AN ASSESSMENT OF ISOLATED FLOOD EVENT CONCEPTUAL MODELS IN DIFFERENT CLIMATIC AND PHYSIOGRAPHIC AREAS - THE MODELS AND INITIAL RESULTS.

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FOREWORD

This report is the first preliminary report on the Water Research Commission project entitled 'Hydrological Research in catchments of the eastern and southern Cape'. The project has two major themes; one associated with isolated event deterministic models and the second with the use of stochastic models in semi-arid regions. This report addresses the former subject and is a continuation of preliminary work begun in an earlier project and reported by Hughes (1983).

The Hydrological Research Unit (HRU) at Rhodes University has been involved in the field of mathematical modelling of the rainfall-runoff process since its inception in 1974. It has established two areas where hydrological data are collected for research purposes. The first is in the semi-arid Ecca catchments of the eastern Cape while the second is in the sub-humid coastal area of the southern Cape Province.

Dr. Hughes has been a member of the HRU since 1980, and Ms Beater is a graduate student carrying out a research programme towards an MSc. degree. The research that has been completed in the past, as well as the continuation of this project, is only possible because of the funding from the Water Research Commission and due to the facilities provided by Rhodes University to my Department. My gratitude and appreciation is accordingly expressed to both organisations.

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ABSTRACT

The first chapters of this report review some aspects of the philosophy underlying deterministic approaches to modelling flood events. The discussion concentrates on isolated event modelling of non-urbanised catchment hydrological response. Consequently, some of the features specific to urban hydrological models (such as flow routing in stormwater drainage systems) are ignored. The introductory chapters are not meant as a full review of all modelling approaches but rather to define the context in which the models tested can be placed.

The four models investigated in this study are, a developed version of an implicit source area model, two simple constant runoff proportion models and a semi-distributed runoff-routing model. The first three models have been formulated as both lumped as well as semi-distributed models. The distribution system for all models is based upon sub-catchments. The structures of the four models are described and their parameters discussed with respect to perceived associations with physical characteristics of either the input rainfall or the catchment or both. Some of the models share common components but have essential differences in part of their structure. By comparing model results it was considered possible that some weaknesses might be identified and isolated.

The models have been calibrated on two physiographically and climatically different sets of catchments. Both represent nested gauging situations and one set (Ecca) is situated in the semi-arid eastern Cape of South Africa while the other (North Danville) is in the humid temperate north eastern United States. The ability of the four models to reproduce a range of observed storm hydrographs is examined from their curve fitting capabilities as well as the degree of parameter stability and acceptability. For each model, comparisons are made between the performance in the different regions and between the performance of the lumped and semi-distributed model versions. The North Danville catchments were generally modelled more successfully, although limitations in the available input data precluded firm conclusions from being made. Improved calibration results were obtained using the semi-distributed versions when the input rainfall was

spatially variable and adequately defined by the available data. Small events in the semi-arid catchments were not modelled successfully by any of the models. This is considered to be a consequence of a disparity between the scale of spatial variations of the real and modelled runoff generating processes during such low runoff response events. There are small differences in the overall ability of the four models to reproduce observed events. However, this was achieved with a more stable set of parameter values for the variable runoff proportion source area model, than for the other three. It is necessary to carry out further investigations to decide whether the variations in some parameter values between storms can be estimated from the storm input characteristics. Similarly, further work involving model testing on more catchments is necessary to examine more completely the physical relevance of the parameters of all the models. This work, as well as investigations into parameter sensitivity and model application forms part of a continuing project on single event modelling.

1. INTRODUCTION

Before discussing mathematical modelling approaches to the estimation of some or all of the characteristics of isolated or single flood events it is desirable to first of all define an 'event'. This is difficult in as much as the processes involved in the redistribution of water within the atmosphere/surface/subsurface system operate on a more or less continuous basis. Most hydrologists would agree that the processes predominantly operative during a 'flood event' differ only in degree from those during 'low flow' conditions. It is nevertheless impossible to define precisely a set of conditions that give rise to a 'flood event' as opposed to a 'non-flood event'. This can only be done in an arbitrary way by defining some peak discharge limit or perhaps a threshold rate of increase in discharge. An example would be the baseflow separation line of Hewlett and Hibbert (1967). A further example could be to choose only those events with peaks or volumes with recurrance intervals greater than a prescribed value. These arbitrary approaches to defining an event make no statements about any special set of conditions or processes that operate during the events. Consequently, it might be expected that modelling approaches to flood events would not be significantly different to modelling approaches to other periods in hydrological time series. However, this is not the case, and often flood models are designed as special case models. Such models ignore processes whichs are otherwise included, in some way, in models designed to simulate a range of hydrological occurrences. They may also concentrate more heavily on other processes deemed less important during lower flow situations.

The difference in approach to flood event modelling could be prompted by several factors. It may be prompted by the particular use for which the model is designed or related to the model designers' perception or understanding of the physical system being modelled. Perhaps the most common reason is an attempt to concentrate on those processes of the hydrological system that are most relevant to simulating flows at short time intervals (such as flow routing and neglect those deemed unimportant during storm rainfall. Event based models may therefore neglect the simulation of evapotranspiration and its effect on soil moisture (Loague and Freeze, 1985). This point is also related to the model designers' understanding of catchment hydrology. Ultimately, all hydrological models represent an attempt to simplify the physical system to a point where the model is operable for practical purposes but remains a sufficiently accurate simulation tool. The way in which a balance is achieved between the degree of simplification and the level of simulation accuracy has not been determined. It is, of course, a difficult problem and one that is inevitably related to the intended use of the model. A model designed to be used in a wide variety of catchments with different physiographic and climatic characteristics is expected to be more sophisticated than one intended for more limited purposes. At our current level of knowledge, hydrologists do not really know how much more complex such a model has to be. Nor do they know which components of the system have to be modelled in a more complex way. It is, admittedly, an enormous task to solve such a problem. A conclusive answer might only be achieved by testing a wide range of model types on an equally wide range of differing catchments (Sorooshian, 1983). The observed data from each catchment would also have to represent the variety of different streamflow responses that could occur from the catchment and be of good 'research' quality. Assuming that such data have been collected, the consolidation of such a test data set would alone be an enormous task.

It is inevitable that less extensive testing of flood event models has taken place and also that the confident use of models is often restricted to the area that they were developed in. The literature on hydrological models abounds with different approaches to model testing. Some contributions have concentrated on isolating the most important (or sensitive) components of models (Pickup, 1977; Mein and Brown, 1978; Bondelid et al., 1982; Sorooshian and Arfi, 1982; Rogers et al., 1985) often with the intention of isolating which model parameters should be most accurately evaluated. Others have concentrated on the application of models to situations or areas where a specific model (or models) has previously not been applied (Hope, 1983; Eyre and Crees, 1984; Devaurs and Gifford, 1986). Still others have investigated whether or not the sub-components of models (such as soil moisture levels or the extent of source areas) are simulated accurately (Manley, 1977; Beven and Kiekby, 1979; Ward, 1984; Bernier, 1985; Moore et al., 1986). Some contributions represent comparitive tests of different modelling approaches (Delleur et al., 1976; Singh and Buapeng, 1977; Lowing and Mein, 1981; Loague and Freeze, 1985) while others concentrate on single models (mein, et al., 1974; Foroud and Broughton, 1981; Diskin et al, 1984; Hughes, 1984; and many others). All such reports in the literature represent a large .and still growing body of information related to the problem referred to in the previous paragraph. However, this problem still remains and until it is solved there will always be a measure of doubt about the successful use of models in practical, applied situations.

This report initially examines some of the principles underlying the different approaches to single event modelling (sections 2 and 3). It attempts to integrate some of the current attitudes to the deterministic modelling of flood events and discusses some of the problems of applying alternative modelling approaches. These sections of the report also place into context the models that have been selected for testing as well as the methods that are used to evaluate and compare the performance of the models. The remainder of the report describes the models under test, the initial test data and the results of calibrating the models on these data. The present report therefore provides the theoretical background to the complete study as well as establishing the authors' attitudes to the development, testing and application of single event models. The initial test data are drawn from two totally different regions. The calibration results reported herein have demonstrated that the models can be applied to simulating storm events in two different rainfall-runoff response situations. A future report (to be prepared in 1988) will discuss the results of further model calibration and verification on a wider range of catchments. This second report will also attempt to draw conclusions about the usefulness of the models for solving problems in applied situations.

It would be impossible to thoroughly test all the single event modelling approaches that have been reported in the literature. The models have therefore been selected to represent a range of approaches from very simple constant runoff proportion models to a more complex model which incorporates more than one runoff generation component. All the models selected represent non-linear approaches to modelling the response of runoff to rainfall. In order to investigate the desirability of using distributed approaches (section 2.3.1 of this report) it was decided to choose models that could be operated in either lumped or distributed format. This excludes some approaches that have been tested by other hydrologists working in this field (kinematic flow routing, for example). The models were also chosen on the basis of their perceived applicability to simulating floods from a relatively wide range of catchment sizes.

2. DETERMINISTIC MODELLING APPROACHES TO THE SIMULATION OF FLOOD EVENTS

In their introduction to a paper which discusses tests carried out on three models, Loague and Freeze (1985) suggest that comparisons should be made between different generic types of model. They consider that many earlier contributions have compared models of the same generic type. James and Hawkins (1981) presented a system of model classification based upon the needs of users and the approach to modelling. Their purpose was to evaluate the reliability of available models for meeting users' needs and to provide a taxonomic system for general model assessment. James and Hawkins (1981) covered a wide range of model types from catchment process models, through flood and drought frequency models to alluvial process models. There is very little reference to the detail of individual modelling approaches. When looking at a more restricted group of models it is difficult to construct a classification scheme that considers the detail of the complete range of approaches that have been adopted. There are a wide range of criteria which could be used to devise a scheme to group models. However, in some cases a model may fall into one group on the basis of one criterion but into a different group using another criterion. This chapter attempts to summarise and discuss the approaches that have been used by examining criteria related to the type of input data required, the detail of the output, the degree of spatial distribution used, and other factors. No attempt is made to define groups which individual models fall into uniquely.

2.1 Continuous or isolated event models

Continuous simulation models have been used to generate sequences of flood peaks or volumes but require long periods of short time interval input data. They may be useful to compare the probability structure of rainfall and resulting streamflow events (Packman and Kidd, 1980; Beaudoin et al., 1983) but long records of short period rainfall data are rarely available. They have also been used extensively for real time flood forecasting (Green, 1979; Anderson and Burt, 1985). One of the advantages is that moisture storages are modelled continuously, precluding the necessity to estimate initial conditions at the start of the storm. This is only an advantage if the model simulates the storages realistically.

An alternative approach is to model continuously but with a coarse time interval between events (Dunsmore, et.al. 1985). Given the condition of realistic simulation, such models have similar advantages to the first type without the stringent data requirements. If the model structure is essentially the same when dealing with event and non-event periods then the model has to be rigorous and flexible enough to operate under a wide variety of hydrological response situations. If, alternatively, the structure of the event model is different, then effectively the user is dealing with two models. He therefore has to establish two sets of parameter values by whatever technique is pertinant to the model or available to him. When the required output is only one isolated event it is necessary to know what length of period prior to the event that continuous simulation must begin. It may be difficult to assume a fixed period as it would still be necessary to set the initial model storage levels. One suggestion would be to begin at a point when the storages could be assumed full, such as the previous large rainfall event. In other cases, such as arid or semi-arid areas, it may be better to begin at the end of a prolonged dry period when storage levels could be assumed to be low.

It is difficult to draw a clear line of distinction between the second approach referred to above and some isolated or single event models (IEM's). IEM's have essentially three basic components: a method of determining initial conditions; a method of determining that proportion of rainfall that contributes to streamflow during the storm (excess rainfall or direct runoff); and some form of flow routing procedure. If a coarse time period model constitutes the first component then this is similar to continuous modelling with a differential time interval. A distinction could be made between those techniques that explicitly model initial storage conditions and those that rely upon some simple surrogate estimate (initial observed flow rate or antecedent precipitation indices, for example).

2.2 Model distinctions based upon intended application

Not all deterministic flood event models have been designed with the same intended application and often their structure is related in some way to the particular problem that they were initially designed to solve. This can lead to difficulties if a model is used for a purpose for which it was not originally intended. This is especially true if the new application is conceptually "in conflict" with the structure of the model. For example, a model that was originally designed to simulate flows from small catchments with little spatial variation in hydrological processes should not be used in relatively large catchments. Such an exercise is unlikely to be successful if the original model is not capable of accounting for either the spatial variation of processes or of rainfall input.

2.2.1 Design flood applications

Perhaps the classic application of single event flood models is for design purposes. In the past this has involved models with relatively simple formulations designed to predict the flood peak or the flood volume or both. Included in this group could be the Rational method, R-index (Hewlett et al., 1977; Hope, 1983; 1984), SCS formulae and various rainfall excess generating equations (Singh and Buapeng, 1977) attached to routing methods such as time-area diagrams, unit-hydrographs or others. One characteristic of some of these models is that they concentrate on estimating the peak flow rate and its timing and sometimes the flood volume. The unfortunate characteristic of most deterministic approaches to design floods is that they rely upon the equivalence of return period (or probability of exceedence) of the storm rainfall event and the resulting flood. Several authors have drawn attention to the inadequacy of such an assumption (Hiemstra, 1969; Cordery, 1970; Marsalek, 1978; Wenzel and Voorhees, 1978; Urbonas, 1979; Beaudoin et al 1983; Dunsmore et al., 1986; Hughes, 1986), identifying the importance of the role played by antecedent moisture as well as other characteristics of the rainfall event apart from simply its depth and duration. This problem is not necessarily model related, as even complex flood models suffer from this basic error in the concept of the design storm.

There is a further, perhaps more fundamental, problem that is inherent in most design flood approaches (deterministic and probabilistic). That is the concept that the probability of exceedance of a specified <u>peak</u> or <u>volume</u> is an adequate definition of the risk of <u>flooding</u>. This can only be true if the damage is directly associated with the single parameter of the flood specified in the probability statement (i.e. peak or volume), and that the other aspects of the event are irrelevant. Even when peak discharge is the dominant factor there may be other considerations that are important to the overall design problem. As long as the flood discharges remain below the design peak there is no problem. However, if it is exceeded, then the length of time it is exceeded and the volume of runoff occurring before the structure is capable of carrying the flow again could be relevant to the resulting amount of damage or inconvenience. Other design situations, although less common, may require information about the complete flood hydrograph. This would certainly be the case when the amount of storage available forms part of the design. The requirements for the effective planning of flood plain development or channel improvement works could involve the estimation of complete hydrographs with realistic shapes owing to the often complex relationships between discharge and overbank inundation (Hughes, 1980). Reference to the probability of peak or volume exceedance is then no longer adequate. Extending the probability statement to include several aspects of a hydrograph in a multivariate distribution approach is difficult although has been attempted in a limited way by Hiemstra and Francis (1979). The alternative of defining the exceedance probability of the event in terms of the important parameters of the causative rainstorm (for example, depth, duration and intensity variations) and antecedent conditions is also difficult to achieve (Hughes, 1986).

There are a large number of models with more complex structures than the relatively simple ones referred to above. Many are quite capable of simulating realistic hydrograph shapes resulting from complex temporal and spatial variations in rainfall intensity. However, the concept of the design event and associated probability statements have not been updated to allow the inclusion of such additional information about the characteristics of a flood. It is doubtful if it is mathematically possible to update the concept in the manner suggested in the previous paragraph. That the concept requires some form of updating and refinement cannot be in doubt, nevertheless the most effective way still remains to be determined.

2.2.2 Real time flood forecasting

A number of models have been designed to be used as flood forecasting models (Green, 1979; Serban, 1976; Beven, et. al. 1984) while others have been adapted for this use (Eyre and Crees, 1984). They are generally moisture accounting models and continuous, using either constant time intervals or reduced time intervals during potential floods. Some sophisticated forecasting systems exist whereby rainfall forecasts, from radar observations, are used as input to a model which continuously updates streamflow predictions (Green, 1979). Within larger catchments, monitored headwater rainfall inputs can be used to predict sub-catchment flows which are then routed to predict the flood levels further downstream. Such practices are only justified where the travel time of the flood wave is of sufficient length to allow adequate warning downstream. Efficient and accurate channel routing functions would form a major component of such models. Although channel routing methods are well developed, given certain basic data, overbank flooding and its attenuating effects can be difficult to model (James et al., 1981).

2.2.3 Land use change, sediment and chemical component models

These models have been grouped together as they are often perceived to require more realistic modelling of the physical processes involved in catchment hydrology (Beven and O'Connell, 1982; Roberts, 1983; Fleming, 1984; Hughes, 1985). With models designed to predict land use change effects on flooding it is essential that the parameters or coefficients of the model have at least quantifiable relationships with the physical characteristics of catchments. In most cases it would also be necessary to allow for spatial variation of parameter values over the catchment. Except in small catchments, it is unlikely that the whole area would be under one land use then change to another. A special case where changes in land use would need to be accommodated, would be those areas experiencing hydrologically significant seasonal differences in land use.

The need for models with a realistic representation of the physical system (physically-based) where chemical or sediment production components are to be included, can be illustrated by a simple example. The hydrological components of a model may simulate a greater proportion of overland flow in relation to rapid subsurface flow than actually occurs. If the majority of the chemical solution processes occur in the subsurface environment then the model is unlikely to predict chemical quantities adequately.

Complex, spatially distributed, physically-based models are often difficult to apply in many flood modelling situations. However, when the extra effort involved in determining the parameter values of such models is rewarded by greatly improved simulation results, then the use of such models is warranted. Although no conclusive tests have been reported in the literature, integrated simulation studies, requiring output of more than just streamflows should be more successful if truly physically-based models are used. Some further comments on the degree of model complexity will be made in later sections.

2.3 Model complexity

Differentiating models on the basis of their complexity can be useful. To a certain extent, it is a measure of the amount of input data required, or number of parameters needing evaluation, before storms can be simulated. However, while it is likely that models having a sound base in the physical hydrology of catchments will be complex, the reverse is not necessarily so. Complex models have a high number of "degrees of freedom", to borrow a statistical term. This statement can be liberally interpreted to mean that there is a lot of scope for errors to be made and for these errors to compound and not necessarily cancel. Simple models can be easier calibrate on individual events, but it is often not possible to find any physical relevence for their parameter values. Consequently, such models may be unreliable if applied to storms not included in the calibration data set.

This report identifies two aspects of model complexity which are discussed separately below. The first is based upon the spatial complexity accommodated in the model while the second addresses the complexity of the way in which the hydrological processes in each spatial element (or linking spatial elements) are treated.

2.3.1 Degree of spatial distribution

There are three possible reasons for incorporating some degree of spatial distribution into a model. The first is to allow for spatially variable input variables, mainly precipitation (Beven and Hornberger, 1982; Corradini and Singh, 1985; Schultz, 1985). The second is to allow for spatial variation in the hydrological response characteristics within catchments (Peck et al., 1977; Clark, 1980; Beven, 1983; Rajendran and Mein, 1986) The final reason could be related to the second and may be a direct consequence of the type of approach used in one or more components of the model. For example, if a kinematic flow routing approach is to be used then the model needs to be spatially distributed. It is not a simple task to suggest which of the first two reasons is most important. This is largely due to the fact that different dominant factors prevail in individual regions, or catchments, or even during individual storm events. For any storm occuring in a catchment it would be necessary to investigate whether any variaton in runoff amount or pattern from sub-areas is a consequence of variations in rainfall characteristics or runoff response characteristics or both. In some circumstances, part of the answer is obvious. Convective thunderstorms are known to have spatially variable intensity patterns even over small areas (Schultz, 1985). Similarly, in catchments with diverse physiographic or land use characteristics, spatial variation in hydrological response can be expected. However, the complete answer is likely to be elusive in many situations.

Having decided that a distributed model is the most applicable approach to a given problem, it is then necessary to provide the input and parameter information at an adequate level of accuracy to justify the distributed approach. In terms of rainfall input, this would mean a sufficient number of gauging locations, or rainfall estimation points, to represent the degree of heterogeneity in either intensity or total storm rainfall. With respect to spatially variable parameter values it would first of all be necessary for the relevent parameters to have at least some definable physical relevance, quantifiable from measurable characteristics of the catchment. Regression-type relationships, suitably tested for the area of application, may be adequate. Directly measurable parameters in physical equations should be the optimum if the physical accuracy of the model structure is the main criterion. However, it has to be remembered that in practice it is not always possible to obtain measurements of certain hydrological characteristics at a large number of locations within catchments. If the point raised earlier about 'degrees of freedom' is also considered, then complex, physically-based, distributed models lose much of their initial attractiveness for solving practical problems.

The importance of measurement techniques and scale corresponding to model structure and distribution scale has been emphasised by several authors (Beven and O'Connell, 1982; Dunne, 1983; Abbott et al., 1986). Loague and Freeze (1985) maintain that the primary barrier to the application of physically-based models lies in our inability to quantify the spatial variability of rainfall and soil hydraulic properties at a satisfactory scale.

There are many different approaches to sub-dividing the catchment area in fully distributed models. Distribution schemes based directly upon physiographic criteria have been used widely. Breaking the catchment down into individual slope elements (Jayawardena and White, 1977, 1979), or utilizing some aspect of the channel network (Lee and Delleur, 1976; Surkan, 1974) are common approaches. Indirect use of physiographic criteria have also been used by dividing catchment areas up into travel time elements (Krzysztofowicz and Diskin, 1978; Watson, 1981). An alternative is to base the network of sub-areas on a uniform grid pattern with an appropriate spacing for the size of the catchment (Gupta and Soloman, 1977). A compromise between lumped and fully distributed models is the semi-distributed approach where an essentially lumped model is applied to sub-catchments within the total area (Mein et al., 1974). Clearly, a channel routing component would be required to delay, attenuate and accumulate the runoff from each sub-catchment. Having developed such a component to add to one lumped model it is usually a simple matter to apply it to others.

2.3.2 Model component complexity

The word 'complexity' has been used in this sub-heading although it does not convey the real essence of the following discussion. The problem lies in the confusion that can be caused by equating model complexity with the model's ability to represent the 'real world' of hydrological response. A model with a complex structure may be based upon false premises or applied in an inappropriate way and therefore be no more representative of the physical system than a relatively simple model. Different names have been used to represent groups of models based upon their complexity or physical reality. Roberts (1979), amongst others, used the black, grey, white box scheme, which is useful as it correctly implies a continuum or spectrum of increasing physical reality. An alternative is to refer to empirical, conceptual and physical (or physically-based) models. However, this scheme immediately raises semantic problems as any model that relies upon calibration with observed data is an empirical model. In addition, many models have sound physically-based components coupled with simple empirical approximations as part of their structure. The following classification scheme is presented to define more accurately how the authors of this report perceive model distinctions.

a) Simple empirical models: This group consists of those models where little or no attempt is made to relate the model components to physical reality. They are essentially curve fitting methods. The most likely approach for predicting storms not used for calibration is through statistical relationships between model parameters and storm or catchment characteristics. It is unlikely that parameters will remain stable even within one catchment due to changing hydrological response characteristics between storms that are not accounted for in the model.

b) Conceptual models: Such models may also be fitted using empirical calibration procedures. However, they can be distinguished from those above by virtue of the fact that the structure of these models is based upon conceptualisations of the processes active during flood events. They may be viewed as an assemblage of empirical components, each representing individual or groups of processes. Their success will be partly dependent upon the accuracy of the model developer's perception of the physical system and the way in which this perception is translated into the mathematical components of a model. Some of the model components may be strongly physically-based. This group represents a wide range of modelling approaches, some being developed as generally applicable models while others are intentionally restricted to certain areas of application (i.e. urban, forested or agricultural catchments, small catchments or humid regions). Models which have a sound conceptual structure relative to their intended area of application, may have a totally unsound structure if used out of context. A distributed model utilizing infiltration equations to determine excess rainfall and a sound surface flow routing procedure (for example kinematic flow routing) could be considered a realistic conceptualisation for some areas. However, in catchments where subsurface flow is an important process during some events the model is no longer realistic. This does not mean that the model could not be calibrated in such catchments. It merely suggests that the parameters would not be evaluated correctly in terms of their original conceptual meaning.

c) Physically-based models: James and Hawkins (1981) state that the 'ultimate surface water model would be comprehensive in its cover-age of the physical factors influencing surface water movement and consequently reliable in its quantitative estimation of stream-flow'. The authors of this report would agree with the first part of the statement but consider the second to be misleading. The reliability of such a model would also depend to a great extent on the user's ability to supply the model with the necessary data requirements (Beven, 1983). It is difficult to conceive of a hydrological model that can be applied in practice and that is formulated from a set of highly physical equations. This is not necessarily so because our understanding of the movement of moisture through and over natural materials is lacking. It is mainly because the hydrological response system at a catchment scale is very complex. In addition it is not possible to measure all the physical characteristics of catchments (which vary temporally and spatially) necessary to evaluate such physical equations. The best that can be achieved is a model which has a sound conceptual structure with parameters demonstrated to have quantifiable physical significance, and which is sufficiently sophisticated to account for the spatial and temporal variation in hydrological processes. The point about the difficulties of applying complex, physically-based, distributed models has already been made in section 2.3.1 above and need not be repeated here. It is sufficient to conclude that a great deal of effort is involved if the parameters are to be evaluated correctly. If this effort is by-passed by estimating parameter values using incompletely substantiated assumptions, then the models can become a highly complex conceptual model. Abbott et al. (1986), in presenting the first readily available description of the SHE model, raise some very valid points about the use of physically-based, distributed models. By utilizing a physically-based structure and having an intimate knowledge of the sensitivity of the model to parameter value variations, the level of uncertainty associated with parameter estimation may be reduced. This uncertainty may also be quantified by carrying out simulations using parameters within a reasonable range of possible values. It is not possible to quantify the uncertainty when there exists no understanding of the physical significance of the parameters.

2.4 Approaches to modelling components

The previous sections have discussed several general aspects of the different approaches to modelling flood events. Reference to individual components of the hydrological response system has only been used to illustrate generalised points. This section looks more specifically at the different components of flood event models and the various ways in which processes have been conceptualised and simplified for use in mathematical models. Most flood event models can be reduced to three main components.

a) The estimation of the catchment moisture status prior to the start of the storm event.
b) A method or methods of converting gross rainfall into excess rainfall or more exactly, that proportion of gross rainfall that contributes to runoff. This will inevitably include procedures for up-dating the levels of any storages used in the model.
c) The routing of runoff across and/or below the land surface and in the network of channels to the catchment outlet.

2.4.1 Antecedent conditions

The different approaches to the estimation of initial conditions has already been partly discussed in section 2.1 Continuous models (with or without variable time intervals) do not require a separate component for these estimations as storages are updated continuously. Where data are available and where the model and its sub-components are physically realistic with respect to the catchment under consideration, such approaches should give the best results. However, the estimation of soil moisture storage levels is rarely tested using observed data and consequently it is often difficult to assess whether these levels are being modelled accurately. Other storages that can be included are interception and surface detention storage. The effects of different initial levels of these on hydrological response during floods is not well understood.

In isolated event models, estimates of initial moisture status have been based on simple decay functions of some number of previous days' rainfall, either modified or not for seasonal influences (Hughes, 1984). The level of catchment outflow at the beginning of the storm has also been used. In the UK, the Meteorological Office use moisture budgeting techniques to estimate soil moisture deficiencies continuously on a regional basis and such values have been used in several models (for example, Pirt and Bramley, 1985). The authors are not aware of any distributed, isolated event models that make use of distributed estimates of initial conditions. This could be a major drawback if it is assumed that antecedent conditions can play a major role in determining the degree of hydrological response and that such conditions could be spatially variable. Whatever method is used to estimate initial conditions it must be compatible with the structure of the rest of the model. The principle is particularly pertinent to the use of a short time interval isolated event model coupled to a longer time interval water balance model.

2.4.2 Estimation of excess rainfall

The term 'excess rainfall' is misleading and is a somewhat outmoded expression. However, even in its literal sense it is still applicable to many models in use today. It also remains a convenient term to refer to that proportion of the gross rainfall that eventually contributes to catchment outflow. The first point to consider is whether specific models are designed to estimate total outflows or stormflows. If stormflows only are modelled then no attempt is made to model the slower responding baseflow. The underlying reason for neglecting this flow component would be that it is considered negligible during the major part of a flood hydrograph. The difficulty is that some form of separation line between the flow components must be assumed. A commonly used method is that of Hewlett and Hibbert (1967) where stormflow begins when flow rises faster than a separation line of gradient 1,13mm $day^{-1}day^{-1}$ (5,47 x $10^{-4}m^3s.^{-1}km^{-2}.h^{-1}$). While this may be a useful generalisation it fails to account for the very big differences that may occur between catchments of different soils and physiography. If total flows constitute model output, then some attempt has to be made to estimate the amounts of baseflow occuring during the event. This may be negligible when antecedent moisture levels are relatively low and events shortlived.

Procedures used to estimate excess rainfall are difficult to group as they really represent a continuous spectrum from simple through to complex, more physically-based, methods. However, in broad terms it is possible to identify three loosely defined categories.

a) Simple methods utilize constant runoff ratios, (NERC, 1975) continuing constant loss rates (Laurenson and Mein, 1985) or infiltration curves (Singh and Buapeng, 1977). Some infiltration loss curves allow for variable losses during a storm and can be soundly based upon observations of the process. They have been included in this group of simple methods as they usually fail to account (either explicitly or implicitly) for the role of subsurface flow processes. However, used in a distributed model, (for example, the model of Huggins and Monke, 1966) infiltration equations could form one component of a strongly physically-based approach to excess rainfall determination. Models using constant runoff ratios or loss ratios can be modified to allow some degree of temporally variable response. Laurenson and Mein (1985) suggest that separate 'bursts' of rainfall within a storm could have different response levels. However, it is not apparent how such relative differences could be quantified.

b) Intermediate approaches include those attempts to vary runoff response as the storm progresses as well as with changes in rainfall intensity. More than one concept of runoff generation may be employed in the estimation of rainfall excess. Examples of this group could include several models that have attempted to use the variable source area concepts of runoff generation in either an implicit or explicit way (Lee and Delleur, 1976; Krzysztofowicz and Diskin, 1977; Hughes, 1984; Pirt and Bramley, 1985). One of the major problems with the first group (a) is that the parameter values of the excess rainfall component will inevitably change for different events even on the same catchment. Consequently, for prediction (not calibration) purposes it would be necessary to estimate loss rates or runoff proportions from a combination of catchment and storm characteristics. It is difficult enough to quantitatively characterise individual storms, let alone relate such measures to model parameters. Intermediate approaches often represent an attempt to allow parameters to remain fixed for any given catchment.

c) Physically-based equations of surface and subsurface flow processes represent the highest level of the spectrum. The authors have no experience of models which fit into this group and can be said to represent the hydrological response system of a wide range of catchments. However, there are models which claim to be physically-based with respect to a limited range of catchment response characteristics (Beven and Kirkby, 1979). The SHE model (Abbott, et al., 1986) may represent a major advance in this area of hydrological modelling.

2.4.3 Flow routing methods

Inevitably the approach to flow routing is closely allied to the other components and structural elements of any model. Simple methods can include linear (Bauer and Midgley, 1974; Ponce, 1979; Green, 1979;) or non-linear (Hughes and Murrell, 1986) storage-routing equations, instantaneous unit hydrograph methods, or time-area diagrams (O'Donnell, 1966; Dooge, 1973; Watson, 1981). They have been used in both lumped and semi-distributed models. Usually, land surface (or subsurface) and tributary channel routing are integrated in one estimation formula. Fully distributed, slope element or grid models often have more complex and physically-based routing approaches such as kinematic flow methods (Stephenson, 1980) or physical hydraulic equations (Danish Hydraulic Institute, 1985).

2.4.4 General

One general observation that may be made is that a model that is expected to have widespread applicability should have components that are compatible with each other. For example, there seems little point in using a physically-based routing method with a simple method for rainfall excess determination. It is likely that the weakensses of the rainfall excess method will have an effect on the routing parameters. Their values may then need to be different to the 'physically realistic' ones in order to account for poor estimation of the time distribution of rainfall excess. Model components should also be compatible with the level of spatial distribution used as well as the time interval used in the model. As these are not independent of the response characteristics of individual catchments it is difficult to make recommendations or define precise guidelines for model development or model application. It appears that more investigations are required to ascertain which approaches to flood event modelling will be most successful in different circumstances.

3. MODEL CALIBRATION, VERIFICATION AND TESTING

3.1 Calibration

Conventionally, the calibration of a deterministic model involves changing the values of the parameter set until a satisfactory correspondence between the simulated and observed data is achieved. The criteria chosen to determine whether a satisfactory fit has been achieved can have an influence on the final parameter values. The choice of fitting criteria has received a great deal of attention in the modelling literature (Diskin and Simon, 1977; Sefe and Brougton, 1982; Görgens, 1983; Sorooshian, 1983; Green and Stephenson, 1986). The selection of criteria depends to a large extent on the important characteristics of the data set relative to the specific aim of the modelling study. In flood event modelling, the following hydrograph characteristics can be considered to be important;

i) total volume of runoff;
ii) peak flow rate;
iii) timing of peak flow rate;
iv) time duration of rise to peak;
v) shape of recession curve.

It is often necessary to assess the degree of correspondence between observed and simulated flows using several statistics (Görgens, 1983; Green and Stephenson, 1980). The following measures should provide a satisfactory assessment:

i) coefficient of efficiency (Aitken, 1973), E;
ii) coefficient of determination, D;
iii) percentage error in total runoff volume, %V;
iv) percentage error in peak discharge, %P;
v) time difference between observed and simulated peak, TP.

Both the coefficients of efficiency and determination could be calculated using untransformed discharge values or using the natural logarithms of the values. The logarithmic transformation removes the bias towards the high values of runoff. Large differences between E and D is indicative of systematic error which may also be illustrated by high percentage errors in both peak and volume. Low percentage errors in peak and volume, low values of D and E and a large time difference between peak discharges is indicative of a time shift of the whole hydrograph.

Models may be calibrated manually, by modifying one or more parameter value, observing the effect on the fitting criteria and then repeating the exercise. This can be time consuming and confusing when there is a high degree of interaction between parameters. The alternative is to use a procedure whereby some or all of the parameters are evaluated using an automatic optimising technique (Rosenbrock, 1960; Ibbit and O'Donnell, 1971; Gupta and Sorooshian, 1985). Only one objective function can be used and it may be necessary to carry out some manual adjustments afterwards to achieve a better overall fit based on several criteria. Interaction between parameters can cause complications and result in sub-optimum results being produced. Similarly, beginning the optimisation with different starting values can result in different final solutions. Whichever method of calibration is used, a knowledge of the degree and patterns of interaction between parameters as well as the sensitivity of the fitting criterion to changes in parameter values is always useful. The definition of model sensitivity to changes in parameter values and plotting of response surfaces are essential if the uniqueness of a particular solution is to be assessed. Where complex interactions between different parameters occur it is not always straightforward to define the full array of response patterns. In addition, different individual events may have different model response patterns depending upon the characteristics of the input rainfall data.

When testing some models, it may be expected that parameter values should remain stable for all storms experienced on the same catchment. Two methods of calibration could be adopted to investigate whether this expectation is realistic. Individual storms may be calibrated separately and the stability of the parameters assessed later. Alternatively all available storms could be calibrated together as one data set but resetting the initial moisture status at the beginning of each storm. The latter approach has certain advantages particularly when it is possible to achieve similar fits with different parameter sets. In the former approach the non-uniqueness of results on individual storms could be confusing and lead to erroneous conclusions. It is important to note that a lack of uniqueness of solutions is not necessarily a weakness of a model. If the model is conceptually sound, with parameters that have some degree of physical interpretation then only one solution may be 'correct'. Other solutions may produce similar fits, but be achieved by setting certain parameter values at levels that do not correspond to the parameters physical interpretation on a specific catchment. Thus, in testing such models intuitive assumptions about the physical interpretation of parameters may play a major role during a calibration exercise. Only after a number of catchments, having different hydrological characteristics, have been modelled can the validity of these intuitive assumptions be assessed and perhaps modified.

Not all models can be expected to have stable parameter values for all storms on the same catchment. Simple models utilising constant loss coefficients are an example. Variations in total rainfall amount, temporal intensity patterns and antecedent conditions, amongst others, inevitably lead to variations in the proportion of rainfall that becomes streamflow. It is therefore not practical to calibrate a series of storms together. Part of the overall assessment of the models' applicability or validity would then include an investigation of the relationships between parameter values and relevant storm characteristics. Without a knowledge of such relationships and the way in which they vary between catchments it is difficult to imagine how such models may be applied.

Calibration of semi-distributed models is an extremely difficult task unless information about the differences in hydrological response between sub-areas is known. In addition this information should be able to be interpreted in terms of differences in parameter values. Without this background knowledge, changing the values of sub-area parameters to achieve improved fits becomes a dangerous and time consuming exercise. It is evident that the potential for reaching spurious conclusions is very high indeed. Despite these disadvantages, semi-distributed approaches should be more successful than lumped models when there is some degree of spatial variability in the rainfall input data. Improvements over lumped modelling approaches may be achieved simply by accounting for this spatial variability even if most model parameters are kept constant for all sub-areas.

In general terms, complete calibration of isolated event models involves three stages. Firstly, it is necessary to achieve a satisfactory correspondence between observed and simulated discharges for individual storm events. Secondly, it is necessary to establish if, and in what way, parameter values vary between storm events on the same catchment. Finally, before a model can be considered satisfactorily calibrated for the range of catchments it is intended to represent, the way in which parameters vary between catchments should be known. Admittedly, the latter represents an extension of the conventional use of the term calibration. However, this extension is warranted if deterministic model calibration is to be considered more than just a curve fitting procedure.

3.2 Verification

There is often a degree of confusion between the use of the words 'verification' and 'validation' and they have been used in the literature to mean the same thing. Sorooshian (1983) uses both terms to refer to a check or test that calibrated parameter values can be used to satisfactorily simulate events not used for calibration. Stedinger and Taylor (1982), referring to stochastic models, used the term 'validation' for this process and 'verification' for ensuring that the computer coding of the model represents the idealized model. Both terms refer to confirming the soundness or truth of a result and therefore could be used interchangeably. It therefore seems to be irrelevant which term is used as long as it is followed by a description of what aspect of the model is being verified or validated.

Verification of the computer model is necessary to ensure that moisture is not lost or gained due to the incorrect operation of a particular function. Solutions to functions should also be checked for stability within the range of parameters or variables over which the model is intended to operate (Hughes and Murrell, 1986). The remainder of this section discusses different aspects of verifying that the model, operated with an identified set of parameter values, can be satisfactorily applied to a specific catchment.

With reference to single event models, the first level of verification would be a check that the model formulation is adequate to simulate a range of storm responses. This stage is likely to occur concurrently with calibration. If the model cannot adequately simulate the hydrographs of the calibration data set, then there is little point in carrying out further model tests on a particular catchment. Having calibrated the model successfully it is then necessary to evaluate the meaningfulness of the resulting parameter values. If the model is a relatively sophisticated one then the parameters may be expected to remain stable for a variety of response characteristics from the same catchment. Thus verification will involve running the model with a series of observed storms not included in the calibration set and evaluating the simulation results. It is important that the storms reserved for verifying the calibration parameter set represent a relatively broad spectrum of the type of hydrological response that the model is designed to simulate. For models of the simpler, curve fitting type, an intermediate stage is necessary. The parameters of these models may be expected to vary with the characteristics of the storm rainfall or antecedent conditions. It would therefore be necessary to evaluate these relationships before any worthwhile verification could take place. The parameters of strongly physically-based models should be able to be evaluated from field based measurements of soil, vegetation or physiographic characteristics when these are available. Verification then consists of testing whether such values produce adequate simulation results.

Regardless of the models complexity and the user's expectations, the verification results may suggest further modification to the parameter values. This implies further calibration to investigate whether a modified parameter set can produce satisfactory results for all the available storm data. This must be considered a legitimate step in model testing as it makes use of the maximum amount of information available. However, the implication is that if additional data became available the parameter set may still require changes. Thus, no conclusive result about the representativeness of the model or the particular parameter set can be achieved. Perhaps the main problem lies in determining whether the available set of observed storm events is representative of the range of response types that can be expected from a specific catchment. This will inevitably depend upon the climate and land use regimes of the catchment. The problem is similar to determining the length of record that is adequate to achieve a stable calibration of a continuous model (Görgens, 1983).

The final level of verification relates to testing the transferability of parameters to other catchments (Hughes, 1985). In this context 'other catchments' also refers to the same catchment used for calibration, but under a different land use regime. The general lack of success associated with attempts at transferring parameters of relatively simple models has prompted many workers in this field to favour the use of physically-based models (Bevan and O'Connell, 1982; Roberts, 1984). However, there are few reports in the literature of physically-based models being tested over a range of different catchments. Perhaps this is because a large amount of fieldwork is necessary to evaluate the parameters of physically-based distributed models. Such fieldwork is obviously difficult and time consuming to undertake on a large scale.

3.3 Model testing

To summarise the points made in the previous two sections, model testing includes the whole range of procedures used to decide whether a specific model is efficient and hydrologically representative with respect to its intended use.

Thorough testing should incorporate the following :

i) Evaluations of calibration efficiency;

ii) Evaluation of the stability of calibration results;

iii) Analysis of the sensitivity of model results to changes in parameter values as well as input data errors;

iv) Assessment of the range of hydrological response types that can be satisfactorily modelled;

v) Assessment of the transferability of model parameters to other situations (storms or catchments) not represented in the calibration or development data sets;

vi) Testing of any hypothesized or perceived associations between model parameters and physical catchment or storm characteristics.

While there may be overlaps between the six points referred to above it is apparent that a complete evaluation of a model's capabilities represents a tremendous task. The amount of data required is difficult to determine and might not be obtainable. It is hardly surprising that many model tests are less than thorough and limited by available data, computer or manpower resources. Most tests that have been reported contribute to an overall understanding of what it is possible to achieve with deterministic hydrological models. However, as more and more new models are designed the amount of comparitive testing that is required grows rapidly.

4. S-CURVE MODEL (OSE2)

4.1 Background

The model described in this section is an extended version of the implicit source area model presented by Hughes (1983; 1984). The central concept of the original model is that the proportion of rainfall that contributes to streamflow varies throughout the storm in relation to the moisture status of the catchment. This relationship was defined in the model using an asymmetric S-curve described by a three parameter hyperbolic tangent (TANH) function (Hughes, 1984). The runoff-ratio in any particular time interval is calculated from the relative moisture status. The runoff-ratio is interpreted as the proportion of the catchment area that functions as a source area. All rain falling on this contributes to streamflow, while rain over the remainder of the catchment contributes to an increasing relative moisture level and an expanding source area. The initial moisture status at the start of the storm was estimated from a decay function of the previous 20 days rainfall. Excess rainfall routing was achieved using a non-linear storage-routing equation (Hughes and Murrell, 1986).

The original model was able to reproduce observed hydrograph shapes reasonably well after calibration in both semi-arid and sub-humid test catchments. However, the model parameters were found to vary quite considerably for different storms on the same catchment (Hughes, 1983; 1984). This was especially true for the semi-arid catchments which are characterised by variable storm producing mechanisms (Hughes, 1983). Only if the model parameters could be related to storm characteristics in some way could the model be used to estimate hydrographs when observed data are unavailable (to generate design hydrographs for example). An alternative is to develop the model further by identifying the conceptual weaknesses and incorporating additional components where necessary to improve the model's flexibility. The following sections discuss the way in which this model has been developed.

4.2 Conceptual weaknesses

One of the weaknesses of the original model is that intense rainfall at the beginning of a storm with low antecedent moisture conditions generates insignificant amounts of runoff. This is inevitable when the model formulation only implicitly incorporates one method of runoff generation and operates as a lumped model. To extend the generality of the model it would be necessary to conceptually incorporate other runoff generation processes that have been identified as being important in a wide range of catchments. Subsurface flow and infiltration-excess overland flow (Ward, 1985) are two processes that could be added using relatively simple model formulations.

The model operates in regular time intervals defined by the user. A large amount of rain falling in one time interval means that the differences between the moisture status at the start and end of the interval can be quite high. The original model used an iteration process to calculate average moisture status within the interval. Conceptually, rain that does not become runoff has to travel over or through the soils of the catchment before contributing to the expansion of source areas. The original model formulation does not allow for a variable amount of time for this to happen in different catchments. The soil depth, drainage characteristics and steepness of the slopes within different catchments must influence the rate at which rain falling on valley tops and sides reach the valley bottom.

The conceptual structure of the model is based upon a lumped formulation. However, a consideration of the spatial variability of both rainfall input and catchment characteristics within some catchments suggests that lumped models will not always perform adequately. Even when such characteristics are relatively uniform there are some processes that are difficult to incorporate in a lumped model, yet may be important in certain catchments. Semi-arid catchments with channels developed in alluvium may experience high degrees of channel losses from streamflow generated in headwater areas. Thus, not only is the amount of streamflow reduced, but the timing of the overall response at the outlet may also be affected. While it is difficult to imagine how this model could be developed into a fully distributed version, the alternative of adopting a semi-distributed approach based upon lumped modelling of sub-catchments is feasible. Such an approach has been used by Mein et al. (1974) and involves the addition of components to route streamflow along the channels connecting nodal points within sub-catchments.

A further potential weakness in the model lies in the simplified approach to the estimation of antecedent moisture status. To improve this part of the model would probably involve the addition of a coarse time interval moisture balance model which would be operated over a specified period prior to an event. Such models are available (for example the ACRU model of Schulze, 1984) but its parameter values would also need to be estimated (by calibration or other methods) for any specific catchment. Consequently, this acknowledged weakness of the model has not been attended to at this stage of the model development.

