMENT' ,
     1'AREA=',F7.0,'SQ.KM ' /12X,33(1H*),2X,27(1H*),2X,15(1H*)/)
      WRITE(6,62)POW,SL,ST,FT,GW,AI
   62 FORMAT(7H   POW=,F4.1,6H   SL=,F7.2,8HMM   ST=,F7.2,8HMM   FT=,F7.
     12,15H MM/MONTH   GW=,F6.2,15H MM/MONTH   AI=,F4.1,1HX/)
      WRITE(6,78)ZMIN,ZMAX,PI,GL,TL,NIT
   78 FORMAT(8H   ZMIN=,F7.2,16HMM/MONTH   ZMAX=,F7.2,14HMM/MONTH   PI=,
     1F5.2,9H MM   GL=,F5.3,13H MONTHS   TL=,F5.3,14H MONTHS   NIT=,I3,6
     2H/MONTH//)
      WRITE(6,103) R
  103 FORMAT(114H   YEAR      JAN      FEB      MAR      APR      MAY      JU
     1N      JUL      AUG      SEP      OCT      NOV      DEC      TOTAL/)
C     ------------------------------------------------------------------
C     LAG MONTHLY RUNOFFS AND CONVERT FROM DEPTHS TO VOLUMES
C     ------------------------------------------------------------------
      IF(TL)86,86,87
   87 NRPM=.5/TL+.99
      RDT=NRPM
      DT=1./RDT
      IF(NRPM-1)86,86,89
   86 NRPM=1
      DT=1.
   89 CF1=DT/(TL+.5*DT)
      CF2=.5*CF1
      CG1=1./(GL+.5)
      CG2=.5*CG1
      QBAR=0.
      SUM=0.
      DO 74 M=13,NM,12
      ME=M+11
```

```
      MY=LY1-1+ME/12
      FYC=0.
      FFYC=0.0
      DO 53 J=M,ME
      FLOW(J)=FLOW(J)*AREA
      GWF(J)=GWF(J)*AREA
      K=J-M+1
      IF(J-1)71,71,72
   71 FIN(K)=FLOW(J)+GWF(J)
      F=FLOW(J)
      G=GWF(J)
      GOTO 73
   72 IF(NRPM-1)99,99,95
   95 F=F+FLOW(J-1)
      DQ=FLOW(J)-FLOW(J-1)
      DO 96 N=1,NRPM
      FQ2=FQ1+DT*DQ
      F=F+CF1*(FQ1-F)+CF2*(FQ2-FQ1)
   96 FQ1=FQ2
      GOTO 97
   99 F=F+CF1*(FLOW(J-1)-F)+CF2*(FLOW(J)-FLOW(J-1))
   97 G=G+CG1*(GWF(J-1)-G)+CG2*(GWF(J)-GWF(J-1))
      FIN(K)=F+G
   73 PERC(K)=PERC(K)+FIN(K)
      FSIM(J-12)=FIN(K)
      OBS(K)=FOBS(J-12)
      FFYC=FFYC+OBS(K)
   53 FYC=FYC+FIN(K)
      IF(FYC)66,68,69
   68 FYC=.0001
   69 Q=ALOG10(FYC)
      QBAR=QBAR+Q
      SUM=SUM+Q*Q
C     ***************************************************************
C     WRITE MONTHLY AND ANNUAL RUNOFFS
C     ***************************************************************
   54 WRITE(6,55)MY,(FIN(N),N=1,12),FYC
      WRITE(6,999) (OBS(N),N=1,12),FFYC
  999 FORMAT(5X,'OBS',12F8.2,/,F10.2)
   55 FORMAT(//I8,12F8.2,F10.2)
   74 CONTINUE
      NM=NM-12
      CALL AFIT(FOBS,FSIM,NM,1)
      STOP
      END
C ##########################################################
C SUBROUTINE AFIT BY P.J.T.ROBERTS***EXTENDED AND MODIFIED
C BY A.M.M.GOORGENS,DURING 1980+1981+1982******
C     X IS THE ARRAY OF OBSERVED MONTHLY DISCHARGE
C     Y IS THE ARRAY OF SIMULATED MONTHLY DISCHARGE
C     NMON IS THE LENGTH OF RECORD IN MONTHS
C     M1 IS THE FIRST MONTH OF RECORD (1,E. 1 FOR CALENDER
C     YEARS AND 10 FOR HYDROLOGICAL YEARS)
C ##########################################################
      SUBROUTINE AFIT(X,Y,NMON,M1)
      DIMENSION X(100),LRUN(200),Y(100),RESX(200),RESY(200)
      DIMENSION DIFRES(200),FDCX(60),FDCY(60),FLEV(60)
      DIMENSION AUTOX(200),AUTOY(200),JM(12),SMONX(12),SMONY(12)
      INTEGER TEMP1,TEMP2,TEMP3,TEMP4
      TN=FLOAT(NMON)
      YEAR=FLOAT(NMON/12)
```

```
SUBFILE:DALM LC=B200 LENGTH:  57    HRAG

      LIST
      PROGRAM(DALM)
      INPUT 3=CR1
      INPUT 4=CR2
      INPUT 5=CRD
      OUTPUT 6=LPO
      COMPRESS INTEGER  AND LOGICAL
      COMPACT DATA
      TRACE U
      END
      MASTER
C     ##################################################################
C     MONTHLY MODEL DALM : DERIVED BY D.HUGHES,H.R.U.,RHODES U.,1982,
C     FROM DAILY MODEL DALT(DEVELOPED BY P.ROBERTS PRE-1978)
C     THIS VERSION MODIFIED BY A.GORGENS,H.R.U.,RHODES,1982,
C     AND USES ONE WARM-UP YEAR (EXCLUDED IN THE STATS.CALCS.)
C
C     THIS PROGRAM GENERATES MONTHLY RUNOFF FROM MONTHLY RAINFALL (MM)
C     AND MONTHLY PAN EVAPORATION(MM).
C     ##################################################################
      DIMENSION RAIN(600),FSIM(600),ORFL(600),PFC(100)
      DIMENSION EVMO(100),PEAD(12),RRR(31),ANX(50),ANY(50)
      ********************************************************************
      PEAD IN CATCHMENT NAME OR RUN IDENTIFICATION
      ********************************************************************
      READ(5,1)G1,G2
    1 FORMAT(2A3)
C     ********************************************************************
C     READ IN CATCHMENT AREA(SQ.KM),
C     NUMBER OF MODEL ITERATIONS REQUIRED PER MONTH,
C     STARTING YEAR (IE 1920) AND MONTH (IE 1 FOR CALENDER YEARS AND
C     10 FOR HYDROLOGICAL YEARS) & END YEAR OF SIMULATION AND
C     IFORS =1 FOR NO FOREST COVER ON CATCHMENT
C           =2 FOR CONSTANT FOREST COVER ON CATCHMENT
C           =3 TO ACCOMMODATE CHANGING FOREST COVER
C     AND LINE AND ILIM TO CONTROL THE NON-LINEAR STORE
C     ********************************************************************
      READ(5,2) AREA,NIT,NYR1,NYR2,NM1,IFORS,LINE,ILIM
    2 FORMAT (F7.2,7I5)
C     ********************************************************************
C     READ IN MODEL PARAMETER VALUES AND INITIALIZE VARIABLES
C     SSL    INITIAL LEVEL OF SOIL MOISTURE STORAGE(MM)
C     SSM    MAXIMUM CAPACITY OF SOIL MOISTURE STORAGE (MM)
C     SSB    STORAGE LEVEL AT WHICH BASE FLOW BEGINS
C     POWER POWER OF BASE FLOW FUNCTION
C     PCUR  POWER OF NON-LINEAR STORAGE DEPTH FUNCTION
C     AMAX  MAXIMUM VALUE OF STORAGE DEPTH FACTOR
C     PERC  MAXIMUM FRACTION OF SOIL MOISTURE TO DEEP PERC
C     AFOR  AFFORESTATION PARAMETER (SET TO 1.0 FOR NO FOREST COVER)
C     ********************************************************************
      READ(5,3) SSL,SSM,SSB,POWER,PCUR,AMAX,PERC,AFOR
    3 FORMAT (8F6.2)
      NMON=(NYR2-NYR1+1)*12
      KMON=NMON-12
C     ********************************************************************
C     IF IFORS=1 NO FORESTRY CARD REQUIRED
```

```
C     IF IFORS=2 READ IN PERCENTAGE FOREST COVER IN FORMAT 1F8.2
C     IF IFORS=3 READ IN PERCENTAGE FOREST COVER FOR EACH YEAR OF RECORD
C                IN FORMAT 10F8.2
C     ******************************************************************
      IF (IFORS.EQ.1) GO TO 420
      IFY=NMON/12
      IF (IFORS.EQ.2) IFY=1
      READ (5,410) (PFC(KR),KR=1,IFY)
  410 FORMAT (10F8.2)
C     ******************************************************************
C     READ IN  MONTHLY VALUES OF AVERAGE PAN EVAPORATION (MM) JAN-DEC
C     ******************************************************************
  420 READ (4,4) (EVMO(NX),NX=1,NMON)
    4 FORMAT (2X,12F6.1)
C     ******************************************************************
C     READ IN 12 PAN TO FREE WATER SURFACE EVAPORATION CONSTANTS JAN-DEC
C     ******************************************************************
      READ (5,444) (PEADJ(K),K=1,12)
444   FORMAT(12F5.1)
C     ------------------------------------------------------------------
C     INITIALIZE OBSERVED RUNOFF ARRAY
C     ------------------------------------------------------------------
      DO 10 JK=1,NMON
   10 OBFL(JK)=0.0
C     ******************************************************************
C     READ IN MONTHLY RAINFALL DATA(MM) FOLLOWED BY OBSERVED MONTHLY
C     RUNOFF DATA (10**3 CUBIC METRES).
C     ******************************************************************
      READ (5,15) (RAIN(I),I=1,NMON)
   15 FORMAT (2X,12F6.2)
      READ (5,15) (OBFL(K),K=1,KMON)
  998 TPR=0
      TPE=0.
      TAE=0.
      TSURF=0.
      TBFL=0.
      TSUM=0.
      YET=0.
      XET=0.
      ICON=1
      IM=0
      NM=NM1-1
      TSL=0.
      TMS=0.
      TDR=0.
      SCEP=0.
      ATER=1.0/FLOAT(NIT)
      PSL=SSL
      BRA=SSB/SSM
      WRITE (6,200) G1,G2
  200 FORMAT (1H1,20HSIMULATION RUN FOR  ,2A3,///)
      WRITE (6,210) AREA,SSL,SSM,SSB,POWER,BCUR,AMAX,PERC
  210 FORMAT (1H0,33HPARAMETER VALUES USED IN THIS RUN,//,5X,4HAREA,5X,
     1'SSL',5X,'SSM',5X,'SSB',3X,'POWER',4X,'BCUR',4X,'AMAX',4X,
     2'PERC',/1X,8F8.2///)
      WRITE (6,212) IFORS,AFOR
  212 FORMAT (4X,5HIFORS,4X,4HAFOR,/,1X,I8,F8.2,///)
      IF (IFORS.EQ.1) GO TO 233
      WRITE (6,215)
  215 FORMAT (1H0,51HLISTING OF VALUES GIVEN FOR PERCENTAGE FOREST COVER,
     1 ///)
```

```
      WRITE (6,234) (PFC(KR),KR=1,IFY)
  234 FORMAT (1X,10F8.2,//)
  233 IF (IFORS.EQ.1) PCH=0.0
      IF (IFORS.GT.1) PCH=PFC(1)
      SSSS=SSM
C     ------------------------------------------------------------------
C     START OF THE MONTHLY LOOP
C     ------------------------------------------------------------------
      DO 100 M=1,NMON
      IM=IM+1
      NM=NM+1
      IF (NM.GT.12) NM=1
      PE=(EVMO(M)*PEADJ(NM))/(FLOAT(NIT))
      PPPP=PE
      IF (PAIN(M).EQ.0.) GO TO 40
      W=-2.0+1.3732*((RAIN(M)+1.6)**0.8)
      W=W/RAIN(M)
      EN=1.28/((1.02-W)**1.49)
      IF (EN.GT.120.) EN=120.
      SP1=0.
      SFAR=0.
   40 TMIT=0.
C     ------------------------------------------------------------------
C     START OF ITERATION LOOP
C     ------------------------------------------------------------------
      DO 50 J=1,NIT
      IF (RAIN(M).NE.0.) GO TO 60
      RRR(J)=0.0
      GO TO 70
C     ------------------------------------------------------------------
C     CALCULATE RAINFALL FOR PRESENT INTERVAL
C     ------------------------------------------------------------------
   60 SFAR=SFAR+(1.0/FLOAT(NIT))
      SP2=RAIN(M)*(SFAR**EN/(SFAR**EN+(1.0-SFAR)**EN))
      RRR(J)=SP2-SP1
      SP1=SP2
   70 TPE=TPE+PE
      TPR=TPR+RRR(J)
      TSL=TSL+SSL
      IF (SSL.GT.TMS) TMS=SSL
      GOTO 4500
C     ------------------------------------------------------------------
C     THE INTERCEPTION FUNCTION OPERATES ON A FINITE LINEAR STORAGE
C     ------------------------------------------------------------------
      EPXM=1.5+0.085*PCH
      SINP=EPXM-SCEP
      IF (SINP.LT.0.) SINP=0.
      IF (RRR(J).GT.SINP) GO TO 440
      SCEP=SCEP+RRR(J)
      RRR(J)=0.
      GO TO 450
  440 RRR(J)=RRR(J)-SINP
      SCEP=EPXM
C     ------------------------------------------------------------------
C     ADJUST SOIL CAPACITY AND POTENTIAL EVAPOTRANS FOR FOREST COVER
C     ------------------------------------------------------------------
  450 FZF=1.0+((AFOR-1.0)/100.0)*PCH
      PE=PPPP*FZF
C     ------------------------------------------------------------------
C     ADD IN RAINFALL AND TAKE AWAY EVAP FROM STORE AND INTERCEPTION
C     ------------------------------------------------------------------
```

```
4500  RAT=SSL/SSM
      IF (RAT.GT.1.0) RAT=1.0
      PRE=2.0*RAT**0.5-RAT
      IF (SCEP.GE.PE) GOTO 500
      TAE=TAE+SCEP
      EDEM=(PE-SCEP)*PRE
      SCEP=0.0
      GOTO 510
  500 SCEP=SCEP-PE
      TAE=TAE+PE
      EDEM=0.0
  510 PLE=SSL+RRR(J)
      IF (PLE.LE.EDEM) GOTO 520
      TAE=TAE+EDEM
      PLE=PLE-EDEM
      GOTO 530
  520 TAE=TAE+PLE
      PLE=0.0
  530 OVF=PLE-SSM
      IF (OVF.GT.0.0) GOTO 540
      SSL=PLE
      OVF=0.0
      GOTO 550
  540 TSURF=TSURF+OVF
      SSL=SSM
  550 IF (ILIM.EQ.1) RANG=SSB
      IF (ILIM.EQ.2) RANG=SSM
      RAT=SSL/RANG
      IF (RAT.GT.1.0) RAT=1.0
      CR=RRR(J)-EDEM
      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
      IF (RAT.GT.BRA) GOTO 240
      BF=0.0
      GOTO 250
  240 HEAD=PSL-SSB
      POTH=SSM-SSB
      PLOS=HEAD*((HEAD/POTH)*PERC)
      SSL=SSL-PLOS
      PSL=PSL-PLOS*FAT
      RAT=PSL/SSM
      TDR=TDR+PLOS
      XBRA=RAT-BRA
      BF=(PSL-SSB)*(XBRA**POWER)
      IF (BF.GT.SSL) BF=SSL
      TBFL=TBFL+BF
      SSL=SSL-BF
      IF (SSL.LT.0.) SSL=0.0
      PSL=PSL-BF*FAT
  250 TSUM=TSUM+OVF+BF
   50 TMIT=TMIT+OVF+BF
C     ------------------------------------------------------------------
C     END OF ITERATION LOOP
C     ------------------------------------------------------------------
      FSIM(M)=TMIT*AREA
      YET=YET+FSIM(M)
      XET=XET+OHFL(M)
```

```
      IF (IM.NE.12) GO TO 100
      ANX (ICON)=XET
      ANY (ICON)=YET
      XET=0.
      YET=0.
      ICON=ICON+1
      IF (IFORS.EQ.1) PCH=0.0
      IF (IFORS.EQ.2) PCH=PFC(1)
      IF (IFORS.EQ.3) PCH=PFC(ICON)
      IM=0
  100 CONTINUE
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     END OF MONTH LOOP
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
      ASL=TSL/FLOAT(NMON*NIT)
      WRITE (6,220)
  220 FORMAT (1HO,48HRUNOFF VALUES GIVEN IN THOUSANDS OF CUBIC METRES,
     1//,1HU,110X,5HTOTAL,//)
      NBEG=1
      NEND=12
      NYR1=NYR1-1
      LMON=NMON/12
      DO 255 J=1,LMON
      NYR=NYR1+J
      IF(J.EQ.1)GOTO 280
      WRITE (6,260) NYR,(FSIM(KZ),KZ=NBEG,NEND),ANY(J)
  260 FORMAT (1H ,I4,5H SIM ,12F8.2,F10.3)
      WRITE (6,270) (OBFL(KZ-12),KZ=NBEG,NEND),ANX(J-1)
  270 FORMAT (5X,5H OBS , 12F8.2,F10.3,//)
  280 NBEG=NBEG+12
  255 NEND=NEND+12
      DO 2550 L=13,NMON
      FSIM(L-12)=FSIM(L)
 2550 CONTINUE
      WRITE (6,290)
  290 FORMAT (1HO,50HDATA COMPONENT SUMMARY - ALL VALUES IN MILLIMETRES,
     1//)
      WRITE (6,300) TPR,TPE,TAE,TSURF,TBFL,TSUM,TDR,SSL,GSL
  300 FORMAT (1HO,17HTOTAL RAINFALL = ,F8.2,//,1X,23HPOTENTIAL EVAPOTRAN
     1S = ,F8.2,//,1X,20HACTUAL EVAPOTRANS = ,F8.2,//,1X,
     215HSURFACE FLOW = ,F8.2//1X,14HBASE FLOW = ,F8.2//1X,
     313HTOTAL FLOW = ,F8.2///,1X,27HTOTAL DRAINAGE FROM SOIL = ,
     4 F8.2,///,1X,21HFINAL VALUE OF SSL = ,F8.2///,1X
     5,21HFINAL VALUE OF GSL = ,F8.2///)
      WRITE(6,310) ASL,TMS
  310 FORMAT(1X,23HAVERAGE VALUE OF SSL = ,F8.2///,
     1 1X,23HMAXIMUM VALUE OF SSL = ,F8.2)
      CALL AFIT(OBFL,FSIM,KMON,NM1)
      STOP
      END
C ##################################################
C SUBROUTINE AFIT BY P.J.T.ROBERTS***EXTENDED AND MODIFIED
C BY A.H.M.GORGENS,DURING 1980+1981+1982******
C     X IS THE ARRAY OF OBSERVED MONTHLY DISCHARGE
C     Y IS THE ARRAY OF SIMULATED MONTHLY DISCHARGE
C     NMON IS THE LENGTH OF RECORD IN MONTHS
C     M1 IS THE FIRST MONTH OF RECORD (I.E. 1 FOR CALENDER
C     YEARS AND 10 FOR HYDROLOGICAL YEARS)
C ##################################################
      SUBROUTINE AFIT(X,Y,NMON,M1)
      DIMENSION X(100),CRUN(200),Y(100),RESX(200),RESY(200)
```

```
C ##########################################################
C SUBROUTINE AFIT BY P.J.T.ROBERTS***EXTENDED AND MODIFIED
C BY A.M.M.GURGENS,DURING 1980+1981**1982******
C     X IS THE ARRAY OF OBSERVED MONTHLY DISCHARGE
C     Y IS THE ARRAY OF SIMULATED MONTHLY DISCHARGE
C     NMON IS THE LENGTH OF RECORD IN MONTHS
C     M1 IS THE FIRST MONTH OF RECORD (I.E. 1 FOR CALENDER
C     YEARS AND 10 FOR HYDROLOGICAL YEARS)
C ##########################################################
      SUBROUTINE AFIT(X,Y,NMON,M1)
      DIMENSION X(100),LRUN(200),Y(100),RESX(200),RESY(200)
      DIMENSION DIFRES(200),FDCX(60),FDCY(60),FLEV(60)
      DIMENSION AUTOX(200),AUTOY(200),JM(12),SMONX(12),SMONY(12)
      INTEGER TEMP1,TEMP2,TEMP3,TEMP4
      TN=FLOAT(NMON)
      YEAR=FLOAT(NMON/12)
      TOTX=0.0
      TOTY=0.0
      N1=0
      N2=0
      NRUN=0
      NPOS=0
      NNN=0
      NPP=0
C     ==========================================================
C       SIGN TEST
C     ==========================================================
      DO 10 I=1,NMON
      SIG=Y(I)-X(I)
      IF (SIG.NE.0.0) GOTO 13
      NNN=0
      NPP=0
      GOTO 12
   13 IF (SIG.LT.0.0) GOTO 11
      IF (NPP.EQ.0) NPOS=NPOS+1
      NPP=NPP+1
      N1=N1+1
      NNN=0
      GOTO 12
   11 NPP=0
      IF (NNN.EQ.0) NRUN=NRUN+1
      NNN=NNN+1
      N2=N2+1
   12 TOTX=TOTX+X(I)
   10 TOTY=TOTY+Y(I)
      PTOT=((TOTY-TOTX)/TOTX)*100
      XMM=TOTX/TN
      YMM=TOTY/TN
      PMM=((YMM-XMM)/XMM)*100
      XMAR=TOTX/YEAR
      YMAR=TOTY/YEAR
```

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      PMAR=((YMAR-XMAR)/XMAR)*100
      SUMXY=0.0
      SXSQ=0.0
      SYSQ=0.0
      SDIF=0.0
      SXDEV=0.0
      IIMX=0
      IIMY=0
      MDTX=1
      MDTY=1
      LGEX=0
      LGEY=0
      IXFLG=0
      IYFLG=0
      SDIFA=0.0
      SYDEV=0.0
      TRX=0.0
      TRY=0.0
      TTRX=0.0
      TTRY=0.0
      STT=0.0
      II=0
      DIF2=1.0
      KC=0
      TA=0.0
      MC=0
      AOT=0.0
      AOZ=0.0
      DO 15 JJ=1,12
      SMONX(JJ)=0.0
      SMONY(JJ)=0.0