4.3 Conceptual structure of the developed model

The model can be divided into three major components; antecedent moisture status estimation, runoff generation estimation and runoff routing components. The model can be operated in either lumped or semi-distributed mode. The essential difference lies in the fact that the sub-catchment version allows for separate modelling of runoff generation from different areas and the use of a different routing function. Figure 4.1 illustrates the structure of the model.

4.3.1 Antecedent moisture

A decay function of the form :

$$API = \sum_{i=1}^{n} DR_i . APF^i$$

where DR_i = rainfall total i days before the event, is used to calculate an antecedent precipitation index (API) from n days of rainfall prior to the event and a model parameter APF ($\leqslant$1,0). The number of days and the parameter APF can be varied between events to allow for seasonal effects. API then becomes the estimate of the initial moisture status of the catchment.

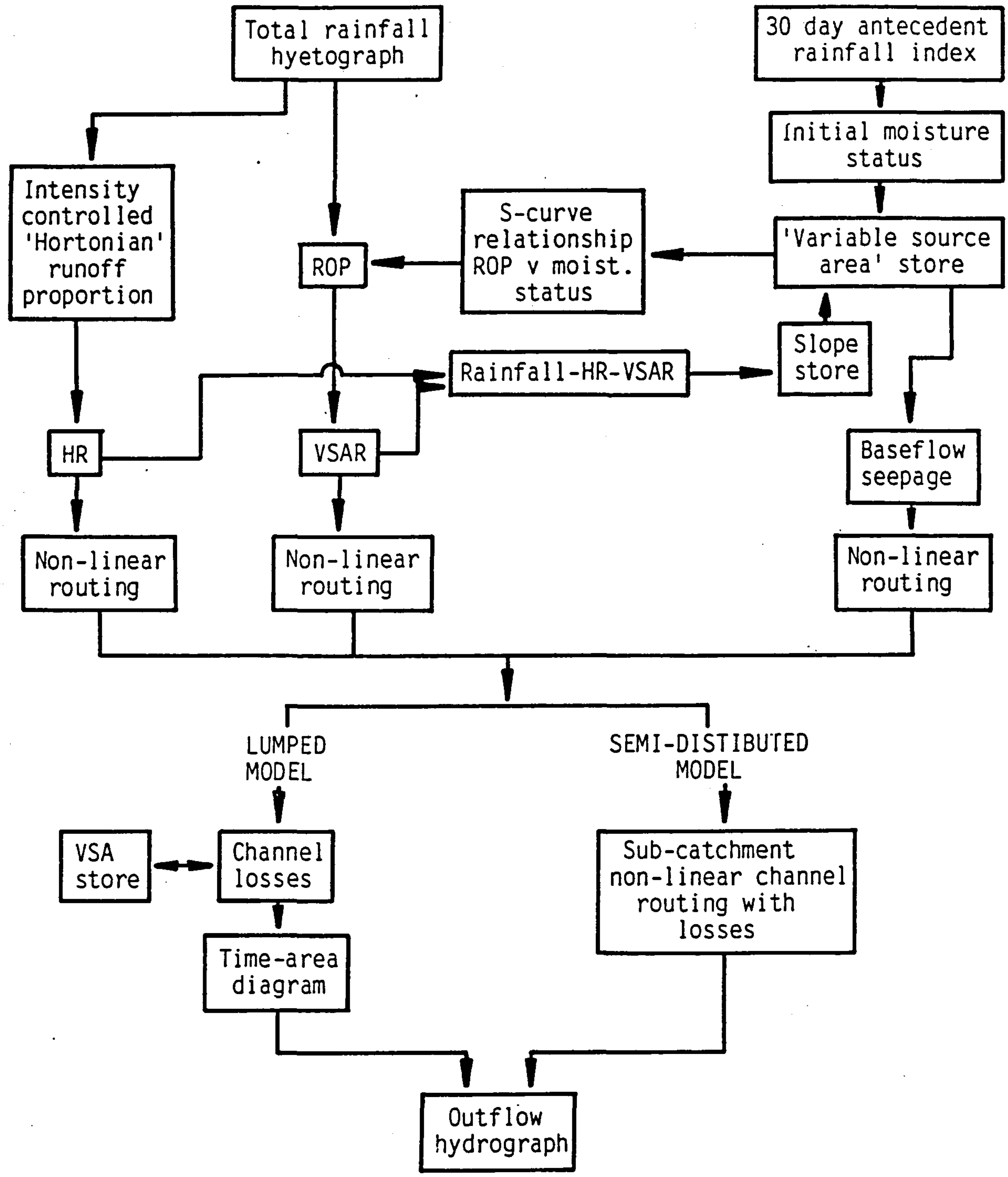


Figure 4.1 Structure of the S-curve model

4.3.2 Runoff generation

Runoff may be generated in any time interval by one or both of two methods. The first is dependent upon the intensity of the rainfall input, whilst the second on the intensity as well as the moisture status of the catchment. Both use a hyperbolic tangent function to estimate a runoff proportion value which is then multiplied by rainfall to produce the runoff amount. The intensity controlled runoff uses a symmetric S-curve function with intensity (mm. hr^{-1}) as a fraction of some maximum value (dependent on the time interval used in modelling) as the abscisa (figure 4.1a). The proportion of the catchment contributing through this mechanism at the maximum intensity is a model parameter (IAF). Conceptually, this element of runoff is viewed as originating from relatively impervious areas close to the channel. It may be thought of as infiltration-excess runoff away from saturated source areas but from zones close to channels such that re-infiltration of surface flow does not occur.

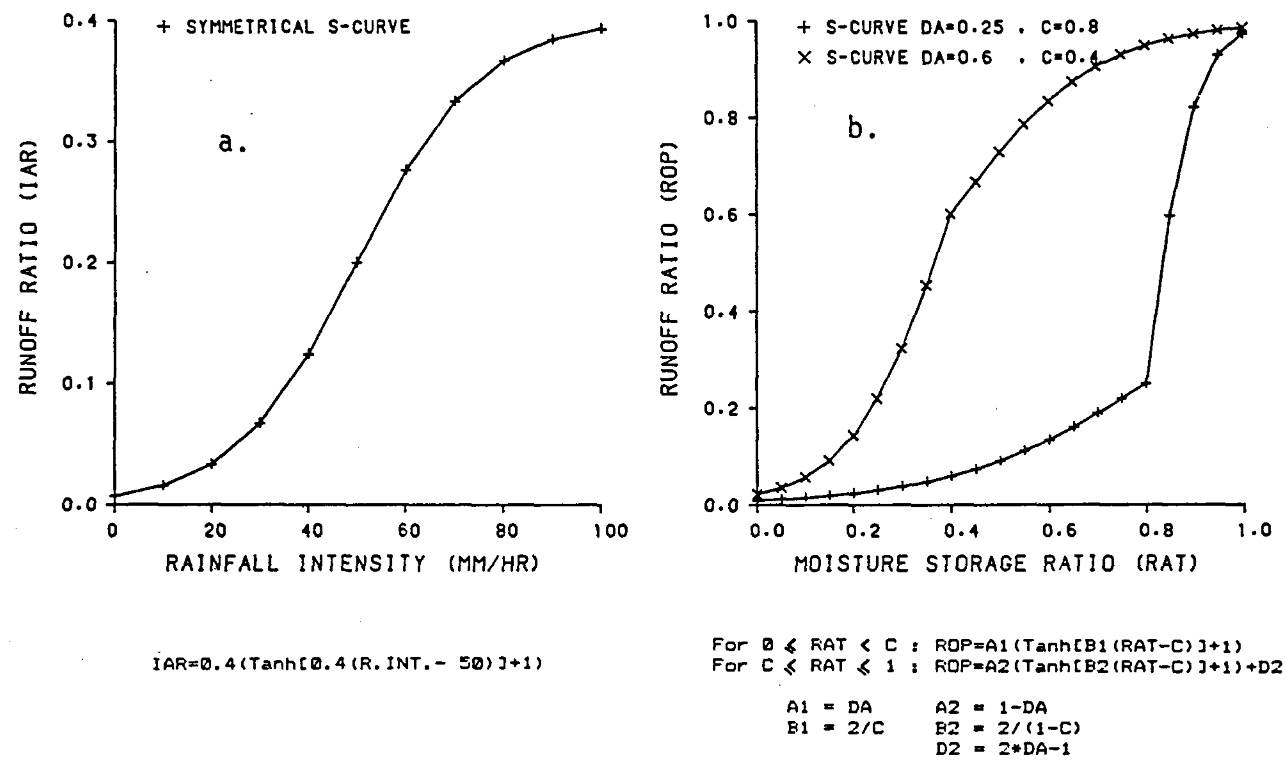


Figure 4.2 S-Curve relationships used in the S-Curve model
a) intensity controlled runoff, b) implicit variable source area runoff.

The moisture status of the catchment (RAT) is defined relative to some maximum value (SMAX). SMAX is conceived as the moisture level (mm) at which the complete catchment (or sub-catchment) is contributing directly to runoff (runoff proportion = 1,0). Thus the runoff proportion (ROP) at any time interval is defined by the relative moisture status and the shape of the assymmetrical S-curve function. As in the earlier model (Hughes, 1984) this function is constructed from two TANH functions having a common point at (DA,C). DA and C are model parameters and their influence on the S-curve shape is illustrated in figure 4.1b. As before, the runoff proportion (ROP) multiplied by the rainfall amount provides the unrouted runoff depth in one time interval. At high moisture levels there is a possibility that the runoff from this equation and the infiltration excess function add up to greater than unity. The model checks for this and adjusts accordingly.

The rainfall proportion that does not contribute to runoff is added to a store, having an infinite maximum value and which starts at zero level for convenience. In each interval a proportion of this conceptual slope storage drains into the conceptual variable source area (VSA) store and increments the moisture status of the catchment. Clearly, this gives rise to higher runoff proportions during later intervals. To account for slow subsurface drainage from the VSA store, a proportion of its absolute amount drains out per interval. For zero rainfall periods during the event, the balance between the drainage from the slope storage (into the VSA store) and the VSA storage determines whether the source area expands or contracts. The amount draining from the two storages are constant proportions of their levels (%. hr^{-1}) and defined by two model parameters (PCSLP and PCVSA). Drainage from the VSA is perceived as being able to flow into the channel or into deeper groundwater. While the former is likely to contribute to streamflow during the event, the latter is not. There is little information on which to base a quantitative differentation of these two components. For convenience, and to avoid adding further parameters, a fraction equal to the relative moisture status of the catchment is considered to flow into the channel during the event. The remainder is not accounted for during the storm duration.

Runoff can thus be generated by three separate components of the model. Two of them are considered to be relatively rapid flow elements, one determined by the rainfall intensity and one by the moisture status of the conceptual variable source area. The third element is the relatively slow drainage from the VSA store to the channel.

4.3.3 Runoff routing

Runoff routing is divided up into two components referred to as the 'land' and 'channel' phases. The land phase routing is the same for both lumped and semi-distributed model versions but for the channel phase different modelling approaches are used. The land phase routing makes use of a non-linear storage-routing relationship of the type $S=KQ^N$, where K and N are model parameters. This equation is combined with the continuity equation $dS/dt=I-Q$ and the solution achieved using the method developed by Hughes and Murrell (1986). In the lumped model this routing component represents the attenuation effects of flow over and below the surface as well as in minor tributaries. In the semi-distributed model, the routed flow is conceived to represent the outflow from a nodal point at the sub-catchment centre. The relatively rapid flow from the VSA and the intensity controlled runoff are combined and routed using parameters K and N. The slower flow component is routed using a higher value of K. This is determined by dividing K by the fractional loss from the VSA store per time interval and the moisture storage ratio. This is an arbitrary scaling factor but avoids incorporating additional parameters.

In the lumped model channel routing is carried out by means of a time-area triangle with an initial delay. Each unit of output from the non-linear land phase routing component is first of all delayed (parameter DEL) and then spread forward in time using an isosceles triangle with variable base length. The base length is calculated from a non-linear function of the output from the land phase routing (in $mm.hr^{-1}$). An inverse power function of the form $TA = A.Q^{-B}$ is used, where TA is the base length in hours, Q is discharge in $mm.hr^{-1}$ and A,B are parameters. As the discharge decreases, the triangle becomes more elongated, implying slower routing. As B increases, the triangle shape becomes relatively more variable .

After initial test results on a semi-arid catchment it was considered desirable to try and include a simple formulation to account for channel losses. The effects that were necessary to achieve were less runoff at low moisture levels than were being modelled, and a more rapid response of the remaining runoff. The latter effect is logical as the majority of the channel losses were considered to be occurring in the upstream reaches. Consequently, only the lower reaches with shorter travel times would be contributing. The effects can be achieved by reducing the runoff volume and the base of the time area triangle by a calculated amount. As this amount is likely to depend upon the moisture status of the catchment it has been made a function of this in the following equation:

$$CLOSS = 1/(RAT*ROP)^{CLP}$$

where RAT is the relative moisture status ($\leq 1,0$), ROP the runoff proportion, CLP is a model parameter and CLOSS is the percentage runoff lost to the channel and the percentage decrease in the base length of the time area triangle. If CLP is greater than unity then losses vary at a lower rate than the moisture status and vice versa. To maintain a water balance, the amount of runoff absorbed by the channel is added to the VSA store to increment the moisture status of the catchment. In the semi-distributed form of the model it is merely necessary to reduce the output from each sub-catchment (by CLOSS percent) and route the remainder in the manner described below.

Semi-distributed routing is achieved by routing sub-catchment outflow through a conceptual channel reservoir to the next downstream sub-catchment node. The downstream sub-catchment outflow is added and then routed further downstream. Where the configuration of sub-catchments is such that more than one group of sequentially linked sub-areas exist then allowance is made for storing hydrograph elements and combining them at a confluence. The routing formulae used is the same as in the land phase but with different parameters. Land phase K is replaced with KC and N with a fixed value of 0,7. A further small difference exists in that the routing input for the land phase is the excess rainfall intensity during a specific time interval. For channel routing this becomes the average of the upstream inflows plus sub-catchment outflow (land routed excess rainfall) at the beginning and end of the time interval. As the non-linear routing function employed only incorporates attenuation, a further group of parameters is necessary to define the delays for each sub-catchment (CDEL).

4.3.4 Summary of parameters

The complete parameter set is given in table 4.1, which also lists the alphanumeric symbols and the parameters relevance to either the lumped or semi-distributed form of the model. Used as a lumped model, 13 parameters are involved. One is used in the antecedent moisture estimation component, six in the conversion of rainfall to runoff depths and six in the routing procedure.

Table 4.1 Summary of parameters used in the developed S-curve model

Description	Symbol	Lumped or Semi-distributed
1. Catchment routing constant	K	Both
2. Catchment routing power	N	Both
3. Channel delay time (hr)	CDEL	S.D.
4. Channel routing constant	KC	S.D.
5. Catchment delay time (hr)	DEL	L
6. Time area base constant (hr)	A	L
7. Time area relation power	B	L
8. Maximum soil moisture level (mm)	SMAX	Both
9. Ordinate S-curve parameter	DA	Both
10. Abscisa S-curve parameter	C	Both
11. Percent flow from slope to VSA store ($\%.hr^{-1}$)	PCSLP	Both
12. Percent flow from VSA store ($\%hr^{-1}$)	PCVSA	Both
13. Impervious area factor	IAF	Both
14. Antecedent precipitation factor	APF	Both
15. Channel losses power	CLP	Both

If the semi-distributed format is to be used then 12 parameters are involved and values must be assigned to these for each sub-catchment. If it is assumed that the runoff characteristics of the sub-areas can be considered uniform then only parameters 3 and 4 and 15 need to be estimated for separate areas. These are the only parameters that logically must be different. In the computer program the model accepts single values for each of the 12 parameters plus a matrix of sub-area factors, expanding the parameter space to 12 * number of sub-areas. This is a useful method of coding as it allows one or more parameters to be changed easily without changing the relative values for each sub-area. Equally, it allows one sub-area parameter to be changed without the others.

The model is not intended to represent a physically-based approach in the normally used sense. Consequently, few if any of the parameters can be evaluated directly from field measurements. However, the model has been designed such that the parameters should have relevance to some aspect of the physical response system of catchments. The likely physical association of the model parameters is discussed in the following section. An attempt is also made to identify those catchment characteristics that may be most important to consider when estimating parameter values. The value of such an approach can only be tested after a thorough assessment of the model on a range of different catchments.

4.4 Physical relevance of parameters and perceived association with catchment characteristics.

This model is designed to be a compromise between strongly physically-based approaches and simpler curve fitting methods. It has never been intended that the parameters should be measurable in the field. However, the model has been designed to include the major elements of runoff generation in some conceptual way. The intention was to build an adequate conceptualisation such that a variety of different storm responses on a single catchment could be represented by one set of parameter values. Thus, parameter values should not vary for different storms on the same catchment. There is inevitably a high degree of interaction between the parameters of this model. If used in semi-distributed format, there are a large number of possible parameter value permutations that could produce a similar hydrograph response to a single storm. Not all such permutations would produce a satisfactory response to another storm. Consequently, the calibration exercise largely consists of finding a unique permutation that is suitable for a wide range of storms. This can be an extremely difficult exercise and would be almost impossible without some kind of guidelines for setting initial parameter values and their relative level on different sub-catchments. This section of the report seeks to identify the physical relevance of the parameters with respect to catchment characteristics. At this stage these associations are of a qualitative nature. Part of the model testing procedure will be to confirm or reject such associations. Only when a range of catchments have been calibrated successfully will it be possible to investigate whether the qualitative associations could be extended into quantitative relationships. This may be considered to be the ultimate goal with respect to testing the usefulness of this particular model.

The antecedent precipitation factor (APF - parameter 14) determines the extent to which an amount of rainfall input, a number of days prior to the storm, has an effect upon the initial moisture status of the catchment. This is in turn dependent upon the proportion of that rainfall that drains out of the catchment and the amount that is lost due to evapotranspiration. There are a number of physical associations including soil drainage properties, land use and vegetation and topography. However, there are also climate factors and meteorological influences prevailing at the time of the rainfall input. It becomes apparent that there are no simple associations for this parameter and it must be recognised that this is a weak component of the model. The advantages and disadvantages of more complex approaches to the determination of initial catchment moisture status were discussed in section 2.4.1 of this report.

The impervious area factor (IAF - 13) determines how much runoff occurs in relation to rainfall intensity regardless of the moisture status of the catchment. It should be related to the area of the catchment close to channels that have low infiltration capacities. The inclusion of such a component is considered justified by the observed response of some catchments to intense rain falling on a dry catchment.

Parameters 11 and 12 (PCSLP and PCVSA) should be related to slope and valley bottom drainage characteristics. PCSLP determines how rapidly rain falling on the slopes drains to and increments a conceptual source area. This may be rapid on steep slopes with thin soils or with well drained upper soil horizons overlaying a relatively impervious layer. Lower values of PCSLP should occur if the valley slopes are gentler despite higher subsurface permeabilities. The length of slopes and hence the drainage density should also be important. PCVSA determines the rate at which moisture is removed from the source area due to drainage into the channel as well as deeper drainage. Consequently, the permeability and drainage characteristics of the valley bottom soils and the sub-stratum will be relevant to the value of this parameter.

Strictly, parameter SMAX (8) represents the amount of moisture in storage at the moment when the whole catchment is saturated. Consequently it should be evaluated as the moisture holding capacity of the catchment (or sub-area). The two parameters DA and C (9 and 10) define the relationship between moisture levels below SMAX and the proportion of the catchment that is saturated at the surface. The S-curve relationship is designed to represent the complex spatial interaction between the topography, and soil water retention capacity of the catchment or sub-area. Various authors have addressed the problem of defining source areas either by direct measurement (Kirkby et. al., 1976) or by estimation (Beven and Kirkby, 1979; O'Loughlin, 1986). It remains to be seen whether the progressive increase in the models conceptual source area is realistic and whether the form of its relationship with relative catchment moisture status can be estimated.

The catchment routing parameters, K and N (1 and 2) represent the attenuation effects of routing the so-called impervious area and variable source area runoff elements to the main channel system. It has been found by other authors who have used the same form of non-linear routing equation that it is better to hold N constant at some value between 0.6 and 0.8 (Mein et al., 1974). K should be related to the predominant mode of flow by which water collects in the stream channels. If this is overland flow then length of flow slope and surface roughness should also affect the value of K. If it is mainly saturated sub-surface flow then K may be higher (slower response) and affected by the lateral drainage characteristics of the soils and sub-stratum. If there exists a high degree of spatial variation in the rate of runoff response then it seems unlikely that a lumped approach will prove adequate even for individual storms.

The time area diagram used in the lumped version of the model has three parameters (DEL, A and B, - parameters 5 to 7). DEL merely represents the time delay before a significant response to any amount of rainfall is experienced at the catchment outlet. It is difficult to propose a physical association for this parameter as at least some response may be expected immediately, if only from rain falling on the channel surfaces close to the outlet. Hence, delay values are usually expected to be small and the parameter is of less importance than A and B which define the length of the symmetrical time area triangle for a given value of runoff in mm. hr^{-1}. B determines the extent to which this relationship is non-linear, lower values of B suggesting more similar triangles for all ranges of flows. The time area triangle should be related to the spatial pattern of the channel network and the channel slope variations within this network. Elongated catchment shapes are expected to have longer triangles than rounded shapes given similar areas and slopes. Higher slopes in channels more distant from the outlet may be expected to indicate shorter triangles. Channel roughness and flow resistance effects may also be important but subsidiary to the other factors already mentioned. Sub-catchment channel routing is controlled by two parameters for each sub-area. CDEL (3) represents the delay before a sub-area begins to contribute to flow at the catchment outlet, while KC represents the attenuation effects of routing the output from the node of one sub-area along the channel to the next. Channel length, dimensions, slope and flow resistance effects are expected to determine the relative values of both these parameters. Problems are likely to arise if strong attenuation effects result from overbank flows within a specific reach above certain flow thresholds. No account of floodplain inundation effects is allowed for in this model.

The final parameter CLP (15) determines the amount of flow that is lost through absorption by the channel and its banks. This parameter also affects the length of the time area triangle in the lumped model version.

The percentage of flow lost to the channel is determined by a power function of the size of the source area and relative moisture status. Channel losses should be related to the permeability of the bed and banks of the channel as well as the spatial positioning of the source area. If channels are developed on permeable materials (alluvium or permeable rock strata) and local groundwater levels are below the channel bed, then channel losses may be relatively high. As source areas can be predominantly surface features it is possible to have a saturated surface adjacent to a channel which has a capacity to absorb water through its bed. This may be a shortlived situation as vertical drainage from the upper soil horizons (and lateral drainage from higher slope areas) begins to reduce the lower zone moisture capacity. During short duration, high intensity events on dry catchments, channel losses may be high enough to absorb most of the runoff generated in upstream areas. It is possible that channel losses are the main reason why few flow events are recorded in some semi-arid areas despite thin soils and high intensity rainfall. Alternatively, channel losses may be insignificant or non-existent in catchments experiencing perennial streamflow. In such cases CLP would be set to a very low value.

It can be seen that it is easier to suggest associations with catchment characteristics for some parameters than others. The eventual usefulness of the model depends, to a certain degree, on the extent to which these associations can be confirmed after calibration and verification exercises have been performed on a number of catchments. It also depends upon whether the parameters to which the model is most sensitive have the highest levels of physical relevance. There is little point in determining quantitative relationships between relatively insensitive parameters and physical catchment characteristics if this is not possible for those parameters that affect runoff response the most.

5. SIMPLE ANTECEDENT MOISTURE MODEL (OSE1)

5.1 Background

The model described in this section is an extended version of the Isolated Event Model (IEM4), discussed in Eyre and Crees (1984), Mandeville (1983) and the Flood Studies Report (1975). The original IEM4 model used an exponential relationship between initial soil moisture deficit at the beginning of a storm and the proportion of gross rainfall that contributes to storm runoff. In OSE1 the exponential relationship is replaced by an assymmetrical S-curve function of the same type used in the S-curve model (OSE2) described in chapter 4 of this report. The model uses an antecedent moisture procedure determined by Hughes (1984), but unlike the S-curve model it applies a constant runoff proportion (ROP) throughout a storm event. A constant ROP has been retained for the purposes of comparing the performance of OSE1 with the Augmented Hydrograph model, which is described later in this report. The two models have similar major components but their order of operation is different (figure 6.3).

IEM4 has been widely tested (Mandeville,1983) and applied in the United Kingdom, not only for flood estimation (its orginal goal) but also for flood forecasting purposes (Eyre and Crees,1984). IEM4 has not been tested on ungauged catchments and it will be necessary to establish whether model parameters can be related to storm and or catchment characteristics in some way.

5.2 Conceptual structure of the model

As with the more complex S-curve model, OSE1 has three basic components; antecedent moisture status estimation, volume reduction and shape transformation and the model has been designed to run in lumped or semi-distributed format (figure 5.1). The method of estimating antecedent moisture status is to that used in the S-curve model and described in section 4.3.1.

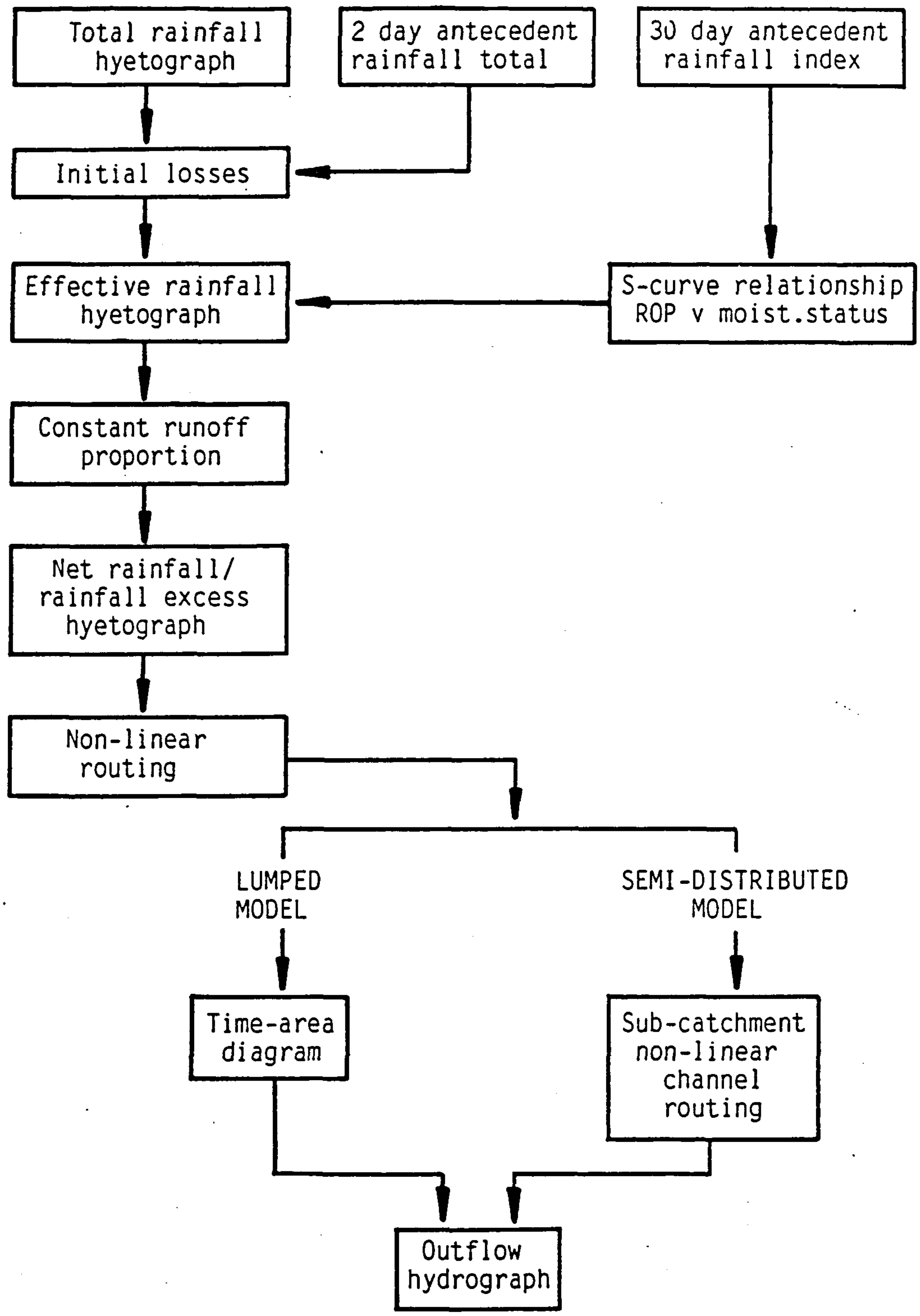


Figure 5.1 Structure of the simple antecedent moisture model (OSE1)

Table 5.1 Summary of parameters used in model OSE1

Description	Symbol	Lumped/semi-distributed
1. Catchment routing constant	K	Both
2. Catchment routing power	N	Both
3. Channel delay time (hr)	CDEL	S.D
4. Channel routing constant	KC	S.D
5. Catchment delay time (hr)	DEL	L
6. Time area base constant (hr)	A	L
7. Time area relation power	B	L
8. Maximum soil moisture level (mm)	SMAX	Both
9. Ordinate s-curve parameter	DA	Both
10. Abscisa S-curve parameter	C	Both
11. not applicable to OSE1		
12. not applicable to OSE1		
13. not applicable to OSE1		
14. Antecedent precipitation factor	APF	Both
15. Initial losses	IL	Both

The volume reduction component of the model begins with an estimation of initial losses (IL). Initial losses are first satisfied by the antecedent rainfall total for the two days prior to the storm event. Any remaining losses must then be satisfied by the rainfall in the early part of the storm. All remaining rainfall amounts are reduced by a fixed proportion (ROP) which is defined by the relative antecedent moisture status and the shape of the S-curve. This method of volume reduction is thus similar to the S-curve model, except that only one runoff proportion is calculated and remains fixed for the rainfall inputs at all time intervals. The moisture status (RAT) is defined relative to a maximum value (SMAX) when ROP is equal to 1,0 and the S-curve shape is fixed by parameters DA and C (table 5.1). The runoff routing or shape transformation components are identical to those described in section 4.3.3 except that the channel losses modification has not been included. OSE1 has fewer parameters than the S-curve model (10 for lumped and 9 for semi-distributed modelling) but where the parameters are shared between the two models they have the same basic meaning.

5.3 Physical relevance of parameters and perceived association with catchment characteristics

In a manner similar to the S-curve model (see section 4.4) this section attempts to identify the physical relevance of the model parameters with catchment and/or storm characteristics. The modelling of a wide range of catchments will be necessary to confirm or reject these associations and thus establish the usefulness of this particular model as a design tool.

Initial losses (IL-parameter 15) gives an indication of the amount of total rainfall which will not contribute to storm runoff. A wide range of factors are expected to be associated with initial losses and include the following:-

a) The catchment antecedent moisture status, that is the 'wetter' the catchment prior to an event, the lower the expected initial losses and vice versa. b) Topographical (depressions causing ponding), soil characteristics (infiltration rate), and vegetation (interception) are also expected to influence initial losses.

c) Loss of storm runoff due to channel losses, for example the infiltration of channel flow into an alluvial bed could result in significant losses.

d) Initial losses are also expected to be related to storm characteristics, in particular the amount, intensity and duration of an event.

It is apparent that there are no simple associations for this parameter as all of the above factors are likely to effect initial losses to varying degrees. It is likely that certain factors may be more dominant in different catchment types. In the semi-arid situation it is expected that the variability in initial losses will be greater than in the sub-humid situation which are thought generally to have more stable antecedent moisture conditions.

The expected physical relevance of parameter 14 (APF) and the parameters determining the ROP (parameters 8, 9 and 10 - SMAX, C and DA) are similar to those proposed in section 4.4 of the S-curve model. The catchment routing parameters, K and N (1 and 2) represent the 'land' phase routing of runoff to the main channel system and have similar expected physical associations as those described in section 4.4. The channel routing phase of the lumped version of the model is controlled by the time-area diagram which has 3 parameters (DEL, A and B, - parameters 5, 6 and 7). The parameters should be related to topographical elements of the channel system, such as the channel network pattern and channel slope variations within the catchment. The shape of the catchment is also expected to effect the shape of the time-area diagram (see section 4.4). The expected physical association of the sub-catchment routing parameters (CDEL and KC - 3 and 4) are identical to those described in section 4.4 of the S-curve model.

6. AUGMENTED HYDROGRAPH MODEL (OSE3)

6.1 Background

The model described in this section is a modified version of the Augmented Hydrograph model presented in Mandeville (1983). The central concept of the orginal model was developed by Mandeville while working on isolated event modelling at the Institute of Hydrology, Wallingford, and represents a novel approach to modelling the rainfall-runoff process. In conceptual modelling the usual procedure is to seperate the rainfall-runoff process into two major components, which are independent of each other (Tennesse Valley Authority, 1965; Rajendran and Mein, 1986; Murray and Görgens, 1981). The first step, traditionally, is to estimate volume reduction (figure 6.1), that is the transformation of rainfall into storm runoff (often referred to as net or excess rainfall). This step generally includes the catchment antecedent moisture status estimation. The volume reduction procedure produces a an excess rainfall hyetograph, which is then applied to the shape transformation component which routes the excess rainfall across and or beneath the land surface and along the channel network to produce delayed and attenuated streamflow at the outlet.

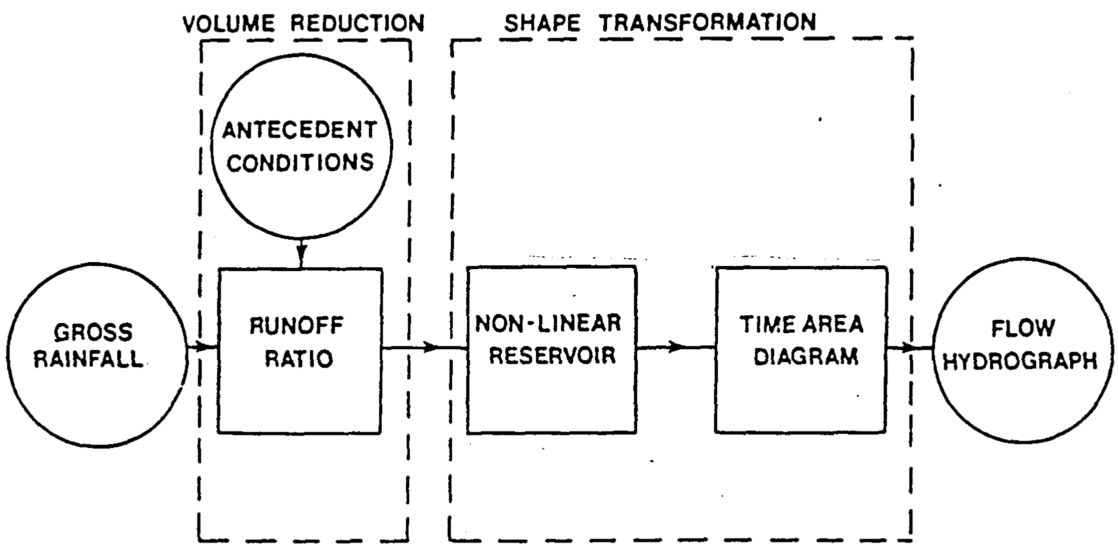


Figure 6.1 Traditional order of model components (from Mandeville,1983)

The Isolated Event Model (IEM4), referred to in chapter 5 is a traditional rainfall-runoff model. Analysis of this model by Mandeville (1983) revealed that the major components were not independent of each other. He therefore proposed a new form of model in which the major components are the same as the IEM4, but their order is changed (figure 6.2). In the new model the parameters of the shape transformation component do not depend in any way on the volume reduction component.

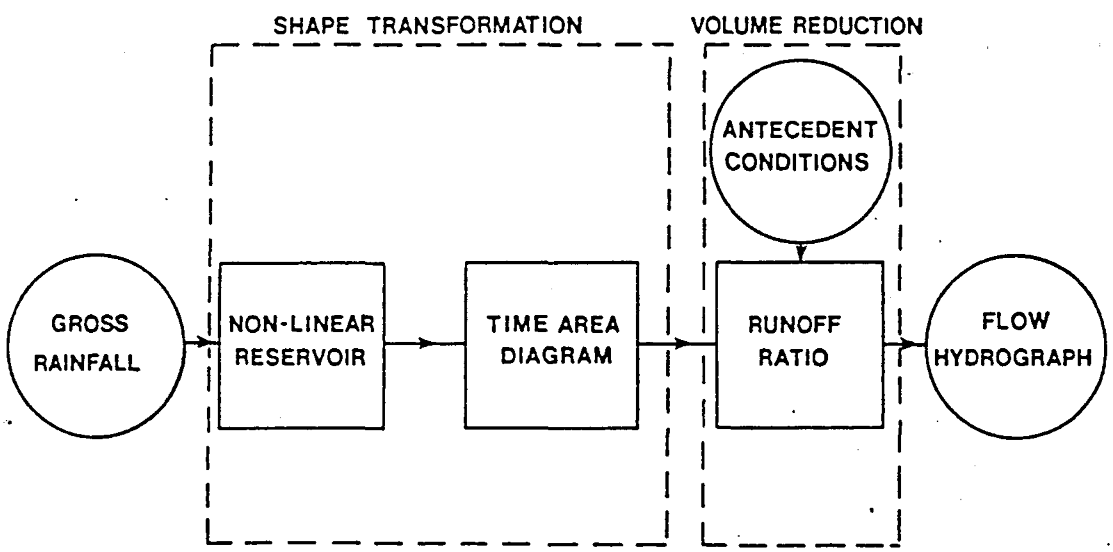


Figure 6.2 Augmented hydrograph model : component order (from Mandeville, 1983)

In the Augmented Hydrograph model, the gross rainfall hyetograph is applied as input to the shape transformation component, the output is a hydrograph with the same volume as that under the gross rainfall hyetograph, but a different shape (Figure 6.3). This intermediate hydrograph is termed the augmented hydrograph. The augmented hydrograph is then applied as input to the volume reduction component of the model to produce the flow hydrograph. The augmented hydrograph has the same shape as the flow hydrograph but a larger volume.

The advantages of this approach include:-

a) By reversing the order of the two subsystems, so that the non-linear reservoir precedes the runoff ratio, the large variations in the size of the non-linear reservoir obtained when fitting the IEM4 model will be reduced (Mandeville, 1983). The new model contains the non-linear reservoir which is fixed for all events followed by the application of a variable runoff ratio appropriate to any one event.

b) The new model has the advantage, if it works, of being able to check routing parameters against shape and then reducing the volume to fit the output hydrograph.

c) There is no seperation of runoff into stormflow and baseflow; another determination which is difficult to physically measure.

The model proposed by Mandeville is based mainly on the results from a detailed study of one catchment and while preliminary tests are promising (Mandeville, 1983) the model hypothesis has not been widely tested and applied. For the model to be of value as a hydrological tool it will be necessary to establish whether model parameters can be related to storm characteristics in some way. Only if this were successful could the model be used to estimate hydrographs in the ungauged or design situation. It might be necessary therefore to develop the model futher without changing its basic structure. This can be done by identifying conceptual weaknesses within the model and incorporating additional components where necessary to improve the models flexibility.

6.2 Conceptual structure of the developed model

The form of the Augmented Hydrograph that is being tested can be divided up into three major components. Initial losses are first removed from the input rainfall, the remainder is then routed, then reduced to equal the runoff volume. As with the models discussed in the previous chapters, the model has been designed to run in lumped and semi-distributed format. On the basis of some preliminary model runs on events from different catchments, the initial losses component was added to account for antecedent rainfall immediately prior to the event. The initial losses component operates the same way as in model OSE1 and has one parameter (IL, table 6.1).

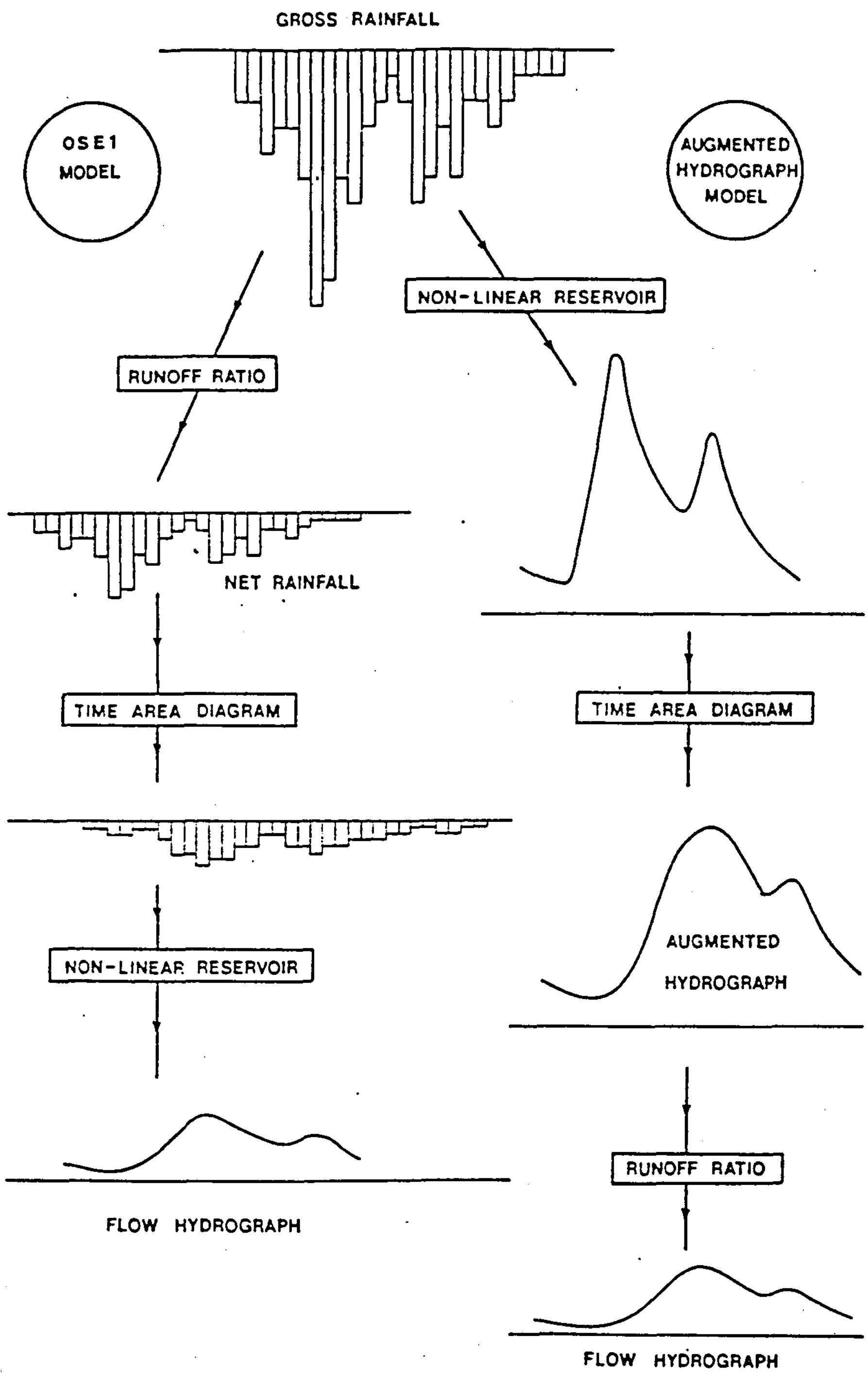


Figure 6.3 Comparison between component responses of OSE1 and augmented hydrograph models (from Mandeville, 1983)

The shape transformation or runoff routing component involves applying the rainfall hyetograph (minus initial losses) to the routing subsystems to give output as a hydrograph with the same volume as the rainfall input but with a different shape. Runoff routing is divided into two subsystems referred to as the 'land' and 'channel' phases in a similar way to that described in section 4.3.3 for model OSE2. The 'land' phase routing makes use of the non-linear storage-routing relationship $S=KQ^N$. In the lumped version, the 'channel' phase routing, uses an isosceles triangle defined by the parameters A, B and DEL (table 6.1). The semi-distributed 'channel' phase routing uses the storage-routing equation to attenuate sub-catchment flows as they pass through downstream sub-areas.

The intermediate hydrograph produced by the routing subsystems is applied as input to the volume reduction component of the model, in which each of its individual ordinates is reduced by multiplying by the runoff ratio (ROP) to give the flow hydrograph as output. The initial value of ROP is estimated as follows (Mandeville, 1983):-

$$ROP = \frac{\text{observed runoff volume}}{\text{observed gross rainfall volume (minus initial losses)}}$$

The complete parameter set is given in table 6.1, which also lists the alphanumeric symbols and the parameters relevance to either the lumped or semi-distributed form of the model. In the lumped format, 7 parameters are involved. One is used to estimate initial losses, five in the shape transformation procedure to produce the intermediate hydrograph and one to effect volume reduction and produce the output hydrograph. If the semi-distributed format is used then 6 parameters are involved and values must be assigned to these for each sub-catchment. If it is assumed that the runoff characteristics of the sub-areas can be considered uniform then only parameters 1 and 2 need to be separately calculated for individual sub-areas.

Table 6.1 Summary of parameters used in the Augmented Hydrograph Model

Description	Symbol	Lumped/semi-distributed
1. Channel delay time (hr)	CDEL	S.D.
2. Channel routing constant	KC	S.D.
3. Runoff Coefficeent	ROP	both
4. Catchment routing power	N	both
5. Catchment delay time (hr)	DEL	L
6. Time area base constant (hr)	A	L
7. Time area relation power	B	L
8. Catchment routing constant	K	both
9. Initial losses (mm)	IL	both

6.3 Physical relevance of parameters and perceived association with catchment characteristics.

Ideally the parameters of a simulation model should be determined objectively and should be closely related to measurable physical catchment characteristics. Differences in parameter values may then be examined in light of physical changes on a catchment or changes in catchment characteristics from one catchment to another (Dickenson and Douglas, 1972).

The expected physical relevance of the initial losses parameter and the shape transformation or routing parameters of this model are identical to those discussed in section 4.3 and 3.3. This section of the report will concentrate on the perceived physical relevance of the volume reduction parameter (ROP - parameter 3). According to Mandeville (1983), by changing the order of the major components of the model, so that runoff routing precedes the volume reduction component, the parameters of the two components should be independent of each other. Therefore the routing parameters should remain constant between events on the same catchment and should not be influenced by the volume reduction parameter (ROP). The routing parameters are expected to be related to topographical catchment characteristics such as slope, slope length, drainage pattern etc, which do not change. It is expected that the volume of runoff (ROP) will be related to storm characteristics and the catchment antecedent moisture status, (which do change between events), as well as soil characteristics (more stable). Rainfall characteristics such as rainfall volume, duration and intensity are expected to influence the runoff proportion. Soil characteristics such as depth of soil, permeability and organic content are expected to influence the volume of runoff. For example, if a long duration, low intensity event occurs on a 'wet' catchment which has deep, permeable soils, the ROP is likely to be fairly high. For the same event on a 'dry' catchment the volume of runoff is expected to be lower because a larger proportion of the rainfall will be required to satisfy the catchment moisture status before runoff can occur. Likewise, if the same event occurred on catchments with similar antecedent moisture conditions but with different soil characteristics the proportion of runoff is expected to be different. For example, the runoff response of shallow, impermeable soils to rainfall is expected to different to the response of deep, permeable soils.

7. RUNOFF-ROUTING MODEL (RORB) (OSE4)

The basic conceptual structure of the rainfall-runoff routing model developed at Monash University, Department of Civil Engineering has been described by Mein et al. (1974). The relatively brief description given in this section is drawn from the User Manual supplied with the computer program by Monash University (Laurenson and Mein, 1985). RORB version 3 is a general rainfall-runoff and streamflow routing model that can take into account amongst others, the effects of retarding basins, storage reservoirs, lakes or flood plain storages. The model program is run interactively from a terminal and operates in different modes depending upon whether the user wishes to FIT the model to observed data; TEST a parameter set or calculate DESIGN hydrographs. The model is arealy distributed and the authors of the manual claim that it is applicable to both urban and rural catchments. The description provided below concentrates on the rainfall-runoff modelling components of the model. For those readers who require more information about the complete range of options that are available reference should be made to the User Manual (Laurenson and Mein, 1985).

7.1 Distribution system and routing method

RORB is a semi-distributed model that operates on a sub-catchment basis by defining nodes to represent the sub-area inflow points or junctions of sub-areas. Between nodes are placed conceptual storages through which sub-area inflows plus upstream flow is routed to the next node downstream. Several types of inflow to, and outflow from the channel network are possible. Sub-area inflow represents the input of excess rainfall from a specific sub-catchment and it is assumed to enter the network at a point close to the sub-area centroid. Concentrated channel inflow allows for the input of streamflow from a source (off-channel storage, tributary or diversion) not being modelled. Distributed inflow can be included over a specified number of reaches and can be used to represent lateral inflow of base flow for example. Concentrated outflow may be required if a diversion channel or effluent stream forms part of the system being modelled. Finally, the reverse of distributed inflow is also possible to represent lateral outflow or channel loss processes.

The model is conceptually an overland flow model and the storage effects of minor channels and overland flow are included in the storage effects of the major channels. Unlike the other models discussed, the land surface and channel routing components are lumped together. However, the model can be adapted to consider these two storages separately. Usually the storage parameters of each reach are assumed to be related to the properties of the reach and not the sub-area. Streamflow routing is based upon a storage-discharge relation of type $S = 3600\ k.Q^m$. Where k is the product of two parameters k_c and k_r. k_c is a parameter applicable to the complete catchment whereas k_r is applicable to individual reach storages. k_r values are calculated in the program from input data of channel reach lengths and type of channel (natural, lined or drowned by a reservoir). The assumption is made that delay time is proportional to flow distance. However, if this assumption is considered inadequate then a user may substitute other values to represent delay times in place of reach lengths. The User Manual (Laurenson and Mein, 1985) suggest that the variable $L/\ S_c$ (L = reach length; S_c = reach slope) may be more appropriate when catchments have extreme slope variations. k_c is a parameter of the model when operating in calibration mode and Laurenson and Mein (1985) offer suggestions for estimating its value. The power m of the storage-discharge equation is also a parameter but has found to be of subsidiary influence to k and a value of 0,8 is recommended.

The program allows a user to specify where observed streamflow data are to be used to compare with simulated flows. This feature can be very useful where streamflow gauging networks are nested. The model then only needs to be run once to allow comparison of results with observed data to be effected at several points within the total catchment.

7.2 Modelling of excess rainfall

RORB is an isolated event model that does not account for evapotranspiration, soil moisture or groundwater redistribution. The latter can only be accounted for through independently determined component inputs to the model. The calculation of rainfall excess is based upon two alternative loss models. In both models an initial loss is assumed and must be satisfied before any rainfall excess can occur. In the first model option the initial loss is followed by a constant runoff coefficient; that is the proportion of rainfall that becomes runoff ramains constant. The second model assumes that the initial loss is followed by a constant, continuing loss rate. Only rainfall inputs higher than this rate can contribute to streamflow.

Variability of losses between sub-areas can be accommodated through a sub-area input parameter referred to as the fraction imperviousness. If the fraction imperviousness is set to anything but zero then the values input for initial loss, runoff coefficient or loss rate are applicable to the most pervious area. The loss parameters for each sub-area are calculated in the model in the following way :

$$IL_i + (1-F_i)\ IL_{perv}$$

if $IL_{perv} >$ Sub-area rainfall then IL_{perv} = sub-area rainfall

$$C_i = F_i C_{imp} + (1-F_i) C_{perv} \quad \text{for } C_{perv} \leqslant C_{imp}$$
$$C_i = C_{imp} \quad \text{for } C_{perv} > C_{imp}$$

$$CL_i = (1-F_i) CL_{perv}$$

where
- IL = initial losses
- C = runoff coefficient
- CL = continuing loss rate
- F = fraction imperviousness
- i = sub-catchment subscript
- imp = impervious subscript
- perv = pervious or most pervious subscript

The parameters subscripted perv are those input (IL_{perv}) or calculated by the program (C_{perv} or CL_{perv}). C_{imp} is set by the program to a value of 0,9. In FIT and TEST runs the constant runoff coefficient or loss rate is determined by an iterative procedure in the model to ensure that the correct volume of runoff is predicted. If more than one set of observed streamflow data are input to the program, then separate loss parameters are calculated for the areas upstream of or between gauging points.

7.3 Input of rainfall data

A number of separate rainfall profiles may be input to the program. Any one of such profiles may then be assigned to each sub-area of the distribution system. The total amount of storm rainfall for each sub-area is also input. Two or more sub-areas may therefore experience the same time distribution of rainfall but different total rainfall depths.

The model makes allowance for total rainfall amount to be entered as a series of separate bursts defined by their start and finishing times. Different loss parameters can then be calculated for different bursts. The streamflow is then assumed to occur in separate "rises" associated with each burst and the proportions of the total streamflow corresponding to each 'rise' must be input. Loss parameters are then calculated from the amounts of rainfall and the proportional amount of resulting streamflow from each burst. This is clearly quite restrictive as it assumes that the user has some knowledge of the relative runoff responses of the different bursts.

8. TEST CATCHMENTS AND AVAILABLE DATA

8.1 Catchment Description

For this preliminary report on the evaluations of the four models two different catchment areas have been used. Both represent nested gauging situations such that observed flow data are available at more than just the total catchment outlet. One of the catchments (Ecca) is situated in the semi-arid eastern Cape Province of South Africa while the other (North Danville) is in the temperate, northeastern American state of Vermont.

8.1.1 Ecca catchments

This set of five nested research catchments (fig. 8.1) were established in 1974 by the Hydrological Research Unit of Rhodes University and funded by the Water Research Commission. Unfortunately, the two smaller sub-catchments have not produced flow data of an acceptable quality due to inadequacies in the design of the flow gauging structures. Both Roberts (1978) and Görgens (1983) provide descriptions of the physical characteristics of the area and consequently only summary information is given in this report. Figure 8.1 shows the boundaries of the gauged catchments and the positions of the 10 autographic raingauges established in 1975. The gauge indicated as BP01 was removed in 1981 and relocated at position CP01. In 1983 a further five continuously recording raingauges were established in a small area close to the position of BP01.

The values given in table 8.1 illustrate the semi-arid nature of the climate with relatively low rainfall amounts and high potential evapotranspiration losses. The area experiences two different rainfall producing mechanisms. Long duration storms with relatively low intensities are caused by large-scale frontal or advection systems. These storms have produced the highest flows in the catchment during the period of gauging. Spatial variation in rainfall amounts during such storms is usually quite low but indicates an orographic effect with higher rainfalls being observed on the southern and eastern borders of the catchment. Although this type of storm is more common during the winter months they have also occurred in summer. However, the main storm type in summer is caused by convectional or convergence uplift resulting in short duration and often high intensity thunderstorms. During convectional thunderstorms the rainfall amounts and intensities can be spatially highly variable. Characteristically, the valley bottoms receive most rain during these storms. The distinct differences between the two types of rainfall event will inevitably be reflected in the characteristics of the resulting runoff response. These catchments should therefore provide a fairly rigorous test of the calibration capabilities of the models.

Table 8.1 Ecca catchments : physical details

Mean annual rainfall (MAP)	487 mm
Standard deviation of annual rainfalls	99 mm
Mean annual number of raindays	101 days
Mean annual free water surface evaporation	1364 mm

	Q9M20	Q9M21	Q9M24
Area (Km^2)	73,1	9,1	23,1
slopes (%area)			
less than 20%	69	52	79
20 - 40%	19	29	13
more than 40%	12	19	8
Geology (% area)			
shales	49	70	55
others	51	30	45
Vegetation density (% area) ground and canopy cover			
Dense	18	15	31
Medium	42	45	34
Sparse	40	40	35

The catchment is underlain by interbedded shales and sandstones dipping at approximately 40°N in the south and almost horizontally bedded in the north. Part of the southern catchment boundary consists of harder formations of quartzite and tillite. Figure 8.1 illustrates the drainage pattern of the area with two dominant channel directions. One follows the strike of the rock formations and the other occurs at right angles to this in highly dissected valleys. Figure 8.2 (taken from Roberts, 1978) shows the distribution of slopes within the catchment. The most noticeable characteristics are the flat headwater areas and main valley bottom separated by very steep slopes in the central parts of most tributary catchments. Soil depth is quite strongly related to slope, being thin and stoney on the steep slopes as well as some hilltops. Alluvial and colluvial deposits are unevenly spread throughout the valley bottoms, and where they exist, associated soils can be up to 2m deep. In some tributaries there is evidence that deeper soils occur on slopes where the geological dip is parallel to the slope. However, this does not appear to be consistant throughout the catchment. Vegetation consists of succulent to sub-succulent bush with a variable density (table 8.1). Ground cover was identified by Roberts (1978) as being relatively sparse over large parts of the catchment. Observations over a number of years have suggested that ground cover is temporaly variable depending upon the previous history of rainfall. During prolonged dry periods ground cover may disappear from large parts of the catchment only to reappear at the end of such a drought. This change appears to constitute the major temporal variation in the vegetation cover rather than any differences related to seasonal influences.

Figure 8.3 shows the way in which the catchment has been divided up into 12 sub-areas for sub-catchment modelling. Sub-catchment modes and conceptual storages for routing modelled flows through the channel network are also indicated. Where relevant, sub-area outlets correspond to gauging locations (Q9M21 and Q9M24) within the total catchment area.

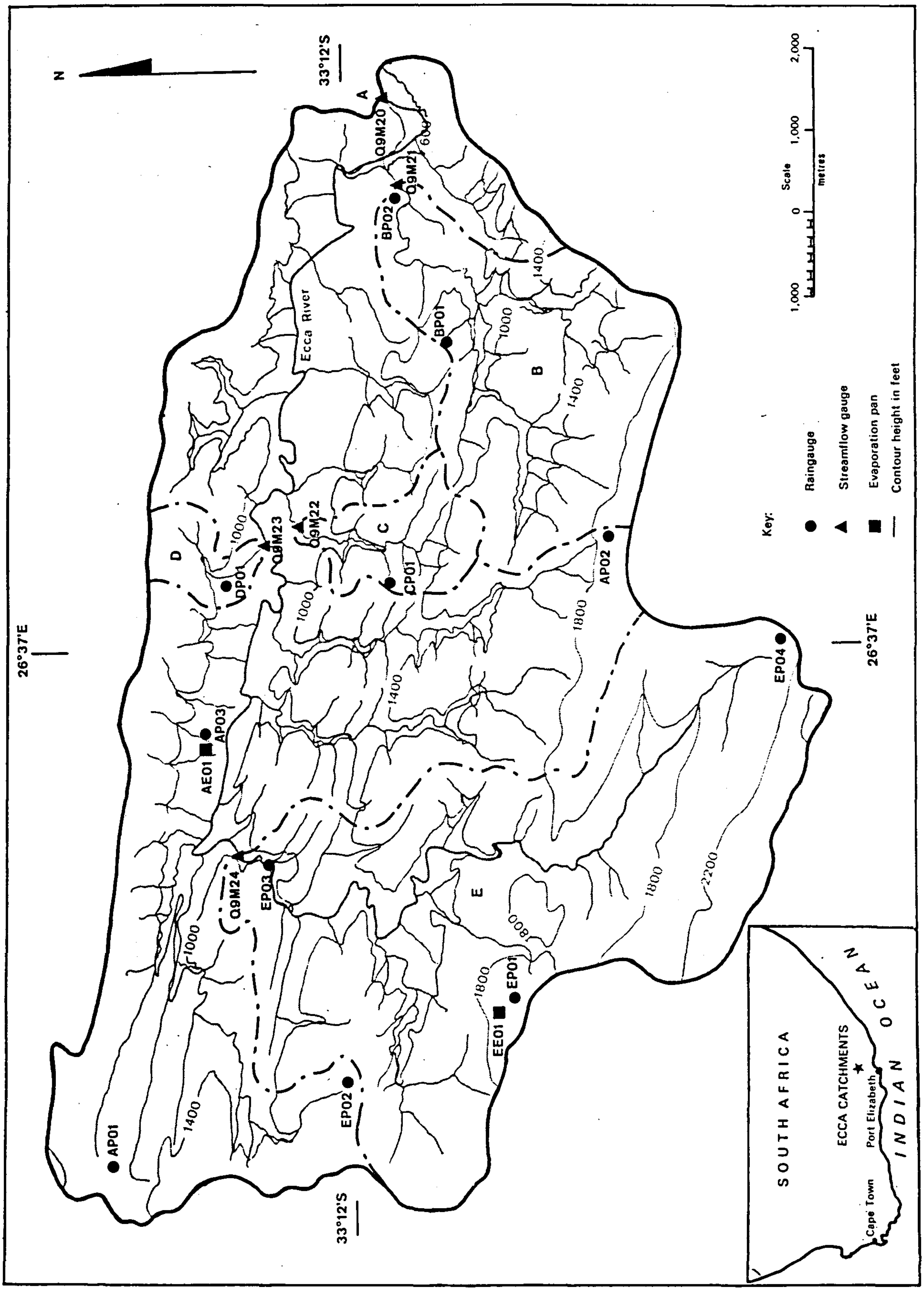


Figure 8.1 The Ecca catchments and gauging network (from Görgens, 1983).

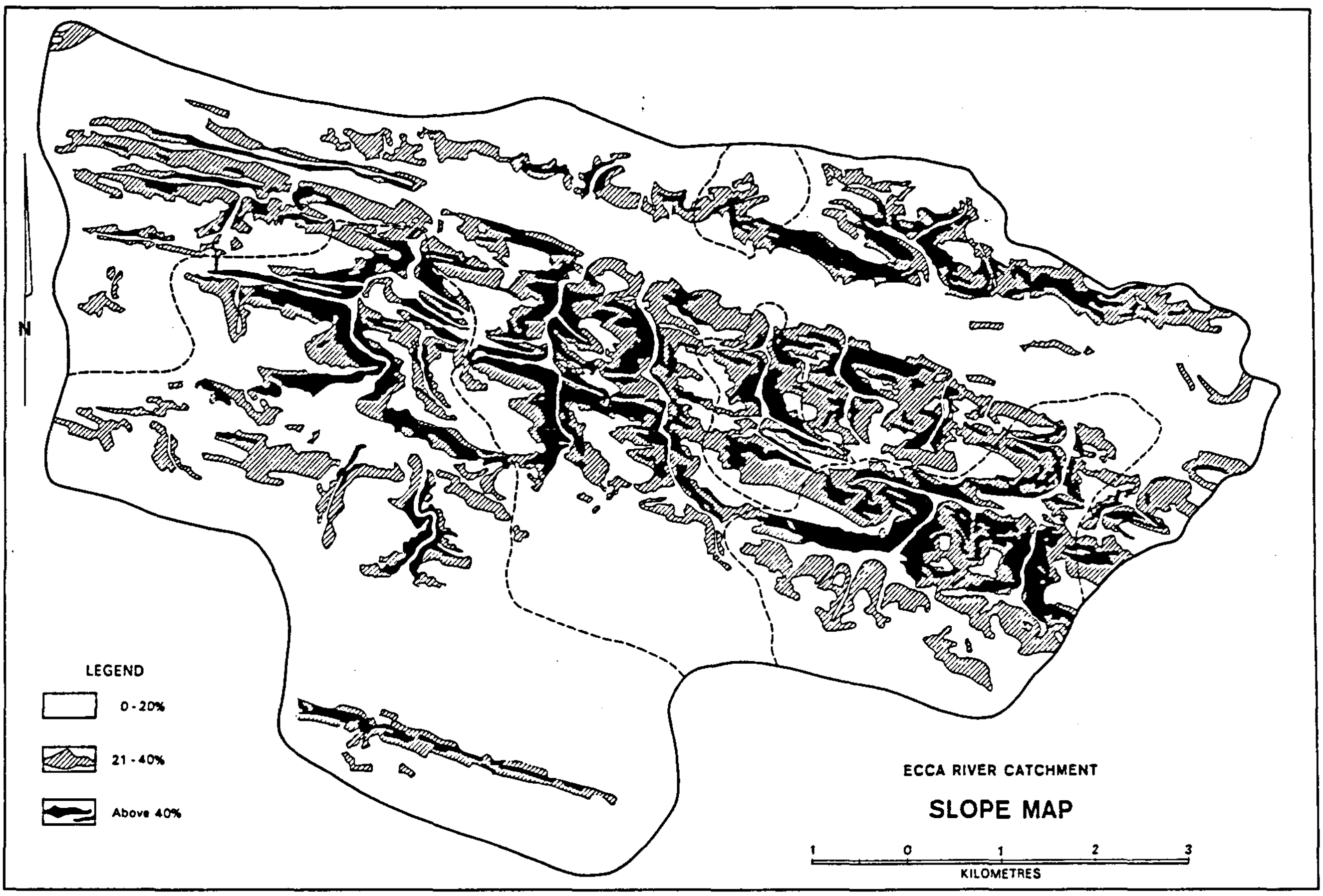


Figure 8.2 The distribution of slope steepness within the Ecca catchments (from Roberts, 1978).

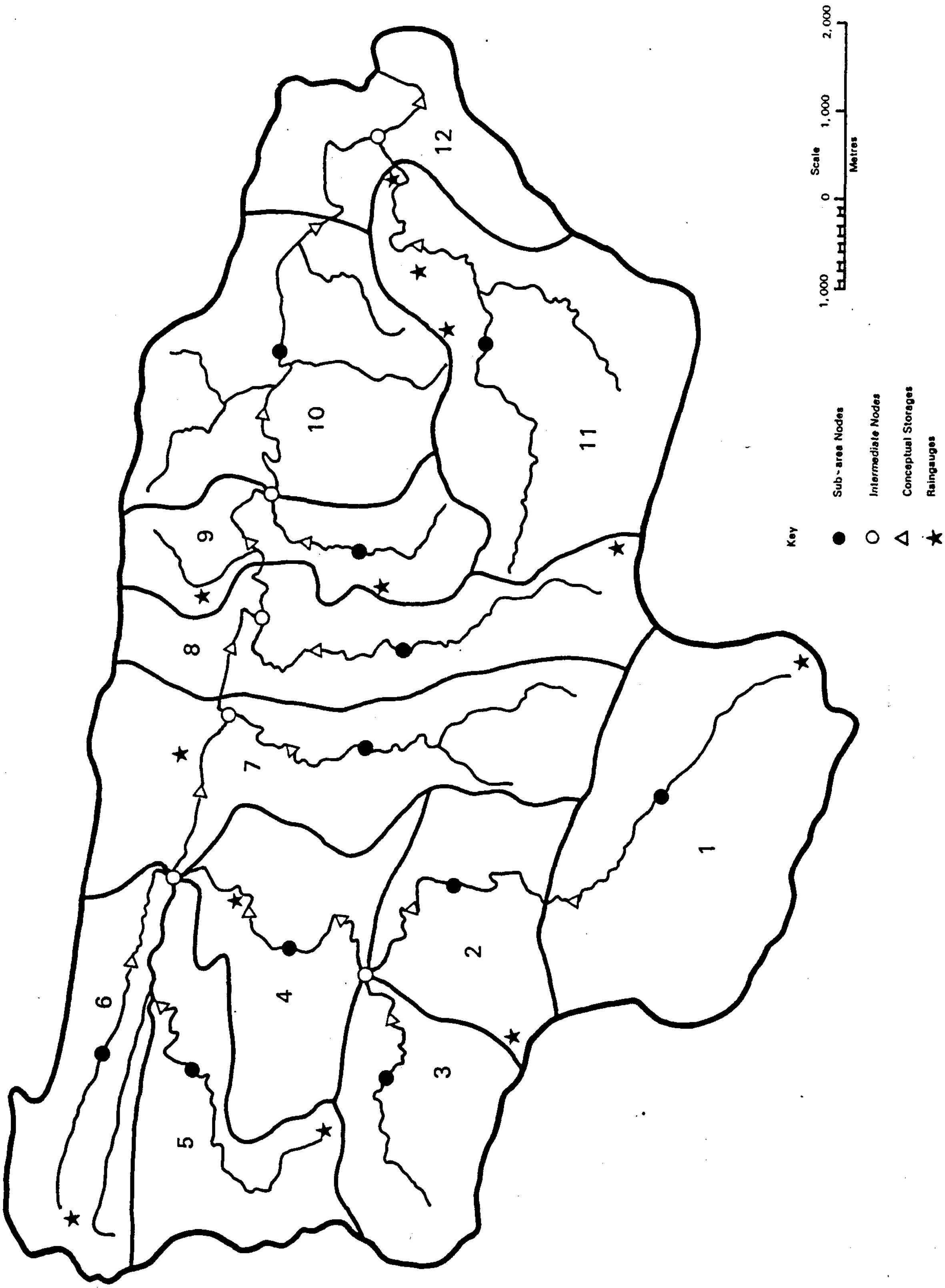


Figure 8.3 Sub-area boundaries in the Ecca catchments.

8.1.2 North Danville Catchments.

The North Danville catchments are situated in Caledonia County, Vermont State in the northeastern USA. They form part of the Connecticut River basin and cover a total area of 111,6km² (figure 8.4 and table 8.2). The information on their physical characteristics and the single event storm data has been drawn from various miscellaneous publications of the United States Department of Agriculture, Agricultural Research Service. (UDSA, 1960 to 1973). These volumes were kindly loaned to the HRU at Rhodes University by Professor R.E.Schulze of the Department of Agricultural Engineering, Natal University, Pietermaritzburg.

Within the largest catchment (ND5) there exist a further 10 streamflow gauging points of which 3 (ND1, ND3 and ND4) have been used in this study. There are 28 recording raingauges within the area but the records for only a few of these are printed in the publications (USDA, 1960 to 1973). Records suggest that five months of the year experience sub-zero temperatures and there appears to be a spring snowmelt period in April and May. Surface drainage is in well defined perennial channels.

The catchment is underlain by calcareous schists and cal-silicate rocks interbedded with quartz-mica schists and micaeous quartzite. Overlaying these formations is an impervious glacial till or boulder clay which ranges in depth from 0 to 27m. Soils vary from rocky, fine sandy loams with rapid permeabilities to silty loams with moderate to slow permeabilities (table 8.2). Soil depths to the substratum varies from 0,3m to 0,8m. While no soil distribution maps are included in the publications used (USDA, 1960-1973) there is little variation in soil characteristics between the gauged catchments. The steepest slopes are on the western catchment boundary and in the northeastern part of ND4 (figure 8.3) where the channels appear to be slightly more incised. The area is predominantly covered by hardwood forest with some softwoods. Similar proportions of the catchment are under cultivation and pasture (table 8.2) while buildings and roads occupy only about 1% of the area.

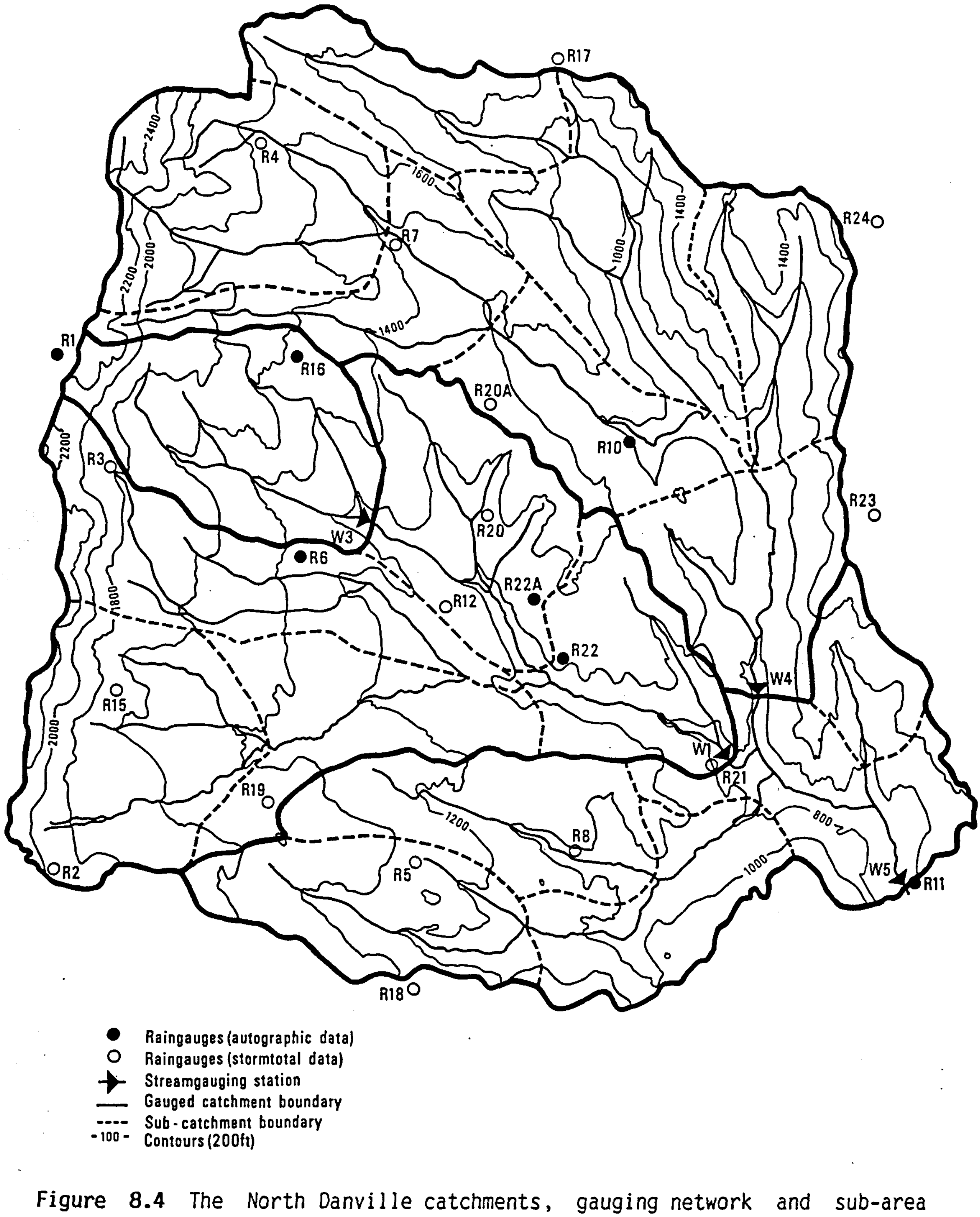


Figure 8.4 The North Danville catchments, gauging network and sub-area boundaries

Figure 8.4 shows the boundaries for the 18 sub-areas that the complete catchment has been divided up into for the purposes of sub-area modelling. As with the Ecca, sub-area outlets correspond where necessary to the gauged sub-catchments (ND1, ND3 and ND4) within ND5. Within ND1 there are 6 sub-areas and 7 within ND4. ND3 constitutes a sub-area on its own.

Table 8.2 North Danville : physical details
Mean annual precipitation (MAP) 1000mm

	ND5	ND1	ND3	ND4
Area (km^2)	111,6	42,9	8,4	43,5
Slopes (% area)				
0-15%	64	74	66	-
15-25%	23	17	22	-
more than 25%	13	9	12	-
Average soil depth (m)				
Top soil	0,2	0,2	0,2	-
Depth to substratum	0,6	0,6	0,6	-
Soil permeabilities (% area)				
Rapid	44	33	36	-
Moderate	53	65	63	-
Slow	3	2	1	-
Land Use (% area)				
Forest	67	64	67	-
Cultivated	17	17	11	-
Pasture	13	15	19	-
Other	3	4	3	-

8.2 Storm data

The storm data for all the catchments modelled are summarised in the tables at the end of this chapter (tables 8.3 to 8.9). Each table is divided into three components. The first summarises the characteristics of the storm rainfall and the antecedent rainfall. The second lists the volumes, discharges and timing of total streamflows while the third concentrates on the streamflows above a separation line of 1,13mm. day $^{-1}$. day $^{-1}$ (5,47 x $10^{-4}M^3.s.^{-1}km.^2h.^{-1}$, Hewlett and Hibbert, 1967). Each table component includes the storm number and the date and time of the beginning of the storms. The catchment name, code, area and data time interval are given at the top of each table.

The tables illustrate that there is a great variety in the amount of rainfall data available for the different storms. The number of rain profiles given in the tables represent the number of separate rainfall time distributions that were used for modelling and do not necessarily reflect the total amount of information available. Total storm rainfall at additional gauge sites has also been used to determine weighting factors for individual sub-areas. For all the storms the maximum amount of information available has been used to decide the weighting factor and profile to use for any sub-area. For some storms there is relatively little information and it is essential to consider this during the interpretation of the results. Isohyetal diagrams of storm total rainfall have been used to obtain estimates of sub-area storm totals. Sub-area weighting factors can then be calculated using the ratio of these estimates to the storm total at the gauge selected to describe the time distribution.

8.2.1 Ecca catchments.

15 events were extracted from the breakpoint data files for the period 1976 to 1986 and vary between short duration, high intensity convectional storms to long duration, low intensity storms. A wide range of antecedent moisture conditions are also represented by the 15 events. The number of rainfall profiles available for each is different due to variations in the number of gauges that operated successfully at the time. Each profile represents a weighted average of the group of possible gauges most relevant to one or more of the sub-areas. Although not apparent from tables 8.3 to 8.5, the degree of spatial variation in rainfall amounts is different for some storms. Storms 6 to 8 represent relatively uniform rainfall examples while the low total rainfall amount on storm 2 is partly due to the fact that 5 of the sub-areas experienced no rainfall for this event.

The discharge components of tables 8.3 to 8.5 suggest that the resulting flow events range from very small and short duration hydrographs (peaks 1,0$m^3 s^{-1}$) to the largest events recorded. During many of the smaller events no flow was recorded at Q9M24 and consequently the data set for this area is made up of only the five large events in 1979 and 1985. The overall runoff coefficients (total storm runoff/total storm rainfall) vary from more than 0,33 to less than 0,01. It is apparent that this data set represents a wide range of storm types both in terms of the type of rainstorm and the antecedent conditions. Many of the events are very small and would certainly not warrent being referred to as floods. However, they have been included as the amount of data on 'real floods' is extremely limited for this semi-arid catchment. It is possible that their inclusion will indicate deficiencies in certain components of the models being tested.

8.2.2 North Danville Catchments

Between 9 and 15 storm events are tabulated in the USDA publications for 1960 to 1973 for the four streamflow gauges used in the North Danville Catchments. The amount of rainfall data available for each storm is highly variable. For some storms the data consist of profiles for several gauges, plus totals for additional gauges and isohyetal maps of the total storm rainfall. However, for the majority of storms, autographic records. for gauges 1 and 10 or 16 and 22 (figure 8.4) only are available. For the storms prior to 1965, totals for some other gauges are given (USDA, 1960 to 1973) and these have been used to estimate weighting factors for sub-area rainfall input. The lack of more rainfall data is bound to have an effect on the interpretation of the modelling results, particularly where the spatial variation in input rainfall is high. The available records do indicate that this variation is important for some events, with gauge totals varying quite considerably (Gauge 1 = 35,0mm, 10 = 17,7mm for storm 11 on ND1 for example). It has been necessary to place greater emphasis during interpretation of the results on those storms with more complete rainfall input information.

As with the Ecca the available storms seem to represent a reasonably wide variation of rainfall input type as well as streamflow response and antecedent conditions type. It is difficult to suggest whether the range of storm types is representative of all storms experienced on these catchments as the full record is not available to the authors. There are two aspects of the flow regime of this area that the data set certainly does not represent. These are precipitation events during winter on frozen catchments and spring snowmelt events. None of the models being tested have components to represent these processes and therefore the exclusions are justified.

SUMMARY TABLES (8.3 to 8.9) OF STORM DATA FOR :

Ecca - Q9M20, Q9M21, Q9M24
North Danville - ND1, ND3, ND4, ND5

Explanatory notes :

a) The rainfall duration includes zero rain periods within the rainstorm.
b) The 30 day API is calculated from the following equation :

$$API = \sum_{i=1}^{30} DR_i . 0,9^i$$

where DR_i = rainfall total i days before the event.

c) The rainfall totals and intensities are derived from catchment averages.
d) For multipeaked events the rising limb refers to flows before the highest peak.
e) In some cases storms with erroneous data have been included in the tables and are clearly marked with aline through the data.

Table 8.3 Summary of storm data : Ecca, Q9M20

SUMMARY OF STORM DATA FOR ECCA AT Q9M20 CATCHMENT AREA (SQ.KM) 73.94 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	28. 2.77	15.00	8	24.61	13.75	14.05	1.79	55.50	91.95	99.77	100.00	46.45
2	6. 3.77	10.00	10	8.05	4.50	16.65	1.79	15.35	29.19	90.50	100.00	48.52
3	7. 5.77	4.00	10	45.53	20.25	28.13	2.25	29.13	55.20	70.81	100.00	16.46
4	19. 4.78	13.00	10	44.87	24.50	8.02	1.83	15.26	29.83	79.29	100.00	10.53
5	21. 4.78	6.00	10	35.50	18.25	15.29	1.95	80.25	98.81	98.81	100.00	43.59
6	20. 7.79	2.00	10	164.86	49.50	20.70	3.33	13.27	37.18	78.35	100.00	1.30
7	23. 7.79	22.00	8	29.07	26.75	5.48	1.09	57.71	94.04	99.24	100.00	100.43
8	19. 8.79	20.00	10	113.91	66.50	8.22	1.71	40.10	83.19	88.57	100.00	16.59
9	26. 3.81	8.00	8	23.45	12.50	6.64	1.88	27.24	87.12	99.59	100.00	51.97
10	22.10.81	13.00	10	48.13	12.50	52.06	3.85	64.06	82.72	99.53	100.00	8.21
11	23.12.81	14.00	10	35.22	13.00	60.11	2.71	35.89	37.42	99.89	100.00	5.86
12	2.11.85	7.00	5	50.80	28.00	11.16	1.81	64.83	86.71	97.73	100.00	60.23
13	25.11.85	19.00	6	65.54	38.25	32.93	1.71	76.82	99.63	99.92	100.00	12.66
14	1.12.85	16.00	10	24.16	24.75	30.48	.98	87.05	99.30	99.33	100.00	44.37
15	3.12.85	8.00	5	30.66	26.50	11.61	1.16	63.06	85.26	94.62	100.00	49.72

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	INITIAL FLOW (M¢3/S)	FINAL FLOW (M¢3/S)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)
1	28. 2.77	15.00	.11	.35	.45	33.31	.021	.516	1.066	6.00
2	6. 3.77	10.00	.10	.56	.66	48.63	.004	.477	3.227	4.00
3	7. 5.77	4.00	.10	.37	.47	34.47	.001	.614	1.158	20.00
4	19. 4.78	13.00	.05	.05	.09	6.76	.000	.248	.411	21.50
5	21. 4.78	6.00	.21	1.19	1.39	103.07	.053	.859	2.586	5.25
6	20. 7.79	2.00	16.79	11.54	28.33	2094.63	.000	2.269	31.582	49.25
7	23. 7.79	22.00	3.68	6.72	10.40	769.11	1.650	2.987	12.238	14.50
8	19. 8.79	20.00	12.69	33.13	45.82	3387.75	.039	3.507	35.678	34.75
9	26. 3.81	8.00	.04	.09	.13	9.32	.020	.300	.550	8.00
10	22.10.81	13.00	.22	.78	1.00	74.06	-.000	.636	1.923	5.50
11	23.12.81	14.00	.05	.05	.10	7.56	.000	.278	.667	10.75
12	2.11.85	7.00	3.65	11.24	14.89	1100.92	1.380	2.930	15.342	12.25
13	25.11.85	19.00	.91	11.38	12.29	908.67	.004	1.761	15.172	5.75
14	1.12.85	16.00	.37	1.88	2.25	166.00	.295	1.236	5.979	5.25
15	3.12.85	8.00	7.56	5.98	13.55	1001.59	1.610	3.342	7.007	26.50

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	28. 2.77	15.00	.09	.19	.28	20.81	.927	3.00	3.00	12.25
2	6. 3.77	10.00	.10	.41	.51	37.55	3.176	1.00	3.00	11.75
3	7. 5.77	4.00	.07	.15	.22	16.61	.983	2.75	17.25	13.50
4	19. 4.78	13.00	.02	.03	.05	3.44	.287	2.25	18.50	5.50
5	21. 4.78	6.00	.18	.74	.92	67.69	2.396	3.25	2.00	20.25
6	20. 7.79	2.00	16.12	9.02	25.14	1858.81	30.537	26.00	23.25	56.75
7	23. 7.79	22.00	2.40	3.92	6.32	467.42	10.141	12.50	2.00	34.75
8	19. 8.79	20.00	11.86	26.37	38.23	2826.48	34.524	26.25	8.50	85.25
9	26. 3.81	8.00	.02	.04	.06	4.39	.415	2.50	5.50	6.75
10	22.10.81	13.00	.21	.52	.73	54.13	1.772	3.50	2.00	16.00
11	23.12.81	14.00	.04	.02	.06	4.40	.487	1.75	9.00	4.00
12	2.11.85	7.00	2.73	7.91	10.63	786.17	13.564	10.50	1.75	39.25
13	25.11.85	19.00	.89	9.46	10.36	765.73	15.005	3.50	2.25	43.50
14	1.12.85	16.00	.28	1.07	1.34	99.26	5.521	4.00	1.25	23.25
15	3.12.85	8.00	2.86	4.89	7.75	573.23	4.911	16.50	.25	49.50

Table 8.4 Summary of storm data : Ecca, Q9M21

SUMMARY OF STORM DATA FOR ECCA B AT Q9M21 CATCHMENT AREA (SQ.KM) 9.10 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	28. 2.77	15.00	1	29.82	5.50	40.56	5.42	4.36	62.89	91.85	100.00	46.45
2	6. 3.77	10.00	1	15.91	4.25	40.20	3.74	23.26	30.17	98.55	100.00	48.52
3	7. 5.77	4.00	1	49.48	18.75	32.00	2.64	28.15	51.84	78.17	100.00	16.46
4	19. 4.78	13.00	1	45.71	24.25	10.04	1.88	25.01	39.66	81.05	100.00	10.53
5	21. 4.78	6.00	1	38.17	17.25	25.48	2.21	71.71	98.56	98.56	100.00	43.59
6	20. 7.79	2.00	1	157.47	48.00	20.56	3.28	12.62	33.68	77.30	100.00	1.30
7	23. 7.79	22.00	1	28.83	26.75	7.00	1.08	59.35	92.47	98.92	100.00	100.43
8	19. 8.79	20.00	1	108.83	66.25	8.04	1.64	37.28	78.94	86.68	100.00	16.59
9	26. 3.81	8.00	1	24.61	12.50	8.52	1.97	20.20	88.95	99.39	100.00	51.97
10	22.10.81	13.00	1	59.30	10.00	49.32	5.93	42.06	77.93	82.68	100.00	8.21
11	23.12.81	14.00	1	33.24	11.00	54.80	3.02	40.94	42.54	97.92	100.00	5.86
12	2.11.85	7.00	1	58.35	26.00	15.84	2.24	53.71	79.54	97.24	100.00	60.23
13	25.11.85	19.00	1	75.91	38.25	42.24	1.98	86.04	99.83	99.91	100.00	12.66
14	1.12.85	16.00	1	9.36	4.25	24.24	2.20	92.09	95.73	98.40	100.00	44.37
15	3.12.85	8.00	1	30.75	26.50	14.32	1.16	73.76	92.20	96.68	100.00	49.72

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	INITIAL FLOW (M¢3/S)	FINAL FLOW (M¢3/S)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)
1	28. 2.77	15.00	.08	.32	.40	3.64	.000	.236	.811	3.00
2	6. 3.77	10.00	.21	.20	.41	3.74	.000	.107	1.156	3.25
3	7. 5.77	4.00	.35	1.58	1.94	17.62	.000	.117	1.213	18.50
4	19. 4.78	13.00	.00	.01	.01	.12	.000	.000	.003	7.75
5	21. 4.78	6.00	.29	.92	1.21	10.97	.000	.082	.433	5.00
6	20. 7.79	2.00	14.18	15.22	29.40	267.56	.000	.300	4.621	45.50
7	23. 7.79	22.00	3.43	8.22	11.65	105.97	.217	.384	1.809	10.75
8	19. 8.79	20.00	13.65	21.76	35.41	322.26	.007	.439	2.501	38.00
9	26. 3.81	8.00	.09	.20	.29	2.67	.001	.054	.187	6.50
10	22.10.81	13.00	.00	.01	.01	.07	.002	.001	.002	.25
11	23.12.81	14.00	.16	.17	.33	3.02	.000	.047	.458	9.25
12	2.11.85	7.00	4.54	11.82	16.36	148.86	.039	.285	1.733	13.00
13	25.11.85	19.00	.01	1.27	1.28	11.67	.089	.059	.089	.25
14	1.12.85	16.00	.10	.17	.27	2.48	.058	.087	.129	3.00
15	3.12.85	8.00	.99	9.63	10.63	96.70	.209	.399	1.115	6.25

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	28. 2.77	15.00	.01	.02	.02	.21	.069	.00	4.25	1.00
2	6. 3.77	10.00	.19	.11	.30	2.71	1.045	.25	3.00	2.00
3	7. 5.77	4.00	.32	1.10	1.42	12.92	1.173	7.75	10.75	23.00
4	19. 4.78	13.00	.12	.60	.72	6.58	.370	14.00	7.75	26.00
5	21. 4.78	6.00	.28	.65	.93	8.44	.419	2.50	2.50	16.25
6	20. 7.79	2.00	13.59	12.22	25.81	234.85	4.500	24.25	21.25	60.00
7	23. 7.79	22.00	2.48	4.70	7.17	65.28	1.562	8.25	2.50	36.00
8	19. 8.79	20.00	6.56	21.12	27.68	251.91	2.329	25.25	5.75	85.25
9	26. 3.81	8.00	.07	.11	.18	1.60	.162	4.50	2.00	10.75
10	22.10.81	13.00	.00	.00	.00	.00	.000	6.50	.00	12.75
11	23.12.81	14.00	.19	.12	.31	2.83	.418	8.00	1.25	10.50
12	2.11.85	7.00	4.21	8.90	13.10	119.25	1.637	11.75	1.25	50.00
13	25.11.85	19.00	.00	.00	.00	.00	.000	13.00	.00	51.25
14	1.12.85	16.00	.02	.05	.07	.62	.062	1.00	1.75	5.25
15	3.12.85	8.00	.50	5.03	5.53	50.34	.902	5.00	1.25	42.50

Table 8.5 Summary of storm data : Ecca, Q9M24

SUMMARY OF STORM DATA FOR ECCA AT Q9M24 CATCHMENT AREA (SQ.KM) 23.30 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	20. 7.79	2.00	1	168.82	48.00	19.76	3.52	11.63	32.69	75.42	100.00	1.30
2	23. 7.79	22.00	1	31.35	25.50	6.92	1.23	58.21	92.44	98.53	100.00	100.43
3	19. 8.79	20.00	1	119.67	59.25	10.80	2.02	38.45	77.51	88.45	100.00	16.59
4	2.11.85	7.00	1	50.81	28.00	17.32	1.81	62.70	84.96	96.24	100.00	60.23
5	25.11.85	19.00	1	40.17	7.00	32.28	5.74	2.44	15.09	58.05	100.00	12.66

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	INITIAL FLOW (M¢3/S)	FINAL FLOW (M¢3/S)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)
1	20. 7.79	2.00	8.37	8.67	17.04	397.01	.000	.579	9.581	46.00
2	23. 7.79	22.00	2.53	5.95	8.48	197.57	.351	.776	3.910	10.75
3	19. 8.79	20.00	6.29	18.28	24.57	572.49	.000	1.064	5.908	31.25
4	2.11.85	7.00	3.38	4.07	7.46	173.73	.135	.583	2.517	16.50
5	25.11.85	19.00	.05	.05	.10	2.27	.001	.046	.301	5.50

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	20. 7.79	2.00	8.07	6.88	14.94	348.21	9.357	17.25	28.75	45.25
2	23. 7.79	22.00	1.87	3.58	5.45	127.02	3.450	9.00	1.75	33.50
3	19. 8.79	20.00	5.65	11.96	17.61	410.33	5.584	25.25	6.00	83.50
4	2.11.85	7.00	2.84	2.57	5.41	126.09	2.203	14.25	2.25	35.50
5	25.11.85	19.00	.05	.03	.08	1.84	.283	1.25	4.25	3.75

Table 8.6 Summary of storm data : N. Danville, ND5

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND5   CATCHMENT AREA (SQ.KM) 111.60 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	30. 7.60	12.00	3	43.98	12.00	14.95	3.66	24.06	61.54	84.59	100.00	11.45
2	2. 6.61	2.00	3	23.09	6.75	12.29	3.42	30.06	41.70	93.54	100.00	15.53
3	31. 7.62	4.00	3	48.55	9.25	34.21	5.25	33.53	63.50	72.16	100.00	24.01
4	30. 7.63	2.00	8	22.61	4.00	14.36	5.65	39.45	49.30	84.44	100.00	9.41
5	22. 7.64	17.00	8	21.78	1.50	43.13	14.52	8.89	30.03	100.00	100.00	27.20
6	7. 6.65	15.15	3	37.48	8.75	29.02	4.28	50.71	76.75	94.88	100.00	9.79
7	19.10.66	20.15	3	29.86	31.75	9.30	.94	58.23	90.98	98.93	100.00	15.15
8	16. 7.67	4.00	3	32.22	10.25	19.08	3.14	63.56	79.77	95.94	100.00	26.67
9	11. 9.68	5.00	3	43.27	30.50	13.75	1.42	70.47	91.53	93.42	100.00	14.02
10	7. 9.69	17.00	3	22.03	12.00	38.48	1.84	96.91	99.28	99.52	100.00	27.33
11	23. 8.71	1.00	3	31.26	23.00	19.44	1.36	77.37	94.66	97.84	100.00	36.39
12	10. 7.72	10.45	3	30.13	13.75	19.74	2.19	7.93	86.53	92.52	100.00	30.50
13	20. 7.72	24.00	1	38.97	25.75	31.79	1.51	14.53	93.79	98.15	100.00	35.49
14	14. 7.73	1.00	1	25.20	6.50	13.85	3.88	22.23	65.11	92.63	100.00	50.07
15	17. 9.73	24.00	3	38.02	16.25	7.62	2.34	11.50	53.33	91.92	100.00	29.97

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	30. 7.60	12.00	.86	2.23	3.09	344.52	.160	1.700	10.200	12.75
2	2. 6.61	2.00	1.27	5.19	6.46	721.18	1.180	3.070	15.690	7.75
3	31. 7.62	4.00	3.03	4.96	7.99	891.96	.230	2.170	21.230	11.25
4	30. 7.63	2.00	.10	.02	.12	13.91	.060	.610	.640	10.50
5	22. 7.64	17.00	.46	1.05	1.51	168.59	.330	1.320	5.070	5.75
6	7. 6.65	15.15	1.03	2.42	3.45	384.85	.330	1.990	8.610	10.00
7	19.10.66	20.15	.73	2.10	2.83	315.37	.300	2.030	4.460	13.00
8	16. 7.67	4.00	.54	4.20	4.74	528.56	.420	2.100	11.430	5.50
9	11. 9.68	5.00	.74	2.76	3.50	390.56	.170	2.120	8.920	12.00
10	7. 9.69	17.00	.49	.83	1.32	147.54	.910	1.880	4.100	7.25
11	23. 8.71	1.00	.91	2.27	3.18	354.63	.700	2.190	7.830	10.50
12	10. 7.72	10.45	.72	3.57	4.29	478.55	.650	2.350	11.590	10.25
13	20. 7.72	24.00	1.71	5.74	7.46	832.26	.750	2.820	20.030	14.75
14	14. 7.73	1.00	1.51	3.52	5.03	561.09	2.020	3.370	14.850	7.50
15	17. 9.73	24.00	1.31	4.14	5.45	609.42	.520	2.280	13.800	13.75

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	30. 7.60	12.00	.70	1.58	2.28	254.27	9.450	7.75	5.00	23.50
2	2. 6.61	2.00	.92	3.34	4.26	475.35	14.070	7.00	.75	30.75
3	31. 7.62	4.00	2.86	3.83	6.69	746.36	20.440	8.75	2.50	31.50
4	30. 7.63	2.00	.00	.01	.02	1.68	.130	2.00	3.25	8.00
5	22. 7.64	17.00	.37	.67	1.04	115.61	4.420	5.00	.75	16.50
6	7. 6.65	15.15	.83	1.58	2.41	269.06	7.700	8.75	1.25	26.25
7	19.10.66	20.15	.51	1.21	1.72	191.43	3.570	8.50	4.50	27.00
8	16. 7.67	4.00	.45	3.12	3.57	398.59	10.780	2.75	2.75	26.50
9	11. 9.68	5.00	.62	1.61	2.23	249.06	8.340	5.25	6.75	30.75
10	7. 9.69	17.00	.23	.35	.58	64.91	2.790	6.25	1.00	15.25
11	23. 8.71	1.00	.62	1.33	1.95	217.44	6.700	6.75	3.75	24.00
12	10. 7.72	10.45	.46	2.43	2.89	322.52	10.530	4.75	5.50	25.50
13	20. 7.72	24.00	1.25	4.07	5.32	594.21	18.670	8.00	6.75	32.25
14	14. 7.73	1.00	.97	2.06	3.04	338.81	12.420	6.50	1.00	21.75
15	17. 9.73	24.00	1.02	2.98	4.00	446.11	12.810	6.75	7.00	28.25

Table 8.7 Summary of storm data : N. Danville, ND1.