   15 JM(JJ)=JJ
      MM=M1-1
C ==========================================
C START OF MAIN LOOP
C==========================================
      DO 20 J=1,NMON
      MM=MM+1
      IF (MM.GT.12) MM=1
      SMONX(MM)=SMONX(MM)+X(J)
      SMONY(MM)=SMONY(MM)+Y(J)
      SUMXY=SUMXY+X(J)*Y(J)
      SXSQ=SXSQ+X(J)*X(J)
      SYSQ=SYSQ+Y(J)*Y(J)
      DIFRES(J)=X(J)-Y(J)
      SDIFA=SDIFA+ABS(DIFRES(J))
      SDIF=SDIF+DIFRES(J)*DIFRES(J)
      XDEV=X(J)-XMM
      YDEV=Y(J)-YMM
      SXDEV=SXDEV+XDEV*XDEV
      SYDEV=SYDEV+YDEV*YDEV
      TRX=TRX+XDEV
      TRY=TRY+YDEV
      RESX(J)=TRX
      RESY(J)=TRY
      TTRX=TTRX+RESX(J)
      TTRY=TTRY+RESY(J)
C
C CALCULATE NO. OF RUNS AND LENGTH OF EACH RUN
C
      II=II+1
```

```
      DIF1=X(J)-Y(J)
      IF(J.EQ.1)GOTO 201
      IF(DIF1.EQ.0.000)GOTO 202
      IF(DIF2.EQ.0.000)GOTO 201
      CIF=DIF1*DIF2
      IF(J.EQ.NMON)GOTO 202
      IF(CIF.GT.0.000)GOTO 201
202   KC=KC+1
      LRUN(KC)=II
      II=0
201   DIF2=DIF1
      IF (J.GT.1) GOTO 30
      FMAX=X(J)
      FYMAX=Y(J)
      XMIN=RESX(1)
      YMIN=RESY(1)
      XMAX=RESX(1)
      YMAX=RESY(1)
   30 IF (RESX(J).GT.XMAX) XMAX=RESX(J)
      IF (X(J).GT.FMAX) FMAX=X(J)
      IF (Y(J).GT.FYMAX) FYMAX=Y(J)
      IF (RESY(J).GT.YMAX) YMAX=RESY(J)
      IF (RESX(J).LT.XMIN) XMIN=RESX(J)
      IF (RESY(J).LT.YMIN) YMIN=RESY(J)
C
C     SET UP DEFICIENT FLOW PERIOD(<MONTHLY MEAN)CALCS
C
      IF(J.EQ.NMON)GOTO 225
      IF(X(J).GE.XMM.OR.X(J+1).GE.XMM)GOTO 220
      GOTO 228
225   IF(X(J).GE.XMM)GOTO 227
      IF(TEMP1.EQ.1)GOTO 227
  228 MDTX=MDTX+1
      TEMP1=0
      TEMP2=0
       IF(MDTX.GT.LGEX)LGEX=MDTX
      IF(J.EQ.NMON)GOTO 223
      GOTO 227
220   TEMP1=1
      IF(J.EQ.1)GOTO 222
      IF(TEMP1.EQ.1.AND.TEMP2.EQ.0)GOTO 223
222   MDTX=1
      TEMP2=1
      GOTO 227
223   IIMX=IIMX+1
      IXFLO=IXFLO+MDTX
      TEMP2=1
227   IF(J.EQ.NMON)GOTO 235
      IF(Y(J).GE.YMM.OR.Y(J+1).GE.YMM)GOTO 230
      GOTO 238
235   IF(Y(J).GE.YMM)GOTO 20
      IF(TEMP3.EQ.1)GOTO 20
  238 MDTY=MDTY+1
      TEMP3=0
       TEMP4=0
      IF(MDTY.GT.LGEY)LGEY=MDTY
      IF(J.EQ.NMON)GOTO 235
      GOTO 20
230   TEMP3=1
      IF(J.EQ.1)GOTO 232
      IF(TEMP3.EQ.1.AND.TEMP4.EQ.0)GOTO 233
```

```
232   MDTY=1
      TEMP4=1
      GOTO 20
233   IIMY=IIMY+1
      IYFLO=IYFLO+MDTY
      TEMP4=1
20    CONTINUE
      XDEFIC=FLOAT(IXFLO)/FLOAT(IIMX)
      YDEFIC=FLOAT(IYFLO)/FLOAT(IIMY)
      ERDEFI=100.0*(YDEFIC-XDEFIC)/XDEFIC
      ERLGE=100.0*(FLOAT(LGEY-LGEX)/FLOAT(LGEX))
C ***********************************************************
C  END OF MAIN LOOP
C ***********************************************************
      DO 150 JJ=1,12
      SMONX(JJ)=SMONX(JJ)/YEAR
  150 SMONY(JJ)=SMONY(JJ)/YEAR
C ***********************************************************************
C PREPARE CALC OF SPECIAL COEFF. OF EFFICIENCY USING EACH MONTH'S MEAN
C ***********************************************************************
      SPEC=0.0
      DO 152 J=1,NMON,12
      ME=J+11
      DO 171 JJ=J,ME
      K=JJ-J+1
      RESM=X(JJ)-SMONX(K)
      RESM=RESM*RESM
      SPEC=SPEC+RESM
171   CONTINUE
152   CONTINUE
      DO 151 JJ=1,12
      SMONX(JJ)=(SMONX(JJ)/XMAR)*100.0
  151 SMONY(JJ)=(SMONY(JJ)/YMAR)*100.0
C
C PREPARE CALC OF COEF. OF PERSISTENCE
C
      DO 203 LL=1,KC
      TS=0.0
      TO=0.0
      DO 204 NN=1,LRUN(LL)
      MC=MC+1
      IF(LL.EQ.1.AND.NN.EQ.1)GOTO 709
      IF(LRUN(LL).NE.1)GOTO 209
  208 IF(LL.EQ.KC)GOTO 207
      DELTA=-DIFRES(MC-1)/(DIFRES(MC)-DIFRES(MC-1))
      AD1=0.50*ABS(DIFRES(MC-1))*DELTA
      GOTO 208
  209 IF(NN.GT.1)GOTO 709
      TO=TO+X(MC-1)
      TS=TS+Y(MC-1)
  709 IF(NN.EQ.LRUN(LL)-1)GOTO 205
      IF(NN.EQ.LRUN(LL))GOTO 206
      TO=TO+X(MC)
      TS=TS+Y(MC)
      GOTO 204
205   IF(LL.EQ.KC)GOTO 207
      TO=TO+0.5U*X(MC)
      TS=TS+0.5U*Y(MC)
      DELTA=-DIFRES(MC)/(DIFRES(MC+1)-DIFRES(MC))
      AD1=0.5U*ABS(DIFRES(MC))*DELTA
      GOTO 204
```

```
206   IF(LL.EQ.KC)GOTO 207
      TO=TO+U.5U*X(MC)
      TS=TS+U,5U*Y(MC)
      GAMMA=1.0-DELTA
      GOTO 204
207   TO=TO+X(MC)
      TS=TS+Y(MC)
204   CONTINUE
      TA=TA+(TO-TS*AD1+AD2)*(TO-TS+AD1+AD2)
      AD2=0,5U*ABS(DIFRES(MC))*GAMMA
203   CONTINUE
C
C     PREPARE CALC OF DURBIN-WATSON 'D'
C
      DURB=U,0
      DU 211 JL=2,NMON
      TEMP=DIFRES(JL)-DIFRES(JL-1)
      DURB=DURB+TEMP*TEMP
211   CONTINUE
C ==========================================================
C   CALCULATE STATISTICS
C ==========================================================
      RAER=100.0*SDIFA/(TN*XMM)
      DURB=DURB/SDIF
      PERSIS=TA/SDIF
      RELPER=100.0*SQRT(TA/FLOAT(KC))/(XMM*XMM)
      RRMCX=XMAX-XMIN
      RRMCY=YMAX-YMIN
      ARX=TTRX/TN
      ARY=TTRY/TN
      PTT=((TTRY-TTRX)/TTRX)*100.0
      CTOP=SUMXY-(TOTX*TOTY)/TN
      BOTX=SXSQ-(TOTX*TOTX)/TN
      BOTY=SYSQ-(TOTY*TOTY)/TN
      CORC=CTOP/SQRT(BOTX*BOTY)
      REGC=CTOP/BOTX
      RCON=YMN-REGC*XMM
      IF (CORC.EQ.1.0) GOTO 22
      SIT=(CORC*SQRT(NMON-2))/SQRT(1.0-CORC*CORC)
   22 STOT=BOTY
      SREG=CTOP*REGC
      SRES=SYSQ-RCON*TOTY-REGC*SUMXY
      SERS=SQRT(SRES/FLOAT(NMON-2))
      CDET=CORC*CORC
      CEFF=(SXDEV-SDIF)/SXDEV
      SPECEF=(SPEC-SDIF)/SPEC
      VARX=(SXSQ/TN)-(XMM*XMM)
      VARY=(SYSQ/TN)-(YMM*YMM)
      PVAR=((VARY-VARX)/VARX)*100.0
      RERR=((RRMCY-RRMCX)/RRMCX)*100.0
C
C     CALCULATE MAX EQUIV CONSTANT ERROR
C
      CYY=SQRT(SDIF/FLOAT(NMON))/YMM
      CEVE=SQRT(SXDEV/FLOAT(NMON-1))/YMM
      CEVE=CEVE*CEVE*FLOAT(NMON-1)/FLOAT(NMON)
      CEVE=((CEVE+1.0)**0.25
      EMECE=100.0*CYY/CEVE
C
C     CALC INDEX OF SEASONAL VARIABILITY
C
```

```
      YBIG=0.0
      YSMAL=0.0
      XBIG=0.0
      XSMAL=0.0
      PXMM=XMM*100.0/XMAR
      PYMM=YMM*100.0/YMAR
      TYM=0.0
      TXM=0.0
      DO 400 L=1,12
      XMRES=SMONX(L)-PXMM
      YMRES=SMONY(L)-PYMM
      TXM=TXM+XMRES
      TYM=TYM+YMRES
      IF(TXM.GT.XBIG)XBIG=TXM
      IF(TYM.GT.YBIG)YBIG=TYM
      IF(TXM.LT.XSMAL)XSMAL=TXM
      IF(TYM.LT.YSMAL)YSMAL=TYM
400   CONTINUE
      XIS=XBIG-XSMAL
      YIS=YBIG-YSMAL
      EIS=100.0*(YIS-XIS)/XIS
      TRESX=0.0
      TCRS=0.0
      DO 40 K=1,NMON
      TRESX=TRESX+((RESX(K)-ARX)*(RESX(K)-ARX))
   40 TCRS=TCRS+((RESX(K)-RESY(K))*(RESX(K)-RESY(K)))
      RMCC=(TRESX-TCRS)/TRESX
      STEP=FMAX/30.0
      UP=-STEP
      DO 70 IFC=1,31
      UP=UP+STEP
      FLEV(IFC)=UP
      NCX=0
      NCY=0
      DO 80 JF=1,NMON
      IF (Y(JF).GE.UP) NCY=NCY+1
   80 IF (X(JF).GE.UP) NCX=NCX+1
      FDCX(IFC)=(FLOAT(NCX)/FLOAT(NMON))*100.0
   70 FDCY(IFC)=(FLOAT(NCY)/FLOAT(NMON))*100.0
      WRITE(6,50)
   50 FORMAT(1H1,43HCOMPARISON OF SIMULATED AND OBSERVED RUNOFF,//,
     1 1X,43(1H-),///)
      WRITE(6,51)
   51 FORMAT(57X,8HOBSERVED,6X,9HSIMULATED,8X,7HPRCENT,/,
     1 59X,6HRUNOFF,9X,6HRUNOFF,10X,5HERROR,//,57X,8(1H-),6X,9(1H-),
     2 8X,7(1H-),///)
      WRITE(6,52) TOTX,TOTY,PTOT,XMAR,YMAR,PMAR
   52  FORMAT(1HO,12HTOTAL RUNOFF,3(1X,3F15.3,///,1HO,18HMEAN ANNUAL RUNOF
     1F,31X,3F15.3,//)
      WRITE(6,53) XMM,YMM,PMM,VARX,VARY,PVAR
   53 FORMAT(1HO,22HAVERAGE MONTHLY RUNOFF,27X,3F15.3,///,
     1 1HO,26HVARIANCE OF MONTHLY VALUES,23X,3F15.3,//)
      WRITE(6,54) RMCX,RMCY,RERR,ARX,ARY,PTT
   54 FORMAT(1HO,28HRANGE OF RESIDUAL MASS CURVE,21X,3F15.3,///,
     1 1HO,22(HMEAN OF RESIDUAL MASS CURVE,2X,3F15.3,//)