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND1 CATCHMENT AREA (SQ.KM) 42.94 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	24.10.59	5.00	1	74.30	17.00	20.83	4.37	44.32	49.49	92.77	100.00	40.89
2	30. 7.60	12.00	3	45.35	12.00	14.77	3.78	24.00	61.52	85.08	100.00	11.37
3	2. 6.61	2.00	3	22.76	6.75	11.98	3.37	30.19	41.95	93.62	100.00	15.53
4	31. 7.62	4.00	3	51.66	9.25	35.60	5.59	32.83	62.97	71.92	100.00	24.01
5	30. 7.63	2.00	8	23.30	4.00	18.25	5.82	42.59	51.15	85.87	100.00	15.63
6	22. 7.64	17.00	8	19.52	1.50	35.98	13.02	8.26	36.50	100.00	100.00	28.42
7	7. 6.65	15.25	3	39.49	8.75	32.51	4.51	53.82	75.52	94.38	100.00	9.79
8	19.10.66	20.15	3	30.05	32.50	8.51	.92	57.52	91.41	98.36	100.00	16.73
9	16. 7.67	4.00	3	33.78	10.25	20.63	3.30	65.02	81.28	96.23	100.00	26.67
10	11. 9.68	4.00	3	43.24	31.25	14.45	1.38	50.33	92.24	94.11	100.00	14.41
11	7. 9.69	17.00	3	20.65	12.00	36.28	1.72	96.74	99.28	99.55	100.00	27.48
12	23. 8.71	3.00	3	30.61	21.00	18.88	1.46	84.33	94.87	98.00	100.00	36.39
13	3. 7.72	11.00	1	26.23	5.50	23.22	4.77	4.45	45.88	92.91	100.00	43.69
14	10. 7.72	10.45	3	34.93	13.75	23.99	2.54	6.99	83.39	86.74	100.00	34.87
15	17. 9.73	24.00	3	37.76	16.25	7.75	2.32	11.49	52.72	92.14	100.00	36.26

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	24.10.59	5.00	15.38	14.90	30.28	1300.19	1.820	4.480	31.180	14.25
2	30. 7.60	12.00	.82	1.83	2.65	113.86	.040	.540	3.970	11.75
3	2. 6.61	2.00	1.52	4.90	6.42	275.74	.370	1.130	6.270	8.00
4	31. 7.62	4.00	3.27	6.24	9.51	408.29	.080	.830	12.410	10.25
5	30. 7.63	2.00	.10	.07	.16	7.00	.050	.240	.320	8.75
6	22. 7.64	17.00	.38	.78	1.16	49.76	.140	.490	1.700	4.75
7	7. 6.65	15.25	1.58	4.05	5.63	241.93	.110	.500	5.520	9.00
8	19.10.66	20.15	1.45	1.68	3.13	134.20	.100	.830	1.880	17.25
9	16. 7.67	4.00	.41	4.26	4.66	200.30	.140	.780	4.100	4.25
10	11. 9.68	4.00	.68	2.19	2.87	123.28	.070	.650	3.730	12.00
11	7. 9.69	17.00	.35	.61	.96	41.41	.250	.560	1.270	6.50
12	23. 8.71	3.00	.51	1.79	2.30	98.97	.180	.670	2.680	6.75
13	3. 7.72	11.00	.56	3.76	4.32	185.63	.270	.870	5.100	7.25
14	10. 7.72	10.45	.74	3.67	4.42	189.62	.230	.850	5.100	9.25
15	17. 9.73	24.00	1.34	3.60	4.94	211.98	.170	.830	5.000	13.25

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	24.10.59	5.00	13.05	12.08	25.13	1079.09	29.070	12.00	2.25	26.75
2	30. 7.60	12.00	.71	1.39	2.10	90.00	3.740	8.00	3.75	21.25
3	2. 6.61	2.00	1.21	3.12	4.33	186.10	5.720	7.25	.75	32.00
4	31. 7.62	4.00	3.14	5.10	8.24	353.98	12.150	7.50	2.75	31.75
5	30. 7.63	2.00	.02	.01	.04	1.61	.130	5.75	3.00	8.00
6	22. 7.64	17.00	.30	.46	.76	32.84	1.450	4.00	.75	14.00
7	7. 6.65	15.25	1.44	4.11	5.55	238.25	5.230	8.75	.25	37.25
8	19.10.66	20.15	1.03	.82	1.85	79.56	1.390	16.25	1.00	31.00
9	16. 7.67	4.00	.35	3.22	3.56	152.96	3.880	2.75	1.50	26.75
10	11. 9.68	4.00	.58	1.50	2.08	89.24	3.530	5.25	6.75	24.00
11	7. 9.69	17.00	.18	.27	.45	19.40	.980	5.75	.75	13.75
12	23. 8.71	3.00	.39	1.14	1.52	65.08	2.370	5.25	1.50	20.75
13	3. 7.72	11.00	.38	2.62	3.00	128.94	4.800	4.25	3.00	25.50
14	10. 7.72	10.45	.53	2.57	3.10	133.27	4.810	5.50	3.75	26.50
15	17. 9.73	24.00	1.09	2.58	3.67	157.44	4.640	7.75	5.50	27.75

Table 8.8 Summary of storm data : N. Danville, ND3.

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND3   CATCHMENT AREA (SQ.KM)   8.37 DATA TIME INTERVAL (HRS)   .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	30. 7.60	12.00	3	47.50	12.00	14.11	3.96	23.63	61.16	86.65	100.00	11.37
2	2. 6.61	2.00	3	21.96	6.75	13.90	3.25	33.84	45.82	95.28	100.00	15.53
3	31. 7.62	4.00	3	48.77	9.25	34.68	5.27	33.81	63.71	72.24	100.00	24.01
4	30. 7.63	2.00	8	22.49	4.00	13.80	5.62	38.59	49.13	84.09	100.00	15.63
5	22. 7.64	17.00	8	10.46	1.50	23.84	6.97	3.81	66.19	100.00	100.00	28.42
6	7. 6.65	15.25	3	43.20	8.75	42.32	4.94	58.77	73.52	93.52	100.00	9.79
7	19.10.66	20.25	3	29.94	19.25	12.56	1.55	44.03	77.45	92.02	100.00	16.73
8	16. 7.67	4.00	3	17.50	10.25	6.32	1.71	36.69	52.00	90.63	100.00	26.67
9	11. 9.68	4.00	3	41.78	27.25	14.08	1.53	31.31	94.35	95.86	100.00	14.41
10	7. 9.69	17.00	3	23.38	12.00	40.64	1.95	97.01	99.23	99.49	100.00	27.48
11	23. 8.71	3.00	3	26.32	19.00	15.24	1.39	91.60	96.58	96.58	100.00	36.39
12	10. 7.72	10.45	3	39.89	13.75	31.96	2.90	6.39	87.24	87.24	100.00	34.87
13	17. 9.73	24.00	3	40.40	16.25	10.16	2.49	11.58	59.06	90.35	100.00	36.26

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	30. 7.60	12.00	.49	3.48	3.97	33.24	.020	.130	1.030	10.50
2	2. 6.61	2.00	1.00	3.82	4.82	40.35	.120	.230	1.060	6.00
3	31. 7.62	4.00	2.58	4.45	7.04	58.89	.030	.150	2.050	9.00
4	30. 7.63	2.00	.21	.29	.50	4.19	.030	.070	.210	5.75
5	22. 7.64	17.00	.17	.28	.45	3.79	.160	.180	.210	2.25
6	7. 6.65	15.25	2.84	3.69	6.53	54.63	.070	.170	1.860	7.50
7	19.10.66	20.25	.62	1.82	2.45	20.47	.050	.150	.370	10.75
8	16. 7.67	4.00	1.01	1.20	2.21	18.53	.060	.140	.470	10.25
9	11. 9.68	4.00	.83	2.22	3.05	25.54	.040	.130	.950	10.50
10	7. 9.69	17.00	.19	1.33	1.51	12.67	.080	.140	.620	2.25
11	23. 8.71	3.00	.50	1.95	2.45	20.52	.070	.150	.760	5.00
12	10. 7.72	10.45	1.17	4.79	5.96	49.90	.100	.210	2.630	8.00
13	17. 9.73	24.00	1.24	4.01	5.24	43.87	.060	.180	1.310	10.50

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	30. 7.60	12.00	.38	2.68	3.06	25.62	.990	5.00	5.50	24.75
2	2. 6.61	2.00	.68	2.20	2.88	24.11	.920	3.75	2.25	23.25
3	31. 7.62	4.00	2.42	3.47	5.89	49.28	1.990	6.75	2.25	27.00
4	30. 7.63	2.00	.11	.13	.24	2.01	.160	5.00	.75	9.50
5	22. 7.64	17.00	.01	.04	.05	.45	.040	.75	1.25	3.75
6	7. 6.65	15.25	2.56	2.76	5.32	44.53	1.760	7.00	.50	22.25
7	19.10.66	20.25	.34	1.04	1.38	11.53	.290	6.75	4.00	22.00
8	16. 7.67	4.00	.67	.69	1.36	11.37	.370	8.50	1.75	18.00
9	11. 9.68	4.00	.63	1.49	2.12	17.78	.890	4.50	6.00	20.25
10	7. 9.69	17.00	.11	.75	.86	7.17	.530	1.25	1.00	11.75
11	23. 8.71	3.00	.33	1.24	1.57	13.18	.670	3.25	1.75	16.75
12	10. 7.72	10.45	.81	3.30	4.10	34.35	2.510	4.50	3.50	24.75
13	17. 9.73	24.00	.90	2.89	3.79	31.71	1.210	7.50	3.00	26.00

Table 8.9 Summary of storm data : N. Danville, ND4.

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND4 CATCHMENT AREA (SQ.KM) 43.51 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	7. 6.65	15.25	3	34.54	8.75	37.64	3.95	45.57	78.86	95.81	100.00	9.79
2	19.10.66	20.25	3	29.88	31.75	10.31	.94	61.49	92.55	99.26	100.00	15.15
3	16. 7.67	4.00	3	35.85	10.25	22.68	3.50	66.75	83.07	96.56	100.00	26.67
4	11. 9.68	5.00	3	43.26	30.50	13.79	1.42	70.64	91.66	93.51	100.00	14.02
5	7. 9.69	17.00	3	18.84	12.00	33.36	1.57	96.48	99.29	99.61	100.00	27.33
6	23. 8.71	1.00	3	29.74	23.00	18.14	1.29	79.84	95.17	97.62	100.00	36.39
7	10. 7.72	10.75	3	31.50	13.75	21.46	2.29	7.64	86.66	91.58	100.00	30.50
8	14. 7.73	1.00	1	25.93	6.50	14.25	3.99	22.23	65.11	92.63	100.00	50.07
9	17. 9.73	24.00	3	38.34	16.25	7.45	2.36	11.51	54.25	91.76	100.00	29.97

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	7. 6.65	15.25	.88	1.28	2.16	93.83	.170	.750	1.770	11.75
2	19.10.66	20.25	1.34	1.40	2.74	119.18	.160	.810	1.530	18.00
3	16. 7.67	4.00	.55	3.84	4.39	190.96	.200	.840	5.140	4.50
4	11. 9.68	5.00	.76	2.80	3.55	154.63	.080	.850	3.190	12.00
5	7. 9.69	17.00	.59	1.36	1.95	84.85	.480	.880	2.330	6.25
6	23. 8.71	1.00	.70	1.77	2.47	107.32	.210	.730	2.570	9.75
7	10. 7.72	10.75	1.19	3.84	5.03	218.92	.290	.970	5.000	10.75
8	14. 7.73	1.00	1.39	3.68	5.06	220.34	.810	1.320	5.590	7.00
9	17. 9.73	24.00	1.68	4.35	6.03	262.40	.260	.990	5.420	13.25

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	7. 6.65	15.25	.58	.60	1.18	51.35	1.330	11.25	.50	24.25
2	19.10.66	20.25	.46	1.09	1.53	66.74	1.150	8.25	4.50	27.50
3	16. 7.67	4.00	.46	2.73	3.19	138.71	4.050	3.25	1.25	26.50
4	11. 9.68	5.00	.63	1.57	2.20	95.84	2.950	6.50	5.50	32.50
5	7. 9.69	17.00	.30	.66	.96	41.69	1.710	5.75	.50	16.75
6	23. 8.71	1.00	.48	1.06	1.55	67.26	2.210	6.25	3.50	21.50
7	10. 7.72	10.75	.88	2.56	3.44	149.54	4.540	7.00	3.75	28.25
8	14. 7.73	1.00	.89	2.17	3.06	133.24	4.650	5.25	1.75	21.00
9	17. 9.73	24.00	1.32	3.02	4.33	188.57	4.930	8.50	4.75	30.25

9. COMPUTER PROGRAMMING CONSIDERATIONS

In order to facilitate the simple application of all models to each data set, the computer coding of three of the models has been included as a subroutine in a larger program. This was not easily possible with RORB model as it was received as an already coded program on magnetic tape. However, the RORB model was modified slightly to accept the input data in the same format as the other models.

The data for the Ecca catchment is drawn from the breakpoint data bank of the Rhodes HRU while the North Danville data was available as breakpoint data from the volumes of the US Department of Agriculture (USDA 1960 to 1973). Additional data are available from several other sources within South Africa. A suite of FORTRAN programs has been established to reduce or extract from the original data a set of fixed time interval values of rainfall depth and instantaneous flow. Stormflows, based on the separation line method of Hewlett and Hibbert (1967) are also calculated and the storm is considered to terminate when such stormflows become zero. The programs allow the extraction of different combinations of raingauges to produce any number of storm profiles for sub-catchment rainfall input. An example of the resulting rainfall and observed streamflow data input file is given in table 9.1. Although a time interval of 15 minutes was used throughout this study all the data extraction programs are flexible and any time interval can be set. The input data files for any one catchment contain all the storm data for that catchment and the model programs select which storm or combinations of storms are to be modelled in any single model run.

Where relevant, the antecedent rainfall data are stored on a separate file. Information about the way in which the model should run (lumped or semi-distributed, optimization or not, etc.) plus the essential information about the parameters and the definition of the sub-catchments is contained within control data files. An example of a control file for the S-curve model is given in table 9.2. These control files are reasonably well labelled to make it simpler to edit them between model runs. The control file for the RORB model has a different format (table 9.3) and closely corresponds to the standard input file for this model (Laurenson and Mein, 1985). The only difference is that the rainfall and streamflow data are read in separately and some of the sub-catchment data are read in interactively during execution of the program.

It is apparent from the format of the control files (table 9.2) that the models (except RORB) can be operated in lumped or semi-distributed format, single run or optimisation and single storm or multiple storm, using the same program. This method of operation makes it very easy to change from one mode to another without having to deal with a large number of different programs and data files. It should also be noted that there is always only one set of parameter values. For the semi-distributed models, sub-area changes in parameter values are determined by the sub-catchment parameter factor values. When running in optimization mode it is more or less impossible to expect sensible results if the parameter values on each sub-catchment were to be included in the optimization exercise. There is simply too much interaction between the different values being optimized. Consequently, the relative values of each parameter for the different sub-catchments must first be determined (or estimated) before optimization of the nominal parameter value can take place. The upper and lower limits associated with each parameter value are used to control the automatic optimization procedure. If these are equal to the actual parameter value then that parameter is excluded from the optimization.

For the first three models (not RORB) any number of the available storms may be run together using the same set of parameter values. This mode of operation allows a single set of parameters to be optimized for a group of storms using an objective function calculated over the whole data set as a fitting criterion. Initial moisture conditions and the internal counters for individual storm fit statistics are reset at the beginning of each storm.

Output from the common model program consists of a summary of the control data, individual and combined storm statistics describing the degree of correspondence between observed and simulated streamflows as well as a lineprinter plot of rainfall and flow data (figure 9.1). In the semi-distributed models the plotted rainfall data represent a single catchment average. Options are also available to output details of the values of different variables at each time interval and the flow from each sub-catchment. If these options are selected when operating in sub-catchment mode the output file can become quite large. However, these options are extremely useful when trying to evaluate the effects of changes in model parameter values or the relative contribution of individual sub-areas to total catchment streamflow. A further option is also possible to output rainfall, observed and simulated flows in a format compatible with a general graph plotting program (GENPLOT) developed by the senior author for use with the Rhodes University CALCOMP plotter.

9.1 Verification of the computer programs

This aspect of model verification (section 3.2) entails ensuring that the computer coding of the model adequately represents the conceptual structure of the model. In this study it was necessary to check the computer coding of models OSE1, 2 and 3 as these were written by the authors. OSE4 was received as an already coded model with accompanying test data and therefore did not require extensive checking. The detailed output option referred to earlier is used to ensure that model storages and outputs are calculated and updated correctly. Examination of the detailed output also ensures that moisture is not unintentionally lost and that changes in modelling time interval do not affect the operation of the computer algorithms.

Table 9.1 Example of rainfall and streamflow input data file.

```
15 ECCA A   09M20    73.1
 1 28. 2.77    15.00    .25 HRS INTERVAL
  62
RAINFALL  FOR 28. 2.77 15.00    62  .25 HR PERIODS  MULT= 1.000   CATCH           8
RAINFALL    1.000     610
     .00     .00     .00     .00     .00    1.57    1.57    1.53     .83     .00    1.02    1.02     .14     .99    1.44
    1.44    1.44    1.44     .59     .38     .38     .38     .05     .00     .09     .70     .70     .70     .70     .42
     .00     .00     .00     .00     .35     .48     .48     .48     .48     .48     .35     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .03     .09     .09     .09     .05     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     60
     .00    1.16     .44     .00     .24     .44     .45    1.28    1.42     .22     .81     .81     .11     .69    1.38
    1.30    1.38    1.15    1.05     .63     .00     .38     .00     .00     .04     .66     .66     .66     .66     .53
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     63 8
     .00    1.00     .49     .11     .47     .29     .38    1.39    1.30    2.48    3.35    1.13     .26     .79    1.01
    1.46    1.46    1.38    1.19     .94     .04     .26     .03     .02     .02     .42     .49     .49     .66     .54
     .87     .01     .01     .01     .01     .15     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     61 8
     .00    1.27     .57     .47     .37     .45     .67     .93     .74     .36     .91     .91     .18    1.06    1.36
    1.36    1.36    1.18    1.10     .64     .03     .35     .00     .00     .02     .53     .58     .58     .58     .40
     .00     .00     .00     .00     .11     .14     .09     .23     .23     .23     .23     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     62 3
     .00     .78     .34     .15     .44     .39     .68    2.47    1.65    2.99    3.80    1.14     .55     .65     .75
    1.30    1.35    1.25    1.19     .98     .09     .24     .04     .02     .22     .33     .43     .43     .63     .44
     .09     .01     .01     .01     .01     .18     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     64
     .00     .31     .59     .00     .48     .00     .78     .08    1.12    2.55   10.14    2.06    1.44    1.44    1.44
    1.44    1.44    1.44    1.02     .95     .13     .33     .07     .00     .00     .17     .51     .51     .51     .51
     .07     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     62 4 5
     .00     .51     .58     .02     .22     .21     .78    1.71    1.44    1.63    7.74    2.13    1.64    1.24    1.24
    1.25    1.28    1.28    1.04     .89     .21     .29     .06     .02     .03     .27     .58     .51     .51     .43
     .10     .00     .00     .00     .00     .05     .01     .06     .00     .00     .00     .02     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL    1.000     6 ALL
     .00     .67     .44     .13     .33     .47     .67    1.59    1.24    1.69    4.10    1.49     .74     .98    1.13
    1.37    1.38    1.29    1.07     .84     .16     .28     .04     .02     .04     .41     .51     .52     .61     .46
     .00     .01     .01     .01     .07     .19     .08     .12     .14     .14     .12     .01     .00     .00     .00
     .00     .00     .00     .00     .00     .01     .01     .01     .01     .01     .00     .00     .00     .00     .00
     .00     .00
TOTALFLOW  0.021
    .021    .021    .020    .020    .020    .019    .019    .018    .018    .018    .017    .023    .064    .105    .167
    .650    .764    .878    .902    .983    .923    .971   1.018   1.066   1.044   1.005    .966    .945    .930    .915
    .900    .885    .870    .856    .841    .826    .811    .796    .781    .768    .759    .751    .742    .734    .725
    .716    .708    .697    .684    .671    .658    .645    .632    .619    .606    .593    .580    .568    .555    .542
    .529    .516
STORMFLOW  0.000
    .000    .000    .000    .000    .000    .000    .000    .000    .000    .000    .000    .004    .036    .067    .119
    .592    .696    .800    .814    .885    .815    .852    .890    .927    .896    .847    .798    .767    .742    .717
    .692    .667    .642    .617    .592    .567    .543    .518    .493    .470    .451    .433    .414    .395    .377
    .358    .339    .319    .296    .273    .250    .227    .204    .181    .158    .135    .112    .089    .066    .043
    .021    .000
 2  6. 3.77    10.00    .25 HRS INTERVAL
  60
RAINFALL  FOR  6. 3.77 10.00    60  .25 HR PERIODS  MULT= 1.000   CATCH           10
```

Table 9.2 Example of S-curve model input control file.

```
ECCA                    NAME OF CATCHMENT
09M20                   CATCHMENT CODE
  73.94                 CATCHMENT AREA
ECCA                    CDC FILENAME HOLDING DATA SOURCE
ECCAA                   CDC FILENAME HOLDING AMI DATA
 1                      TOTALFLOWS ON FILE (1 IF YES)
 1                      STORMFLOWS ON FILE (1 IF YES)
 1                      DATA FOR USE (1=TOTAL,2=STORM)
 1                      HEMISPHERE (1=SOUTH,0=NORTH)
 1.0000                 CONVERSION FACTOR - FLOWS TO CUMECS
 1.0000                 CONVERSION FACTOR - RAINS TO MM
 0.25                   DATA INTERVAL (HOURS)
 15                     NUMBER OF STORMS ON FILE
INCLUSION ARRAY FOR INDIVIDUAL STORMS (1=YES,0=NO)
 1  2  3  4  5  6  7  8  9 10 11 12 13 14 15
 1  0  0  0  0  1  0  0  0  0  0  1  0  0  0
S-CURVE (S.D)           MODEL TYPE
 15                     NUMBER OF PARAMETERS
 VALUE   UPPER   LOWER           DESCRIPTION
   1.000   1.000   1.000   1 CHANNEL TIME DELAY
   0.500   0.500   0.500   2 CHANNEL ROUTING K
   0.500   0.500   0.500   3 BASIN TIME DELAY
   6.000   6.000   6.000   4 BASIN ROUTING K
   0.600   0.600   0.600   5 BASIN ROUTING N
   2.700   3.000   0.500   6 CHANNEL LOSS PARAM
   0.150   0.150   0.150   7 TIME AREA B
 200.000 250.000 100.000   8 MAX STORE
   0.250   0.600   0.050   9 DA IN TANH-
   0.695   0.900   0.300  10 C IN TANH
 400.000 400.000 400.000  11 % FLOW FROM SLOPE
   0.600   0.600   0.600  12 % FLOW FROM VSA
   0.960   0.990   0.900  13 WINTER API FACT.
   0.600   0.990   0.600  14 MAX. IAR
   1.000   1.000   1.000  15 A IN TANH
 1                      LUMPED OR SEMI-DIST. (0 OR 1)
12                      NUMBER OF SUBCATCHMENTS
        SUBCATCHMENT PARAMETER FACTORS
SUB-CATCH    1    2    3    4    5    6    7    8    9   10   11   12
AREA %     13.0  5.9  5.6  7.0  6.4  7.0 11.4  7.9  6.0  9.7 12.9  7.4
PARAMETER 1 5.25 4.50 4.50 4.00 4.00 4.00 3.00 2.75 2.25 1.25 0.75 0.25
PARAMETER 2 0.80 0.90 0.90 1.00 0.75 0.75 0.50 0.62 0.96 1.40 1.00 0.60
PARAMETER 3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 0.00 1.00 1.00
PARAMETER 4 1.00 0.92 0.92 0.92 0.90 0.90 0.85 0.80 0.65 0.95 1.05 0.80
PARAMETER 5 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
PARAMETER 6 1.00 0.89 0.89 0.94 0.85 0.85 0.75 0.75 0.75 0.88 0.85 0.88
PARAMETER 7 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
PARAMETER 8 1.10 0.95 0.95 0.90 0.82 0.82 0.78 0.78 0.78 0.90 0.80 0.90
PARAMETER 9 0.72 0.84 0.84 0.92 1.05 1.05 1.15 1.15 1.15 1.07 0.99 1.07
PARAMETER10 0.83 0.93 0.93 0.95 0.95 0.95 0.95 0.95 0.95 0.92 0.99 0.92
PARAMETER11 0.75 0.82 0.82 0.90 0.90 0.90 0.92 0.92 0.92 0.90 0.92 0.90
PARAMETER12 1.00 0.83 0.83 0.83 0.83 0.83 0.83 0.90 0.90 1.00 0.83 1.00
PARAMETER13 1.00 1.00 1.00 0.99 1.00 1.00 1.00 1.00 1.00 1.01 0.99 1.01
PARAMETER14 0.92 1.03 1.03 1.05 1.10 1.10 1.30 1.30 1.30 1.20 1.40 1.20
PARAMETER15 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
NUMBER OF STORM PROFILES FOR EACH STORM
STORM NO.     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15
N.OF PROFS.   8  10  10  10  10  10   8  10   8  10  10   5   6  10   5

continued

STORM PROFILE AND MULTIPLIER FOR USE IN EACH SUBCATCHMENT
SUB-CATCH    1    2    3    4    5    6    7    8    9   10   11   12
ST. 1        1    2    2    3    4    4    5    5    5    8    7    7
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 2        1    2    2    3    4    4    5    6    7    9    9    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 3        3    3    3    3    3    3    5    7    7    7    8    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 4        1    2    2    3    4    4    5    6    6    7    8    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 5        1    2    2    3    4    4    5    6    6    7    8    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 6        1    2    2    3    4    4    5    6    6    7    8    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 7        1    2    2    3    4    4    5    5    6    6    6    6
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 8        1    2    2    3    4    4    5    5    6    7    8    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 9        1    3    3    3    3    3    3    3    6    6    1    4
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.10        1    2    2    3    5    5    8    8    8    9    8    8
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.11        1    2    2    3    4    4    5    6    6    7    8    9
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.12        2    2    2    2    2    2    3    3    4    4    4    4
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.13        1    1    1    1    2    2    3    3    3    3    4    5
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.14        1    2    2    3    4    4    5    5    5    5    9    8
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.15        1    2    2    3    3    3    2    2    4    4    4    4
          1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
RUN INFORMATION CONTROL
 0                      OPTIMISATION OR NOT (1=YES)
  5                     NUMBER OF OPTIMISATIONS
 1                      COEFF. OF EFFICIENCY (NO TRANS.)
 0                      COEFF. OF EFFICIENCY (LN TRANS.)
 0                      ABS.FRACTION ERROR IN PEAK AND VOL.
OS*I-                   LINEPRINTER PLOTTING SYMBOLS
  1.000   1.000         LINEPRINTER PLOT SCALES
 0                      OUTPUT TABLE (0=NO ,1=YES ,2=NODAL FLOWS)
   SUBCATCHMENT SEQUENCE CODES
 22
 99  1  2 99  3 88  4 99  5 99  6 88 88  7  8  9 10 99 11 88 12 77
 0                      MOVING STORM CODE (0=STATIC,1=MOVING)
```

Table 9.3 Example of RORB model input control file.

```
ECCA 09M20
 1 ,     NATURAL REACH
 1, 3.42,-99,     SUB-AREA A
 8, 3,-99
 2, 2.02,-99,     SUB-AREA B
8, 2,-99
 3,     STORE H/G
 1, 1.95,-99,     SUB-AREA C
8, 2,-99
 4,     ADD UP H/G'S
 5, 1.95,-99,     ROUTE TO TO D
 8, 2,-99
 2, 1.93,-99,     SUB-AREA D
 0, 2,-99
 7,     P/O FOR 09M24
P/O FOR 09M24
 3,     STORE H/G
 1, 3.12,-99,     SUB-AREA E
8, 3,-99
 3,     STORE H/G
 1, 2.18,-99,     SUB-AREA F
8, 2,-99
 4,     ADD UP H/G'S
 4,     ADD UP H/G'S
 5, 2.41,-99,     ROUTE TO G
 8, 3,-99
 3,     STORE H/G
 1, 2.58,-99,     SUB-AREA G
8, 3,-99
 4,     ADD UP H/G'S
 5, 1.31,-99,     ROUTE TO H
 8, 1,-99
 3,     STORE H/G
 1, 3.07,-99,     SUB-AREA H
8, 3,-99
 4,     ADD UP H/G'S
 5, 2.06,-99,     ROUTE TO I
 8, 2,-99
 3,     STORE H/G
 1, 1.31,-99,     SUB-AREA I
8, 1,-99
 4,     ADD UP H/G'S
 5, 1.8,-99,     ROUTE TO J
 8, 2,-99
 2, 4.05,-99,     SUB-AREA J
 8, 4,-99
 3,     STORE H/G
 1, 3.01,-99,     SUB-AREA K
 8, 3,-99
 7,     P/O FOR 09M21
P/O FOR 09M21
 4,     ADD UP H/G'S
 2, 1.21,-99,     SUB-AREA L
 8, 1,-99
 7.1,     P/O FOR 09M20
 0 ,     END OF CONTROL VECTOR
 9.629999, 4.38, 4.13, 5.19, 4.74, 5.16, 8.390001, 5.83, 4.42, 7.14, 9.5, 5.45,-99     SUB-AREA AREAS (KM**2)
1,0.02,0.02,0.02,0.02,0.10,0.10,0.20,0.20,0.20,0.15,0.08,0.10,-99
12.00
FIT
```

```
 .25, 90, 1, 10, 1,-99,     STORM DATA DETAILS
 0, 90
GAUGE 1
GAUGE 2
GAUGE 3
GAUGE 4
GAUGE5
GAUGE 6
GAUGE 7
GAUGE 8
GAUGE 9
GAUGE 10
 1 1 1  23.0  18.2  18.2  24.8  20.1  20.1  26.0  26.0  26.8  25.7  27.6  27.6
 2 1 1   0.0   0.0   0.0   2.2   1.2   1.2   0.1  12.1  10.0  15.9  15.9  15.9
 3 1 1  44.9  44.9  44.9  44.9  44.9  44.9  54.6  40.8  40.8  40.8  55.5  42.6
 4 1 1  46.1  34.0  34.0  45.5  36.1  36.1  44.9  49.4  49.4  53.9  45.7  51.8
 5 1 1  39.1  34.3  34.3  29.7  31.0  31.0  31.6  37.1  37.1  37.9  38.2  38.9
 6 2 1 135.7 133.3 133.3 131.4 130.7 130.7 132.1 133.1 133.1 125.7 124.4 118.4
 6 2 2  36.1  35.5  35.5  34.9  34.7  34.7  35.1  35.4  35.4  33.4  33.1  31.5
 7 1 1  32.0  31.1  31.1  27.8  27.7  27.7  28.4  28.4  28.0  28.0  28.8  28.8
 8 1 1 122.5 119.7 119.7 115.1 114.4 114.4 115.6 115.6 113.9 106.0 108.8  99.5
 9 1 1  24.6  22.9  22.9  22.9  22.9  22.9  22.9  22.9  23.6  23.6  24.6  22.1
10 1 1  30.1  43.4  43.4  26.5  44.4  44.4  59.3  59.3  59.3  59.3  59.3  59.3
11 1 1  29.8  36.7  36.7  39.7  42.6  42.6  34.3  33.1  33.1  33.6  33.2  34.7
12 1 1  50.8  50.8  50.8  50.8  50.8  50.8  46.1  46.1  58.4  58.4  58.4  58.4
13 1 1  58.5  58.5  58.5  58.5  51.6  51.6  70.6  70.6  70.6  70.6  75.9  76.8
14 1 1  28.6  41.6  41.6  30.7  33.9  33.9  17.7  17.2  17.2  17.2  16.9   7.8
15 1 1  28.0  30.2  30.2  32.6  32.6  32.6  30.2  30.2  30.8  30.8  30.8  30.8
 0, 90,-99
09M20
```

INDIVIDUAL STORM FITS

STORM	RAIN(MM)	FLOW(MM)	%ERROR	PEAK	%ERROR	C.EFF	C.EFF(LN)	R**2
3 OBS	48.6	7.99		21.230				
SIM		7.56	-5.34	18.749	-11.69	.9639	.9475	.9679

STATISTICS FOR ALL STORMS

	FLOW(MM)	%ERROR	C.EFF	C.EFF(LN)	R**2
OBS	7.992				
SIM	7.565	-5.343	.9639	.9475	.9679

STORM PLOTTED - DATE 31. 7.62 FLOW SCALING FACTOR- 1 PLOT UNIT = .0685 MM/HR
RAIN SCALING FACTOR- 1 PLOT UNIT = 10.0000 MM/HR

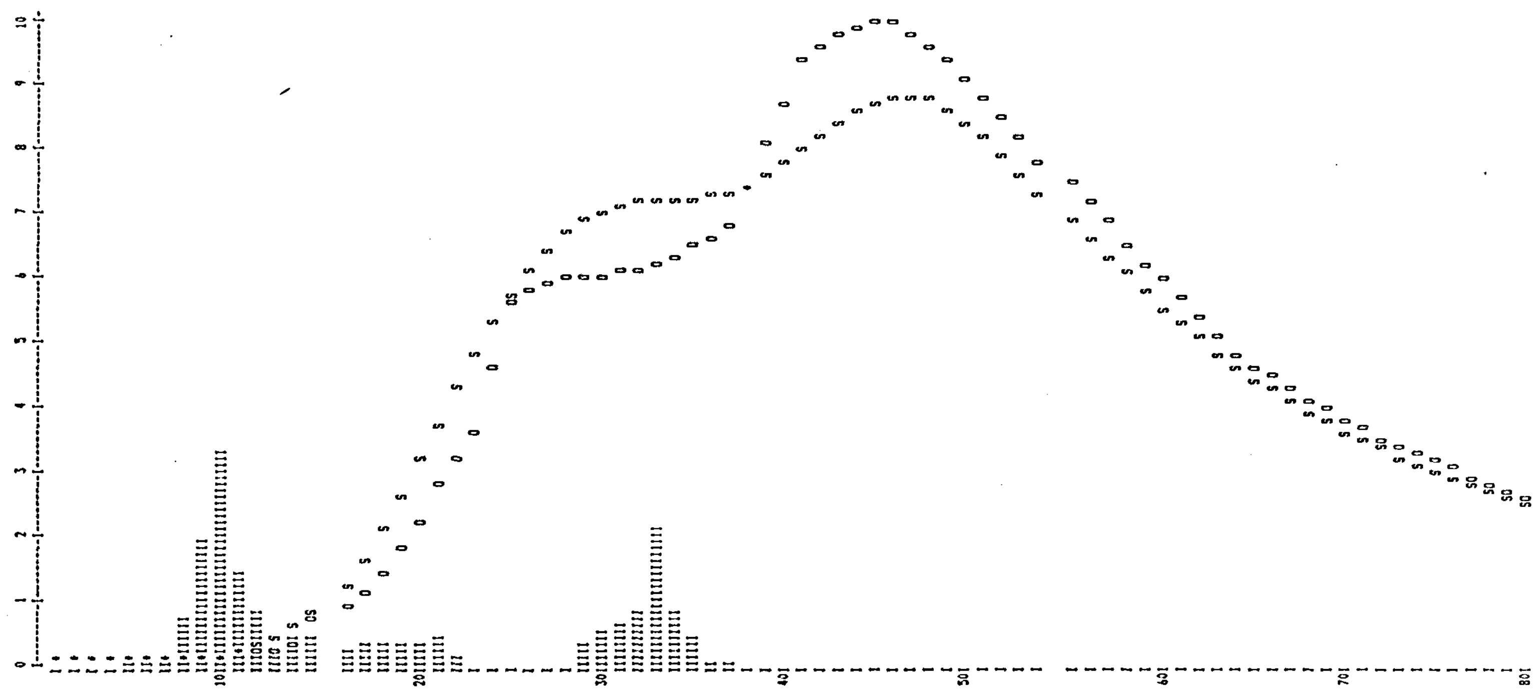


Figure 9.1 Output from the model program for OSE1, 2 and 3

10. MODEL FITTING RESULTS

This chapter discusses the results and the degree of success with which the four models have been able to reproduce the observed hydrographs. Comparisons between the individual model results are also discussed. To avoid breaking the text up with a large number of tables and diagrams most of the numerical and graphical results are contained in appendices A and B respectively. Appendix A consists of tables containing the parameter values and some statistics of fit for all the models in both lumped and semi-distributed format where applicable. Appendix B contains a number of graphical plots of storms that have been selected to illustrate a range of different results. There are several aspects associated with the results of fitting conceptual models to observed storm data. The following topics are discussed under separate headings for each of the models.

a) Ability of the models tc reproduce a range of hydrograph responses to a range of input rainfall types. This may be thought of as the models curve fitting capabilities.

b) The extent to which a) can be achieved with a reasonable degree of parameter stability and with parameter values that are intuitively acceptable. It may not always be easy to determine what is an intuitively acceptable value. To a large extent this depends upon the type of model and whether it is being operated in lumped or semi-distributed mode. Semi-distributed models have an extremely large parameter 'space' and there are consequently a large number of values that could be changed to vary the simulation result. For all the models, intuitive ideas about the sub-catchments variation in response have been used to determine the sub-catchment parameter factors. In some cases sub-catchment factors have been calculated from relative differences in measurable physiographic factors. To a certain extent the calibration results constitute a test of the applicability of these relationships. The factors have only been changed during calibration runs when changes in global parameter values have not been able to achieve a satisfactory result. In such cases, the characteristics of the sub-areas have been re-examined to try and rationalise such changes to the original intuitive reasoning.

c) The ease or difficulty of achieving acceptable fits to the observed data. This is an important consideration if a model is to have a future practical value.

During the discussions of these three topics comparisons are made between the temperate and semi-arid catchments. Comparisons are also made between the lumped and semi-distributed versions of the models to investigate whether or not the more complex semi-distributed approach is warrented. In the following sections reference is often made to 'acceptable' fits. This is of course a very difficult description to define. For the purposes of this report an 'acceptable' fit is one where the peak and volume estimations are within approximately 20% of the observed values and where the overall shape of the hydrograph is well simulated. This rather loose definition is considered adequate at this stage of the model evaluations especially if the term 'acceptable' is qualified by reference to specific features or statistics of the fits.

10.1 OSE2 - S-Curve model.

Before discussing the aspects of this model's results, it is essential to re-state the point that the model has been designed with a number of sub-components to account for differences in runoff response characteristics between storms on the same catchment. Part of the model evaluation has been to determine whether or not this is achieved successfully. Whereas the other models have been calibrated for each storm individually, the calibration of this model has been based on the assumption that the model parameters will remain the same for all storms in the same catchment. Therefore the exercise really consists of calibrating the model for the catchment not for individual storms.