      WRITE(6,401)XIS,YIS,EIS
401   FORMAT(1X,29HINDEX OF SEASONAL VARIABILITY,20X,3F15.3//)
      WRITE(6,404)XDEFIC,YDEFIC,EROEFI,LGEX,LGFY,ERLGE
404   FORMAT(1X,34HMEAN DEFICIENT FLOW PERIOD(MONTHS),15X,3F15.3//1X,
     *37HMAXIMUM DEFICIENT FLOW PERIOD(MONTHS),12X,2I15,F15.3//)
      WRITE(6,155)
```

```
  155  FORMAT(1HO,64HSEASONAL DISTRIBUTION OF RUNOFF (EXPRESSED AS PERCE
     1NT OF M.A.R.)//,1X,64(1H-)///)
       WRITE(6,156) (JM(KN),KN=1,12),(SMONX(KN),KN=1,12),(SMONY(KN),KN=1
     1,12)
  156 FORMAT(1HU,5X,5HMONTH,1X,12I7,//,1HO,2X,8HOBSERVED,1X,12F7.2,//,
     1 1HO,1X,9HSIMULATED,1X,12F7.2///)
       WRITE(6,55)
   55  FORMAT(1H1,38HSTATISTICAL MEASURES OF CORRESPONDENCE,//,1X,
     1 38(1H-),///,1X,38HSIMULATED RUNOFF IS DEPENDENT VARIABLE,//)
       WRITE(6,56) CORC,SIT,REGC,BCON
   56  FORMAT(1HU,23HCORRELATION COEFFICIENT,26X,F10.3,///,
     1 1HO,16HSTUDENTS T VALUE,33X,F10.3,///,1HO,22HREGRESSION COEFFICIEN
     1T,27X,F10.3,///,1HO,36HBASE CONSTANT OF REGRESSION EQUATION,
     1 13X,F10.3,//)
       WRITE(6,57) SREG,SRES,STOT,SEES,EMECE,RAER
   57  FORMAT(1HO,25HREGRESSION SUM OF SQUARES,24X,F10.3,///,1HO,
     1 23HRESIDUAL SUM OF SQUARES,26X,F10.3,//,1HO,20HTOTAL SUM OF SQUAR
     2ES,29X,F10.3,///,1HO,26HSTANDARD ERROR OF ESTIMATE,23X,F10.3,//,
     *1X,36HMAXIMUM EQUIVALENT CONSTANT ERROR(%),13X,F10.3,
     */,1X,26HRELATIVE ABSOLUTE ERROR(%),13X,F10.3//)
       WRITE(6,58) CDET,CEFF,RMCC,SPECFF,PERSIS,RELPER,DURB
   58  FORMAT(1HO,28HCOEFFICIENT OF DETERMINATION,21X,F10.3,///,
     1 1HO,34HSTANDARD COEFFICIENT OF EFFICIENCY,15X,F10.3,//,1HO,
     2 31HRESIDUAL MASS CURVE COEFFICIENT,18X,F10.3,
     3 //,1X,33HSPECIAL COEFFICIENT OF EFFICIENCY,16X,F10.3,
     4 //,1X,'COEFFICIENT OF PERSISTENCE',23X,F10.3,
     5//,1X,'RELATIVE MEAN PERSISTENCE(%)',24X,F10.3,
     6//1X,25HDURBIN-WATSON D-STATISTIC,14X,F10.3//)
C
C      CALCULATE SIGN TEST
C
       ENEXP=FLOAT((2*N1*N2)/(N1+N2) +1.0
       RUNSD=FLOAT(2*N1*N2*(2*N1*N2-N1-N2))
       RUNSD=RUNSD/FLOAT((N1+N2)*(N1+N2)*(N1+N2-1))
       RUNSD=SQRT(RUNSD)
       ZET=FLOAT(NRUN+NPOS)-ENEXP
       ZET=ABS(ZET/RUNSD)
       WRITE(6,90) NRUN,NPOS,ENEXP,N2,N1,ZET
   90  FORMAT(1HU,9HSIGN TEST,//,1X,9(1H-),///,1X,13HNEGATIVE RUNS,
     1 I5,///,1X,13HPOSITIVE RUNS,I5///,1X,13HEXPECTED RUNS,F5.1//,
     *1X,15HNEGATIVE RESID.,I5//1X,15HPOSITIVE RESID.,I5//,
     *1X,22HSTAND.NORMAL VARIATE 7,F6.2//)
       WRITE(6,59)
   59  FORMAT(1H1,43HLISTING OF THE OBSERVED RESIDUAL MASS CURVE,
     1 //,1X,43(1H-),//)
       WRITE(6,60) (RESX(L),L=1,NMON)
   60  FORMAT(1HU,10F10.3)
       WRITE(6,61)
   61  FORMAT(1H1,44HLISTING OF THE SIMULATED RESIDUAL MASS CURVE,
     1 //,1X,44(1H-),//)
       WRITE(6,60) (RESY(L),L=1,NMON)
       WRITE(6,91)
   91  FORMAT(1H1,35HLISTING OF THE FLOW DURATION CURVES,//,1X,35(1H-),
     1 //,1HU,23HMONTHLY DISCHARGE LEVEL,10X,33HPERCENT TIME EQUALLED OR
     2EXCEEDED,//,44X,8HOBSERVED,6X,9HSIMULATED,10X,5HERROR,//,1X,23(1H-),
     310X,33(1H-),10X,5(1H-),///)
       DO 100 IK=1,31
       ERROR=FDCY(IK)-FDCX(IK)
       WRITE(6,110) FLEV(IK),FDCX(IK),FDCY(IK),ERROR
  110  FORMAT(9X,F15.3,13X,3F15.3)
  100  CONTINUE
```

```
  155  FORMAT(1HO,64HSEASONAL DISTRIBUTION OF RUNOFF (EXPRESSED AS PERCE
     1NT OF M.A.R.)//,1X,64(1H-)//)
       WRITE(6,156) (JM(KN),KN=1,12),(SMONX(KN),KN=1,12),(SMONY(KN),KN=1
     1,12)
  156 FORMAT(1HU,5X,5HMONTH,1X,12I7//,1HO,2X,8HOBSERVED,1X,12F7.2,//,
     1 1HO,1X,9HSIMULATED,1X,12F7.2///)
       WRITE(6,55)
   55 FORMAT(1H1,38HSTATISTICAL MEASURES OF CORRESPONDENCE//,1X,
     1 58(1H-),///,1X,38HSIMULATED RUNOFF IS DEPENDENT VARIABLE,//)
       WRITE(6,56) CORC,SIT,REGC,BCON
   56 FORMAT(1HU,23HCORRELATION COEFFICIENT,26X,F10.3,//,
     1 1HO,16HSTUDENTS T VALUE,33X,F10.3///,1HO,22HREGRESSION COEFFICIEN
     1T,27X,F10.3,///,1HO,36HBASE CONSTANT OF REGRESSION EQUATION,
     1 13X,F10.3,//)
       WRITE(6,57) SREG,SRES,STOT,SEES,EMECE,RAER
   57 FORMAT(1HO,25HREGRESSION SUM OF SQUARES,24X,F10.3,//,1HO,
     1 23HRESIDUAL SUM OF SQUARES,26X,F10.3,//,1HO,20HTOTAL SUM OF SQUAR
     2ES,29X,F10.3,//,1HO,26HSTANDARD ERROR OF ESTIMATE,23X,F10.3,//,
     *1X,36HMAXIMUM EQUIVALENT CONSTANT ERROR(%),13X,F10.3,
     */11X,26HRELATIVE ABSOLUTE ERROR(%),13X,F10.3//)
       WRITE(6,58) CDET,CEFF,RMCC,SPECFF,PERSIS,RELPER,DURB
   58 FORMAT(1HU,28HCOEFFICIENT OF DETERMINATION,21X,F11.3,//,
     1 1HO,34HSTANDARD COEFFICIENT OF EFFICIENCY,15X,F10.3,//,1HO,
     2 31HRESIDUAL MASS CURVE COEFFICIENT,18X,F10.3,
     3 //,1X,33HSPECIAL COEFFICIENT OF EFFICIENCY,16X,F10.3,
     4 //,1X,'COEFFICIENT OF PERSISTENCE',23X,F10.3,
     5//,1X,'RELATIVE MEAN PERSISTENCE(%)',24X,F10.3,
     6//1X,25HDURBIN-WATSON D-STATISTIC,14X,F10.3//)
C
C      CALCULATE SIGN TEST
C
       ENEXP=FLOAT((2*N1*N2)/(N1+N2))+1.0
       RUNSD=FLOAT(2*N1*N2*(2*N1*N2-N1-N2))
       RUNSD=RUNSD/FLOAT((N1+N2)*(N1+N2)*(N1+N2-1))
       RUNSD=SQRT(RUNSD)
       ZET=FLOAT(NRUN+NPOS)-ENEXP
       ZET=ABS(ZET/RUNSD)
       WRITE(6,90) NRUN,NPOS,ENEXP,NC,N1,ZET
   90 FORMAT(1HU,9HSIGN TEST,//,1X,9(1H-),//,1X,13HNEGATIVE RUNS,
     1 I5,//,1X,13HPOSITIVE RUNS,I5//,1X,13HEXPECTED RUNS,F5.1//,
     *1X,15HNEGATIVE RESID.,I5//1X,15HPOSITIVE RESID.,I5//,
     *1X,22HSTAND.NORMAL VARIATE Z,F6.2///)
       WRITE(6,59)
   59 FORMAT(1H1,43HLISTING OF THE OBSERVED RESIDUAL MASS CURVE,
     1 /,1X,43(1H-),//)
       WRITE(6,60) (RESX(L),L=1,NMON)
   60 FORMAT(1HU,10F10.3)
       WRITE(6,61)
   61 FORMAT(1H1,44HLISTING OF THE SIMULATED RESIDUAL MASS CURVE,
     1 /,1X,44(1H-),//)
       WRITE(6,60) (RESY(L),L=1,NMON)
       WRITE(6,91)
   91 FORMAT(1H1,35HLISTING OF THE FLOW DURATION CURVES//,1X,35(1H-),
     1 //,1HU,23HMONTHLY DISCHARGE LEVEL,10X,33HPERCENT TIME EQUALLED OR
     2EXCEEDED,//,44X,8HOBSERVED,6X,9HSIMULATED,10X,5HERROR,/,1X,23(1H-),
     31UX,33(1H-),10X,5(1H-),//)
       DO 100 IK=1,31
       ERROR=FDCY(IK)-FDCX(IK)
       WRITE(6,110) FLEV(IK),FDCX(IK),FDCY(IK),ERROR
  110 FORMAT(9X,F15.3,13X,3F15.3)
  100 CONTINUE
```

```
      WRITE(6,120) FMAX,FYMAX
  120 FORMAT(//1HO,30HOBSERVED MAXIMUM MONTHLY VALUE,1X,F10.3,//,1HO,
     1 31HSIMULATED MAXIMUM MONTHLY VALUE,F10.3)
      LAGS=NMON/4
      DO 165 L=1,LAGS
      CSUMX=0.0
      CSUMY=0.0
      NCO=NMON-L
      TN=FLOAT(NCO)
      DO 160 KN=1,NCO
      CSUMX=CSUMX+(X(KN)-XMM)*(X(KN+L)-XMM)
  160 CSUMY=CSUMY+(Y(KN)-YMM)*(Y(KN+L)-YMM)
      AUTOX(L)=(CSUMX/TN)/(SXDEV/TN)
  165 AUTOY(L)=(CSUMY/TN)/(SYDEV/TN)
      WRITE(6,180)
  180  FORMAT(1H1,60HCOMPARISON OF DEPENDENCE STRUCTURE (AUTO-SERIAL COR
     1RELATION),//,1X,60(1H-),///,1HO,4X,6HLAG IN,15X,15HCORRELOGRAM FOR,
     2 15X,15HCORRELOGRAM FOR,/,5X,6HMONTHS,15X,15HOBSERVED RUNOFF,14X,
     3 16HSIMULATED RUNOFF,/,5X,6(1H-),15X,15(1H-),14X,16(1H-),//)
      DO 190 KX=1,LAGS
      WRITE(6,195) KX,AUTOX(KX),AUTOY(KX)
  195 FORMAT(4X,I6,20X,F10.4,20X,F10.4)
  190 CONTINUE
      RETURN
      END



C ***************************************************************************
C SUBROUTINE BFIT FOR THE CALCULATION OF GOODNESS-OF-FIT STATS FOR USE
C WITH DAILY OUTPUT RAINFALL-RUNOFF MODELS.THE OBSERVED DAILY FLOW RECORD
C IS READ IN BY THE SUBROUTINE AND THE MODEL PROGRAM STEERING LINES
C MUST MAKE PROVISION FOR THIS !!!
C       X=OBSERVED DAILY FLOWS IN X(MONTH,DAY) FORMAT
C       Y=MODEL DAILY OUTPUT,NMON=NO.MONTHS OF FITTED RECORD,M1=NO.OF
C       FIRST MONTH,I.E.1 FOR JAN & 10 FOR OCT.,LY1=FIRST YEAR OF FIT
C DEVELOPED BY A.GORGENS AT H.R.U.,RHODES UNIVERSITY,1982
C ***************************************************************************
      SUBROUTINE BFIT(Y,NMON,M1,LY1)
      DIMENSION X(72,31),Y(72,31),SMONX(12),SMONY(12),DC(54),NTX(54),
     *NPK(72),NTY(54),IDAY(12),SMONXL(12),SMONYL(12),XBIG(72),YBIG(72)
      DIMENSION XLOW(600),YLOW(600)
      DATA IDAY/31,28,31,30,31,30,31,31,30,31,30,31/
      INTEGER TEMP1,TEMP2,TEMP3,TEMP4
      WRITE(6,100)
100   FORMAT(/////10X,70('*')//20X,'STATISTICS CALCULATED FOR MEAN',
     *' DAILY FLOWS'//10X,70('*')////)
      DO 5 MM=1,12
      SMONXL(MM)=0.0
      SMONYL(MM)=0.0
      SMONX(MM)=0.0
5     SMONY(MM)=0.0
      Q=0.0
      MDTX=1
      MDTY=1
      IMX=0
      IMY=0
      IXFLO=0
      IYFLO=0
      LGEX=0
      LGEY=0
      CUMX=0
      CUMY=0.0
      QAB=0.0
```

```
      XBV=0.0
      YBV=0.0
      NDTOT=0
      AVEX=0.0
      AVEY=0.0
      AVEXL=0.0
      AVEYL=0.0
      TY=FLOAT(NMON/12)
      TM=FLOAT(NMON)
      XVAR=0.0
      YVAR=0.0
      SRES=0.0
      SSRES=0.0
      DURR=0.0
      XVARL=0.0
      YVARL=0.0
      SSRESL=0.0
      XMAX=0.0
      NFDC=27
      SSXRES=0.0
      SXLRES=0.0
      DO 11 L=1,NMON
      XBIG(L)=0.0
11    YBIG(L)=0.0
      XBTOT=0.0
      YBTOT=0.0
      KA=0
      XBVAR=0.0
      YBVAR=0.0
      SBRES=0.0
      SSBRES=0.0
      AVFDC=0.0
      SFDC=0.0
      SXFDC=0.0
C
C     FIRST MAIN LOOP - SET UP VARIABLES FOR USE IN SECOND MAIN LOOP
C
      MM=M1-1
      DO 1 J=1,NMON
      MM=MM+1
      IF(MM.GT.12)MM=1
C
C     READ OBSERVED DAILY FLOW RECORD
C
      READ(3,3)LY,(X(J,I),I=1,31)
3     FORMAT(13,3X,(11F5.3))
      KDAY=IDAY(MM)
      LYL=4*(LY/4)
      IF(LY.EQ.LYL.AND.MM.EQ.2)KDAY=KDAY+1
      DO 1 K=1,KDAY
      NDTOT=NDTOT+1
      SMONX(MM)=SMONX(MM)+X(J,K)
      SMONY(MM)=SMONY(MM)+Y(J,K)
      IF(X(J,K).NE.0.0)GOTO 5555
      XL=ALOG(X(J,K)+0.001)
      GOTO 5556
5555  XL=ALOG(X(J,K))
5556  IF(Y(J,K).NE.0.0)GOTO 5557
      YL=ALOG(Y(J,K)+0.001)
      GOTO 5558
5557  YL=ALOG(Y(J,K))
```

```
5558  SMONXL(MM)=SMONXL(MM)+XL
      SMONYL(MM)=SMONYL(MM)+YL
      IF(X(J,K),GT,XMAX)XMAX=X(J,K)
1     CONTINUE
      TD=FLOAT(NDTOT)
      DO 4 I=1,12
      AVEXL=AVEXL+SMONXL(I)
      AVEX=AVEX+SMONX(I)
      AVEYL=AVEYL+SMONYL(I)
      AVEY=AVEY+SMONY(I)
      SMONXL(I)=SMONXL(I)/(TY*FLOAT(IDAY(I)))
      SMONX(I)=SMONX(I)/(TY*FLOAT(IDAY(I)))
      SMONYL(I)=SMONYL(I)/(TY*FLOAT(IDAY(I)))
      SMONY(I)=SMONY(I)/(TY*FLOAT(IDAY(I)))
4     CONTINUE
      AVEX=AVEX/TD
      AVEY=AVEY/TD
      AVEXL=AVEXL/TD
      AVEYL=AVEYL/TD
      MM=M1-1
      IF(XMAX,GT,10,0)NFDC=36
      IF(XMAX,GT,100,0)NFDC=45
      DO 8 I=1,9
8     DC(I)=FLOAT(I)/100,0
      DO 9 N=1,NFDC
      NTX(N)=0
      NTY(N)=0
      IF(N,LE,9)GOTO 9
      DC(N)=10,0*DC(N-9)
9     CONTINUE
C
C     START OF SECOND MAIN LOOP
C
      KLO=0
      LY=LY1
      DO 17 J=1,NMON
      MM=MM+1
      IF(MM,GT,12)LY=LY1+1
      IF(MM,GT,12)MM=1
      KDAY=IDAY(MM)
      LYL=4*(LY/4)
      IF(LY,EQ,LYL,AND,MM,EQ,2)KDAY=KDAY+1
      DO 7 K=1,KDAY
      XDIF=X(J,K)-AVEX
      YDIF=Y(J,K)-AVEY
      RES=X(J,K)-Y(J,K)
      XVAR=XVAR+XDIF*XDIF
      YVAR=YVAR+YDIF*YDIF
      SRES=SRES+ABS(RES)
      SSRES=SSRES+RES*RES
      IF(X(J,K),NE,0,0)GOTO 7777
      XL=ALOG(X(J,K)+0,001)
      GOTO 7776
7777  XL=ALOG(X(J,K))
7776  IF(Y(J,K),NE,0,0)GOTO 7778
      YL=ALOG(Y(J,K)+0,001)
      GOTO 7779
7778  YL=ALOG(Y(J,K))
7779  XDIFL=XL-AVEXL
      YDIFL=YL-AVEYL
      XVARL=XVARL+XDIFL*XDIFL
```

```
      YVARL=YVARL+YDIFL*YDIFL
      RESL=XL-YL
      SSRESL=SSRESL+RESL*RESL
      DO 10 KK=1,NFDC
      IF(X(J,K).GE.DC(KK))NTX(KK)=NTX(KK)+1
      IF(Y(J,K).GE.DC(KK))NTY(KK)=NTY(KK)+1
10    CONTINUE
      XRES=X(J,K)-SMONX(MM)
      SSXRES=SSXRES+XRES*XRES
      XLRES=XL-SMONXL(MM)
      SXLRES=SXLRES+XLRES*XLRES
C
C     SET UP ARRAYS FOR MONTHLY PEAK FLOWS AND FOR NON-ZERO
C     LOW-FLOW DAYS
C
      IF(X(J,K).GT.XBIG(J))XBIG(J)=X(J,K)
      IF(Y(J,K).GT.YBIG(J))YBIG(J)=Y(J,K)
      IF(X(J,K).GE.2.0*AVEX)GOTO 48
      IF(X(J,K).EQ.0.0)GOTO 48
      KLO=KLO+1
      XLOW(KLO)=X(J,K)
      YLOW(KLO)=Y(J,K)
      CUMX=CUMX+XLOW(KLO)
      CUMY=CUMY+YLOW(KLO)
C
C     SET UP DEFICIENT FLOW(<2.0*DAILY MEAN)PERIOD CALCS
C
   48 IF(J.EQ.NMON.AND.K.EQ.KDAY)GOTO 45
      IF(K.EQ.KDAY)GOTO 40
      IF(X(J,K).GE.2.0*AVEX.OR.X(J,K+1).GE.2.0*AVEX)GOTO 41
      GOTO 42
40    IF(X(J,K).GE.2.0*AVEX.OR.X(J+1,1).GE.2.0*AVEX)GOTO 41
      GOTO 42
45    IF(X(J,K).GE.2.0*AVEX)GOTO 47
      IF(TEMP1.EQ.1)GOTO 47
42    MDTX=MDTX+1
      TEMP1=0
      YEMP2=0
      IF(MDTX.GT.LGEX)LGEX=MDTX
      IF(J.EQ.NMON.AND.K.EQ.KDAY)GOTO 43
      GOTO 47
41    TEMP1=1
      IF(J.EQ.1.AND.K.EQ.1)GOTO 44
      IF(TEMP1.EQ.1.AND.TEMP2.EQ.0)GOTO 43
44    MDTX=1
      TEMP2=1
      GOTO 47
43    IMX=IMX+1
      IXFLO=IXFLO+MDTX
      TEMP2=1
47    IF(J.EQ.NMON.AND.K.EQ.KDAY)GOTO 55
      IF(K.EQ.KDAY)GOTO 50
      IF(Y(J,K).GE.2.0*AVEY.OR.Y(J,K+1).GE.2.0*AVEY)GOTO 51
      GOTO 52
50    IF(Y(J,K).GE.2.0*AVEY.OR.Y(J+1,1).GE.2.0*AVEY)GOTO 51
      GOTO 52
55    IF(Y(J,K).GE.2.0*AVEY)GOTO 7
      IF(TEMP3.EQ.1)GOTO 7
52    MDTY=MDTY+1
      TEMP3=0
      TEMP4=0
```

```
      IF(MDTY.GT.LGEY)LGEY=MDTY
      IF(J.EQ.NMON.AND.K.EQ.KDAY)GOTO 53
      GOTO 7
51    TEMP3=1
      IF(J.EQ.1.AND.K.EQ.1)GOTO 54
      IF(TEMP3.EQ.1.AND.TEMP4.EQ.0)GOTO 53
54    MDTY=1
      TEMP4=1
      GOTO 7
53    IMY=IMY+1
      IYFLO=IYFLO+MDTY
      TEMP4=1
7     CONTINUE