10.1.1 Curve fitting capabilities

The curve fitting capability of a model refers to its ability to fit a range of disparate rainfall-runoff responses regardless of the values that the parameters have to assume to achieve this. With respect to the lumped model there are some situations where acceptable fits cannot be obtained. These are exclusively associated with storms having a high degree of spatial variability in the rainfall input (Q9M20 storm 2 - table A1, storms 30.07.63 and 22.07.64 on ND1, ND3, ND5 - tables A4, 5 and 7). The observation does not apply to all spatially variable storms and in some cases the smoothing effect of the catchment is such that the lumped model simulates the result satisfactorily.

The semi-distributed model produces better results for spatially variable storms when the space/time pattern of input is well defined. Examples are illustrated in figures B1A (Q9M20) and B10 to 12 (ND1, 4 and 5). However, little improvement is experienced for storm 22.07.64 on the North Danville catchments (fig. B8A). The information available for this storm consists of 4 rainfall profiles (gauges 1, 11, 16 and 22 - fig. 8.4) plus storm totals for most of the other gauges in the catchment. Storm totals as well as intensities are extremely variable and one possible reason for the unsatisfactory results is the inadequate definition of the time distribution of rainfall over some sub-areas. Even less information is available about the spatial variation during two other events (1963 and 1969). There is enough to demonstrate a high degree of spatial variation but not enough to define it. Where the rainfall is more uniformly distributed in space there is little difference in the modelling capabilities of the lumped and semi-distributed versions of the model.

Figure B3A illustrates an intense storm (maximum intensity 25.5mm/hr) on Q9M21 where the response was relatively low. The first peak of the storm is apparently a rapid response to the high intensity rain period from the lower parts of this small catchment. A much finer distribution system would have to be used to accommodate this degree of response sensitivity. Even then the model would be unlikely to reproduce the three clear peaks of this hydrograph. Comparison with figures B2A and B illustrates that the effects of time differentiated runoff generation are smoothed in the larger catchment (Q9M20). The hydrograph shape and peak are reasonably well reproduced although the timing of the response is still too late, especially using the lumped version.

The response characteristics of the small storms on the semi-arid Ecca prompted the inclusion of the channel losses function. The volume of runoff from any sub-area is reduced as a non-linear function of the product of the moisture status (RAT) and contributing area (ROP). In the lumped version the base of the time area triangle is reduced by the same proportion. These functi ns have the desired general effect of reducing the runoff more so from the upper catchment areas and hence simulating the smaller but more rapid response. However, it is pe haps naive to expect the same proportional decrease to apply to the volume and timing. This point will be considered further in the next section.

10.1.2 Parameter stability and acceptability.

The calibration results for this model on all catchments are given in tables A1 to A17 in appendix A. As well as listing the storm fit statistics for each storm. the values of the parameters are given when they differ between storms. The values of those parameters that are constant for all storms are given at the bottom of the tables. In the model the antecedent rainfall factor entered through the control file is considered to apply to all winter season storms (October to March in the northern hemisphere. April to September in the southern hemisphere). The summer season APF is set at 0.05 lower than the winter value. This facility was included in the model to allow storms from different seasons to be calibrated together in a single model run. However. it is recognised that the simple seasonal differential is likely to be inadequate. It is designed to account for lower evaporation rates and shorter day lengths in the winter period but APF may be more correctly expected to vary more smoot ly between the hottest month and the coldest. The tables as well as some of the figures (B9A and B14) illustrate that in some cases poor fits are due to systematic errors indicated by large differences between the coefficients of efficiency and determination. Examples are storms 2, 7, 8 and 12 on ND1 (tables A4 and A12 and 1, 7, 12, 13, 14 on ND5 (tables A7 and A16). The fits can be easily improved by making adjustments to the APF parameter (increase for negative errors. decrease for positive). The degree of change in APF necessary depends on the percentage errors as well as the history of rainfall in the previous 30 days.

The values for APF given in the tables for the Ecca results represent attempts to improve the fits by initially varying this parameter only. In some cases this was possible but in others additional parameters had to be changed to achieve, or come closer, to an acceptable fit. In table A1 it can be seen that for most storms parameters 6 (time area A) and 15 (channel losses parameter) have values of 5,38 and 2,32 respectively. It was found necessary to change these values on some of the small storms to achieve a satisfactory reproduction of the timing of the observed flows. It was mentioned at the end of the previous section that the channel losses parameter adjusts the volume and timing of flow in the same proportion. The changes in the values of parameter 6 (A) are thought to reflect the inadequacy of this simple relationship when trying to model a variety of very s...all responses to different rainfall input patterns.

Of the four large runoff events in the Ecca data set (20.07.79, 23.07.79, 19.08.79 and 2.11.85) only the August 1979 event requires a different APF value to produce an acceptable fit. This event occurs one month after the earlier events in July and the most suitable APF value for the other storms appears to overestimate the degree of catchment drying that actually takes place. However, it should also be noted that the 1985 event occurs in summer when the model would normally assume that the APF should be 0,05 lower. This November event occurred after a month long period of intermittant rain and cloudy cool conditions. Such conditions are more characteristic of the winter months in the Ecca and would therefore seem to justify the higher APF value. The APF values for the small events on the Ecca are highly variable and do not demonstrate any clear pattern. These va iations are f..r greater than the adjustments that were neces ary in the North Danville catchments to remove the systematic errors referred to e rlier. This may be a reflection of the greater variability of catchment drying out processes in the semi-arid Ecca. Alternatively, the variability in this parameter value may be accounting for other deficiencies in the model when it is applied to a semi-arid area. No final conclusion can be r ached on the basis of the limited number of catchments calibrated so far.

The tables in appendix A indicate that the other parameters not referred to above can remain constant for individual catchments. In the North Danville catchments this results in good fits over most of the storms (assuming systematic errors are removed by adjusting APF). For the Ecca catchments, the same can be said for the large storms but there are still several of the smaller storms which are relatively poorly reproduced. This model is conceived as being a flood model and many of the smaller events can hardly be defined as flood. It may be concluded that the results are better than is initially apparent and that most of the parameters can be considered stable for the range of 'flood' events modelled.

Table 10.1 lists comparitive parameter values for ND5 and Q9M20 for both the lumped and semi-distributed model versions. It is apparent that a greater degree of delay and attenuation occurs in the Ecca catchments than in ND5. For the lumped model the basin routing parameter K and the time area base A are both higher for Q9M20. Although the semi-distributed K and KC values are lower for the Ecca. the channel delays for the remote sub-areas are greater than for ND5. The semi-distributed values correspond reasonably well with intuitive expectations. Valley side slopes are steeper with thinner soils in the Ecca suggesting more rapid runoff to the channel system than from the more gentle slopes and deeper soils of the North Danville valley sides. In fact, experience of the North Danville catchments (R. Schulze. pers. c mm.) suggests that the predominant runoff generation processes is sub-surface flow. If this sub-surface flow is relatively rapid and the valley bottom alluvium in the Ecca plays an attenuating role then it might be expected that the two catchments would have sim_lar basin routing characteristics. With respect to channel routing, the Ecca is more elongated and has fewer main channel segments per unit catchment area. The runoff generated in some of the upstream areas therefore has a greater distance to travel than in ND5.

The SMAX values for the two catchments are not very different but the shape of the S-curves are. The ND5 S-curve implies greater runoff proportions at lower moisture values than Q9M20. This is logical in view of the fact that the main moisture storage in the Ecca is in the valley bottom alluvial soils and on some of the flatter hilltops. A greater proportion of the total storage must therefore be satisfied before relatively high runoff proportions can be achieved. The soil depth distribu ion in ND5 is more uniform suggesting that valley bottom soils will become saturated more quickly and hence generate runoff at lower catchment moisture values. These characteristics of the two catchments seem to be reflected in the PCSLP parameters as well. The steep slopes and low moisture storage of the Ecca valley sides suggest little slope storage and high PCSLP values. The lower permeabilities (particularly lateral permeabilities) observed in the soils of the Ecca (Moolman. 1984) compared with those indicated in the USDA (1960-1973) volumes support the relative differences in the values of PCVSA (table 10.1).

Table 10.1 Comparison between parameter values for OSE2 on ND5 and Q9M20

Parameter	ND5		Q9M20	
	lumped	Semi-Dist.	lumped	Semi-Dist.
1. K	5.75	4,3 - 9,8	10,0	3,9 - 6,3
2. N	0.7	0,7	0.6	0,6
3. CDEL	-	0.0 - 2,25	-	0,25 - 5,25
4. KC	-	0,3 - 1.15	-	0,25 - 0,7
5. DEL	0.5	-	0,25	-
6. A	2,68	-	5,38	-
7. B	0,15	-	0,10	-
8. SMAX	218,0	196,2 - 239,8	175,1	156,0 - 220,0
9. DA	0,451	0.451	0,282	0,180 - 0,287
10. C	0.245	0,245	0.672	0,576 - 0,688
11. PCSLP	131,0	105,0 - 143.0	340,0	300,0 - 368,0
12. PCVSA	3,87	3,1 - 4,2	0.43	0,50 - 0,60
13. IAF	0,3	0,27 - 0,34	0.67	0,55 - 0,84
14. APF	0,898	0,889 - 0,907	0,963	0,95 - 0.97
15. CLP	0,0	0,0	2,32	2,16 - 2.70

The values listed under semi-distributed represent the range over the sub-catchments.

There are a number of areas in the Ecca where virtually bare slopes are adjacent to channels. Coupled with the fact that infiltration rates are expected to be lower in the Ecca it is not surprising that parameter IAF is a great deal higher for Q9M20 than ND5. The values given for APF in table 10.1 represent the winter values and suggest that the Ecca dries out more slowly for a given antecedent rain input than North Danville. This parameter has to represent the combined effects of evapotranspiration and drainage. The Ecca however experiences higher potential evaporation effects due to higher temperatures. Higher unsaturated lateral permeabilities and more dense vegetation cover in ND5 may be accounting for the greater drying effect. As mentioned earlier the component of the model controlled by this parameter has many weaknesses and this parameter is less stable than the others.

The channel losses component was incorporated after the North Danville modelling exercise had been completed and is therefore assumed to be 0,0. This parameter also has a minor effect on the large storms experienced in the Ecca. Its effect is to remove very s all flows generated by some of the rainfall that serves to wet the catchment before widespread streamflow occurs. This is illustrated in figure B4A. Because small amounts of runoff are generated by the S-curve even at a low moisture status. without the CLP parameter there would be low flow in the 5-25 hour period of storm 20.7.79. An alternative would be to begin modelling at approximately 20 hours and include the earlier rain as antecedent conditions.

The method used to set initial values for the sub-catchment parameter factors was largely intuitive and based upon the ideas expressed in section 4.4. During calibration these were only modified if an improved fit could not be obtained by changing the global parameter values or if the characteristics of the generated flow from gauged sub-areas did not approximately match the observed data. It was generally found necessary to adjust the channel delays on both catchments but few other adjustments were necessary for the North Danville catchments.

The basin routing parameter (K) factors for the North Danville sub-areas were determined by calculating the time of concentration (Tc) based on the equation :

$$Tc = 0.00025 * \frac{(L * 1000)^{0.8}}{(S)^{0.5}}$$

where L = sub-catchment area (km^2)/total channel length (km)
S = Average sub-catchment slope (mm^{-1}).

An area weighted average Tc for the whole catchment was calculated and all individual Tc values divided by this average to give the sub-area factors. The sub-area CDEL factors were initially calculated from Tc values using the length (L) from the outlet to the sub-area centre and the average slope (S) over that length. It was then found necessary to reduce these values by approximately 0.75 to obtain CDEL values (table A17) that produced acceptable fits. KC factor values were fixed by relative channel distances from the sub-area node to the next downstream node. Maximum storage (SMAX) parameter factors were subjectively related to the soils information given in the USDA (1960-1973) reports. PCSLP and PCVSA factors were estimated from relative values of average sub-catchment slopes and rounded up or down to the nearest 0.05 according to slope alignment. Thus, if the slopes are predominantly aligned toward the channel (incised situation) the values were rounded upwards. If slopes are predominantly aligned in a downstream direction then factor-values were rounded downwards. implying slower drainage from the slopes (or VSA) to the VSA (or channel). Similarly, those sub-catchments with higher slopes were assigned slightly higher IAF parameter factors.

A similar procedure was followed for determining the initial values of the sub-area factors for running the semi-distributed model in the Ecca c tchments. There is less formal information on the soil depth variations in this area than North Danville. Personal observations and experience have consequently played a greater role. The first comment that can be made is that more changes to the sub-area factors were made during the Ecca calibrations. The K parameter factors were determined largely through a consideration of both sub-catchment areas and slopes. Thus the relatively small (6% of total) and steep sub-area 9 has the lowest value, while the larger, more rounded or flatter sub-areas 1 and 11 have the highest values (figures 8.2 and 8.3). An indication of the CDEL factors is given by the calibrated value of the time area triangle used in the lumped model but these and the KC values were largely determined by consideration of the timing of observed flows at the three gauging points within Q9M20.

Factors for SMAX, DA, C and CLP, were found to be very difficult to fix. While some consideration was given to the distribution of soil depth within sub-areas (from observation, not formal measurement), the response characteristics of various observed events also helped to determine the factor values given in table A9. Q9M24 has failed to produce runoff for many of the smaller events included in the test data set. This could imply greater storage or higher channel losses or a combination of both. The latter implication has been used to fix the values given in table A9. The generally lower runoff response (c.f. tables 8.5 to 8.7) from Q9M24 relative to Q9M20 and Q9M21 is also reflected in the values of parameter factors for DA, C and IAF. While the North Danville storms could be modelled with uniform sub-area factors for DA and C, this was not the case for the Ecca storms. The authors have insufficient experience of this model to suggest how the detail of the S-curve shape changes with physiography. This will require further investigation after more catchments have been calibrated.

The model was re-run for three of the ND5 storms, setting the sub-catchment factors equal to the area weighted average for all sub-areas. This exercise was carried out for individual parameters (except CDEL) and then for all parameters combined. The largest deterioration in fit occurs when the K and SMAX factors are set equal. Errors change by only a few percent at the most and coefficients of efficiency decrease by a maximum of 6%. Setting all the factors for PCSLP, PCVSA and IAR constant has little effect on the overall fit. If all factors except CDEL and KC are set to be equal then the largest decrease in coefficient of efficiency is 8%, % volume errors remain similar and the % peak error for one storm changed from -11% to -18%. The equivalent results for 3 storms in Q9M20 (storms 1,6 and 12) are less clear. For some parameters the volume errors improve, while the peak errors deteriorate and vice versa. The largest effects occur on storm 1 and are caused by setting the main volume parameter factors equal (SMAX, DA and C). Changes to the other parameter factors cause negligible effects. If all factors (except CDEL and KC) are set equal then the coefficients of efficiency change from 0,70 to 0,46 (storm 1), 0.97 to 0,93 (storm 6) and 0.67 to 0.85 (storm 12). It is interesting to note that the one to one fit for storm 12 improves.

10.1.3 Ease of calibration

In some respects the model was easier to calibrate on the North Danville storms than the Ecca. However. it should be noted that calibration was stopped for some North Danville events when a high value for the coefficient of determination was achieved despite relatively high percent errors in peak and volume. These situations suggest systematic error and usually occurred on storms where there is a lack of information about the spatial variation in rainfall. For some of the storms, information is only available for rainfall input at gauges 1 and 10 (figure 8.4). Sometimes the storm profiles for these gauges are very different. implying a high degree of spatial variability. At other times they are similar. but unfortunately this does not necessarily imply low spatial variability. Figure B14 illustrates an example where profiles 1 and 10 are similar. The fits for ND3 and ND4 are good while those for ND1 and ND5 are systematically in error. Best fit APF values for the full range of storms on ND3 and 4 are higher (more moist antecedent conditions) than ND1 and 5. If the APF values for this storm on ND1 and 5 were adjusted to be more in line with those on ND3 and 4 the fits would be much better. In contrast, figure B15 indicates that the APF values are satisfactory over the four catchments. It is possible that errors in input data and antecedent moisture status are cancelling each other out. Where insufficient information is available about the storm rainfall input and where one (or more) component of the model is considered to be weak. it is difficult to attribute reasons for poor simulations.

A great deal of effort was required to achieve the fits on the Ecca catchment storms. This was especially true when attempting to obtain acceptable results for both the large and small events using a stable parameter set. As the tables in appendix A illustrate, this was not actually achieved. However, it was also true when attempting to simulate just the large events with one parameter set. This semi-arid catchment appears to have more complex response characteristics than the North Danville area. A closer inspection of the various sub-area outputs (with respect to relative timing and volumes) as well as the outputs of different model components was necessary in order to reach decisions about how to modify global parameter or sub-area factor values for the Ecca. Automatic optimisation techniques were useful in the lumped model version, but rerely provided the best overall fit without further manual parameter modification. Automatic optimization of the semi-distributed model took a great deal of time to run on the computer. If the sub-set of storms being optimised were of long duration then the program often ran into job step limits on the Rhodes Cyber computer before an optimal fit was reached.

It was originally intended to calibrate the semi-distributed model on Q9M20 and subsequently evaluate the results for Q9M21 and Q9M24 using the equivalent parameter values. However, after repeated attempts this procedure was abandoned and the smaller gauged catchments calibrated first. Acceptable calibrations were achieved in a shorter period of time, illustrating the advantage of some knowledge about sub-catchment response characteristics for calibrating a larger catchment.

10.1.4 Summary observations

In general, the results of calibrating model OSE2 were satisfactory for both areas. The main weakness of the model appears to be in the estimation of the initial moisture status of the catchment using an index of the previous 30 days of rainfall. With the exception of the antecedent moisture parameter a high degree of stability is evident in parameter values when calibrating a group of storms on the same catchment. In general the differences in parameter values both between catchments and within catchments (between sub-areas) are explicable in terms of physiographic differences. It is considered to be too soon to attempt to derive more definite, quantitative relationships. Further catchments need to be calibrated to obtain a better understanding of the model operation under different hydrological response characteristics. It will also be necessary to examine whether the relative insensitivity of the model to averaging sub-catchment factors found in the North Danville catchments is also found elsewhere.

10.2 OSE1 - Simple antecedent moisture model

10.2.1 Curve fitting capabilities

The curve fitting capability of the model for the North Danville catchments, over the range of storms, appears adequate (figure B6B, for example). However, an acceptable fit was not obtained for some storms with a high degree of spatial variability in the rainfall input (storms 2.06.61, 30.07.63, 22.07.64 for ND1 and storms 30.07.73, 14.07.73 for ND5). The curve fitting capabilities for storms on ND5 are better, implying perhaps that the larger catchment has a smoothing effect on spatially variable rainfall events. Individual storm simulations may be significantly better in the different formats of the model but there is little difference in the overall fitting capabilities of the lumped or semi-distributed versions. For the event of 1967 on the North Danville catchments, a significantly better result is obtained using the semi-distributed format (tables A21 and A26). However, the 1969 event, which is adequately reproduced using the lumped model, cannot be reproduced by the semi-distributed version. The curve fitting capabilities for the Ecca storms are less satisfactory. Without the incorporation of initial losses the fits would have been even worse. Simulation of the 'large' events is generally adequate, although neither version of the model can reproduce the large, twin peaked event (20.7.79), suggesting the need for a variable ROP. As is the case with North Danville, spatially variable rainfall events were difficult to simulate satisfactorily (storm 6.03.77, fig. B1B). It was also found that simulations were generally better for the larger catchment (table A18 and A19). The overall curve fitting capabilities of the lumped and semi-distributed model formats are not significantly different, however on an individual storm basis there are differences (figure B1 B and C). The model has distinctly poorer fitting capabilities on the 'small' events.

10.2.2 Parameter stability and acceptability

The lumped and semi-distributed calibration results for OSE1 are given in tables A18 - A27 in appendix A. For the North Danville catchments it was possible to use constant non-linear routing and initial loss parameters. Basin delay is the only routing parameter which needed to be varied in the lumped and semi-distributed version of the model. SMAX was held constant but the shape of the S-curve had to be varied to get adequate fits. The APF parameter was varied according to the season in which the event occurred. The APF for winter (Oct-Mar) was set 0.10 higher then the APF for summer (Apr-Sept). Generally this simple separation produced acceptable results, indicating that in summer there is higher evaporation and therefore a greater drying effect, while in winter the evaporation is lower and the catchment is more moist for the same amount of antecedent rainfall. The calibration results for the Ecca (table A18, A22) indicate how difficult it was to establish constant parameter values for the set of events. In particular. the results for the so-called 'small' events are very variable. due possibly to the fact that these 'small' events can hardly be classed as floods. The four 'larger' floods (20.07.79, 23.07.79, 19.08.79 and 2.11.85). indicate less variation in parameters, particularly the semi-distributed model parameters. The problem with modelling the 'small' events is that only a limited area near the catchment outlet appears to be generating the runoff. Evidence for this feature is that the response of the catchment to the low flows is very quick. The result is that the model needs low A and K values to simulate the rapid response (tables A18. A19 and A22).

Table 10.2 lists comparative parameter values for ND1, ND5 and Q9M20. for both versions of the model. Parameters for ND1 and ND5 are similar and as would be expected the channel delay on ND1 is generally less than ND5. The lumped results indicate that a greater degree of delay and attenuation occurs in the semi-arid Ecca catchment. This is also the case for the semi-distributed version which in addition has initial losses a kind of delay). far greater than those applied to ND5.

Table 10.2 Comparison between parameter values for OSE1 on ND1. ND5 & Q9M20

Parameter	ND1		ND5		Q9M20*	
	lumped	Semi-Dist.	lumped	Semi-Dist.	lumped	Semi-Dist.
1. K	5,5	6,0	6,0	6,0	9,0-11,5	5,40-11,5
2. N	0.7	0,7	0,7	0.7	0,7	0,7
3. CDEL	_	0,0-1,25	_	0.0-2,25	_	0,75-5,25
4. KC	_	0,4-0,8	_	0,31-1,15	_	0,40-1,04
5. DEL	0,0-1.50	_	0,0-3,0	_	1,5	
6. A	4,0	_	5,5	_	4,5-7,0	_
7. B	0,15	_	0,15	_	0,15	_
8. SMAX	150	150	150	150	200	200
9. DA	0.42-0,88	0,43-0,68	0,50-0,60	0,55-0,63	0,26-0,94	0.20-0,90
10. C	0,10-0.75	0,056-0,32	0.06-0,42	0.05-0,26	0,03-0,58	0,03-0,58
14. APF	0.80/0.90	0,80/0,90	0,80/0,90	0,85/0,90	0,85/0,95	0,85/0,95
15. IL	0,0	0,0	0,0	0,0	1,0-50,0	1,0-45,0

The values listed under semi-distributed represent the range over the sub-catchments.

* Parameters for 'large' events only.

SMAX values for the two catchments are different as is the general shape of the S-curves (see section 10.1.2 for an explanation for the different S-curves). There is a great deal of variation in the S-curve parameters which is not easily explicable in terms of physical storm or catchment characteristics. The parameter APF differs between catchments and is generally higher on the Ecca. However, the effect of changing this parameter is closely associated with changes in the S-curve parameters. These associations require further investigation specifically to find out whether a stable set of S-curve parameters can be used together with more variable APF values. The initial losses parameter was included once modelling on North Danville had been completed and has been assumed to be 0,0. On the Ecca, initial losses improved the calibration results quite significantly, especially for events with 'dry' antecedent conditions. The improvement occurs because even at a low moisture status, the S-curve generates runoff. Without the IL parameter, flow would occur in the period prior to actual catchment response (e.g. storm 20.07.79). The initial losses parameter allows catchment moisture requirements to be satisfied prior to producing runoff.

10.2.3 Ease of calibration

Although OSE1 was found to be more difficult to calibrate than OSE3, it was easier to calibrate on the temperate North Danville catchments than the semi-arid Ecca catchments. OSE1 has more parameters than OSE3, which makes it more difficult to operate. It was often felt that the best result was rarely achieved with OSE1, whereas with OSE3 it was generally possible to recognise the best result. In particular, problems were encountered with the volume reduction stage of the model, which in OSE1 has 3 parameters, all of which were difficult to stabilize. It was also more difficult to combine the effects of the APF and IL parameters, as both reflect antecedent moisture conditions. Calibration would be made a great deal easier if the S-curve parameters could be stabilised and response variations between storms accounted for using other parameters.

10.2.4 Summary observations

The fact that OSE1 uses a constant runoff proportion precludes adequate reproduction of complex, multi-peaked events. Storm events on the larger catchments were modelled more successfully. Apart from some events with a high level of spatial variability in rainfall input, there seems to be l ttle difference between the lumped and semi-distributed versions. One of the main proble s with calibrating this model is in the determination of the S-curve parameters. It is extremely difficult to fix the shape of the S-curve when modelling the storms separately. Some pre-calibration investigations of the variation in storm response characteristics may help and ways of doing this effectively are being studied.

10.3 OSE3 - Augmented hydrograph model

10.3.1 Curve fitting capabilities

The curve-fitting capabilities of the model on the North Danville catchments are considered to be adequate in both the lumped and semi-distributed formats, for the range of storms used (tables A30, A31, A34, A35 and figures B7A and B9B). However, with respect to the lumped model and particularly the smaller catchment (ND1), there are several situations where acceptable fits are not possible. As with the previous two models this feature is associated with the degree of spatial variability in the rainfall input.

The semi-distributed format of the model did not produce significantly better results for the spatially variable events, the exception being storm 10 (7.09.69) on ND5. For the storms of 1963 (ND1 and ND5) and 1969 (ND1) there was not sufficient information to define the distribution of rainfall over the sub-areas, therefore adequate simulation was not possible. However, it is likely that the flexibility of the semi-distributed format of the model has not been adequately exploited. Figures B13A and B, illustrate a situation where the semi-distributed fit is an improvement on the fit obtained using the lumped format. The curve fitting capabilities of OSE3 on the Ecca catchment, are generally less adequate and without the inclusion of initial losses would have been worse (figure B4B). To facilitate modelling, the storm events on the Ecca were divided into 'large' and 'small' runoff events. With the exception of storm 13 (25.11.85), the 'larger' events are reproduced adequately, especially those events with 'wet' antecedent moisture conditions (storms: 23.07.79 amd 2.11.85, figure B5B). The smaller storms were generally less satisfactorily reproduced as were events with a high degree of spatial variation of rainfall input (storm 2, 6.03.77). For most events the curve fitting capabilities of the semi-distributed format were better than the lumped model. The sub-catchment factors determined for initial losses improved the response of the model (table A33). However, even in semi-distributed format the model was not capable of reproducing double peaked events on the Ecca catchments (figure B4B), suggesting that a constant ROP is inadequate in this semi-arid area.

10.3.2 Parameter stability and acceptability

Both lumped and semi-distributed calibration results for OSE3 are given in tables A28-A37. For the temperate North Danville catchments it was possible to simulate observed flows acceptably with constant routing and initial loss parameters (see tables A30, A31, A34, A36). Although the catchment delay of the time-area routing function was allowed to vary, this is not considered a serious problem and only effects the timing of the hydrographs to a limited extent. As expected, the volume reduction parameter (ROP), does vary between events (see Section 6.3). The variation of the ROP parameter is much the same for storm events on ND1 and ND5. At present it is difficult to evaluate the suitability of the ROP's achieved, although it is possible to establish intuitively a degree of acceptability. For example the 24.10.59 storm is a large event, the rainfall is fairly intense and the catchment is 'wet' prior to the event, therefore a high ROP is not u expected (ROP=0.420). The 30.07.60 storm is a long duration, low intensity rainfall event with 'dry' antecedent conditions, therefore a low ROP is expected. The general stability of parameters on North Danville appears to suggest that catchment charactersitics are not very variable, thus making it possible to model events with reasonable success even in lumped format.

For the semi-arid Ecca catchments, parameter stability appears to be dependent on the size of the event and the format of the model. There is little stability when the model is in lumped format (table A28, A29) and when small events are calibrated (table A28, A29 and A32). In the semi-distributed version, the channel routing parameters are constant (table A32) and the range of the basin routing parameter (K) for the large storms is small. The poor results achieved for the 'small' storms is possibly due to the fact that these events can hardly be classed as floods and that the 'large' events reflect true flood conditions for the semi-arid Ecca. The general lack of stability of parameters in the lumped format suggests that, in the semi-arid situation, catchment and storm characteristics are very variable. It is extremely difficult to determine a single value for a parameter that is suitable for all events.

Table 10.3 lists comparative values for ND1, ND5 and Q9M20 (large events only), for both versions of the model. As intuitively expected, ND1 (smaller catchment) has lower delays then ND5 in the semi-distributed format and a smaller time-area base (A) in the lumped version of the model. For ND5 and Q9M20 the table indicates that a greater degree of delay and attentuation occurs in the Ecca catchment. For the lumped version, basin routing K and A are generally higher for Q9M20. In the semi-distributed version of the model, K can be lower (less attenuation on some sub-catchments) for Q9M20, but initial losses (which can include channel losses) for the Ecca are higher than for ND5. The methods used to set initial values for the sub-catchment parameter factors are similar to those described in section 10.1.2 for the S-curve model.

Table 10.3 Comparison between parameter values for OSE3 on ND1, ND5 & Q9M20

Parameter	ND1		ND5		Q9M20*	
	lumped	Semi-Dist.	lumped	Semi-Dist.	lumped	Semi-Dist.
1. CDEL	_	0.0-1.25	_	0,0-2,25	_	0,75-5,25
2. KC	_	0,4-0,8	_	0,13-0,85	_	0,43-1,10
3. ROP	0,09-0,43	0,09-0,44	0,10-0.37	0.10-0,38	0,19-0,54	0,31-0,58
4. N	0,5	0,5	0,5	0,5	0,5	0,5
5. DEL	0.0-1,75	_	0,0-1.75	_	0,0-1,50	_
6. A	4.0	_	5.0	_	4.5-8,0	_
7. B	0,15	_	0,15	_	0,15	_
8. K	15	15	15	15	15-24	9,7-25.2
9. IL	2.5	2,5	2,5	2,5	0-65	0-98

The values listed under semi-distributed represent the range over the sub-catchments.

* Only 'large' events considered.

10.3.3 Ease of calibration

It was generally easier to calibrate both forms of the Augmented Hydrograph on the North Danville catcments. This is possibly due to the greater degree of parameter stability obtained on the North Danville catchments.

In most cases it was easier to establish when the best possible result had been achieved. when the model was in the lumped version. This was due in part to inexperience with semi-distributed modelling and because of the fewer parameters involved in the lumped version. Therefore the sub-catchment parameter factor values need to be investigated futher to improve the understanding of the semi-distributed version of the model.

10.3.4 Summary observations

This model was found to be easier to calibrate than the previous constant runoff proportion model, OSE1. This is largely because the volume reduction component is simpler than in OSE1. With respect to the North Danville catchments the semi-distributed version does not achieve better results than the lumped model. However, the semi-distributed model is better able to reproduce storm hydrographs in the Ecca catchment. As with OSE1, multi-peaked and spatially variable rainfall events are not well modelled.

10.4 OSE4 - RORB model

Before discussing the results of calibrating this model it should be emphasised that OSE4 has been applied in its basic form only. Few of the options that are available to refine the model beyond its basic structure have been tested. Thus, the sub-area routing factors have been calculated on the basis of the channel length between nodes and no attempt has been made to incorporate a sub-area routing component as suggested in Laurensen and Mein (1985). A further component could also be incorporated to include distributed channel losses. The observed flows for this model refer to s ormflows and not totalflows as in the other models. There is unfortunately no simple or direct way of allowing for the decay of an initial observed flow at the beginning of the storm. An additional difference is that the OSE4 program does not calculate coefficients of efficiency or determination but rather a statistic referred to as the 'average absolute ordinate error' (AAOE in tables A38 to A40). The percentage errors for volume and peak are included in the program printout and are comparible with the other models.

10.4.1 Curve fitting capabilities

Although only the results for the constant runoff coefficient version of the model are reported in appendices A and B, the continuing losses model was also tested. The latter proved to be inadequate especially for the Ecca storms and generally for those storms with large intensity variations during the rainfall input. Some events begin with relatively high intensity rainfall which initiates runoff, followed by lower intensity rainfall which sustains flow. The continuing losses model ignores the later rainfall as it lies below the continuing loss level. This situation is exacerbated for the small storms on the Ecca where the runoff proportion is extremely low and is therefore derived from the highest 15 minute intensity fall occuring after the period of initial losses.

The runoff proportion model is more flexible in its fitting capabilities but nevertheless it is still difficult to fit to some situations. Figure B2D illustrates that the model assumes that some of the flow is derived from upper catchment areas when in fact no flow was observed at Q9M24. To decrease the amount of flow derived from upstream areas it would be necessary to include a spatially variable channel losses component. The alternative method of introducing spatial variability in runoff amount is to allow some proportion of the sub-areas to be impervious to rainfall. However, when the runoff response is very low (5%) this usually means that more runoff is generated from these impervious areas than was observed. The model will therefore not run. Figure B4C illustrates that despite dividing this twin peaked event into two bursts (table A38 - storm 6) the first peak is still underestimated. The latter fit could be improved by adjusting the proportion of flow resulting from each rainfall burst. However, this example serves to illustrate the difficulty of defining these proportions. It is of interest to note that the twin peaked event on ND1 (figure B7B) was reproduced satisfactorily without resorting to seperated rainfall bursts.

The model calculates the runoff coefficient from the rainfall (after removing initial losses and the observed flow volume. The large volume errors result when some of the simulated flow volume has not been routed out at the end of the observed duration. The mean and standard deviations for the three fit statistics given in Tables A38 to 40 suggest that OSE4 is more successful in modelling the North Danville catchments than the Ecca. While Q9M20 was the only Ecca catchment calibrated with this model, summary data for output from Q9M21 and Q9M24 was examined during each run. Only during the larger events did the volumes, peaks and timing of flows from these gauged sub-catchments come close to matching the observed data.

10.4.2 Parameter stability and acceptability

As with models OSE1 and OSE3, the parameters of OSE4 were not necessarily expected to be constant for all storms. However, it was expected (or hoped) to find greater stability in the routing parameter KC than is indicated by the results given in tables A38 to 40. These values are extremely variable for the Ecca ranging from 0,8 for the smallest storm to 15,0 for the largest. The variation is much less for the North Danville storms (ND1 and ND5) and could possibly be reduced by adopting a different N value.

No attempt has been made in this preliminary study to examine in detail any relationships between initial losses or the runoff coefficient and antecedent moisture status and storm parameters. However, a casual comparison of the model parameters with storm characteristics does not reveal any obvious structure. Further investigations into this matter will follow after more catchments have been calibrated and will closely parallel similar studies involving models OSE1 and OSE3.

10.4.3 Ease of calibration

The simple version of the model used in this study (that is without attempting to use some of the optional components) is relatively straightforward to calibrate. There is commonly only one combination of KC and initial losses that produces the best fit to a single storm. After only a few test runs it becomes quite simple to roughly estimate the effects of changing KC or I.Loss values. For those storms where an acceptable fit is not possible it becomes apparent after several parameter changes that further improvement is beyond the models capabilities. Increasing initial losses inevitably delays the start of runoff as well as increasing the proportion of later rainfall amounts that contribute to runoff. The effect of such a parameter change on the hydrograph shape is dependent upon the shape of the rainfall profile particularly at that point where initial losses are satisfied. The rainfall profile shape also has a strong influence on how sensitive the model is to changes in initial loss.

10.4.4 Summary observations

The use of the continuing losses model was not successful for both catchment areas. The runoff proportion model was relatively easy and rapid to calibrate but little stability exists in the parameter values. This is especially true over the range of events from the Ecca catchments. Sub-catchment outflows at Q9M21 and Q9M24 were not simulated satisfactorily even when the results for Q9M20 were good.

10.5 Discussion of model comparisons

The mean values for the fitting criterion are compared in table 10.4. Comparisons are made between model types as well as between the two groups of catchments. The table suggests that model OSE3 most accurately reproduces the observed hydrographs with model OSE2 performing least successfully. The relatively higher values for the percentage volume and peak errors associated with OSE2, appear to be largely due to systematic error. This feature is illustrated by the larger differences between the two coefficients for OSE2 (lumped and semi-distributed). The figures in table 10.4 do not provide a complete impression of the comparitive success of the models. OSE2 has a far more stable set of parameter values which can, to a large extent, be intuitively justified on the basis of known differences between catchments or sub-areas within catchments. The other models have a greater amount of parameter variability which has no immediately apparent relationship with storm characteristics. This is particularly true when modelling the Ecca storms. Model OSE1 has more parameters than OSE3 and OSE4 due to the S-curve component designed to estimate the constant runoff proportion from antecedent conditions. The parameters of this component are extremely variable but this could be a consequence of the way in which the model was calibrated. More emphasis was placed on stabilising the routing and APF parameters than the S-curve parameters. The alternative, of trying to fix DA and C and modify other parameters to achieve a satisfactory fit, requires investigation. It might then be simpler to find reasons for variations in the other parameters than it is to find reasons for differences in the S-curve parameters. The results obtained so far suggest that the additional component in OSE1 for estimating the runoff proportion is not justified and merely makes the calibration procedure more complex.

Table 10.4 Comparison of model fit statistics

		Mean values				
		% Vol.	% Peak	C. Eff.	C. Det.	AAOE %
All catchments						
OSE2	lumped	12,6	15,6	0,700	0,844	
	semi-dist.	16,5	15,4	0,633	0,862	
OSE1	lumped	6,4	7,9	0,857	0,885	
	semi-dist.	6,4	7,9	0,879	0,916	
OSE3	lumped	4,4	4,5	0,875	0,903	
	semi-dist.	3,9	5,1	0,904	0,916	
OSE4	lumped	6,0	7,0			25,0
All models						
Ecca		8,5	9,1	0,754	0,832	36,2
North Danville		9,4	10,9	0,812	0,915	19,5

AAOE - Average absolute ordinate error.

The tables in appendix A present a relatively confusing impression of the differences between lumped and semi-distributed modelling. The patterns are similar regardless of the actual model type (OSE1, 2 or 3). Some of the storms are modelled more successfully with the lumped versions while others favour the semi-distributed approach. Figures B10 to B13 illustrate a situation where, given well defined spatial variation of rainfall input, the semi-distributed versions of the models produce improved overall fits. This is not always the situation and figure B8 illustrates that the semi-distributed versions are not always successful. For this particular event OSE4 appears to come closest to the observed hydrograph (figure B8C). It is difficult to draw firm conclusions at this stage but it would appear that inadequate definition of the spatial variation in rainfall input contributes to some of the poor modelling results in the North Danville catchments. This factor certainly makes it difficult to compare the relative success of the lumped and semi-distributed approaches. Further model tests, in catchments with more complete data, are required to investigate this problem further.

The small storms on the Ecca catchments are difficult to simulate with all the models. The authors believe that the scale of operation of the hydrological processes during these storms is much smaller than the distribution scale of the models. It is suggested that the streamflow during these events is generated in the lower parts of the catchment and only in areas close to river channels. The rapid and very small responses of the observed hydrographs support this view and suggest that surface runoff generated elsewhere in the catchment is re-absorbed into the soils or valley bottom alluvium. The incorporation of a channel losses parameter into both versions of OSE2 proved to be useful with respect to modelling the small Ecca storms. However, table A1 illustrates that it was still necessary to reduce the time area base parameter (A) to achieve the faster response in the lumped model. The values for the basin routing parameter (K) are lower for models OSE1 and 2 than for OSE3. This might be expected as gross rainfall is being routed in OSE3 while only excess rainfall is routed in the other models. The other routing parameters (KC, A, B and CDEL) have very similar values for models OSE1 and 3.

Only model OSE2 could satisfactorily reproduce the two peaks of storm 20.07.79 on the Ecca catchments (figure B4) although OSE4 could produce a better fit if the proportions of flow from the two rainfall bursts were adjusted. It is therefore apparent that a model having some way of accounting for a variable runoff proportion during a storm is necessary for the semi-arid catchments. Figures B6 and B7 suggest that the same is not true for the North Danville catchments. All the models are capable of reproducing the two peaks of the 24.10.59 event on ND1.

With respect to ease of calibration, OSE3 and OSE4 are more straightforward to calibrate than the other models. However. this conclusion does not take into account the additional work that will have to be done in the future to obtain a better understanding of the variation in model parameter values. The semi-distributed version of OSE2 is the most difficult model to calibrate while the results obtained so far indicate that this more complex approach is not justified for most storms. After a larger number of catchments have been calibrated. the physical relevence of the parameters of OSE2 may become better defined. If this is possible then some of the difficulties of calibrating OSE2 will be removed.

11. CONCLUSIONS AND FUTURE INVESTIGATIONS

There are very few clear guidelines in the hydrological modelling literature to suggest what degree of si...plification is permissable to produce acceptable simulation results in different situations. Simplification can refer to many different things. The whole structure of a model may be a simplified concept of the real physical system. Alternatively the model may have a complex, spatially distributed structure but be applied in a simplified way because of the users inability to accurately evaluate certain physically-based parameters. Such simplifications may imply the evaluation of parameters through indirect methods (Bathurst, 1986) rather than by direct measurement. Association of parameter values with physical factors such as vegetation, soil type, slope or geology may be the only way in which physically-based, distributed models can be applied. The situation then becomes very similar to less strongly physically-based conceptual models where the parameters have some demonstrated physical significance. If the realistic range of possible parameter values is known, as well as the simulation sensitivity to variations within that range, then quantifiable levels of uncertainty may be defined (Abbott, et al, 1986). This is an important characteristic and one that has been lacking in many of the existing models having very simple structures and parameters which ave little physical relevance.

The models tested include three essentially simple conceptualisations of the generation of flood hydrographs and use a rainfall-runoff ratio that is constant during a single event. One of these models (OSE1) has a component which attempts to relate the rainfall-runoff ratio to antecedent moisture conditions. Non-linear routing procedures are then used to delay and attenuate the resulting channel discharge. The fourth model (OSE2) incorporates more components in the runoff generation structure of the model in an attempt to make the model more conceptually realistic. The rainfall-runoff ratio at any time during a storm is variable and controlled partially by the moisture status of the catchment and partly by the rainfall intensity. All four models can be operated in semi-distributed mode through lumped modelling of user defined sub-catchments and channel routing procedures. Three of the models have separate lumped model formulations while the fourth (OSE4) can also be used in a lumped way by setting the number of sub-areas to unity.

The models have been calibrated using data from two different regions: the humid forested catchments of North Danville, Vermont, USA and the semi-arid Ecca catchment of South Africa. Appendix A lists the parameter values and fit statistics for all the model-catchment combinations while appendix B uses computer generated graphical plots to illustrate some of the fitting characteristics of the models. Some general conclusions can be made.

a) There is very little apparent difference between the lumped and semi-distributed versions of the model. However, the summary statistics in table 10.4, ignore the fact that there were fewer storms where totally unacceptable fits were possible with the semi-distributed versions than the lumped. There were also demonstrable improvements using the SD version when the spatially variable rainfall input was well defined.

b) There is a large variation in the amount of rainfall input data available for individual events. When the rainfall input is known to be variable, but is inadequately defined by the available data, model results must be interpreted with caution. Research studies designed to test the performance of models will always be faced with this problem. If model tests are confined to those few research areas where high density rainfall information is available then it is unlikely that models will ever be tested over a wide range of catchment types. Models are frequently applied where input data is deficient and it is important to investigate how successfully they perform in these situations as well. However, without at least some high level quality data, it would be difficult to conclude to what extent a model is truly able to reproduce the rainfall-runoff characteristics of a catchment.

c) The semi-distributed models were more difficult to calibrate due to the need to evaluate the sub-area parameter factors. Given more experience of the models and the physical relevance of parameter values these difficulties should be reduced. The importance and sensitivity of the sub-area parameter factors is unclear at present.

d) Table 10.4 suggests that the simple models can reproduce observed hydrograph shapes better than the more complex OSE2 model. However, the poorer overall OSE2 results are partly a consequence of the systematic errors in the fits on the North Danville catchments. This can be seen by comparing the coefficient of efficiency values of OSE2 with the others ($\pm$20% less and the coefficient of determination values of OSE2 with the others ($\pm$5% less). The poorer fits may be caused by inadequate storm input definition for some storms but a deficiency in the antecedent moisture status component is also considered to play a major role. This component. together with the S-curve function. in model OSE1 requires further investigation. The large differences in the S-curve parameters between storms are dif icult to explain and a new approach to calibration will be investigated in the future (section 10.2.2). Such problems are irrelevant to models OSE3 and 4 Systematic errors do not occur in these models as the volume of runoff is fixed by the single runoff proportion which has no constraints placed on it.

e) With respect to conclusion c) it should be noted that the results for OSE2 are achieved with a much higher degree of parameter stability. The antecedent precipitation parameter is the main exception to this conclusion although other parameters were also changed in order to simulate some of the very low response events on the Ecca catchments. Further work is necessary before any conclusions can be drawn about the variable parameter values on the simple models. There do not appear to be any simple relationships with the runoff coefficients and storm characteristics or antecedent precipitation for example. A more complete evaluation of possible relationships will only take place after more catchments have been calibrated.

Some of the results that have emerged from the calibrations of the model on the two different sets of catchments are encouraging. The parameter values of model OSE2 can be generally interpreted in terms of differences between catchments or sub-area physical characteristics. No firm quantitative relationships have been investigated and this will only be carried out after more experience of the model is obtained through application to a broader range of catchments.

The programme of future investigations (1986-1988) is designed to follow three main interlinked directions :

a) Further calibration and verification on more catchments from both humid and semi-arid parts of southern Africa and the United States. The available data cover a range of physiographic characteristics. Some of the data are of a better quality than those used in this report while some are of a poorer quality and less complete.

b) Sensitivity analyses of model parameters and sub-area parameter factors and investigations into an alternative calibration approach to OSE1.

c) Investigations into the association of parameter values with measurable storm or catchment characteristics or both and the feasibility of applying the models to ungauged situations.