      IF(J.EQ.1)GOTO 16
      TEMP=X(J,1)-Y(J,1)-X(J-1,KDAY)+Y(J-1,KDAY)
      DURB=DURB+TEMP*TEMP
16    DO 17 K=2,KDAY
      TEMP=X(J,K)-Y(J,K)-X(J,K-1)+Y(J,K-1)
      DURB=DURB+TEMP*TEMP
17    CONTINUE
C
C     SET UP MAXIMUM DAILY FLOWS / MONTH
C
      DO 12 L=1,NMON
      IF(XBIG(L).LE.2.0*AVEX)GOTO 12
      KA=KA+1
      NPK(KA)=L
      XBIG(KA)=XBIG(L)
      YBIG(KA)=YBIG(L)
      XBTOT=XBTOT+XBIG(KA)
      YBTOT=YBTOT+YBIG(KA)
12    CONTINUE
      TK=FLOAT(KA)
      XBTOT=XBTOT/TK
      YBTOT=YBTOT/TK
      DO 13 J=1,KA
      XBDIF=XBIG(J)-XBTOT
      YBDIF=YBIG(J)-YBTOT
      BRES=XBIG(J)-YBIG(J)
      XBVAR=XBVAR+XBDIF*XBDIF
      YBVAR=YBVAR+YBDIF*YBDIF
      SBRES=SBRES+ABS(BRES)
      SSBRES=SSBRES+BRES*BRES
13    CONTINUE
C
C     SET UP LOW FLOW CALCS
C
      CUMX=CUMX/FLOAT(KLO)
      CUMY=CUMY/FLOAT(KLO)
      DO 70 L=1,KLO
      XQ=XLOW(L)-CUMX
      YQ=YLOW(L)-CUMY
      QDIFF=XLOW(L)-YLOW(L)
      QQD=QQD+QDIFF*QDIFF
      XQV=XQV+XQ*XQ
      YQV=YQV+YQ*YQ
      Q=Q+ABS(QDIFF)
70    CONTINUE
C
C     CALCULATE STATS ON ALL DAILY FLOWS
C
```

```
      XVAR=XVAR/(TD-1.0)
      YVAR=YVAR/(TD-1.0)
      XVARL=XVARL/(TD-1.0)
      YVARL=YVARL/(TD-1.0)
      ERAVEL=100.0*(AVEYL-AVEXL)/AVEXL
      ERVAR=100.0*(YVAR-XVAR)/XVAR
      ERVARL=100.0*(YVARL-XVARL)/XVARL
      CEM=1.0-SSRES/SSXRES
      CEML=1.0-SSRESL/SXLRES
      RAE=100.0*SRES/(AVEX*TD)
      AA=SQRT(SSRES/TD)/AVEX
      BB=SQRT(XVAR)
      BB=(BB/AVEX)*(BB/AVEX)
      BB=(BB*(TD-1.0)/TD+1.0)**0.25
      EMECE=100.0*AA/BB
      DO 14 KK=1,NFDC
14    AVFDC=AVFDC+NTX(KK)
      AVFDC=AVFDC/FLOAT(NFDC)
      DO 15 KK=1,NFDC
      RFDC=NTX(KK)-NTY(KK)
      XRFDC=NTX(KK)-AVFDC
      SFDC=SFDC+RFDC*RFDC
15    SXFDC=SXFDC+XRFDC*XRFDC
      CEFDC=1.0-SFDC/SXFDC
      DURB=DURB/SSRES
C
C     CALCULATE STATS ON MAXIMUM DAILY FLOW/MONTH
C
      BCE=1.0-SSRES/BVAR
      XBVAR=XRVAR/(TD-1.0)
      YBVAR=YBVAR/(TD-1.0)
      BERMN=100.0*(YBTOT-XBTOT)/XBTOT
      BERVAR=100.0*(YBVAR-XBVAR)/XBVAR
      BRAE=100.0*SRES/(XBTOT*TK)
      WRITE(6,18)
18    FORMAT(5X,'COMPLETE SET OF MEAN DAILY FLOWS'/5X,32('-'))
      WRITE(6,19)AVEXL,AVEYL,ERAVEL,XVAR,YVAR,ERVAR,XVARL,YVARL,ERVARL
19    FORMAT(/8X,'LOG,DAILY MEAN : OBSERVED=',F10.5,' SIMULATED=',
     *F10.5,'  % ERROR= ',F6.2,
     *//8X,'NATURAL DAILY VARIANCE : OBSERVED=',F10.5,
     *' SIMULATED=',F10.3,'  % ERROR= ',F6.2///8X,'LOG,DAILY VARIANCE :',
     *' OBSERVED=',F11.4,' SIMULATED= ',F11.4,'  %ERROR= ',F6.2///)
      WRITE(6,20)CEM,CEML,RAE,EMECE,CEFDC,DURB
20    FORMAT(8X,'SPECIAL COEF OF EFFICIENCY(NATURAL)=',F8.3//8X,
     *'SPECIAL COEF OF EFFICIENCY(LOG,)=',F6.3//8X,'RELATIVE MEAN',
     *' ABS. ERROR(%)=',F7.3,//8X,'MAX.EQUIVALENT CONSTANT ERROR(%)=',
     *F6.2///8X,'COEF OF EFFICIENCY OF FLOW DURATION CURVE=',F7.5//8X,
     *'DURBIN-WATSON D-STATISTIC=',F6.3///)
      WRITE(6,21)
21    FORMAT(/5X,'MONTHLY PEAK MEAN DAILY FLOWS > 2.0 * DAILY MEAN',
     *//5X,50('-'))
      WRITE(6,22)XBTOT,YBTOT,BERMN,XBVAR,YBVAR,BERVAR,BCE,BRAE
22    FORMAT(//8X,'MONTHLY PEAK FLOW MEAN : OBSERVED=',F8.3,
     *' SIMULATED= ',F8.3,'  % ERROR= ',F6.2//8X,'MONTHLY PEAK ',
     *'FLOW VARIANCE : OBSERVED=',F10.3,' SIMULATED=',F10.3,'  % ',
     *'ERROR =',F6.2///8X,'COEF OF EFFICIENCY(PEAKS)=',F6.3//8X,
     *'RELATIVE MEAN ABS. ERROR(PEAKS)(%)= ',F7.3////)
      WRITE(6,24)
24    FORMAT(//5X,'DAILY FLOW DURATION CURVE'/5X,26('-')//6X,
     *'CUMECS EXCEEDED',3X,' OBS.(%)',3X,' SIM.(%)',5X,'% ERROR'/)
      DO 25 I=1,NFDC
```

```
      IF(NTX(I).EQ.0)GOTO 25
      ERFDC=100.0*(FLOAT(NTY(I))-FLOAT(NTX(I)))/FLOAT(NTX(I))
      ZNTX=100.0*FLOAT(NTX(I))/TD
      ZNTY=100.0*FLOAT(NTY(I))/TD
      WRITE(6,23)DC(I),ZNTX,ZNTY,ERFDC
23    FORMAT(8X,4F11.2)
25    CONTINUE
      WRITE(6,32)
32    FORMAT(///5X,'LISTING OF MONTHLY PEAK FLOWS(CUMEC) > 2.0*MEAN'/,
     *5X,43('-')//6X,'MONTH NO.',7X,'OBS. PEAK',5X,'SIM.PEAK',5X,
     *'% ERROR')
      DO 30 I=1,KA
      BIGER=100.0*(YBIG(I)-XBIG(I))/XBIG(I)
      WRITE(6,31)NPK(I),XBIG(I),YBIG(I),BIGER
31    FORMAT(5X,I10,3F14.2)
30    CONTINUE
C
C
C     CALCULATE STATS ON LOW FLOW PERIODS
C
      QCE=1.0-QQD/XQV
      XQV=XQV/FLOAT(KLO-1)
      YQV=YQV/FLOAT(KLO-1)
      ERQV=100.0*(YQV-XQV)/XQV
      EXCUM=100.0*(CUMY-CUMX)/CUMX
      QRAE=-100.0*Q/(CUMX*FLOAT(KLO))
      XIFLO=FLOAT(IXFLO)/FLOAT(IMX)
      YIFLO=FLOAT(IYFLO)/FLOAT(IMY)
      ERIF=100.0*(YIFLO-XIFLO)/XIFLO
      ERLGE=100.0*(FLOAT(LGEY-LGEX)/FLOAT(LGEX))
      WRITE(6,60)
60    FORMAT(/5X,'LOW FLOW PERIOD (<2.0*DAILY MEAN) STATISTICS'/
     *5X,41('-'))
      WRITE(6,61)CUMX,CUMY,ERCUM,XQV,YQV,ERQV
61    FORMAT(//5X,'MEAN NON-ZERO DAILY LOW FLOW : OBS.=',F8.4,
     *' SIM.=',F8.4,' % ERROR=',F6.2//5X,'VARIANCE NON-ZERO DAILY',
     *' LOW FLOW : OBS.=',F8.4,' SIM.=',F8.4,' % ERROR=',F6.2////)
      WRITE(6,62)QCE,QRAE
62    FORMAT(5X,'COEF.OF EFFICIENCY OF NON-ZERO LOW FLOWS=',F7.3,
     *//5X,'RELATIVE MEAN ABS. ERROR """""""""""(%)=',F7.3////)
      WRITE(6,63)XIFLO,YIFLO,ERIF,LGEX,LGEY,ERLGE
63    FORMAT(5X,'MEAN DEFICIENT FLOW PERIOD(DAYS) : OBS.=',F6.1,
     *' SIM.=',F6.1,' % ERROR =',F6.2//5X,'MAXIMUM DEFICIENT FLOW',
     *' PERIOD(DAYS) : OBS.=',I6,' SIM.=',I6,' % ERROR=',F6.2)
      RETURN
      END
```

```
SUBFILE:OPDA LG=8200 LENGTH:  42     HRAG


       LIST
       PROGRAM(DALM)
       INPUT 5=CK5
       OUTPUT 6=LP0
       COMPRESS INTEGER AND LOGICAL
       TRACE 0
       END
       MASTER DALM
C      ##########################################################################
C              === DALM OPTIMIZER ==
C      THIS PROGRAM GENERATES MONTHLY RUNOFF FROM MONTHLY RAINFALL (MM)
C      AND MONTHLY PAN EVAPORATION(MM).