This present report constitutes the first part of the overall study designed to investigate several aspects of the general applicability of isolated-event flood models. It has investigated the models' calibration performance in two areas with different rainfall-runoff response characteristics. This report has not addressed the problem of verifying the calibration results. Verification of the applicability of model parameters to events or catchments not used for calibration is an essential part of a thorough test of any models performance. The second report, which will be compiled during 1988, will concentrate on verification testing and try to reach some conclusions about the general applicability of the models discussed.

REFERENCES

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986) An introduction to the European Hydrological System - Systeme Hydrologique Europeen, "SHE", 1: History and Philosophy of a physically-based distributed modelling system, and 2: Structure of a physically-based, distributed modelling system. **J. Hydrol.** 87, 45-59 and 61-77.

Aitken, A.P. (1973) Assessing systematic errors in rainfall-runoff models. **J. Hydrol.**, 20, 121-136.

Anderson, M.G. and Burt, T.P. (editors) (1985) **Hydrological Forecasting**, John Wiley and Sons, England.

Bathurst, J.C. (1986) Physically-based distributed modelling of an upland catchment using the Systeme Hydrologique Europeen. **J. Hydrol.**, 87. 79-102.

Bauer, S.W. and Midgley, D.C. (1974) **A simple procedure for synthesizing direct runoff hydrographs.** Report no. 1/74, Hydrological Research Unit, University of the Witwatersrand and CSIR, Johannesburg, South Africa.

Beaudoin, P., Rouselle, J. and Marchi, G. (1983) Reliability of the design storm concept in evaluating runoff peak flow. **Water Res. Res.**, 19(3), 483-487.

Bernier, P.Y. (1985) Variable source areas and storm-flow generation : an update of the concept and a simulation effort. **J. Hydrol.**, 79, 195-213.

Beven, K.J. (1983) Surface water hydrology : Runoff generation and basin structure. **Reviews of Geophysics and Space Physics**, 21(3), 721-730.

Beven, K.J. and Hornberger, G.M. (1982) Assessing the effect of spatial pattern of precipitation in modelling stream flow hydrographs. **Water Res. Bull.** 18(5), 823-829.

Beven, K. J. and Kirkby, M.J. (1979) A physically based, variable contributing area model of basin hydrology. **Hydrol. Sci. Bull.** 24(1), 43-69.

Beven, K.J., Kirkby, M.J., Schofield, N. and Tagg, A.F. (1984) Testing a physically-based flood forecasting model (Top model) for three UK catchments. **J. Hydrol.**, 69, 119-143.

Beven, K.J. and O'Connell, P.E. (1982) **On the role of physically-based distributed modelling in hydrology.** Inst. of Hydrology, Wallingford, England, Report No. 81.

Bondelid, T.R., McCuen, R.H. and Jackson, T.J. (1982) Sensitivity of SCS models to curve number variation. **Water Res. Bull.** 18(1), 111-116.

Clark, R.D.S. (1980) Rainfall stormflow analysis to investigate spatial and temporal variability of excess rainfall generation. **J. Hydrol.**, 47, 91-101.

Cordery, I. (1970) Antecedent wetness for design flood estimation. **Civil Eng. Trans.**, Inst. of Engineers Australia, 12, 181-184.

Corradini, C. and Singh, V.P. (1985) Effect of spatial variability of effective rainfall on direct runoff by a geomorphogic approach. **J. Hydrol.**, 81, 27-43.

Danish Hydraulic Institute (1985) **Introduction to SHE, Systeme Hydrologique Europeen.** Danish Hydraulic Institute, Horsholm, Denmark.

Delleur, J.W., Tao, P.C. and Kawas, M.L. (1976) An evaluation of the practicality and complexity of some rainfall and runoff time series models. **Water Res. Res.**, 12(5), 953-970.

Devaurs, M. and Gifford, G.F. (1986) Applicability of the Green and Ampt infiltration equations to rangelands. **Water Res. Bull.**, 22(1), 19-28.

Dickenson, W.T. and Douglas, J.R. (1972) **A conceptual runoff model for the Cam catchment.** Inst. of Hydrology, Wallingford, England. Report No. 17.

Diskin, M.H., and Simon, E. (1977) A procedure for the selection of objective functions for hydrologic simulation models. **J. Hydrol.**, 34, 129-149.

Diskin, M.H., Wyseure, G. and Feyan, J. (1984) Application of a cell model to the Bellebeck watershed. **Nordic Hydrol.**, 15(1), 25-38.

Dooge, J.C.I. (1973) Linear theory of hydrologic systems. **Agric. Res. Service, U.S. Dept. of Agric. Bull.**, No. 1468.

Dunne, T. (1983) Relation of field studies and modelling in the prediction of storm runoff. **J. Hydrol.**, 65, 25-48.

Dunsmore, S.J., Schulze, R.E. and Schmidt, E.J. (1986) **Antecedent soil moisture in design stormflow estimation.** ACRU. Report no. 23. Dept. of Agricultural Engineering, Univ. of Natal, Pietermaritzburg, South Africa. pp 114.

Eyre, W.S. and Crees, M.A. (1984) Real-time application of the isolated event rainfall-runoff model. **J. Inst. Water Eng. and Sci.**, 38(1), 70-78.

Fleming, G. (1984) The successes and failures of contemporary approaches to integrated catchment modelling. In : H. Maaren (editor), **South African National Hydrological Symposium - Proceedings**, Dept. of Environment Affairs and Water Research Commission, Tech. Rep. TR 119, 1-17.

Flood Studies Report (1975) Natural Environment Research Council, London.

Foroud, N. and Broughton, R.S. (1981) Flood hydrograph simulation model. **J. Hydrol.** 49, 139-172.

Görgens, A.H.M. (1983) **Conceptual modelling of the rainfall-runoff process in semi-arid catchments.** Hydrological Research Unit, Report 1/83, Rhodes University, Grahamstown, South Africa.

Green, C.S. (1979) **An improved subcatchment model for the River Dee.** Inst. of Hydrology, Wallingford, Report No. 58, 45 pp.

Green, I.R.A. and Stephenson, D. (1986) Criteria for comparison of single event models. **Hydrol. Sci. Journ.**, 31, 395-411.

Gupta, S.K. and Solomon, S.I. (1977) Distributed numerical model for estimating runoff and sediment discharge of ungauged rivers. 1. The information system. **Water Res. Res.**, 13(3), 613-636.

Gupta, V.K. and Sorooshian, S. (1985) The relationship between data and the precision of parameter estimates of hydrologic models. **J. Hydrol.** 81, 57-77.

Hewlett, J.D. and Hibbert, A.R. (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In W.E. Sopper and H.W. Lull (editors). **Forest Hydrology**, Pergamon, London, 275-290.

Hiemstra, L.A.V. (1969) Joint probabilities in the rainfall-runoff relations. **Highway Research Record**, no. 261, 1-17, Highway Research Board, Pennsylvannia.

Hiemstra, L.A.V. and Francis, D.M. (1979) **The runhydrograph theory and application for flood predictions.** Univ. of Natal and Water Research Commission, Pretoria, South Africa.

Hope, A.S. (1983) An assessment of the R-index method for calculating stormflow volumes in Natal, South Africa. **J. Hydrol.**, 60, 243-255.

Hope, A.S. (1984) Estimation of stormflow volumes from small semi-arid catchments using the R-Index method. **J. Hydrol.**, 67, 129-139.

Huggins, L.F. and Monke, E.J. (1966) **Mathematical simulation of the hydrology of small watersheds**, Report no. 1, Water Res. Res. Cen., Purdue University, USA.

Hughes, D.A. (1980) Floodplain inundation : processes and relationships with channel discharge. **Earth Surface Processes**, 5, 297-304.

Hughes, D.A. (1983) **Preliminary investigations into isolated flood event modelling with specific reference to the southern Cape coastal lakes region.** Hydrological Research Unit, Report no. 3/83, Rhodes University, Grahamstown, South Africa.

Hughes, D.A. (1984) An isolated event model based upon direct runoff calculations using an implicit source area concept. **Hydrol. Sci. Journ.**, 29(3), 311-325

Hughes, D.A. (1985) Conceptual catchment model parameter transfer investigations in the southern Cape. **Water S.A.** 11(3), 149-156.

Hughes, D.A. (1986) Bivariate relationship between extreme rainfalls and antecedent catchment moisture status. In : R.E.Schulze (editor), **Proc. 2nd South African National Hydrology Symposium**, Sept. 1985, Pietermaritzburg, South Africa, 454-464.

Hughes, D.A. and Murrell, H.C. (1986) Non-linear runoff-routing - a comparison of solution methods. **J. Hydrol.**, 85, 339-347.

Ibbit, R.P. and O'Donnell, T. (1971) Fitting methods for conceptual catchment models. **J. Hydraul. Div. Amer. Soc. Civil Eng.**, 97 (HY9), 1331-1342.

James, L.D. and Hawkins, R.H. (1981) A taxonomy for evaluating surface water quantity model reliability. In, V.P. Singh (ed.) **Applied modelling in catchment hydrology,** Proc. Int. Sym. on Rainfall-Runoff modelling, May 1981, Mississippi, USA., 189-228.

Jayawardena, A.W. and White, J.K. (1977) A finite-element distributed catchment model, I. Analytical basis. **J. Hydrol.**, 34, 269-286.

Jayawardena, A.W. and White, J.K. (1979) A finite-element distributed catchment model, II. Application to real catchments. **J. Hydrol.**, 42, 231-249.

Kirkby, M.J. and Callen, J., Weyman, D.R. and Wood, J. (1976) **Measurement and modelling of dynamic contributing areas in very small catchments.** Working paper no. 167, School of Geography, University of Leeds.

Krzystofowicz, R. and Diskin, M.H. (1978) A moisture-accounting watershed model for single storm events based on time-area concept. **J. Hydrol.**, 37, 261-294.

Laurenson, E.M. and Mein, R.G. (1985) **RORB-version 3, Runoff Routing Program,** User Manual. Monash University, Dept. of Civil Engineering. Melbourne, Australia

Lee, M.T. and Delleur, J.W. (1976) A variable source area model of the rainfall-runoff process based upon the watershed stream network. **Water Res. Res.**, 12(5), 1029-1036.

Loage, K.M. and Freeze, R.A. (1985) A comparison of rainfall-runoff modelling techniques on small upland catchments. **Water Res. Res.**, 21(2), 229-248.

Lowing, M.J. and Mein, R.G. (1981) Flood event modelling - A study of two methods. **Water Res. Bull.** 17(4), 599-606.

Mandeville, A.N. (1983) **Augmented hydrograph hypothesis : Discussion of principles.** Inst. of Hydrology, Wallingford, England, Report No. 82.

Manley, R.E. (1977) The soil moisture component of mathematical catchment simulation models. **J. Hydrol.** 35, 341-356.

Marsalek, J. (1978) Research on design storm concept. ASCE, **UWRR Program**, Technical Memorandum no. 33, ASCE, New York.

Mein, R.G. and Brown, B.M. (1978) Sensitivity of optimized parameters in watershed models. **Water Res. Res.**, 14(2), 299-303.

Mein, R.G., Laurenson, E.M. and McMahon, T.A. (1974) Simple non-linear model for flood estimation. **J. Hydraulics Div. ASCE.**, 100, 1507-1518.

Moolman, J.H. (1985) **Data collection for the study of runoff, solute and sediment generating processes in a semi-arid catchment.** Hydrological Research Unit, Report 1/85, Rhodes University, Grahamstown, South Africa.

Moore, I.D., Mackay, S.M., Wallbrink, P.J., Burch, G.J. and O'Loughlin, E.M. (1986) Hydrologic characteristics and modelling of a small forested catchment in south eastern New South Wales. Pre-logging condition. **J. Hydrol.** 83, 307-335.

Murray, D.L. and Görgens, A.H.M. (1981) Storm runoff analyses on three semi-arid catchments. **Water S.A.**, 7(4), 223-233.

O'Donnell, T. (1966) Methods of computation in hydrograph analysis and synthesis. Recent trends in Hydrograph Synthesis Paper III. TNO Proc. no. 13, TNO, The Hague.

O'Loughlin, E.M. (1986) Saturation regions in catchments and their relations to soil and topographic properties. **J. Hydrol.**, 53, 229-246.

Packman, J.C. and Kidd, G.H.R. (1980) A logical approach to the design storm concept. **Water Res. Res.**, 16(6), 994-100.

Peck, A.J., Luxmoore, R.J. and Stolzy, J.L. (1977) Effect of spatial variability of soil hydraulic properties in water budget modelling. **Water Res. Res.**, 13, 348-354.

Pickup, G. (1977) Testing the efficiency of algorithms and strategies for automatic calibration of rainfall-runoff models. **Hydro. Sci. Bull.**, 22(2), 257-274.

Pirt, J. and Bramley, E.A. (1985) The application of simple moisture accounting models to ungauged catchments. **J. Inst. Water. Eng. Sci.** 39, 169-177.

Ponce, V.M. (1979) A simplified Muskingham routing equation. **J. Hydraul. Div. Am. Soc. Civ. Eng.**, 105(HY1), 85-91.

Rajendran, R. and Mein, R.G. (1986) Determination of rainfall excess on spatially variable catchments,. **J. Hydrol.**, 83, 67-89.

Roberts, P.J.T. (1978) **A comparison of the performance of selected conceptual models of the rainfall-runoff process in semi-arid catchments near Grahamstown.** Hydrological Research Unit, Report 1/78, Rhodes University, Grahamstown, South Africa.

Roberts, P.J.T. (1984) The need to adapt research effort in deterministic hydrology to meet changing requirements for water resource managememt in South Africa. In: H. Maaren (editor), **South African National Hydrological Symposium - Proceedings.** Dept. of Environment Affairs and Water Research Commission, Tech. Rep. TR119, 109-112.

Rogers, C.C.M., Beven, K.J., Morris, E.M. and Anderson, M.G. (1985) Sensitivity analysis, calibration and predictive uncertainty of the Institute of Hydrology distributed model. **J. Hydrol.**, 81, 179-191.

Rosenbrock, H.H. (1960) An automatic method for finding the greatest or least value of a function. **Computer J.**, 4, 175-184.

Schultz, C.B. (1985) **The sensitivity of output from a distributed hydrological model to rainfall input.** Unpublished MSc. Thesis, University of Natal, Pietermaritzburg, South Africa.

Schulze, R.E. (1984) **Hydrological models for application to small rural catchments in Southern Africa : Refinements and development.** ACRU Report No. 19, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Sefe, F.T. and Broughton, W.C. (1982) Variation of model parameter values and sensitivity with type of objective function. **J. Hydrol. (New Zealand)**, 21(2), 117-132.

Serban, P. (1976) A mathematical model of the 'reservoir' type designed for flood-wave modelling and forecasting. **Hydrol. Sci. Bull.**, 21(1), 139-147.

Singh, V.P. and Buapeng, S. (1977) Effect of rainfall-excess determination on runoff computation. **Water Res. Bull.** 13(3), 499-514.

Sorooshian, S. (1983) Surface water hydrology : On-line estimation. **Reviews of Geophysics and Space Physics**, 21(3), 706-721.

Sorooshian, S. and Arfi, F. (1982) Response surface parameter sensitivity analysis methods for post calibration studies. **Water Res. Res.** 18(5), 1531-1538.

Stedinger, J.R. and Taylor, M.R. (1982) Synthetic streamflow generation. 1. Model verification and validation. **Water Res. Res.** 18(4), 900-918.

Stephenson, D. (1980) Peak runoff from small areas - A kinematic approach. **Water S.A.** 6(2), 59-65.

Surkan, A.J. (1974) Simulation of storm velocity effects on flow from distributed channel networks. **Water Res. Res.** 10(6), 1149-1160.

Tennesse Valley Authority (1965) Area-stream factor Correlation, **Hydrol. Sci. Bull.**, 10(2), 22-37.

Urbonas, B. (1979) Design storm use in a semi-arid climate. In: **The Design Storm Concept.** Proc. Seminar, Ecole Polythechnique, Montreal, May 29, 1979, Report GREMU 79/02, Montreal Canada.

U.S.D.A. (1960-1973). **United States Department of Agriculture, Agricultural Research Service, Hydrologic data for experimental agricultural watersheds in the United States.** Misc. Publ. Series compiled by H.W. Hobbs, J.B. Burford and J.M. Clark.

Ward, R.C. (1984) Hypothesis testing by modelling catchment response. **J. Hydrol.**, 67, 281-205.

Watson, M.D. (1981) **Time area method of flood estimation for small catchments.** Report no. 7/81, Hydrological Research Unit, University of the Witwatersrand, Johannesburg.

Wenzel, H.G. and Voorhees, M.L. (1978) **Evaluation of the design storm concept.** Proc. Fall Meeting, AGU, San Francisco, California.

APPENDIX A

MODEL CALIBRATION RESULTS : TABLES

The tables are arranged in the follcwing way.

Model name and type	Q9M20	Q9M21	Q9M24	ND1	ND3	ND4	ND5
OSE2 Lumped	A1	A2	A3	A4	A5	A6	A7
S.dist.	A8		A10	A12		A14	A16
sub-area factors	A9		A11	A13		A15	A17
OSE1 Lumped	A18	A19		A20			A21
S.dist.	A22			A24			A26
sub-area factors	A23			A25			A27
OSE3 Lumped	A28	A29		A30			A31
S.dist.	A32			A34			A36
sub-area factors	A33			A35			A37
OSE4 S.dist.	A38			A39			A40

(Catchment columns: Q9M20, Q9M21, Q9M24, ND1, ND3, ND4, ND5)

Notes: a) Parameter values that change between storms on the same catchment are listed in the tables, other are given below the tables.

b) Coefficients Eff. = Efficiency = $1 - \frac{\sum(\text{Obs-Sim})^2}{\sum(\text{Obs-Obs.mean})^2}$

Det. = Determination = (corr.coefficient)^2

c) AAOE (OSE4) Average absolute ordinate error %

$$\frac{1}{N}\sum \frac{\text{Obs-Sim}}{\text{Obs}} * 100$$

where N = number of data points.

Table **A1** Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters A (6)	APF (14)	CLP (15)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	2,00	0,913	2,32	8,8	-1,9	0,772	0,824
2	6.03.77	Not modelled (rainfall very spatially variable)						
3	7.05.77	5,38	0,880	2,32	-21,3	9,8	0,725	0,761
4	19.04.78	3,00	0,975	2,32	-12,8	-13,6	0,827	0,845
5	21.04.78	2,00	0,920	2,32	6,7	11,9	0,303	0,637
6	20.07.79	5,38	0,963	2,32	3,2	-2,0	0,972	0,974
7	23.07.79	5,38	0,963	2,32	-1,6	-3,8	0,902	0,911
8	19.08.79	5,38	0,970	2,32	3,2	4,9	0,856	0,869
9	26.03.81	1,75	0,810	2,32	5,9	-2,7	0,941	0,956
10	22.10.81	5,38	0,913	1,80	1,1	44,3	-0,142	0,519
11	23.12.81	No acceptable fit possible						
12	2.11.85	5,38	0,963	2,32	-8,4	-18,3	0,923	0,946
13	25.11.85	5,38	0,963	2,32	-15,4	3,1	0,534	0,597
14	1.12.85	5,38	0,945	2,32	7,7	-19,3	0,583	0,612
15	3.12.85	Not modelled (data errors)						
Mean					8,0	11,3	0,683	0,788
St. dev.					6,0	12,1	0,327	0,159

Other parameters:

K(1) =	10,00	N(2) =	0,6
DEL(5) =	0,25	B(7) =	0,098
SMAX(8) =	175,05	DA(9) =	0,282
C(10) =	0,672	PCSLP(11) =	340,0
PCVSA(12) =	0,43	IAF(13) =	0,67

Table A2 Calibration results

Catchment Ecca, Q9M21 — Area 9,1km²

Model S-curve model - OSE2 — Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	28.02.77	0,870	23,0	-40,2	0,313	0,438
2	6.03.77	0,897	16,6	-24,2	0,778	0,794
3	7.05.77	0,956	5,8	-1,3	0,557	0,673
4	19.04.78	not modelled	(suspect data)			
5	21.04.78	0,800	-1,6	3,9	0,300	0,506
6	20.07.79	0,943	-0,6	-9,6	0,981	0,981
7	23.07.79	0,943	-1,1	13,7	0,955	0,980
8	19.08.79	0,960	5,2	13,9	0,858	0,864
9	26.03.81	0,850	2,3	-19,1	0,157	0,395
10	22.10.81	not modelled	(zero flow)			
11	23.12.81	0,870	-26,9	18,5	-0,656	0,039
12	2.11.85	0,943	-1,7	-4,7	0,948	0,949
13	25.11.85	not modelled	(missing data)			
14	1.12.85	0,918	-13,9	9,7	0,354	0,790
15	3.12.85	not modelled	(data errors)			
Mean			9,0	14,4	0,504	0,673
St. dev.			9,5	11,1	0,490	0,299

Other parameters:

K(1) =	6,69	N(2) =	0,6
DEL(5) =	0,0	A(6) =	1,45
B(7) =	0,1	SMAX(8) =	159,0
DA(9) =	0,248	C(10) =	0,693
PCSLP(10) =	370,1	RCVSA(12) =	0,656
IAF(13) =	0,839	CLP(15) =	2,43

Table **A3** Calibration results

Catchment Ecca, **Q9M24** Area 23,1km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	20.07.79	0,960	25,9	3,9	0,847	0,934
2	23.07.79	0,960	-2,8	-11,4	0,945	0,947
3	19.08.79	0,956	-7,2	10,5	0,859	0,919
4	2.11.85	0,910	4,2	4,4	0,793	0,833
Mean			10,0	7,5	0,861	0,908
St. dev.			10,7	3,9	0,063	0,051

Other parameters:

K(1) = 6,83 N(2) = 0,6

DEL(5) = 0,25 A(6) = 2,00

B(7) = 0,098 SMAX(8) = 200,8

DA(9) = 0,21 C(10) = 0,62

PCSLP(11) =327,9 PCVSA(12) = 0,53

IAF(13) = 0,60 CLP(15) = 2,70

Table **A4** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	24.10.59	0,90	-1,0	9,5	0,990	0,991
2	30.07.60	0,85	35,9	17,3	0,790	0,970
3	2.06.61	No acceptable fit possible				
4	31.07.62	0,85	-11,8	-17,4	0,903	0,953
5	30.07.63	Not modelled (rainfall very spatially variable)				
6	22.07.64	Not modelled (rainfall very spatially variable)				
7	7.06.65	0,85	-25,3	-33,2	0,773	0,978
8	19.10.66	0,90	-26,4	-26,3	0,667	0,980
9	16.07.67	0,85	8,7	8,6	0,661	0,772
10	11.09.68	0,85	10,2	-4,4	0,959	0,972
11	7.09.69	0,85	20,9	21,4	-0,277	0,527
12	23.08.71	0,85	62,2	59,5	-0,786	0,981
13	3.07.72	0,85	10,0	16,4	0,510	0,637
14	10.07.72	0,85	4,0	-3,0	0,941	0,945
15	17.09.73	0,85	4,4	-10,9	0,961	0,967
Mean			18,4	19,0	0,591	0,889
St. dev.			17,4	15,5	0,555	0,157

Other parameters:

K(1) =	5,0	N(2) =	0,7
DEL(5) =	0,25	A(6) =	2,9
B(7) =	0,15	SMAX(8) =	214,5
DA(9) =	0,377	C(10) =	0,251
PCSLP(11) =	127,7	PCVSA(12) =	3,8
IAF(13) =	0,39	CLP(15) =	0,0

Note: Some of the poorer fits (e,g, 2,8 and 12) can be improved by modification to APF only.

Table **A5** Calibration results

Catchment North Danville, **ND3** Area 8,37km²

Model S-curve model - **OSE2** Type **Lumped**

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,868	23,9	11,2	0,495	0,619
2	2.06.61	No acceptable fit				
3	31.07.62	0,868	9,0	-4,9	0,934	0,953
4	30.07.63	No acceptable fit				
5	22.07.64	No acceptable fit				
6	7.06.65	No acceptable fit				
7	19.10.66	0,918	6,3	2,6	0,678	0,723
8	16.07.67	No acceptable fit				
9	11.09.68	0,868	3,7	-28,1	0,903	0,933
10	7.09.69	No acceptable fit				
11	23.08.71	0,868	28,7	16,6	0,726	0,973
12	10.07.72	0,868	-5,4	-42,9	0,696	0,729
13	17.09.73	0,868	6,0	-31,7	0,864	0,886
Mean			11,8	19,7	0,756	0,831
St. dev.			10,1	14,9	0,154	0,139

Other parameters:

K(1) =	4,6	N(2) =	0,7
DEL(5) =	0,001	A(6) =	1,5
B(7) =	0,15	SMAX(8) =	227,0
DA(9) =	0,394	C(10) =	0,279
RCSLP(11) =	126,0	PCVSA(12) =	3,70
IAF(13) =	0,43	CLP(15) =	0,0

Table **A6** Calibration results

Catchment North Danville, ND4 Area 43,51km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	errors: Volume	Peak	Coefficients: Eff.	Det.
1	7.06.65	0,872	7,0	16,7	0,749	0,820
2	19.10.66	0,922	-13,7	-9,3	0,894	0,987
3	16.07.67	0,872	14,1	-19,9	0,384	0,486
4	11.09.68	0,872	-8,3	-16,1	0,937	0,968
5	7.09.69	no acceptable fit possible				
6	23.08.71	0,872	45,3	36,6	0,007	0,959
7	10.07.72	0,872	6,5	2,8	0,843	0,854
8	14.07.73	0,872	-2,1	-5,2	0,961	0,968
9	17.09.73	0,872	-12,6	-29,2	0,841	0,936
Mean			13,7	17,0	0,702	0,872
St. dev.			13,4	11,6	0,335	0,167

Other parameters:

K(1) =	5,5	N(2) =	0,7
DEL(5) =	0,25	A(6) =	2,82
B(7) =	0,15	SMAX(8) =	200,0
DA(9) =	0,359	C(10) =	0,290
PCSLP(11) =	130,0	PCVSA(12) =	3,80
IAF(13) =	0,29	CLP(15) =	1,0

Table **A7** Calibration results

Catchment North Danville, ND5 — Area 111,60km²

Model S-curve model - OSE2 — Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	30.07.60	0,848	34,0	22,3	0,757	0,919
2	2.06.61	No acceptable fit possible				
3	31.07.62	0,848	1,0	19,1	0,957	0,957
4	30.07.63	Not modelled (rainfall very spatially variable)				
5	22.07.64	Not modelled (rainfall very spatially variable)				
6	7.06.65	0,848	-1,5	-2,9	0,918	0,920
7	19.10.66	0,898	-21,5	-19,9	0,789	0,989
8	16.07.67	0,848	2,8	-4,9	0,874	0,877
9	11.09.68	0,848	12,6	10,3	0,934	0,974
10	7.09.69	No acceptable fit possible				
11	23.08.71	0,848	34,9	41,8	0,280	0,954
12	10.07.72	0,848	-21,2	-19,0	0,795	0,909
13	20.07.72	0,848	-32,6	-33,7	0,700	0,974
14	14.07.73	0,848	-24,8	-28,2	0,732	0,985
15	17.09.73	0,848	-8,3	-21,3	0,921	0,961
Mean			17,7	20,3	0,787	0,947
St. dev.			13,2	11,6	0,190	0,036

Other parameters:

K(1) =	5,75	N(2) =	0,7
DEL(5) =	0,5	A(6) =	2,68
B(7) =	0,15	SMAX(8) =	218,0
DA(9) =	0,451	C(10) =	0,245
PCSLP(11) =	131,0	RCVSA(12) =	3,87
IAF(13) =	0,30	CLP(15) =	0,0

Table A8 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model S-curve model - OSE2 Type Semi-distributed

Storm No.	Date	Parameters APF (14)	CLP (15)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,910	2,70	11,0	4,6	0,704	0,776
2	6.03.77	0,925	2,70	-1,9	2,5	0,615	0,745
3	7.03.77	0,948	2,70	-17,4	10,2	0,428	0,502
4	19.04.78	0,968	2,70	4,1	-6,7	0,971	0,974
5	21.04.78	0,930	2,70	-10,1	3,6	0,277	0,667
6	20.07.79	0,960	2,70	-8,3	-6,2	0,966	0,971
7	23.07.79	0,960	2,70	-11,8	6,9	0,725	0,855
8	19.08.79	0,965	2,70	-10,4	-10,1	0,814	0,830
9	26.03.81	0,880	2,70	12,7	-6,3	0,878	0,918
10	22.10.81	0,915	2,40	-17,9	16,1	-0,069	0,526
11	23.12.81	0,910	2,33	-39,3	60,1	-0,901	0,001
12	2.11.85	0,960	2,70	2,9	11,1	0,673	0,871
13	25.11.85	0,960	2,70	-0,3	127,8*	0,113	0,804
14	1.12.85	0,910	2,20	-46,8	2,2	-0,030	0,532
15	3.12.85	Not modelled (data errors)					
Mean				13,9	11,3**	0,440	0,712
St. dev.				13,5	15,2**	0,522	0,259

Other parameters: K(1) = 6,0 N(2) = 0,6
CDEL(3) = 1,0 KC(4) = 0,5
SMAX(8) = 200,0 DA(9) = 0,25
C(10) = 0,695 PCSLP(11) = 400,0
PCVSA(12) = 0,6 IAF(13) = 0,6

Sub-catchment weighting factors are given in Table A9

* Large error possibly caused by data errors.

** Does not include result for storm 13.

Table **A9** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M20** Area 73,9km²

Model S-curve model - OSE2 Type **semi-distributed**

		Parameters										
Sub-cat.	Area	1	3	4	8	9	10	11	12	13	14	15
No.	(%)	K	CDEL	KC	SMAX	DA	C	PCSLP	PCVSA	IAF	APF	CLP
1	13,0	1,00	5,25	0,80	1,10	0,72	0,83	0,75	1,00	0,92	1,00	1,00
2	5,9	0,92	4,50	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
3	5,6	0,92	4,50	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
4	7,0	0,92	4,00	1,00	0,90	0,92	0,95	0,90	0,83	1,05	0,99	0,94
5	6,4	0,90	4,00	0,75	0,82	1,05	0,95	0,90	0,83	1,10	1,00	0,85
6	7,0	0,90	4,00	0,75	0,82	1,05	0,95	0,90	0,83	1,10	1,00	0,85
7	11,4	0,85	3,00	0,50	0,78	1,15	0,95	0,92	0,83	1,30	1,00	0,75
8	7,9	0,80	2,75	0,60	0,78	1,15	0,95	0,92	0,90	1,30	1,00	0,75
9	6,0	0,65	2,25	0,96	0,78	1,15	0,95	0,92	0,90	1,30	1,00	0,75
10	9,7	0,95	1,25	1,40	0,90	1,07	0,92	0,90	1,00	1,20	1,01	0,88
11	12,9	1,05	0,75	1,00	0,80	0,99	0,99	0,92	0,83	1,40	0,99	0,85
12	7,4	0,80	0,25	0,60	0,90	1,07	1,07	0,90	1,00	1,20	1,01	0,80

Parameter N(2) all weights = 1,00

Table **A10** Calibration results

Catchment Ecca, **Q9M24** Area 23,1km²

Model S-curve model - OSE2 Type **Semi-distributed**

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	20.07.79	0,960	14,8	-3,8	0,936	0,965
2	23.07.79	0,960	-6,8	-6,5	0,953	0,971
3	19.08.79	0,960	-9,7	10,1	0,857	0,887
4	2.11.85	0,910	-9,8	-4,1	0,713	0,775
Mean			10,3	6,1	0,865	0,899
St. dev.			3,3	2,9	0,109	0,091

Other parameters:

K(1) =	6,0	N(2) =	0,60
CDEL(3) =	1,0	KC(4) =	0,50
SMAX(8) =	200,0	DA(9) =	0,25
C(10) =	0,965	PCSLP(11) =	400,0
PCVSA(12) =	0,6	IAF(13) =	0,6

Table **A11** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M24** Area 23,1km²

Model S-curve model - **OSE2** Type **Semi-distributed**

Sub-cat. No.	Area (%)	1 K	3 CDEL	4 KC	8 SMAX	9 DA	10 C	11 PCSLP	12 PCVSA	13 IAF	14 APF	15 CLP
1	41,2	1,00	1,50	0,80	1,10	0,72	0,83	0,75	1,00	0,92	1,00	1,00
2	18,8	0,92	0,75	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
3	17,8	0,92	0,75	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
4	22,0	0,92	0,00	0,90	0,90	0,92	0,95	0,90	0,83	1,05	0,99	0,94

Parameter N(2) all weights = 1,00

Table **A12** Calibration results

Catchment North Danville, ND1 — Area 42,94km²

Model S-curve model - OSE2 — Type Semi-distributed

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	24.10.59	0,90	-2,2	3,7	0,983	0,985
2	30.07.60	0,85	46,9	20,8	0,651	0,975
3	2.06.61	No acceptable fit possible				
4	31.07.62	0,85	-10,2	-20,9	0,913	0,963
*5	30.07.63	0,85	334,6	297,6	-51,8	0,559
*6	22.07.64	0,85	52,2	43,6	-1,218	0,787
7	7.06.65	0,85	-25,6	-38,4	0,731	0,943
8	19.10.66	0,90	-25,2	-25,7	0,682	0,987
9	16.07.67	0,85	2,5	0,7	0,933	0,942
10	11.09.68	0,85	13,6	-4,0	0,955	0,978
*11	7.09.69	0,85	152,4	201,7	-30,3	0,258
12	23.08.71	0,85	83,8	72,9	-2,002	0,992
13	3.07.72	0,85	12,3	9,9	0,444	0,579
14	10.07.72	0,85	-1,2	-10,0	0,959	0,961
15	17.09.73	0,85	2,9	-12,0	0,906	0,973
Mean			20,6	19,9	0,565	0,934
St. dev.			25,1	20,8	0,869	0,119

Other parameters:

K(1) =	5,0	N(2) =	0,7
CDEL(3) =	1,0	KC(4) =	0,85
SMAX(8) =	214,5	DA(9) =	0,251
C(10) =	0,251	PCSLP(11) =	127,7
PCVSA(12) =	3,8	IAF(13) =	0,39
CLP(15) =	0,0		

* Values not used to calculate mean and St. dev.

Note: Some of the poorer fits (eg, 2,3,6,8,12) can be improved by modification to APF only.

Table **A13** Sub-catchment parameter weighting factors

Catchment North Danville, **ND1** Area 42,94km²

Model S-curve model - OSE2 Type Semi-distributed

		Parameters							
Sub-catch.	Area	1	3	4	8	11	12	13	14
No.	%	K	CDEL	KC	SMAX	PCSLP	PCVSA	IAF	APF
1	19,5	1,00	1,00	0,80	1,00	1,00	1,00	1,11	0,99
2	13,4	1,50	0,50	0,87	1,15	0,85	0,85	0,89	1,00
3	18,0	1,00	0,75	1,35	1,00	1,00	1,00	1,00	1,00
4	19,6	0,80	0,80	0,85	0,90	1,10	1,10	1,11	0,99
5	16,9	0,90	0,90	0,77	1,00	1,00	1,00	0,94	1,00
6	12,6	0,80	0,80	0,73	0,95	1,05	1,05	0,95	1,01

Parameters N(2), DA(9), C(10), CLP(15) all weights = 1,00

Table **A14** Calibration results

Catchment North Danville, ND4 Area 43,51km²

Model S-curve model - OSE2 Type Semi-distributed

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	7.06.65	0,872	11,4	24,9	0,582	0,713
2	19.10.66	0,922	-6,8	-4,4	0,952	0,965
3	16.07.67	0,872	29,1	-5,5	0,686	0,740
4	11.09.68	0,872	1,9	-5,9	0,981	0,983
5	7.09.69	No acceptable fit possible				
6	23.08.71	0,872	57,7	44,6	-0,429	0,335
7	10.07.72	0,872	-25,9	-31,6	0,735	0,850
8	14.07.73	0,872	-5,9	-12,3	0,934	0,958
9	17.09.73	0,872	-19,8	-32,9	0,786	0,909
Mean			19,8	20,3	0,653	0,807
St. dev.			18,2	15,3	0,459	0,216

Other parameters:

K(1) =	5,55	N(2) =	0,7
CDEL(3) =	1,00	KC(4) =	0,85
SMAX(8) =	200,0	DA(9) =	0,359
C(10) =	0,245	PCSLP(11) =	130,0
PCVSA(12) =	3,80	IAF(13) =	0,30
CLP(15) =	0,0		

Table **A15** Sub-catchment parameter weighting factors

Catchment North Danville, **ND4** Area 43,51km²

Model S-curve model - OSE2 Type Semi-distributed

Sub-catch. No.	Area %	1 K	3 CDEL	4 KC	8 SMAX	11 PCSLP	12 PCVSA	13 IAF	14 APF
1	18,5	0,75	1,50	0,60	1,00	1,00	1,00	1,12	0,99
2	12 6	0,85	1,25	0,65	1,05	0,90	0,90	0,94	0,99
3	12 6	1,45	0,75	1,00	1,15	0,85	0,85	0,91	1,00
4	11 4	1,20	1,50	0,87	1,05	1,00	1,00	1,11	0,99
5	19,2	0,90	1,00	1,05	0,95	1,05	1,05	1,15	1,00
6	11,8	0,75	0,50	0,75	0,90	1,10	1,10	1,15	0,99
7	13,9	1,00	0,00	0,42	0,90	1,10	1,10	1,15	1,01

Parameters N(2), DA(9), C(10), CLP(15) all weights = 1,00

Table **A16** Calibration results

Catchment North Danville, ND5 Area 111,60km²

Model S-curve model - OSE2 Type Semi-distributed

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	30.07.60	0,848	34,2	13,7	0,816	0,971
2	2.06.61	No acceptable fit possible				
3	31.07.62	0,848	-4,9	-1,2	0,937	0,946
4	30.07.63	No acceptable fit possible				
5	22.07.64	No acceptable fit possible				
6	7.06.65	0,848	-1,9	-7,8	0,957	0,959
7	19.10.66	0,898	-20,0	-18,9	0,810	0,986
8	16.07.67	0,848	0,4	-11,0	0,944	0,947
9	11.09.68	0,848	1,6	1,6	0,964	0,979
10	7.09.69	No acceptable fit possible				
11	23.08.71	0,848	44,6	51,1	0,040	0,990
12	10.07.72	0,848	-23,0	-28,6	0,813	0,976
13	20.07.72	0,848	-21,0	-23,6	0,838	0,937
14	14.07.73	0,848	-22,9	-30,1	0,691	0,920
15	17.09.73	0,848	-13,2	-26,9	0,885	0,958
Mean			17,7	19,5	0,790	0,960
St. dev.			13,7	14,7	0,262	0,022

Other parameters:

K(1) =	5,75	N(2) =	0,7
CDEL(3) =	1,0	KC(4) =	0,85
SMAX(8) =	218,0	DA(9) =	0,451
C(10) =	0,245	PCSLP(11) =	131,0
PCVSA(12) =	3,87	IAF(13) =	0,30
CLP(15) =	0,0		

Table **A17** Sub-catchment parameter weighting factors

Catchment North Danville, **ND5** Area 111,60km²

Model S-curve model - OSE2 Type **Semi-distributed**

Sub-catch.	Area	Parameters							
		1	3	4	8	11	12	13	14
No.	%	K	CDEL	KC	SMAX	PCSLP	PCVSA	IAF	APF
1	7,5	0,85	1,50	0,80	1,00	1,00	1,00	1,11	0,99
2	5,2	1,40	1,00	0,87	1,10	0,80	0,80	0,89	1,00
3	6,9	0,80	1,25	1,35	1,05	0,90	0,90	1,00	1,00
4	7,5	0,75	1,50	0,85	0,95	1,05	1,05	1,11	0,99
5	6,5	0,80	1,00	0,77	1,05	0,90	0,90	0,94	1,00
6	4,8	0,75	0,50	0,73	1,00	1,00	1,00	1,11	1,01
7	5,2	1,20	1,00	0,97	1,05	0,95	0,95	1,00	0,99
8	5,6	1,35	0,75	0,45	1,10	0,80	0,80	0,91	0,99
9	4,3	1,30	0,50	0,67	1,05	1,00	1,00	1,00	1,00
10	7,7	0,75	2,25	0,65	0,95	1,05	1,05	1,12	0,99
11	4,9	0,85	2,00	0,70	1,10	0,90	0,90	0,94	0,99
12	4,9	1,45	1,50	1,00	1,10	0,85	0,85	0,91	1,00
13	4,4	1,20	2,25	0,95	1,00	1,00	1,00	1,11	0,99
14	7,5	0,90	1,75	1,05	0,90	1,05	1,05	1,15	1,00
15	4,6	0,75	1,25	0,75	0,90	1,10	1,10	1,15	0,99
16	5,4	1,00	0,75	0,80	0,90	1,10	1,10	1,15	1,01
17	2,0	0,80	0,00	0,37	0,95	1,05	1,05	1,13	0,99
18	5,1	1,70	0,00	0,50	1,05	1,00	1,00	1,00	1,02

Parameters N(2), DA(9), C(10), CLP(15) all weights = 1,00

Table **A18** Calibration results

Catchment Ecca, **Q9M20** Area 73,9km²

Model Simple antecedent moisture model - **OSE1** Type **Lumped**

Storm No.	Date	DEL (5)	K (1)	A (6)	DA (9)	C (10)	APF (14)	IL (15)	% errors: Volume	Peak	Coeff: Eff.	Det.
1	28.02.77	0,00	3,0	2,0	0,147	0,600	0,90	1,0	-4,6	1,2	0,915	0,923
2	6.03.77	0,00	6,0	1,0	0,300	0,290	0,90	1,0	30,2	-31,0	0,622	0,748
3	7.05.77	0,00	2,5	3,0	0,260	0,420	0,90	25,0	-4,0	1,4	0,735	0,742
4	19.04.78	0,00	2,5	2,5	0,250	0,380	0,90	22,0	-7,5	-4,3	0,845	0,847
5	21.04.78	0,00	6,0	1,0	0,170	0,495	0,95	1,0	-3,6	0,8	0,790	0,878
* 6	20.07.79	1,50	9,0	4,5	0,940	0,030	0,95	50,0	-15,6	15,1	0,744	0,770
* 7	23.07.79	1,50	10,0	6,5	0,265	0,500	0,95	1,0	-3,9	-5,8	0,949	0,962
* 8	19.08.79	1,50	10;0	7,0	0,660	0,095	0,90	30,0	-10,8	-1,6	0,861	0,887
9	26.03.81	0,00	5,0	1,5	0,095	0,600	0,90	1,0	15,8	-11,6	0,923	0,955
10	22.10.81	0,00	5,5	2,0	0,450	0,130	0,85	1,0	-1,6	-4,4	0,871	0,884
11	23.12.81	0,00	1,5	2,0	0,350	0,180	0,85	16,0	5,3	-12,2	0,957	0,959
*12	2.11.85	1,50	11,5	5,5	0,610	0,580	0,90	1,0	-1,7	-6,6	0,934	0,943
*13	25.11.85	0,00	10,0	4,0	0,360	0,280	0,90	1,0	-4,2	2,6	0,551	0,617
14	1.12.85	1,00	4,5	4,0	0,350	0,380	0,90	1,0	2,2	-18,7	0,819	0,832
15	3.12.85		Not modelled (data errors)									
Mean									7,9	8,4	0,822	0,853
St. dev.									7,9	8,6	0,123	0,102

Other parameters: N(4) = 0,7 B(7) = 0,15

SMAX(8) = 200,0

* 'Large' storm events.

Table **A19** Calibration results

Catchment Ecca, **Q9M21** Area 9,1km²

Model Simple antecedent moisture model - **OSE1** Type **Lumped**

Storm No.	Date	K (1)	A (6)	DA (9)	C (10)	APF (14)	IL (15)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,5	0,5	0,170	0,880	0,90	1,0	9,0	-19,9	0,806	0,815
2	6.03.77	1,0	0,5	0,150	0,370	0,90	10,0	26,3	-17,2	0,794	0,794
3	7.05.77	2,5	1,5	0,700	0,100	0,85	40,0	-18,4	-21,5	0,836	0,836
4	19.04.78			not modelled		(suspect data)					
5	21.04.78	3,0	0,5	0,160	0,560	0,95	10,0	-0,9	-0,4	0,660	0,779
* 6	20.07.79	7,5	0,5	0,950	0,028	0,95	58,0	-15,4	-4,9	0,773	0,794
* 7	23.07.79	10,0	1,5	0,190	0,510	0,95	0,1	-4,3	-3,8	0,952	0,975
* 8	19.08.79	17,0	5,0	0,600	0,095	0,90	25,0	1,7	-0,7	0,897	0,912
9	26.03.81	2,0	1,0	0,120	0,690	0,90	1,0	13,6	-14,4	0,409	0,524
10	22.10.81			not modelled		(zero flow)					
11	23.12.81	1,0	1,5	0,400	0,120	0,85	15,0	2,1	-21,5	0,710	0,729
*12	2.11.85	11,5	1,5	0,490	0,560	0,90	1,0	-6,9	-9,3	0,927	0,957
*13	25.11.85			not modelled		(missing data)					
14	1.12.85	3,5	1,5	0,250	0,500	0,90	1,0	-0,1	1,3	0,977	0,984
15	3.12.85			Not modelled		(data errors)					
Mean								9,0	10,4	0,794	0,827
St. dev.								8,5	8,7	0,162	0,133

Other parameters: N(2) = 0,7 DEL(5) = 0,0

SMAX(8) = 200,0

* 'Large' storm events.