C      ##########################################################################
       LOGICAL ICS
       COMMON RAIN(100),FSIM(100),OBFL(100),PEC(100),
     * READJ(12),RRN(12),AMX(50),ANY(50),
     *NMON,NYR1,NM1,IFORS,LINE,ILIM,ISTAT,SSL,SSM,SSB,POWER,
     * BCUR,AMAX,PERC,GSL,AFOR,EVM0(100),
     * X(12),A(12,12),Z(3,12),NPAR,MOPT,LOPT,IST1,ICS,NOPT,
     * F,F1,SRESD,VARD,OMAR,NTT,AREA
       DIMENSION SOHS(12)
C
C      READ NOPT AND NPAR
C
       READ (5,741)NOPT,NPAR
741    FORMAT(2I2)
C      ***************************************************************
C      READ IN CATCHMENT NAME OR RUN IDENTIFICATION - 32 COLUMNS
C      ***************************************************************
       READ(5,1) G1,G2,AREA,NIT
    1  FORMAT(2A5,F7.0,I3)
C      ***************************************************************
C      NUMBER OF MODEL ITERATIONS REQUIRED PER MONTH,
C      STARTING YEAR (IE 1920) AND MONTH (IE 1 FOR CALENDER YEARS AND
C      10 FOR HYDROLOGICAL YEARS) OF SIMULATION AND
C      IFORS =1 FOR NO FOREST COVER ON CATCHMENT
C            =2 FOR CONSTANT FOREST COVER ON CATCHMENT
C            =3 TO ACCOMMODATE CHANGING FOREST COVER
C      AND LINE AND ILIM TO CONTROL THE NON-LINEAR STORE
C      ***************************************************************
       READ(5,2) NYR1,NYR2,NM1,IFORS,LINE,ILIM
    2  FORMAT (6I5)
C      ***************************************************************
C      READ IN MODEL PARAMETER VALUES AND INITIALIZE VARIABLES
C      SSL   INITIAL LEVEL OF SOIL MOISTURE STORAGE(MM)
C      SSM   MAXIMUM CAPACITY OF SOIL MOISTURE STORAGE (MM)
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 PERC
C      GSL   INITIAL VALUE OF GROUNDWATER STORAGE LEVEL (MM)
C      AFOR  AFFORESTATION PARAMETER (SET TO 1.0 FOR NO FOREST COVER)
C      ***************************************************************
       READ(5,3) SSL,SSM,SSB,POWER,BCUR,AMAX,PERC,AFOR
    3  FORMAT (6F5.2)
```

```
C     ***********************************************************************
C     IF IFORS=1 NO FORESTRY CARD REQUIRED
C     IF IFORS=2 READ IN PERCENTAGE FOREST COVER IN FORMAT 1F8.2
C     IF IFORS=3 READ IN PERCENTAGE FOREST COVER FOR EACH YEAR OF RECORD
C                IN FORMAT 10F8.2
C     ***********************************************************************
      IF (IFORS.EQ.1) GO TO 420
      IFY=NMON/12
      IF (IFORS.EQ.2) IFY=1
      READ (5,410) (PFC(KR),KR=1,IFY)
  410 FORMAT (10F8.2)
C
C
C      SET INITIAL VALUES OF PARAMETERS
C
  420 Y(1)=SSM
      X(3)=SSE
      X(2)=POWER
      X(4)=PERC
      MOPT=0
      IST1=0
      OMAR=0.0
      VARO=0.0
      NMON=NYR2-NYR1 + 1
      NMON=NMON*12
C     ***********************************************************************
C     READ IN MONTHLY VALUES OF AVERAGE PAN EVAPORATION (MM) JAN-DEC
C     ***********************************************************************
      READ (5,4) (EVMO(NX),NX=1,NMON)
    4 FORMAT (2X,12F6.1)
C     ***********************************************************************
C     READ IN 12 PAN TO FREE WATER SURFACE EVAPURATION CONSTANTS JAN-DEC
C     ***********************************************************************
      READ (5,1119) (PEADJ(K),K=1,12)
1119  FORMAT(12F5.0)
C     -----------------------------------------------------------------------
C     INITIALIZE OBSERVED RUNOFF ARRAY
C     -----------------------------------------------------------------------
      DO 10 JK=1,NMON
   10 OBFL(JK)=0.0
C     ***********************************************************************
C     READ IN MONTHLY RAINFALL DATA(MM) FOLLOWED BY OBSERVED MONTHLY
C     RUNOFF DATA (THOUSANDS OF CUBIC METRES).
C     ***********************************************************************
      READ (5,15) (RAIN(I),I=1,NMON)
   15 FORMAT (2X,12F6.2)
      READ (5,15) (OBFL(K),K=1,NMON)
      L=0
      DO 778 J=1,NMON
      L=L+1
      IF(L.GT.12)L=1
      OMAR=OMAR+OMFL(J)
778   SUBS(L)=SUBS(L)+OMFL(J)
      DO 896 K=1,12
896   SUBS(K)=SUBS(K)/FLOAT(NMON)
      OMAR=OMAR/FLOAT(NMON)
      K=0
      DO 748 J=1,NMON
      K=K+1
      IF(K.GT.12)K=1
      VARO=VARO+(OBFL(J)-RAIN(J)*(OBFL(J)-OMAR)
```

```
      SRESU=SRESO+(OBFL(J)-SOBS(K))*(OBFL(J)-SOBS(K))
748   CONTINUE
      VARO=SQRT(VARO/FLOAT(NMON-1))
      WRITE (6,200) G1,G2
200   FORMAT (1H1,20HSIMULATION RUN FOR  ,2A5,//)
      WRITE (6,210) AREA,SSL,SSM,SSB,POWER,BCUR,AMAX,PERC,GSL
210   FORMAT (1H0,3SHPARAMETER VALUES USED IN THIS RUN,//,5X,6HAREA,5X,
     1'SSL',5X,'SSM',5X,'SSB',3X,'POWER',4X,'BCUR',4X,'AMAX',4X,
     2'PERC',5X,3HGSL,/,1X,10F8.2,//)
      WRITE (6,212) IFORS,AFOR
212   FORMAT (4X,5HIFORS,4X,4HAFOR,/,1X,I8,F8.2,///)
C*************************************************************
      CALL OPTM
C*************************************************************
C
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      CALL OUTPUT
C+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      STOP
      END
C ************************************************************
C
C     MONTHLY FLOW SUMMARY SUBROUTINE
C
C
C ************************************************************
      SUBROUTINE OUTPUT
      COMMON HAIN(100),FST1(100),OBFL(100),PFC(100),
     * PERQ(12),PRR(51),ANX(50),ANY(50),
     *NMON,NYR1,NM1,IFORS,LINE,ILI,ISTAT,SSL,SSM,SSB,POWER,
     * BCUR,AMAX,PERC,GSL,AFOR,EVMQ(100),
     * X(12),A(12,12),Z(3,10),NPAR,NOPT,LOPT,IST1,ICS,NOPT,
     * F,F1,SRESO,VARO,QMAX,MIT,AREA
      DIMENSION FIN(12),XOBS(12)
      F2=1.0-F1*F1
      WRITE(6,3)F5
      WRITE(6,10)(I,X(I),I=1,NPAR)
10    FORMAT(1X,4(3X,I2,F9.5))
3     FORMAT(1X,F7.4)
      DO 74 M=1,NMON,12
      ME=M+11
      NYR=NYR1-1+ME/12
      FYC=0.0
      XYC=0.0
      DO 53 J=M,ME
      K=J-M+1
      XOBS(K)=OBFL(J)
      FIN(K)=FST1(J)
      XYC=XYC+OBFL(J)
   53 FYC=FYC+FST1(J)
   54 WRITE(6,55)NYR,(FIN(N),N=1,12),FYC
   55 FORMAT(//I8,1CF8.1,F10.1)
      WRITE(6,491)(XOBS(N),N=1,12),XYC
491   FORMAT(2X,'OBS.',2X,12F8.1,F10.1)
74    CONTINUE
      RETURN
      END
C ************************************
C  MAIN OPTIMISING SUBROUTINE
C ************************************
      SUBROUTINE OPTM
```

```
      LOGICAL ICS
      COMMON RAIN(100),FSI1(100),OBFL(100),PFC(100),
     * PEADJ(12),RRR(31),ANX(50),ANY(50),
     *NMON,NYR1,NM1,IFORS,LINF,ILIM,ISTAT,SSL,SSM,SSB,POWER,
     * BCUR,AMAX,PENC,GSL,AFOR,EVRO(100),
     * X(12),A(12,12),Z(3,12),NPAR,MOPT,LOPT,IST1,ICS,NOPT,
     * F,F1,SRESO,VARO,OMAR,NIT,AREA
      ICS=.TRUE.
C ***********************************
C  TEST FOR ZERO STARTING VALUES
C
C ***********************************
      DO 250 I=1,NPAR
      IF(ABS(X(1)).GE.0.0001) GOTO 210
      IF(X(1)) 211,212,212
  211 X(I)=-0.0001
      GOTO 210
  212 X(I)=0.0001
  210 Z(1,I)=0.04
      Z(2,I)=1.00
      Z(3,I)=X(I)
      DO 240 J=1,NPAR
      A(I,J)=0.00
  240 CONTINUE
      A(I,I)=1.00
  250 CONTINUE
C ***************************************************
C  GET THE FIRST VALUE OF F TO PUT IN F1
C ***************************************************
      F=0.0
      CALL CALCFX
      F1=F
C ************************
C  THE ENDLESS ITERATION BEGINS HERE
C ************************************
  300 DO 500 LOPT=1,NPAR
      AA=0.6*Z(1,LOPT)
      B=0.00000
      CALL AUG(AA)
      CALL CALCFX
      IF(F1.GT.F) GOTO 310
      CALL AUG(-2.0*AA)
      F=F1
      CALL CALCFX
      IF(F1.GE.F) GOTO 310
      CALL AUG(AA)
      TOP=F-F2
      BOT=2.0*(F+F2-2.0*F1)
      GOTO 320
  310 IF(F1.EQ.F) AA=-1.0*AA
C ************************************
C
C  DO SUCCESS LOOP
C ************************************
  200 F1=F
      B=B+AA
      AA=1.3*AA
      CALL AUG(AA)
      CALL CALCFX
      IF(F1.GT.F) GOTO 200
```

```
C ***********************************
C  FAILURE ROUTINE STARTS HERE
C ***********************************
      CALL AUG(-AA)
      AA=AA/1.5
      Z(1,LOPT)=AA
      BOT=5.0*F*F-5.0*F1+2.0*F
      TOP=2.25*F2-1.25*F1-F
C ***********************************
C  END OF SUCCESS ROUTINE
C ***********************************
  320 IF(BOT,LE.0.000000000001) GOTO 400
      B=AA*TOP/BOT
      CALL AUG(B)
      CALL CALCFX
      IF(F.GT.F1) GOTO 340
C ***********************************
C  ELSE ACCEPT PREDICTED POINT
C ***********************************
      Z(1,LOPT)=AA+B
      F1=F
      B=B+B
      GOTO 400
  340 CALL AUG(-B)
  400 IF(B.EQ.0.000000) B=AA/10.0
      DO 410 J=1,NPAR
      A(J,LOPT)=B**A(J,LOPT)
  410 CONTINUE
  500 CONTINUE
C ***********************************
C  WRITE A SET OF VARIABLES AND TEST THE TERMINATING CRITERION
C ***********************************
      CALL SCRIPT
C ***********************************
C  THE ORTHOGONALISATION LOOP BEGINS HERE
C ***********************************
      DO 510 J=2,NPAR
      LOPT=NPAR-J+1
      DO 505 I=1,NPAR
  505 A(I,LOPT)=A(I,LOPT)+A(I,LOPT+1)
  510 CONTINUE
      DO 600 J=1,NPAR
      IF(J,EQ.1) GOTO 540
      I=J-1
      DO 550 LOPT=1,I
      AA=0.000
      DO 520 K=1,NPAR
  520 AA=AA+A(K,J)*A(K,LOPT)
      DO 525 K=1,NPAR
  525 A(K,J)=A(K,J)-AA*A(K,LOPT)
  530 CONTINUE
  540 AA=0.000
      DO 550 K=1,NPAR
  550 IF(ABS(A(K,J)),GT.0.000000000001) AA=AA+A(K,J)**2
      IF(AA,LT.0.000000000001) AA=0.000000001
      AA=1.00/SQRT(AA)
      DO 560 K=1,NPAR
      A(K,J)=AA*A(K,J)
  560 CONTINUE
  600 CONTINUE
      IF(ICS) GOTO 300
```

```
      WRITE(6,12) MOPT
   12 FORMAT(//18//)
      RETURN
      END
C ***************************************************************
C  CALCFX CALCS THE MODEL VALUES AND COMPUTES THE OPTIMISING FUNCTION
C ***************************************************************
      SUBROUTINE CALCFX
      COMMON RAIN(100),FSIM(100),OBFL(100),PFC(100),
     * PEAK(12),RRR(31),ANX(50),ANY(50),
     *NMON,NYR1,NM1,IFORS,LINE,ILIM,ISTAT,SSL,SSM,SSB,POWER,
     * BCUR,AMAX,PERC,GSL,ARUR,EVAO(100),
     * X(12),A(12,12),Z(5,12),NMAR,MOPT,LOPT,IST1,ICS,NOPT,
     * F,F1,SRESD,VARO,OMAR,NIT,AREA
      IF(X(1).GT.270.0.OR.X(1).LT.100.0)GOTO 150
      IF(X(3).GT.100.0.OR.X(3).LT.10.0)GOTO 150
      IF(X(2).GT.10.0.OR.X(2).LT.0.0)GOTO 150
      IF(X(4).GT.0.01.OR.X(4).LT.0.0)GOTO 150
C
C     SET UP NEW PARAMETER VALUES
C
      SSM=X(1)
      SSB=X(3)
      POWER=X(2)
      PERC=X(4)
  998 TPR=0
      TPE=0.