Table A20 Calibration results

Catchment North Danville, ND1 Area 42,94km²

Model Simple antecedent moisture model - OSE1 Type Lumped

Storm No.	Date	Parameters DEL (5)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	0,25	0,420	0,280	0,90	-2,5	3,2	0,914	0,928
2	30.07.60	0,50	0,710	0,115	0,80	6,3	-25,7	0,831	0,850
3	2.06.61	No acceptable fit possible							
4	31.07.62	0,25	0,830	0,110	0,80	4,7	-13,9	0,863	0,891
5	30.07.63	Not modelled (rainfall very spatially variable)							
6	22.07.64	Not modelled (rainfall very spatially variable)							
7	7.06.65	1,50	0,885	0,103	0,80	3,4	-3,8	0,910	0,942
8	19.10.66	1,25	0,620	0,260	0,90	-7,8	6,9	0,875	0,942
9	16.07.67	0,00	0,697	0,204	0,80	-6,0	6,2	0,803	0,875
10	11.09.68	0,00	0,705	0,163	0,80	3,3	-10,2	0,977	0,980
11	7.09.69	1,00	0,650	0,750	0,80	-5,5	-4,7	0,810	0,881
12	23.08.71	0,00	0,420	0,256	0,80	-2,3	-5,2	0,974	0,977
13	3.07.72	1,00	0,590	0,245	0,80	-8,3	3,2	0,921	0,946
14	10.07.72	0,00	0,506	[illegible]	0,80	-3,4	-2,2	0,945	0,952
15	17.09.73	0,25	0,528	[illegible]	0,80	3,5	-5,8	0,936	0,936
Mean						4,7	7,6	0,896	0,925
St. dev.						2,0	6,6	0,060	0,041

Other parameters: K(1) = 5,5 N(2) = 0,7

A(6) = 4,0 B(7) = 0,15

SMAX(8) = 150,0 IL(15) = 0,0

Table A21 Calibration results

Catchment North Danville, ND5 Area 111,60km²

Model Simple antecedent moisture model - OSE1 Type Lumped

Storm No.	Date	Parameters DEL (5)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	1,00	0,585	0,088	0,80	5,0	-21,5	0,882	0,892
2	2.06.61	0,00	0,585	0,060	0,80	-12,8	6,1	0,913	0,970
3	31.07.62	0,25	0,585	0,098	0,80	2,0	-3,9	0,965	0,972
4	30.07.63	Not modelled (rainfall very spatially variable)							
5	22.07.64	0,00	0,600	0,230	0,80	3,0	-1,1	0,772	0,797
6	7.06.65	3,00	0,575	0,063	0,80	-9,1	10,9	0,924	0,970
7	19.10.66	0,25	0,620	0,240	0,90	-5,0	5,4	0,956	0,978
8	16.07.67	0,00	0,550	0,160	0,80	2,5	-0,2	0,859	0,884
9	11.09.68	0,00	0,575	0,126	0,80	1,9	-0,6	0,963	0,966
10	7.09.69	0,75	0,575	0,423	0,80	0,6	-0,8	0,936	0,963
11	23.08.71	0,00	0,605	0,281	0,80	-3,9	1,8	0,974	0,984
12	10.07.72	0,00	0,640	0,150	0,80	-4,9	-1,4	0,933	0,943
13	20.07.72	0,00	0,500	0,135	0,80	2,3	-2,0	0,893	0,909
14	14.07.73	No acceptable fit possible							
15	17.09.73	0,25	0,585	0,218	0,80	0,9	-8,9	0,938	0,938
Mean						4,1	5,1	0,916	0,936
St. dev.						3,4	5,9	0,055	0,053

Other parameters: K(1) = 6,0 N(2) = 0,7

A(6) = 5,5 B(7) = 0,15

SMAX(8) = 150,0 IL(15) = 0,0

Table A22 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Simple antecedent moisture model - OSE1 Type Semi-distributed

Storm No.	Date	K (1)	DA (9)	C (10)	APF (14)	IL (15)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	28.02.77	0,5	0,150	0,610	0,90	1,0	6,6	-4,8	0,944	0,960
2	6.03.77	0,5	0,200	0,330	0,90	1,0	5,7	-15,3	0,819	0,846
3	7.05.77	No acceptable fit possible								
4	19.04.78	0,5	0,250	0,360	0,90	30,0	1,1	-6,4	0,950	0,961
**5	21.04.78	1,0	0,130	0,510	0,95	1,0	-15,1	10,7	-0,367	-0,321
* 6	20.07.79	6,0	0,930	0,034	0,95	45,0	-23,4	-23,5	0,654	0,779
* 7	23.07.79	11,0	0,200	0,510	0,95	1,0	-1,9	-5,8	0,960	0,970
* 8	19.08.79	10,0	0,700	0,090	0,90	34,0	-8,1	-4,0	0,869	0,970
9	26.03.81	0,5	0,080	0,800	0,90	1,0	7,9	-7,4	0,795	0,825
10	22.10.81	2,0	0,370	0,160	0,85	1,0	-3,2	1,1	0,648	0,774
11	23.12.81	0,5	0,300	0,200	0,85	15,0	-14,8	-32,1	0,751	0,795
*12	2.11.85	11,0	0,610	0,580	0,90	1,0	-2,2	-4,0	0,962	0,972
*13	25.11.85	No acceptable fit possible								
14	1.12.85	2,0	0,350	0,380	0,90	5,0	-16,6	4,1	0,670	0,881
15	3.12.85	No acceptable fit possible								
Mean							8,8	9,9	0,820	0,885
St. dev.							7,0	9,3	0,126	0,084

Other parameters: N(2) = 0,7 CDEL(3) = 1,0

KC(4) = 0,8 SMAX(8) = 200,0

** Does not include the result for storm 5.

* 'Large' storm events.

Table **A23** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M20** Area 73,9km²

Model Simple antecedent moisture model - OSE1 Type **Semi-distributed**

Sub-cat. No.	Area (%)	Parameters 1 K	3 CDEL	4 KC	15 IL
1	13,0	1,00	5,25	0,80	1,50
2	5,9	0,92	4,50	0,90	1,50
3	5,6	0,92	4,50	0,90	1,50
4	7,0	0,92	4,00	1,00	1,50
5	6,4	0,90	4,00	0,75	1,50
6	7,0	0,90	4,00	0,75	1,50
7	11,4	0,85	3,00	0,50	1,30
8	7,9	0,80	2,75	0,60	1,20
9	6,0	0,65	2,25	0,96	1,10
10	9,7	0,95	1,25	1,40	0,95
11	12,9	1,05	0,75	1,00	0,90
12	7,4	0,80	0,75	0,60	0,85

Parameters N(2), SMAX(8), DA(9), C(10), APF(14), all weights = 1,00

Table **A24** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model Simple antecedent moisture model - **OSE1** Type **Semi-distributed**

Storm No.	Date	CDEL (3)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	1,50	0,560	0,310	0,90	-1,1	0,4	0,929	0,936
2	30.07.60	1,75	0,613	0,090	0,80	26,2	-14,2	0,732	0,816
3	2.06.61	1,75	0,545	0,056	0,80	-11,9	9,6	0,867	0,943
4	31.07.62	1,75	0,650	0,095	0,80	2,6	-21,7	0,884	0,891
5	30.07.63	No acceptable fit							
6	22.07.64	No acceptable fit							
7	7.06.65	2,50	0,490	0,068	0,80	3,9	-5,2	0,862	0,894
8	19.10.66	4,00	0,570	0,237	0,90	-4,7	4,5	0,935	0,967
9	16.07.67	1,25	0,580	0,173	0,80	-7,2	7,3	0,857	0,916
10	11.09.68	1,50	0,680	0,150	0,80	5,4	-12,8	0,972	0,978
11	7.09.69	No acceptable fit							
12	23.08.71	1,25	0,630	0,328	0,80	-1,7	-7,4	0,992	0,993
13	3.07.72	2,50	0,435	0,200	0,80	-1,8	0,8	0,825	0,853
14	10.07.72	1,25	0,620	0,153	0,80	-2,0	-0,9	0,952	0,962
15	17.09.73	1,50	0,613	0,280	0,80	2,0	7,2	0,921	0,921
Mean						5,9	7,7	0,894	0,922
St. dev.						7,1	6,3	0,072	0,052

Other parameters: K(1) = 6,0 N(2) = 0,7

KC(4) = 0,80 SMAX(8) = 150,0

IL(15) = 0,0

Table **A25** Sub-catchment parameter weighting factors

Catchment North Danville, **ND1** Area 42,94km²

Model Simple antecedent moisture model - **OSE1** Type **Semi-distributed**

		Parameters	
Sub-catch.	Area	3	4
No.	%	CDEL	KC
1	19,5	1,00	0,50
2	13,4	0,50	0,75
3	18,0	0,75	0,90
4	19,6	1,25	0,65
5	16,9	0,50	0,70
6	12,6	0,00	1,00

Parameters N(2), SMAX(8), DA(9), C(10), APF(14), IL(15) all weights = 1,00

Table A26 Calibration results

Catchment North Danville, ND5 Area 111,60km²
Model Simple antecedent moisture model - OSE1 Type Semi-distributed

Storm No.	Date	Parameters CDEL (3)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	1,75	0,620	0,090	0,80	9,0	-20,0	0,844	0,857
2	2.06.61	1,50	0,550	0,056	0,80	-10,7	10,7	0,889	0,970
3	31.07.62	1,25	0,585	0,100	0,80	-5,3	-11,7	0,960	0,968
4	30.07.63	No acceptable fit possible							
5	22.07.64	1,00	0,630	0,263	0,80	-0,7	-1,9	0,926	0,931
6	7.06.65	2,00	0,585	0,095	0,80	2,2	-6,6	0,902	0,909
7	19.10.66	1,25	0,585	0,225	0,90	-4,6	1,0	0,960	0,976
8	16.07.67	1,25	0,585	0,160	0,80	-2,4	-4,2	0,930	0,937
9	11.09.68	1,25	0,585	0,125	0,80	1,7	0,5	0,954	0,960
10	7.09.69	No acceptable fit possible							
11	23.08.71	1,25	0,560	0,267	0,80	-4,7	3,9	0,957	0,985
12	10.07.72	1,25	0,585	0,140	0,80	-8,7	4,5	0,924	0,954
13	20.07.72	1,50	0,585	0,148	0,80	1,9	-1,7	0,869	0,869
14	14.07.73	1,00	0,565	0,135	0,80	-5,6	2,9	0,971	0,994
15	17.09.73	1,50	0,585	0,215	0,80	-0,1	-8,6	0,917	0,918
Mean						4,4	6,0	0,923	0,941
St. dev.						3,4	5,5	0,042	0,043

Other parameters: K(1) = 6,0 N(2) = 0,7
KC(4) = 0,85 SMAX(8) = 150,0
IL(15) = 0,0

Table **A27** Sub-catchment parameter weighting factors

Catchment North Danville, **ND5** Area 111,60km^2

Model Simple antecedent moisture model - OSE1 Type **Semi-distributed**

		Parameters	
Sub-catch.	Area	3	4
No.	(%)	CDEL	KC
1	7,5	1,50	0,80
2	5,2	1,00	0,87
3	6,9	1,25	1,35
4	7,5	1,55	0,85
5	6,5	1,00	0,77
6	4,8	0,50	0,73
7	5,2	1,00	0,97
8	5,6	0,75	0,45
9	4,3	0,50	0,67
10	7,7	2,25	0,65
11	4,9	2,00	0,70
12	4,9	1,50	1,00
13	4,4	2,25	0,95
14	7,5	1,75	1,05
15	4,6	1,25	0,75
16	5,4	0,75	0,80
17	2,0	0,00	0,37
18	5,1	0,00	0,50

Parameters K(1), N(2), SMAX(8), DA(9), C(10), APF(14), I,L(15) all weights 1,0

Table A28 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Augmented Hydrograph - OSE3 Type Lumped

Storm No.	Date	Parameters ROP (3)	DEL (5)	A (6)	K (8)	IL (9)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,029	0,00	2,5	13,5	0,0	-1,9	2,6	0,938	0,942
2	6.03.77	0,110	0,00	2,0	4,0	0,0	-0,2	3,0	0,737	0,830
3	7.05.77	0,022	0,00	6,0	9,0	30,0	-21,3	5,4	0,735	0,775
4	19.04.78	0,006	0,25	5,5	8,0	22,0	-0,3	-2,9	0,960	0,961
5	21.04.78	0,064	0,00	1,0	21,0	0,0	-4,2	-0,4	0,828	0,888
* 6	20.07.79	0,320	1,50	4,5	24,0	65,0	-1,0	2,1	0,876	0,879
* 7	23.07.79	0,470	1,25	7,0	15,0	0,0	-0,6	-0,7	0,950	0,900
* 8	19.08.79	0,540	1,50	8,0	16,0	32,0	-6,5	1,8	0,917	0,936
9	26.03.81	0,008	0,00	4,0	8,5	0,0	2,2	-1,2	0,938	0,939
10	22.10.81	0,030	0,00	5,0	10,0	0,0	-16,7	14,4	0,356	0,694
11	23.12.81	0,007	0,50	5,5	6,0	11,0	0,3	-3,5	0,979	0,980
*12	2.11.85	0,300	1,25	7,5	16,5	0,0	-6,8	2,5	0,928	0,962
*13	25.11.85	0,191	0,00	5,0	18,0	0,0	-19,1	4,6	0,524	0,628
14	1.12.85	0,130	1,00	5,5	9,0	0,0	-3,9	-23,8	0,821	0,825
15	3.12.85	No acceptable fit possible								
Mean		0,159					6,1	4,9	0,821	0,867
St. dev.		0,180					7,4	6,4	0,189	0,106

Other parameters: N(4) = 0,5 B(7) = 0,15

* 'Large' storm events.

Table A29 Calibration results

Catchment Ecca, Q9M21 Area 9,1km²

Model Augmented Hydrograph - OSE3 Type Lumped

Storm No.	Date	ROP (3)	A (6)	K (8)	IL (9)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,018	1,0	3,0	1,0	9,5	-10,6	0,848	0,872
2	6.03.77	0,045	1,0	2,5	10,0	5,3	-6,8	0,866	0,868
3	7.05.77	0,190	2,0	6,0	40,0	-12,9	-18,9	0,870	0,892
4	19.04.78		Not modelled		(suspect data)				
5	21.04.78	0,041	0,5	13,0	1,0	-1,6	3,9	0,664	0,771
* 6	20.07.79	0,310	1,5	23,0	50,0	1,2	2,9	0,832	0,841
* 7	23.07.79	0,435	1,5	16,0	1,0	-1,8	2,6	0,960	0,978
* 8	19.08.79	0,480	2,0	25,0	32,0	-5,6	9,4	0,938	0,967
9	26.03.81	0,014	1,0	6,5	1,0	-5,1	4,6	0,598	0,656
10	22.10.81		Not modelled		(zero flow)				
*11	23.12.81	0,026	5,0	1,0	15,0	-2,7	-16,4	0,760	0,783
*12	2.11.85	0,305	1,5	20,0	1,0	-4,1	1,9	0,896	0,956
13	25.11.85		Not modelled		(missing data)				
14	1.12.85	0,049	2,5	6,4	3,0	-0,0	-0,2	0,967	0,968
15	3.12.85		Not modelled		(data errors)				
Mean		0,174				4,5	7,1	0,836	0,868
St. dev.		0,179				3,8	6,1	0,119	0,101

Other parameters: N(4) = 0,5 DEL(5) = 0,001

B(7) = 0,15

* 'Large' storm events.

Table **A30** Calibration results

Catchment North Danville, ND1 Area 42,94km²

Model Augmented Hydrograph - OSE3 Type Lumped

Storm No.	Date	Parameters ROP (3)	DEL (5)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	0,435	0,25	-0,9	7,1	0,991	0,991
2	30.07.60	0,090	1,00	7,3	-8,8	0,900	0,908
3	2.06.61	0,385	0,25	-1,8	0,1	0,974	0,975
4	31.07.62	0,238	0,50	6,6	-3,8	0,958	0,967
5	30.07.63	Not modelled (rainfall very spatially variable)					
6	22.07.64	0,068	0,25	-2,0	5,9	0,284	0,511
7	7.06.65	0,165	1,75	5,3	0,3	0,945	0,958
8	19.10.66	0,135	0,75	-4,1	2,5	0,930	0,961
9	16.07.67	0,160	0,00	-2,4	-2,2	0,856	0,888
10	11.09.68	0,090	1,00	-3,2	-1,9	0,981	0,982
11	7.09.69	No acceptable fit possible					
12	23.08.71	0,110	0,50	2,3	-1,5	0,963	0,970
13	3.07.72	0,240	1,25	3,0	0,1	0,967	0,969
14	10.07.72	0,140	0,50	-1,8	0,7	0,969	0,971
15	17.09.73	0,170	0,75	4,4	-6,8	0,977	0,980
Mean		0,187		3,5	3,2	0,899	0,925
St. dev.		0,112		2,0	3,0	0,189	0,128

Other parameters: N(3) = 0,5 A(6) = 4,0

B(7) = 0,15 K(8) = 15,0

IL(9) = 2,5

Table **A31** Calibration results

Catchment North Danville, ND5 Area 111,60km^2

Model Augmented hydrograph - OSE3 Type Lumped

Storm No.	Date	Parameters ROP (3)	DEL (5)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,100	1,75	4,8	-2,4	0,925	0,929
2	2.06.61	0,370	0,25	-4,2	0,3	0,961	0,965
3	31.07.62	0,195	0,50	-0,9	8,2	0,986	0,988
4	30.07.61	No acceptable fit possible					
5	22.07.64	0,135	0,00	1,6	0,6	0,923	0,925
6	7.06.65	0,110	2,00	-0,6	-0,2	0,945	0,950
7	19.10.66	0,125	0,00	-1,2	4,9	0,945	0,957
8	16.07.67	0,190	0,00	5,7	-3,7	0,900	0,916
9	11.09.68	0,093	1,25	-9,0	8,4	0,968	0,983
10	7.09.69	0,215	1,00	1,8	-8,5	0,887	0,894
11	23.08.71	0,125	0,75	-2,5	4,6	0,985	0,993
12	10.07.72	0,160	0,75	-3,9	5,1	0,963	0,969
13	20.07.72	0,235	0,50	-0,7	0,8	0,966	0,967
14	14.07.73	0,300	0,00	4,4	-2,1	0,931	0,937
15	17.09.73	0,185	0,50	6,3	-2,6	0,950	0,958
Mean		0,181		3,4	2,9	0,945	0,952
St. dev.		0,080		2,5	2,6	0,029	0,029

Other parameters: N(4) = 0,5 A(6) = 5,0

B(7) = 0,15 K(8) = 15,0

IL(9) = 2,5

Table A32 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Augmented Hydrograph - OSE3 Type Semi-distributed

Storm No.	Date	Parameters CDEL (1)	ROP (3)	K (8)	IL (9)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,5	0,022	5,0	20,0	-3,8	3,5	0,889	0,909
2	6.03.77	1,0	0,095	3,5	6,0	-6,5	-3,4	0,744	0,846
3	7.05.77	0,5	0,062	7,5	30,0	-3,4	0,3	0,807	0,819
4	19.04.78	0,5	0,010	4,5	22,0	12,1	-7,5	0,944	0,949
**5	21.04.78	0,5	0,030	5,0	1,0	-25,1	9,4	-0,438	0,587
* 6	20.07.79	1,0	0,350	16,0	65,0	-0,7	-13,8	0,910	0,915
* 7	23.07.79	1,0	0,410	16,0	0,0	0,23	1,9	0,966	0,933
* 8	19.08.79	1,0	0,580	17,0	32,0	-6,75	-1,2	0,953	0,966
9	26.03.81	0,5	0,008	3,0	0,0	9,8	-12,3	0,950	0,962
10	22.10.81	0,5	0,028	9,0	10,0	-2,8	11,1	0,493	0,736
11	23.12.81	0,5	0,007	1,0	13,0	4,0	-11,2	0,747	0,783
*12	2.11.85	1,0	0,310	18,0	0,0	-3,4	0,8	0,949	0,972
*13	25.11.85	No acceptable fit possible							
14	1.12.85	0,5	0,130	9,5	4,0	-0,5	-3,7	0,898	0,925
15	3.12.85	No acceptable fit possible							
Mean			0,157			6,1	6,2	0,854	0,868
St. dev.			0,190			6,7	4,9	0,138	0,113

Other parameters: KC(2) = 0,8 N(4) = 0,5

** Does not include the result for storm 5.

* 'Large' storm events.

Table **A33** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M20** Area 73,9km²

Model Augmented Hydrograph - OSE3 Type **Semi-distributed**

		Parameters			
Sub-cat.	Area	1	2	8	9
No.	(%)	CDEL	KC	K	IL
1	13,0	5,25	0,80	1,00	1,50
2	5,9	4,50	0,90	0,92	1,50
3	5,6	4,50	0,90	0,92	1,50
4	7,0	4,00	1,00	0,92	1,50
5	6,4	4,00	0,75	0,90	1,50
6	7,0	4,00	0,75	0,90	1,50
7	11,4	3,00	0,50	0,85	1,30
8	7,9	2,75	0,60	0,80	1,20
9	6,0	2,25	0,96	0,65	1,10
10	9,7	1,25	1,40	0,95	0,95
11	12,9	0,75	1,00	1,05	0,90
12	7,4	0,75	0,60	0,80	0,85

Parameters ROP(3), N(4) all weights = 1,00

Table **A34** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model Augmented Hydrograph - OSE3 Type Semi-distributed

Storm No.	Date	Parameters ROP (3)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	24.10.59	0,438	-3,8	2,5	0,987	0,991
2	30.07.60	0,090	11,6	-10,8	0,869	0,886
3	2.06.61	0,405	0,9	3,7	0,983	0,989
4	31.07.62	0,230	2,4	-10,5	0,972	0,973
5	30.07.63	Not modelled (rainfall very spatially variable)				
*6	22.07.64	0,100	-1,4	-0,9	0,043	0,378
7	7.06.65	0,190	7,5	-6,6	0,906	0,915
8	19.10.66	0,148	-2,1	-0,3	0,967	0,986
9	16.07.67	0,198	-5,3	-12,3	0,871	0,883
10	11.09.68	0,095	1,7	-2,7	0,996	0,997
11	7.09.69	No acceptable fit possible				
12	23.08.71	0,091	-1,3	-1,3	0,972	0,984
13	3.07.72	0,242	-1,3	-12,6	0,797	0,779
14	10.07.72	0,168	2,7	-0,6	0,957	0,966
15	17.09.73	0,165	1,9	-7,0	0,972	0,972
Mean		0,197	3,4	5,5	0,934	0,943
St. dev.		0,112	3,1	4,7	0,062	0,066

Other parameters: CDEL(1) = 1,0 KC(2) = 0,80
N(4) = 0,5 K(8) = 15,0
IL(9) = 2,5

*Does not include the result for storm 6.

Table **A35** Sub-catchment parameter weighting factors

Catchment North Danville, **ND1** Area 42,94km²

Model Augmented Hydrograph - OSE3 Type **Semi-distributed**

		Parameters	
Sub-catch.	Area	1	2
No.	%	CDEL	KC
1	19,5	1,00	0,50
2	13,4	0,50	0,75
3	18,0	0,75	0,90
4	19,6	1,25	0,65
5	16,9	0,50	0,70
6	12,6	0,00	1,00

Parameters ROP(3), N(4), K(8), IL(9) all weights = 1,00

Table A36 Calibration results

Catchment North Danville, ND5 Area 111,60km²

Model Augmented hydrograph - OSE3 Type Semi-distributed

Storm No.	Date	Parameters ROP (3)	errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,100	6,8	-6,8	0,838	0,859
2	2.06.61	0,385	1,2	10,1	0,938	0,960
3	31.07.62	0,205	-0,1	0,9	0,994	0,995
4	30.07.61	No acceptable fit possible				
5	22.07.64	0,101	-1,5	2,7	0,901	0,914
6	7.06.65	0,120	-0,9	-9,6	0,911	0,912
7	19.10.66	0,125	-1,6	3,9	0,965	0,968
8	16.07.67	0,170	0,3	3,2	0,947	0,958
9	11.09.68	0,100	-6,8	0,0	0,981	0,988
10	7.09.69	0,080	0,2	-0,1	0,718	0,773
11	23.08.71	0,125	-1,2	1,0	0,976	0,983
12	10.07.72	0,205	2,6	2,8	0,978	0,985
13	20.07.72	0,238	1,4	3,6	0,937	0,949
14	14.07.73	0,270	2,8	1,7	0,871	0,881
15	17.09.73	0,195	1,7	-2,9	0,978	0,980
Mean		0,173	2,1	3,5	0,924	0,936
St. dev.		0,084	2,1	3,2	0,075	0,063

Other parameters: CDEL(1) = 1,0 KC(2) = 0,85

N(4) = 0,5 K(8) = 15,0

IL(9) = 2,5

Table **A37** Sub-catchment parameter weighting factors

Catchment North Danville, ND5 Area 73,9km²

Model Augmented Hydrograph - OSE3 Type **Semi-distributed**

		Parameters	
Sub-catch	Area	1	2
No.	(%)	CDEL	KC
1	7,5	1,50	0,50
2	5,2	1,00	0,70
3	6,9	1,25	0,85
4	7,5	1,55	0,60
5	6,5	1,00	0,65
6	4,8	0,50	0,95
7	5,2	1,00	0,55
8	5,6	0,75	0,25
9	4,3	0,50	0,55
10	7,7	2,25	0,45
11	4,9	2,00	0,55
12	4,9	1,50	0,90
13	4,4	2,25	0,50
14	7,5	1,75	0,65
15	4,6	1,25	0,40
16	5,4	0,75	1,05
17	2,0	0,00	0,15
18	5,1	0,00	1,00

Parameters ROP(3), N(4), K(8), IL(9) all weights = 1,0

Table A38 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Runoff-routing - OSE4 Type Semi-distributed

Storm No.	Date	KC	Parameters I.Loss.	R.Coeff	% errors: Volume	Peak	AAOE %
1	28.02.77	1,0	15,0	0,03	-8,8	-7,3	34,7
2	6.03.77	4,0	8,0	0,15	-3.6	-2,8	35,2
3	7.05.77	3,0	42,0	0,05	-12,0	-4,8	63,8
4	19.04.78	0,8	45,0	0,02	-25,7	-1,9	50,5
5	21.04.78	3,0	5,0	0,03	-2,6	-26,8	32,7
*6	20.07.79	9,0	65,0(0)	0,05(0,38)	0,1	-4,6	18,8
7	23.07.79	8,0	10,0	0,25	-3,3	-12,1	15,1
8	19.08.79	15,0	50,0	0,60	-0,7	-2,1	20,8
9	26.03.81	1,0	12,0	0,01	-33,7	-61,4	64,0
10	22.10.81	2,5	5,0	0,02	-4,1	-0,2	28,3
11	23.12.81	No acceptable fit possible					
12	2.11.85	10,0	10,0	0,17	-2,6	4,5	19,3
13	25.11.85	8,0	10,0	0,19	-0,6	27,8	31,1
14	1.12.85	13,0	13,0	0,12	-2,6	-3,3	56,0
15	3.12.85	Not modelled (data errors)					
Mean				0,148	8,4	12,3	36,2
St. dev.				0,169	10,4	17,3	17,1

Other parameters: Parameter N = 0,7

* 2 rainfall bursts in storm - figures in parenthesis refer to 2nd burst.

Table **A39** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model Runoff - routing - OSE4 Type Semi-distributed

Storm No.	Date	KC	Parameters I.Loss	R.Coeff	errors: Volume	Peak	AAOE %
1	24.10.59	9,0	8,0	0,38	-3,9	-5,4	13,7
2	30.07.60	5,0	25,0	0,10	-7,0	-4,5	18,0
3	2.06.61	8,0	10,0	0,34	-4,4	2,5	13,4
4	31.07.62	7,0	20,0	0,26	-1,9	-3,3	14,2
5	30.07.63	no acceptable fit possible					
6	22.07.64	3,5	0,0	0,04	-7,6	3,6	34,3
7	7.06.65	10,0	12,0	0,20	-5,1	-4,2	26,6
8	19.10.66	3,8	10,0	0,09	-5,9	-6,1	20,2
9	16.07.67	8,0	25,0	0,35	-5,3	6,0	20,6
10	11.09.68	4,0	22,0	0,10	-10,0	-3,6	29,8
11	7.09.69	no acceptable fit possible					
12	23.08.71	3,5	15,0	0,10	-4,6	-2,6	21,2
13	3.07.72	6,0	22,0	0,71	-3,7	2,7	38,2
14	10.07.72	5,8	10,0	0,12	-4,5	-5,9	13,8
15	17.09.73	6,0	15,0	0,16	-4,1	1,9	10,6
Mean				0,227	5,2	4,0	21,1
St. dev.				0,183	2,1	1,4	8,7

Other parameters: N = 0,7

Table **A40** Calibration results

Catchment North Danville, **ND5** Area 111,60km²

Model Runoff-routing - **OSE4** Type Semi-distributed

Storm No.	Date	KC	Parameters I.Loss	R.Coeff	% errors: Volume	Peak	AAOE %
1	30.07.60	5,5	22,0	0,10	-3,4	-1,5	17,5
2	2.06.61	9,0	10,0	0,32	-3,6	1,3	17,1
3	31.07.62	8,0	20,0	0,24	-1,7	6,8	14,8
4	30.07.61		No acceptable fit possible				
5	22.07.64	5,0	10,0	0,08	-6,5	10,5	26,2
6	7.06.65	6,5	18,0	0,12	-4,1	-2,7	8,2
7	19.10.66	4,5	10,0	0,08	-5,8	-9,5	11,5
8	16.07.67	6,0	15,0	0,11	-2,1	-12,1	16,7
9	11.09.68	5,0	20,0	0,10	-3,3	-2,1	26,0
10	7.09.69	4,0	22,0	0,12	-11,5	-8,9	31,4
11	23.08.71	5,5	15,0	0,11	-6,5	-0,5	24,1
12	10.07.72	7,0	5,0	0,12	-4,3	-3,7	15,9
13	20.07.72	7,0	10,0	0,18	-2,0	-0,1	20,6
14	14.07.73	5,5	5,0	0,15	-3,1	1,7	9,8
15	17.09.73	7,0	15,0	0,17	-2,8	-3,1	10,0
Mean				0,143	4,3	4,6	17,8
St. dev.				0,067	2,6	4,1	7,0

Other parameters: N = 0,7

APPENDIX B

MODEL CALIBRATION RESULTS : GRAPHICAL PLOTS

Figure	Catchment	Storm date	Different models A	B	C	D
B1	Q9M20	6.03.77	OSE2-SD	OSE1-LM	OSE3-SD	OSE4-SD
B2	Q9M20	21.04.78	OSE2-LM	OSE2-SD	OSE3-LM	OSE4-SD
B3	Q9M21	21.04.78	OSE2-LM	OSE3-LM		
B4	Q9M20	20.07.79	OSE2-LM	OSE3-LM	OSE4-SD	
B5	Q9M20	23.07.79	OSE2-LM	OSE3-LM	OSE4-SD	
B6	ND1	21.10.59	OSE2-SD	OSE1-SD		
B7	ND1	21.10.59	OSE3-SD	OSE4-SD		
B8	ND1	22.07.64	OSE2-SD	OSE3-SD	OSE4-SD	
B9	ND1	19.10.66	OSE2-LM	OSE3-LM		
B10	ND1	16.07.67	OSE2-LM	OSE2-SD		
B11	ND4	16.07.67	OSE2-LM	OSE2-SD		
B12	ND5	16.07.67	OSE2-LM	OSE2-SD		
B13	ND5	16.07.67	OSE3-LM	OSE3-SD		
B14	ND1-ND5	19.10.67	OSE2-SD			
B15	ND1-ND5	11.09.68	OSE2-SD			

Note: The same scale is used for streamflow discharges (always in cumecs) and rainfall (in mmh^{-1} multiplied by a variable factor). Thus using mmh^{-1}*0.1-2.0 on the axis represents $20mmh^{-1}$.

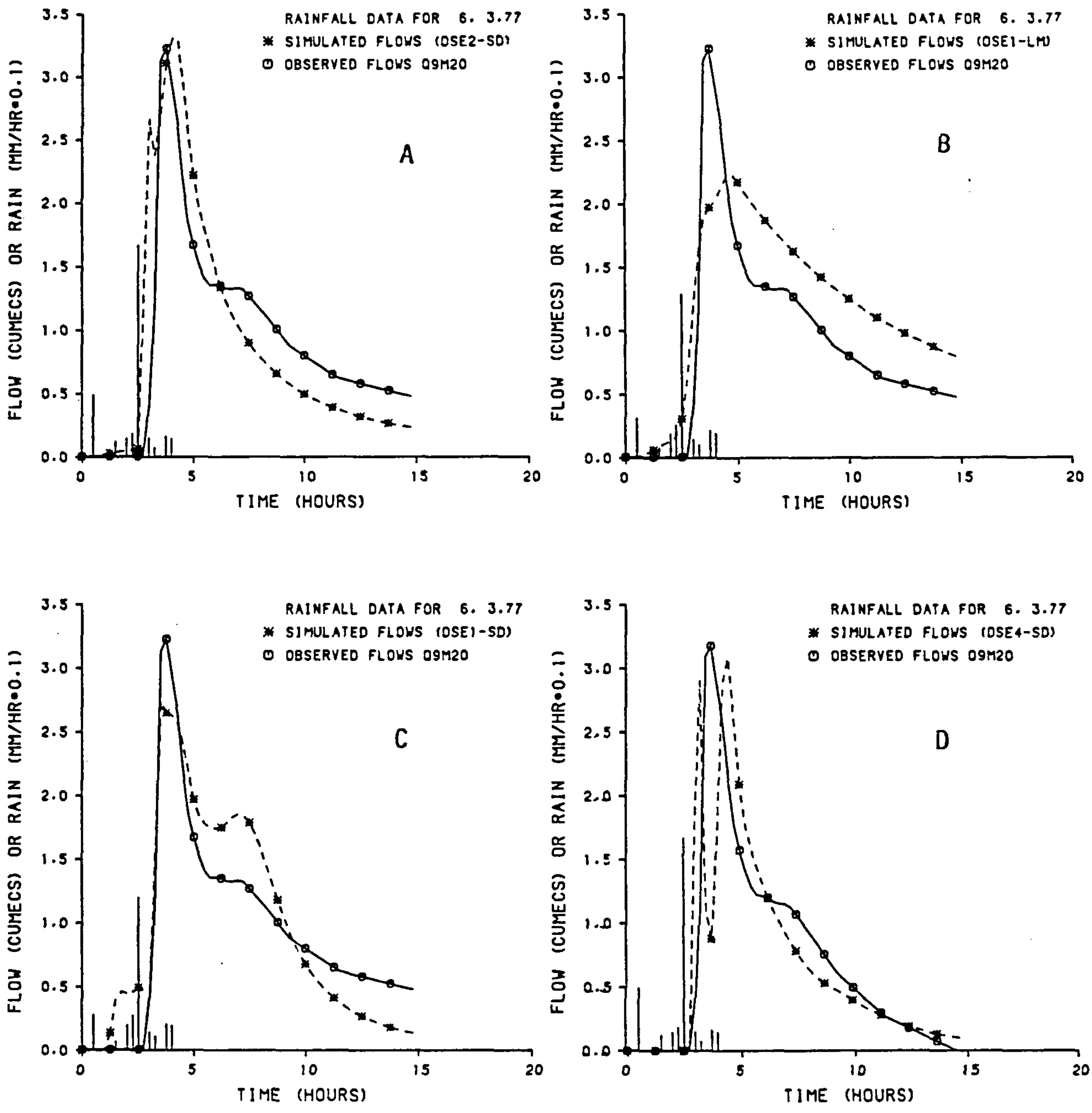


FIGURE B1 A-D Ecca Q9M20

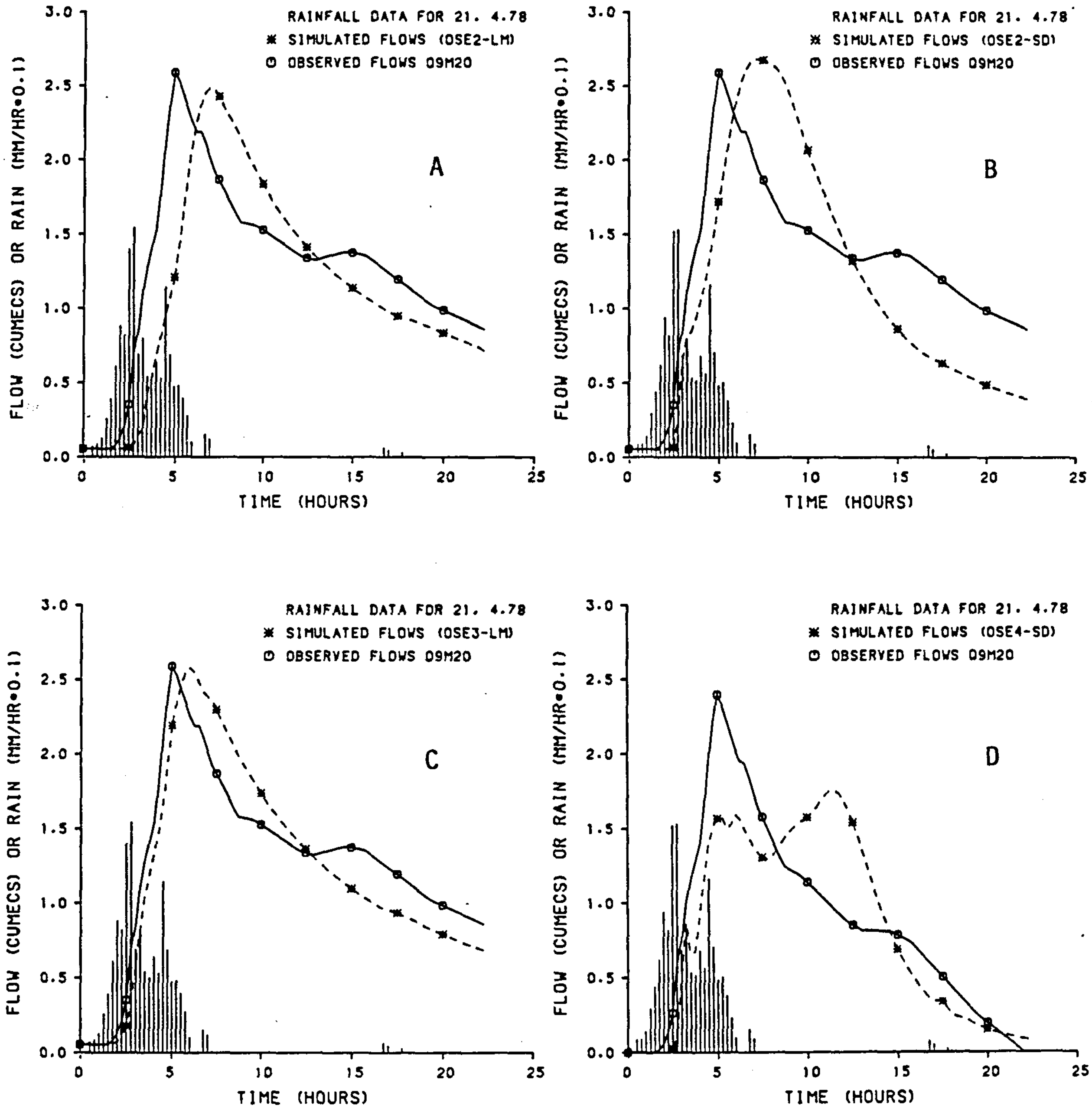
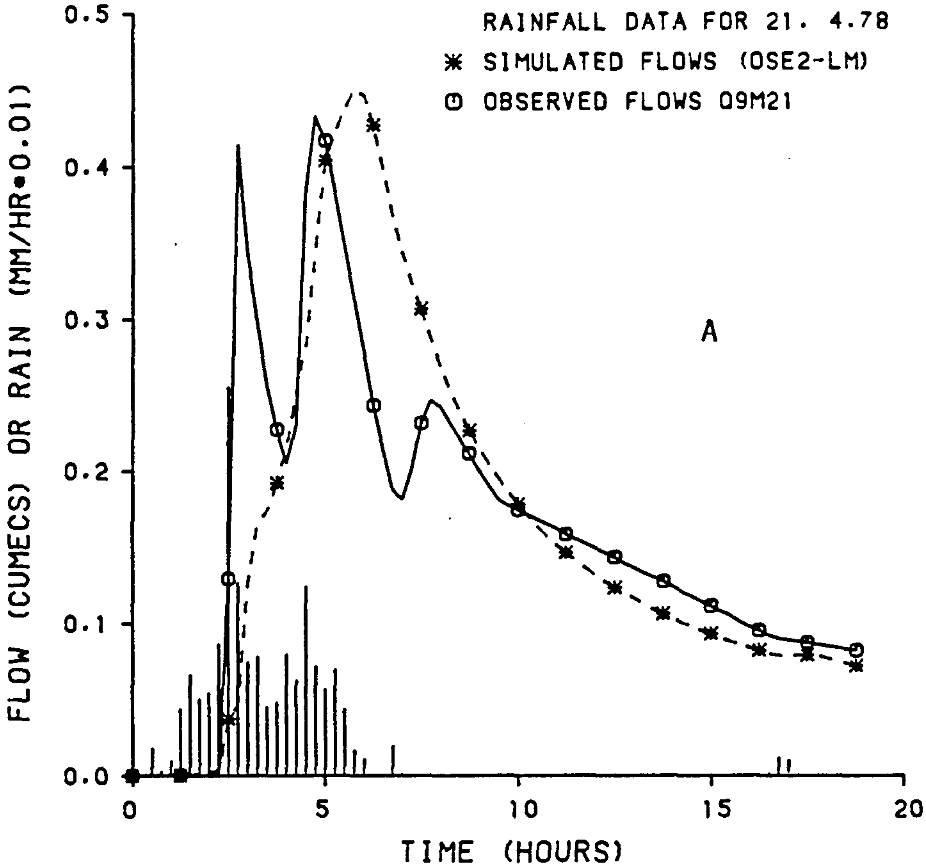