      TAE=0.
      TSURF=0.
      TBFL=0.
      TSUM=0.
      YBT=0.
      XBT=0.
      ICON=1
      IM=0
      NM=NM1-1
      TSL=0.
      TMS=0.
      TPR=0.
      SCEP=0.
      ATER=1.0/FLOAT(NIT)
      PSL=SSL
      BRA=SSB/SSM
      VARS=0.0
      SMAR=0.0
      SKESC=0.0
  233 IF (IFORS.EQ.1) PCH=0.0
      IF (IFORS.GT.1) PCH=PFC(1)
      SSS=SSM
C     ---------------------------------------------------------------
C     START OF THE MONTHLY LOOP
C     ---------------------------------------------------------------
      DO 100 M=1,NMON
      IM=IM+1
      NM=NM+1
      IF (NM.GT.12) NM=1
      PE=(EVAO(M)*PEAK(NM))/(FLOAT(NIT))
      PPPP=PE
      IF (RAIN(M).EQ.0.) GO TO 40
      W=-2.0+1.3732*((RAIN(M)+1.6)**0.5)
      W=W/RAIN(M)
```

```
      EN=1.26/((1.0Z-W)**1.49)
      IF (EN.GT.120.) EN=120.
      SP1=0.
      SFAR=0.
   40 TMIT=0.
C  ------------------------------------------------------------------
C     START OF ITERATION LOOP
C  ------------------------------------------------------------------
      DO 50 J=1,NIT
      IF (RAIN(M).NE.0.) GO TO 60
      RRR(J)=0.0
      GO TO 70
C  ------------------------------------------------------------------
C     CALCULATE RAINFALL FOR PRESENT INTERVAL
C  ------------------------------------------------------------------
   60 SFAR=SFAR+(1.0/FLOAT(NIT))
      SP2=RAIN(M)*(SFAR**EN/(SFAR**EN+(1.0-SFAR)**EN))
      RRR(J)=SP2-SP1
      SP1=SP2
   70 TPE=TPE+PL
      TPR=TPR+RRR(J)
      TSL=TSL+SSL
      IF (SSL.GT.TMS) TMS=SSL
C  ------------------------------------------------------------------
C     THE INTERCEPTION FUNCTION OPERATES ON A FINITE LINEAR STORAGE
C  ------------------------------------------------------------------
      GOTO 1344
      EPXM=1.5+0.05*PCH
      SINP=EPXM-SCEP
      IF (SINP.LT.0.) SINP=0.
      IF (RRR(J).GT.SINP) GO TO 440
      SCEP=SCEP+RRR(J)
      RRR(J)=0.
      GO TO 450
  440 RRR(J)=RRR(J)-SINP
      SCEP=EPXM
C  ------------------------------------------------------------------
C     ADJUST SOIL CAPACITY AND POTENTIAL EVAPOTRANS FOR FOREST COVER
C  ------------------------------------------------------------------
  450 FCF=1.0+((AFOR-1.0)/100.0)*PCH
      PL=PPPP*FCF
C  ------------------------------------------------------------------
C     ADD IN RAINFALL AND TAKE AWAY EVAP FROM STORE AND INTERCEPTION
C  ------------------------------------------------------------------
 1344 RAT=SSL/SSP
      IF (RAT.GT.1.0) RAT=1.0
      PRE=RAT**0.5+RAT**0.5-RAT
      IF (SCEP.GE.PE) GOTO 500
      TAE=TAE+SCEP
      EDEM=(PE-SCEP)*PRE
      SCEP=0.0
      GOTO 510
  500 SCEP=SCEP-PE
      TAE=TAE+PL
      PRE=0.0
  510 PLE=SSL*RRR(J)
      IF (PLE.LE.EDEM) GOTO 520
      TAE=TAE+EDEM
      PLE=PLE-EDEM
      GOTO 530
  520 TAE=TAE+PLE
```

```
      PLE=0.0
  530 OVF=PLE-SSM
      IF (OVF.GT.0.0) GOTO 540
      SSL=PLE
      OVF=0.0
      GOTO 550
  540 TSURF=TSURF+OVF
      SSL=SSM
  550 IF (ILIR.EQ.1) RANG=SSB
      IF (ILIM.EQ.2) RANG=SSM
      RAT=SSL/RANG
      IF (RAT.GT.1.0) RAT=1.0
      CK=RRK(J)-EDEM
      FAT=AMAX-((AMAX-1.0)*(RAT**BCUR))
      IF (LINE.EQ.1) FAT=1.0
      PSL=PSL+(CK*FAT)
      IF (PSL.GT.SSM) PSL=SSM
      IF (PSL.LT.SSL) PSL=SSL
      RAT=PSL/SSM
      IF (RAT.GT.BRA) GOTO 240
      BF=0.0
      GOTO 250
  240 HEAD=PSL-SSB
      PUTH=SSM-SSB
      PLOS=HEAD*((HEAD/PUTH)**PEXC)
      SSL=SSL-PLOS
      PSL=PSL-PLOS*FAT
      RAT=PSL/SSM
      TOR=TOK+PLOS
      XBRA=RAT-BRA
      BF=(PSL-SSB)*(XBRA**POWER)
      IF (BF.GT.SSL) BF=SSL
      TBFL=TBFL+BF
      SSL=SSL-BF
      IF (SSL.LT.0.) SSL=0.0
      PSL=PSL-BF*FAT
  250 TSUM=TSUM+OVF+BF
   50 TMIT=TMIT+OVF+BF
C     ------------------------------------------------------------------
C     END OF ITERATION LOOP
C     ------------------------------------------------------------------
      FSIM(M)=TMIT*AREA
      YET=YLT+FSIM(M)
      ICON=ICON+1
      IF (IFORS.EQ.1) PCH=0.0
      IF (IFORS.EQ.2) PCH=PEC(1)
      IF (IFORS.EQ.3) PCH=PEC(ICON)
      I=0
  100 CONTINUE
C     ------------------------------------------------------------------
C     END OF MONTH LOOP
C     ------------------------------------------------------------------
      SMAR=YET/FLOAT(NMON)
      DO 922 M=1,NMON
      CRES=OUFL(M)-FSIM(M)
      CKES=CKES+CRES
      SRESC=SRESC+CRES
      VARS=VARS+(FSIM(M)-SMAR)*(FSIM(M)-SMAR)
922   CONTINUE
      VARS=SQRT(VARS/FLOAT(NMON-1))
      CHEKT=100.0*(SMAR-QMAR)/QMAR
```

```
      CHEK2=100.0*(VARS-VARO)/VARO
      F=SRESC/SRESO
      F=SQRT(F)
      FREAL=F
      FMF=1.0-SRESC/SRESO
      IF(ABS(CHEK1).LT.5.0)GOTO 1114
      F=F*(1.0+(CHEK1-5.0)*(CHEK1-5.0)/10.0)
1114  IF(ABS(CHEK2).LT.10.0)GOTO 1115
      F=F*(1.0+(CHEK2-10.0)*(CHEK2-10.0)/10.0)
1115  WRITE(6,1112)(I,X(I),I=1,NPAR)
1112  FORMAT(1X,7(I2,F8.3))
      WRITE(6,1113)F,FREAL,FMF,CHEK1,CHEK2
1113  FORMAT(1X,3F12.6,2F10.3)
      NOPT=NOPT+1
150   F=F*2.0
      RETURN
      END
C *********************************
C  AUGMENTING VARIABLES
C *********************************
      SUBROUTINE AUG(N)
      REAL M
      COMMON RAIN(100),FSIM(100),OBFL(100),PFC(100),
     * PEAQJ(12),RRK(31),ANX(50),ANY(50),
     *NMON,NYR1,NM1,IFORS,LINE,ILIM,ISTAT,SSL,SSM,SSB,POWER,
     * QCUR,QMAX,QFPC,QSL,AFOR,EVMO(100),
     * X(12),A(12,12),Z(3,12),NPAR,NOPT,LOPT,IST1,ICS,NOPT,
     * F,F1,SRESO,VARO,QMAR,NIT,AREA
      DO 160 I=1,NPAR
      Z(2,1)=Z(2,I)+A(1,LOP1)*M
      X(I)=Z(3,1)*Z(2,I)
  160 CONTINUE
      RETURN
      END
C ***********************************************************
C  SCRIBE WRITES THE NEW VALUES AND HALTS THE OPTIMISER
C ***********************************************************
      SUBROUTINE SCRIBE
      LOGICAL ICS
      COMMON RAIN(100),FSIM(100),OBFL(100),PFC(100),
     * PEAQJ(12),RRK(31),ANX(50),ANY(50),
     *NMON,NYR1,NM1,IFORS,LINE,ILIM,ISTAT,SSL,SSM,SSB,POWER,
     * QCUR,QMAX,QFPC,QSL,AFOR,EVMO(100),
     * X(12),A(12,12),Z(3,12),NPAR,NOPT,LOPT,IST1,ICS,NOPT,
     * F,F1,SRESO,VARO,QMAR,NIT,AREA
      IST1=IST1+1
      F3=1.0-F1*F1
      WRITE(6,5) F3
      WRITE(6,10) (I,X(I),I=1,NPAR)
   10 FORMAT(1X,7(I2,F10.3))
    3 FORMAT(1X,E12.6)
      IF(IST1.GE.NOPT) ICS=.FALSE.
      IF(.NOT.ICS) IST1=0
      RETURN
      END
      FINISH
```

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