FIGURE B2 A-D Ecca Q9M20



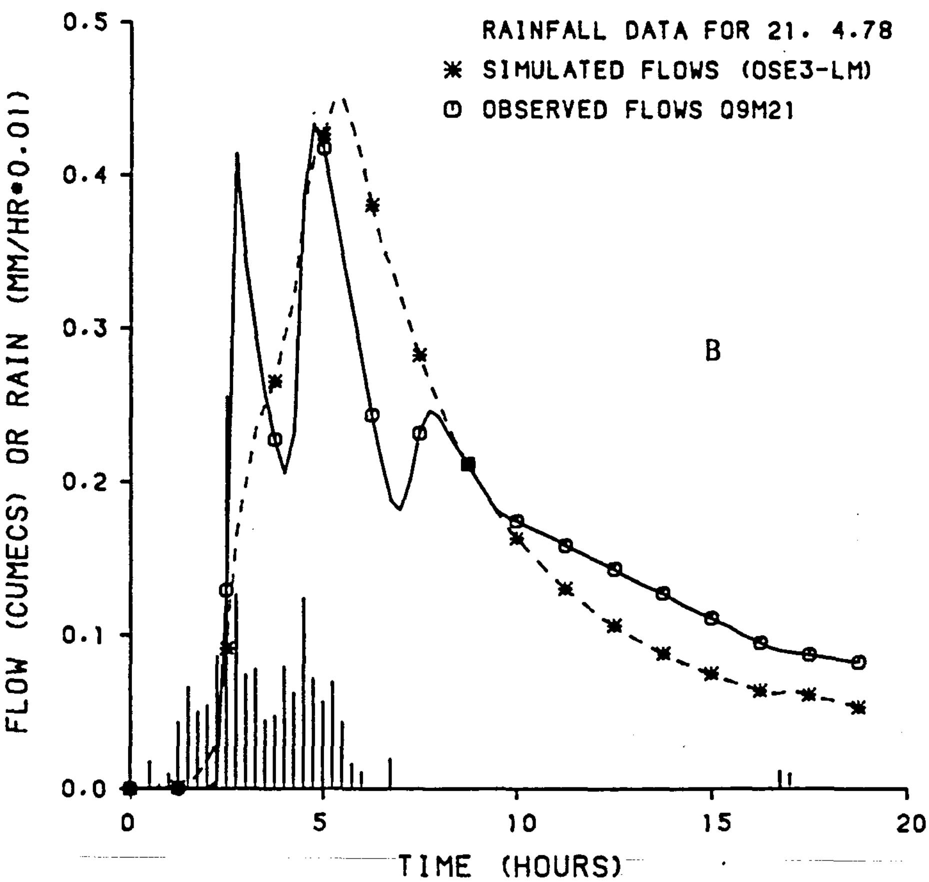


FIGURE B3 A-B Ecca Q9M21

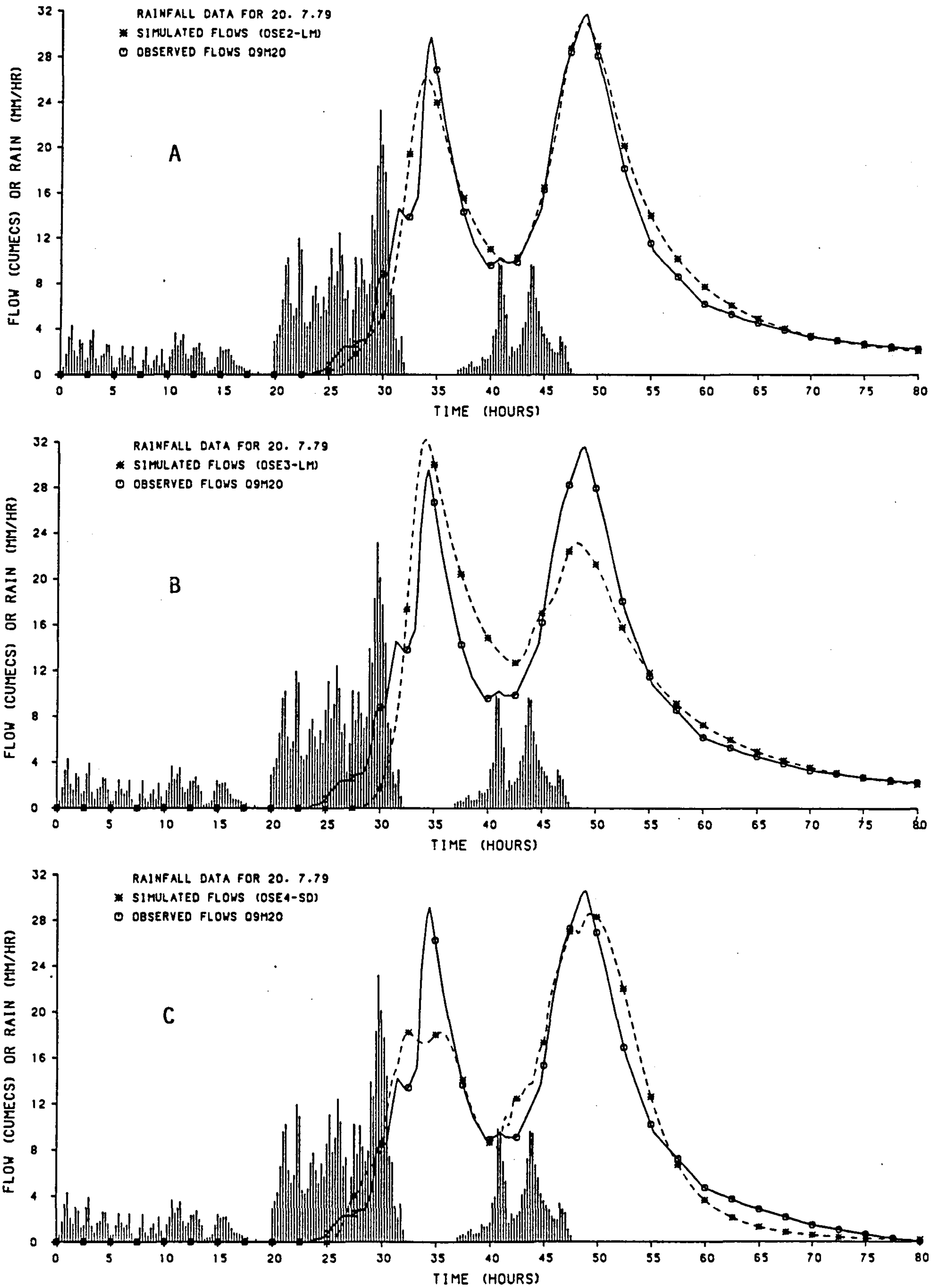


FIGURE B4 A-C Ecca Q9M20

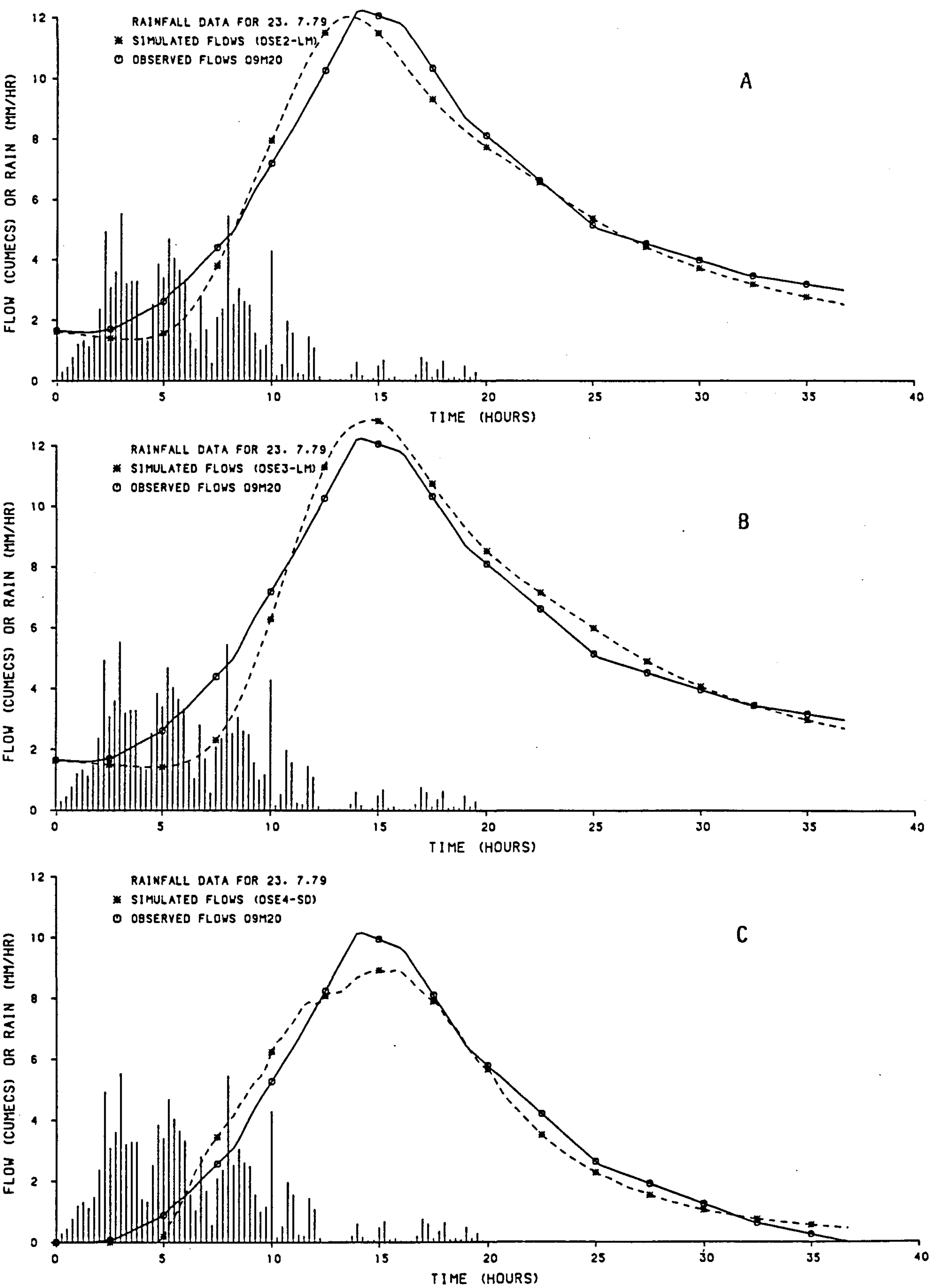
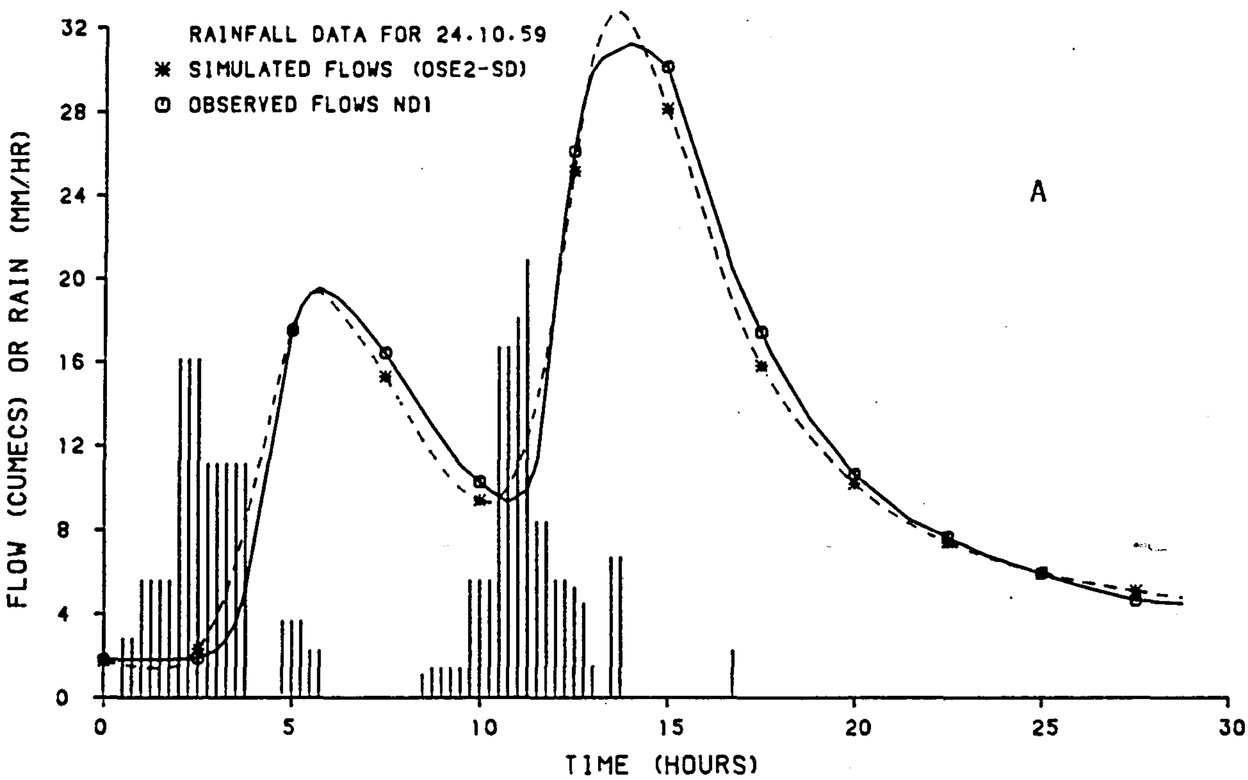


FIGURE B5 A-C Ecca Q9M20



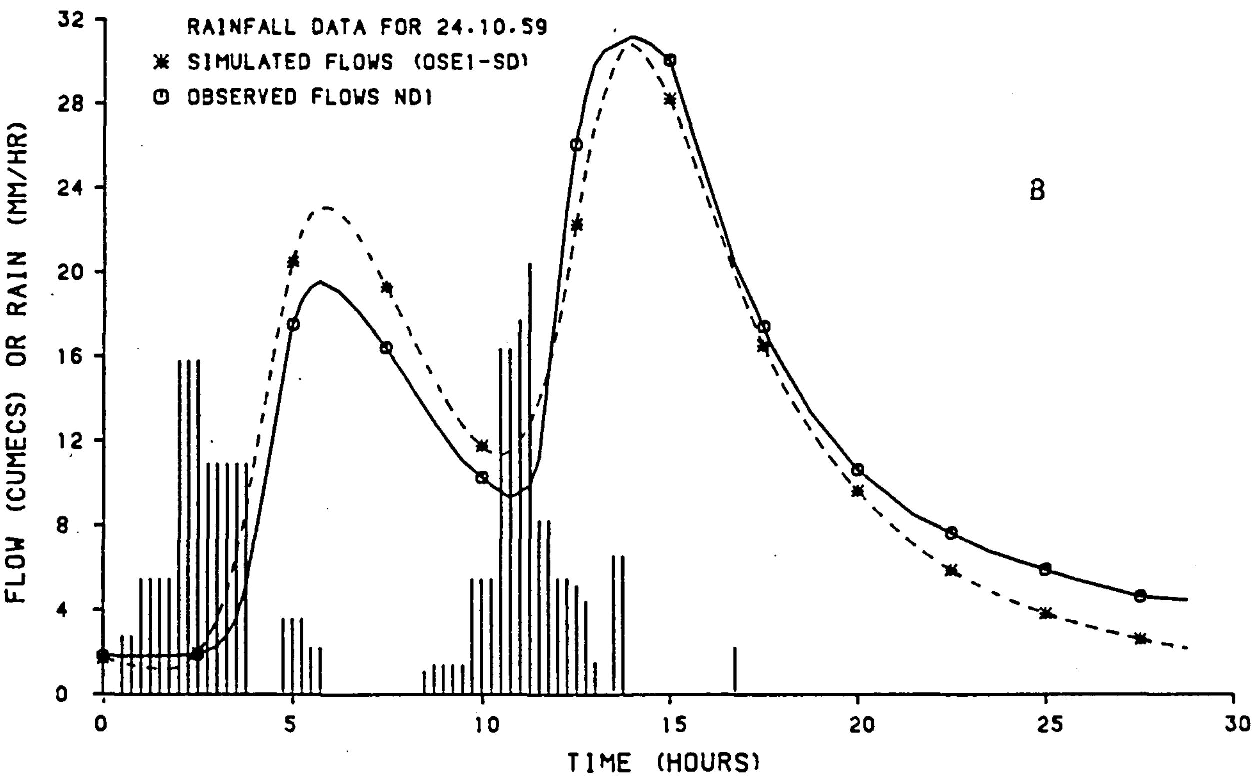


FIGURE B6 A-B N.Danville ND1

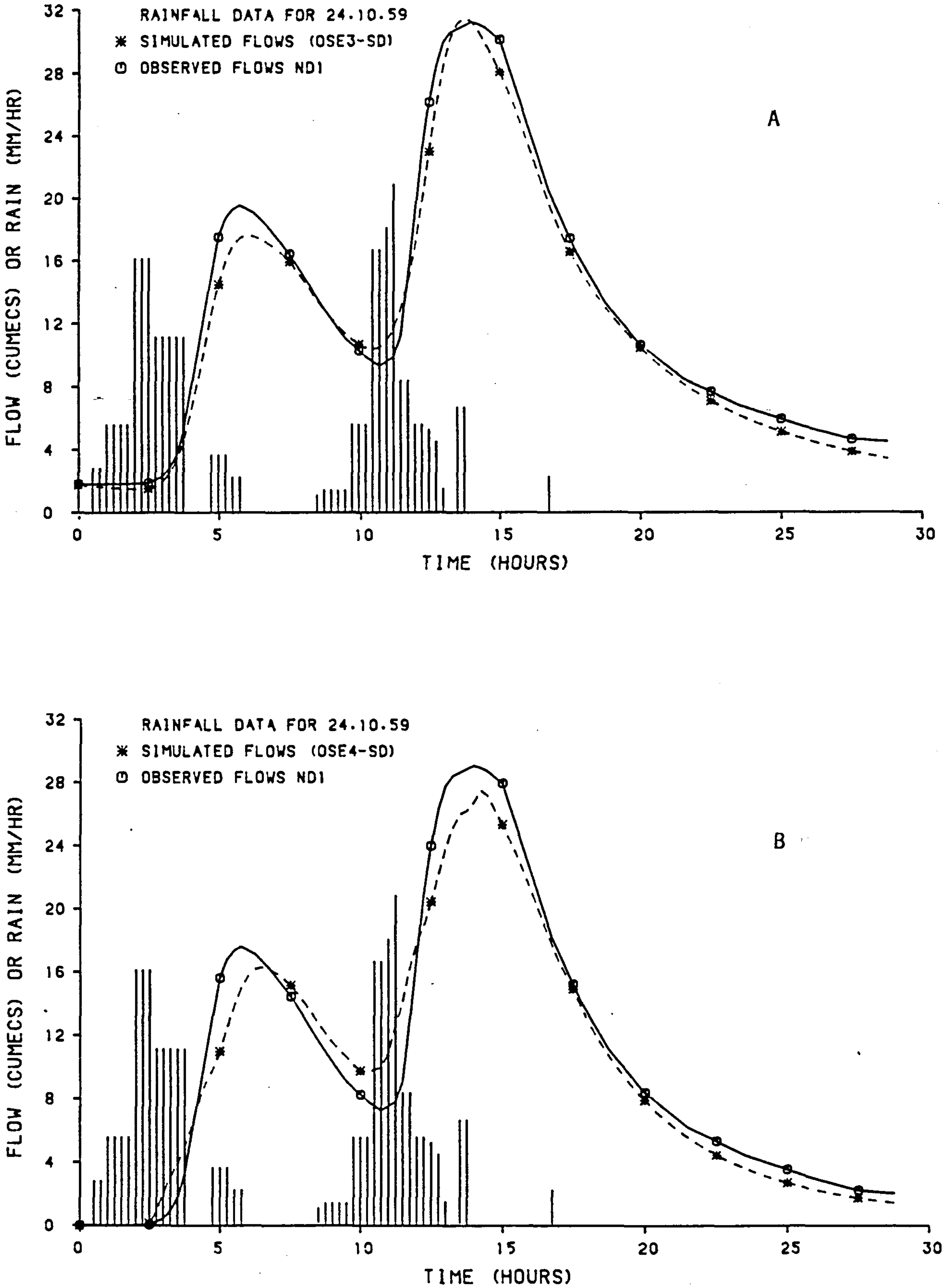


FIGURE B7 A-B N.Danville ND1

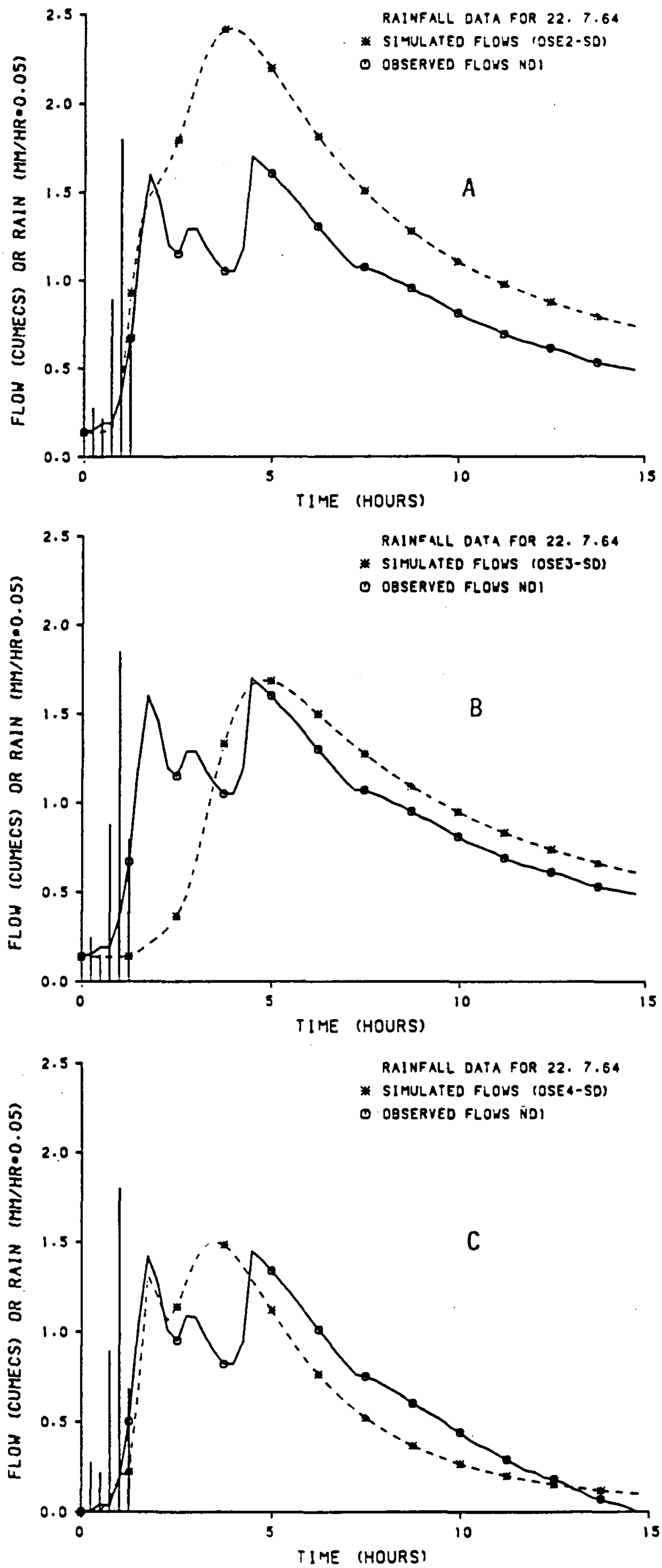


FIGURE B8 A-C N.Danville ND1

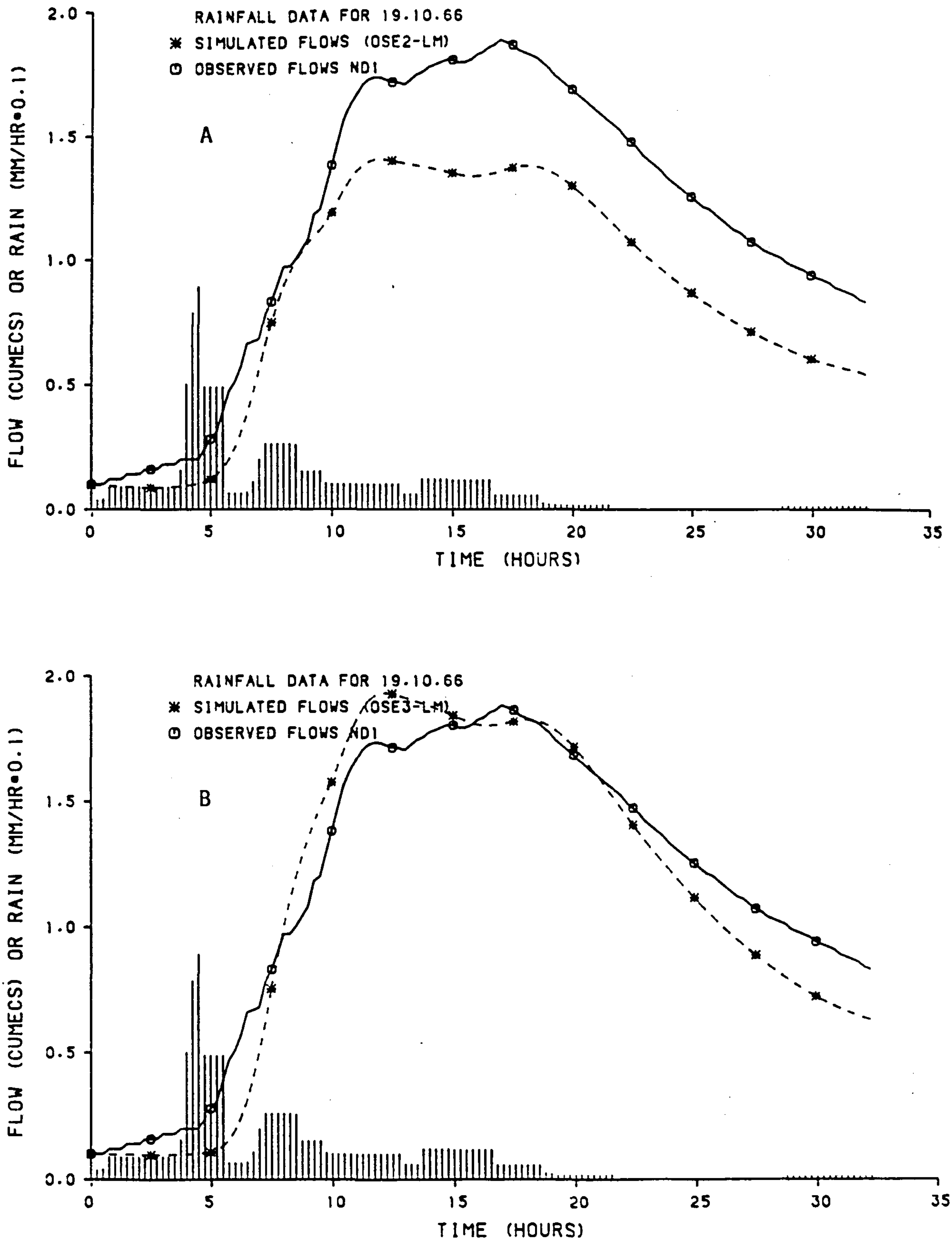
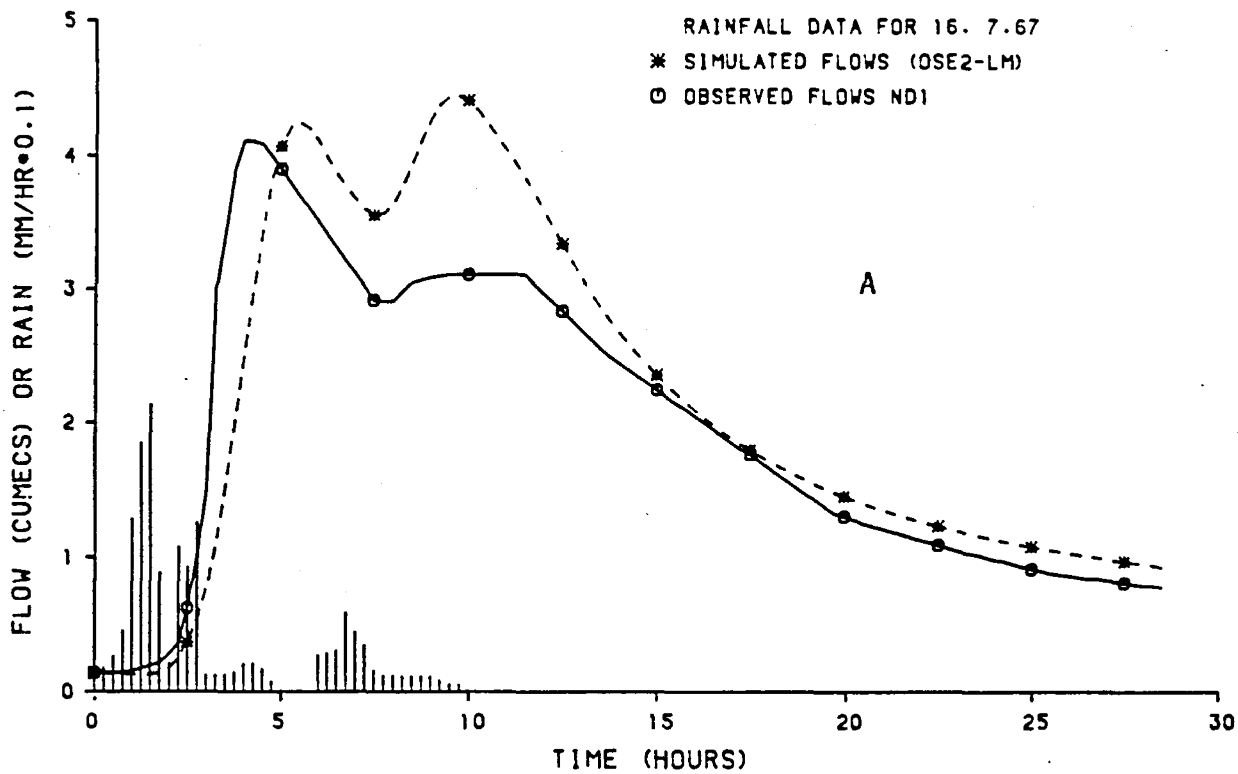


FIGURE B9 A-B N.Danville ND1



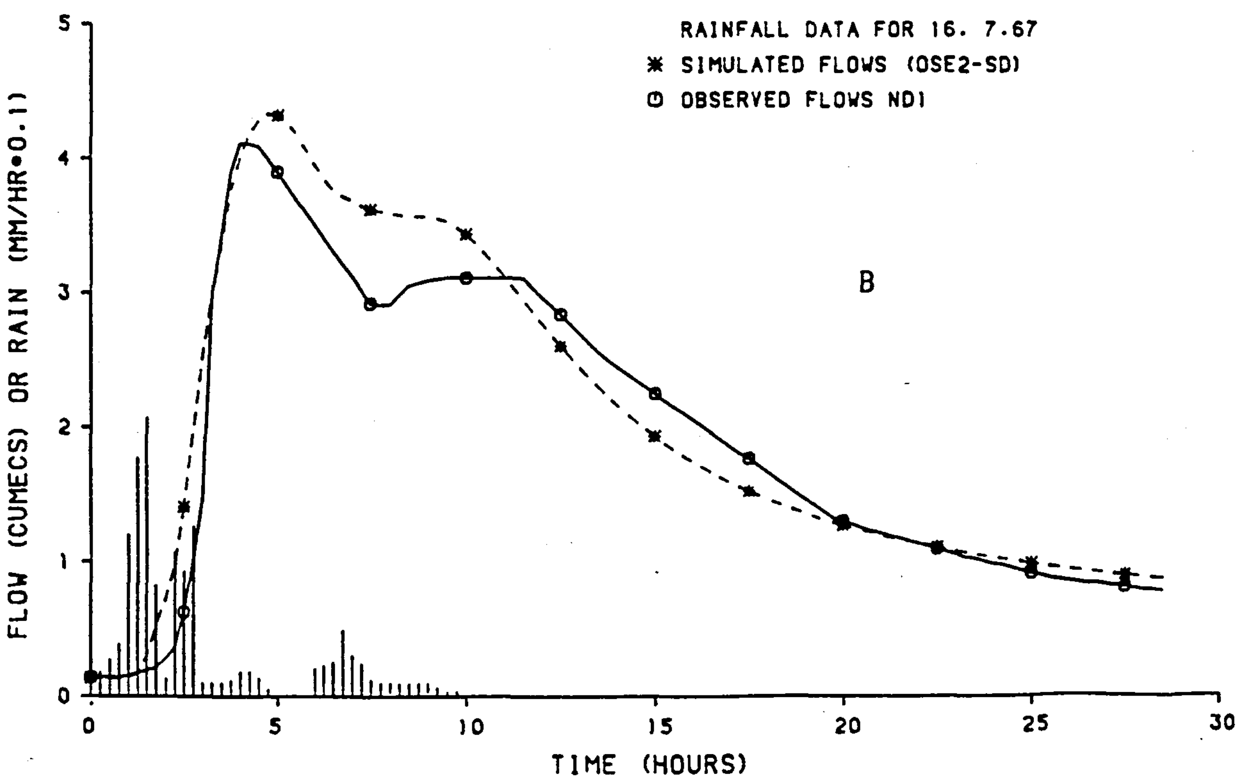
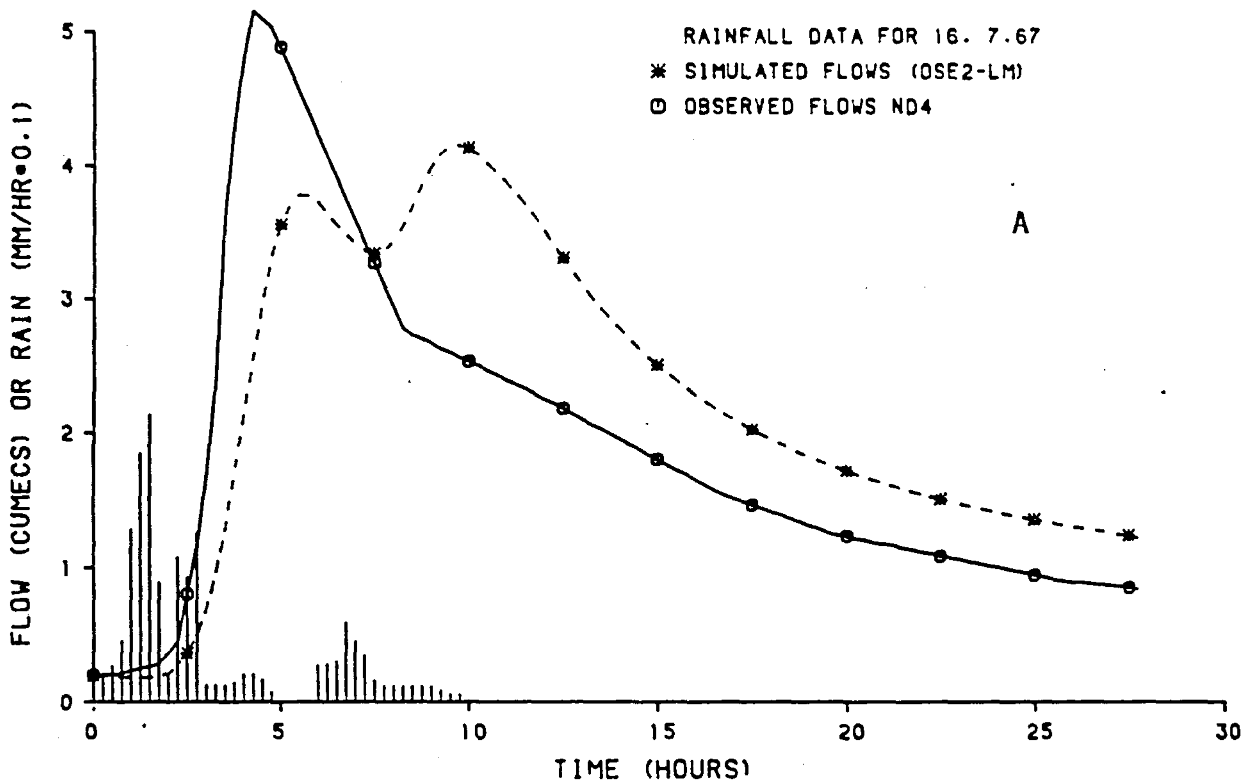


FIGURE B10 A-B N.Danville ND1



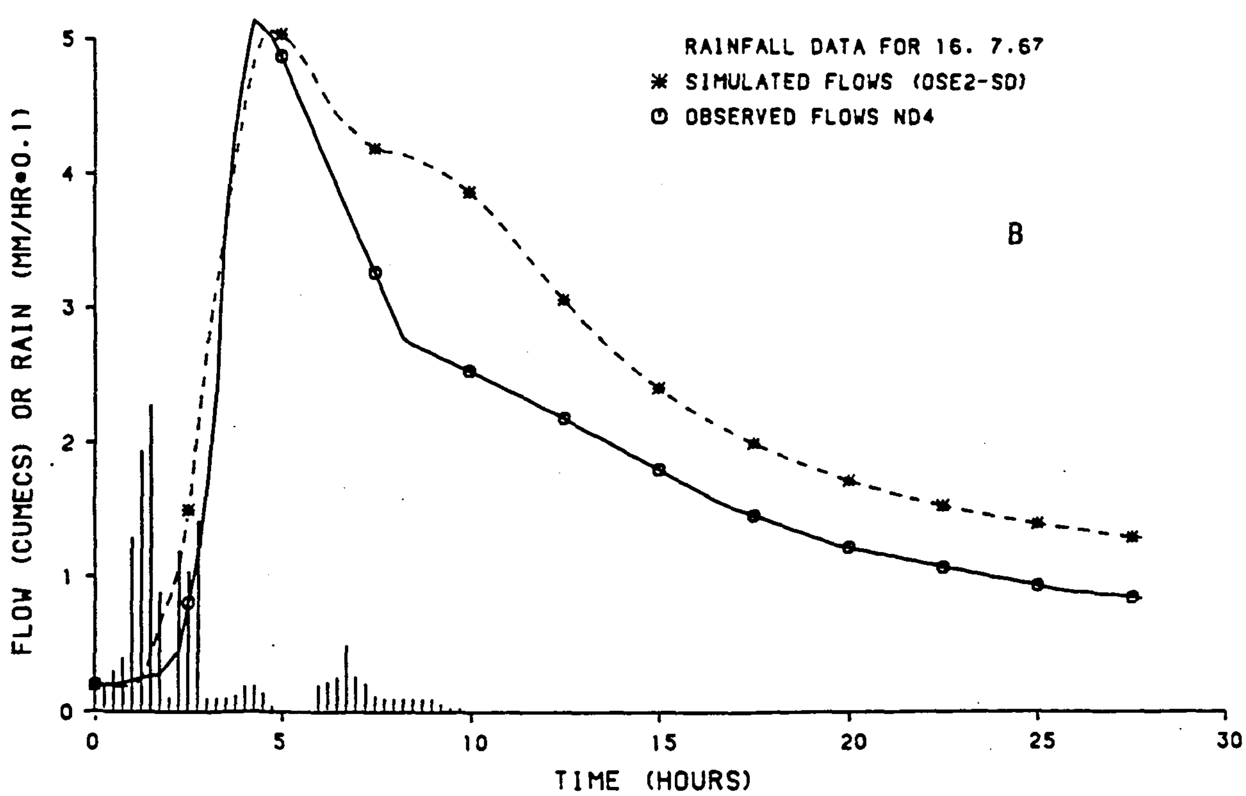
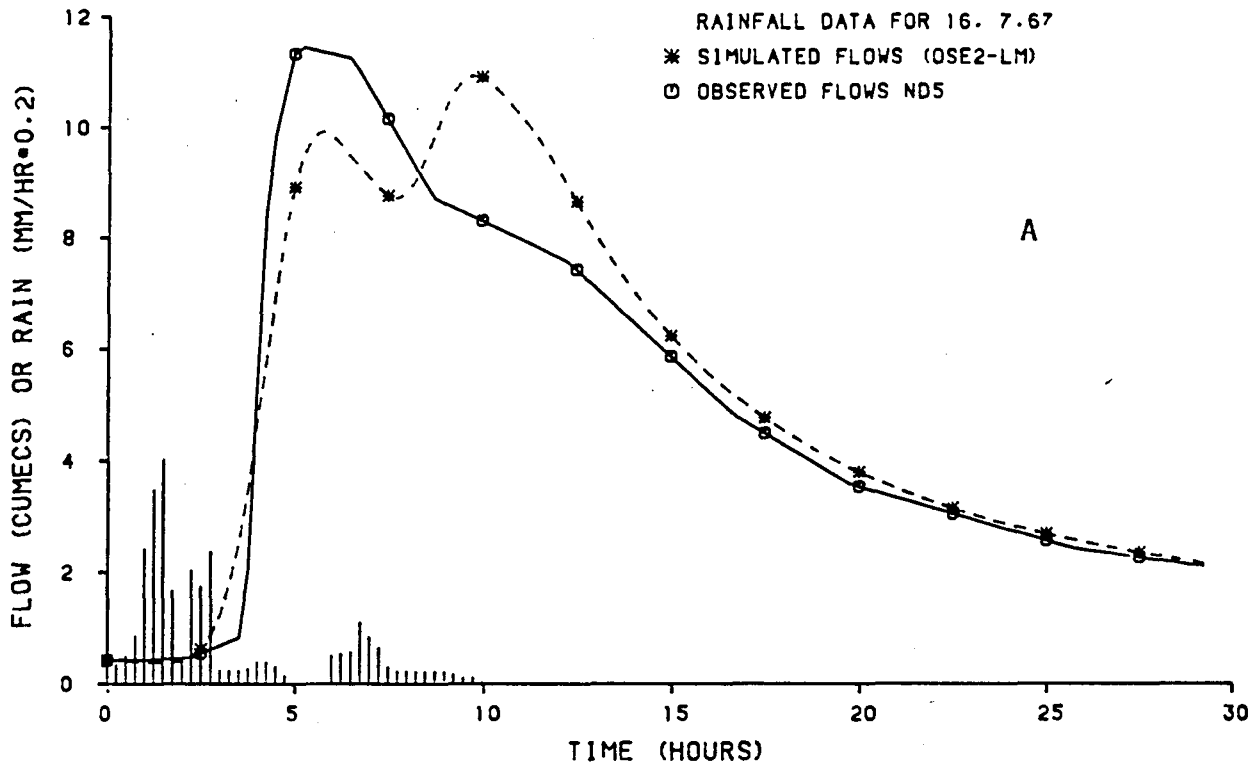


FIGURE B11 A-B N.Danville ND4



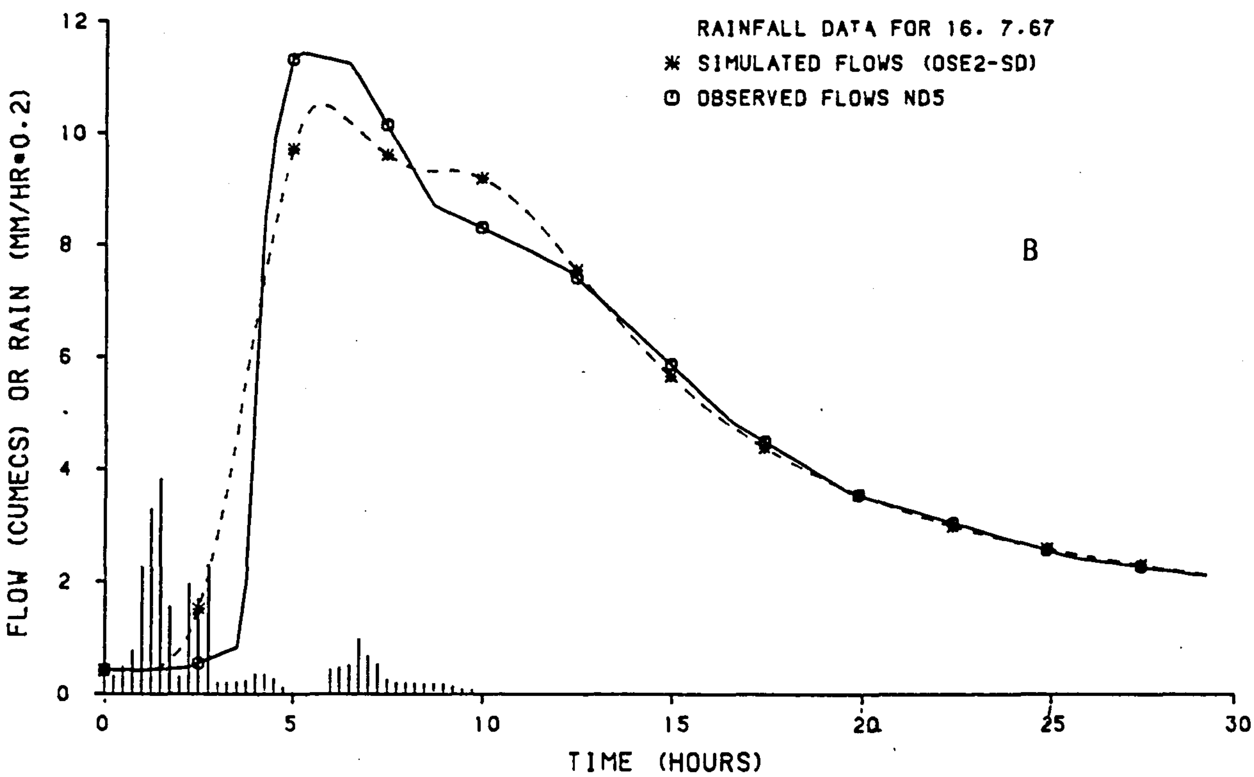
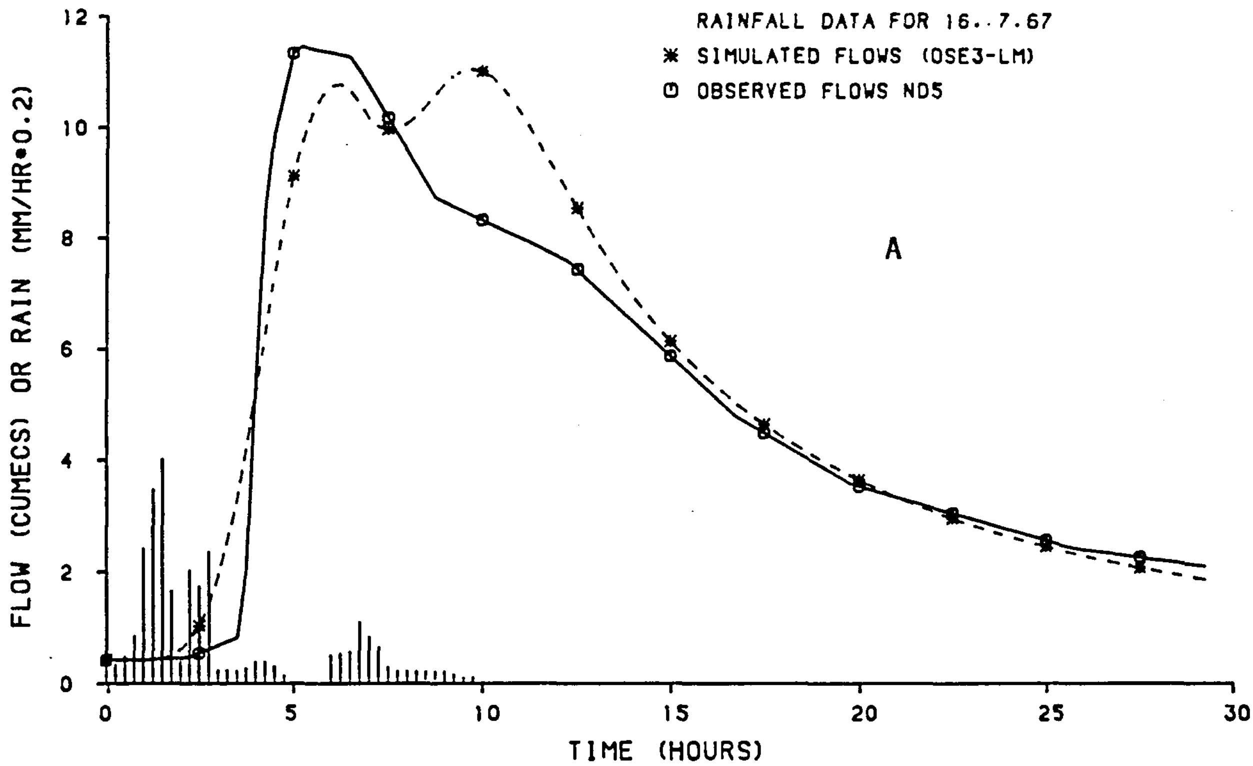


FIGURE B12 A-B N.Danville ND5



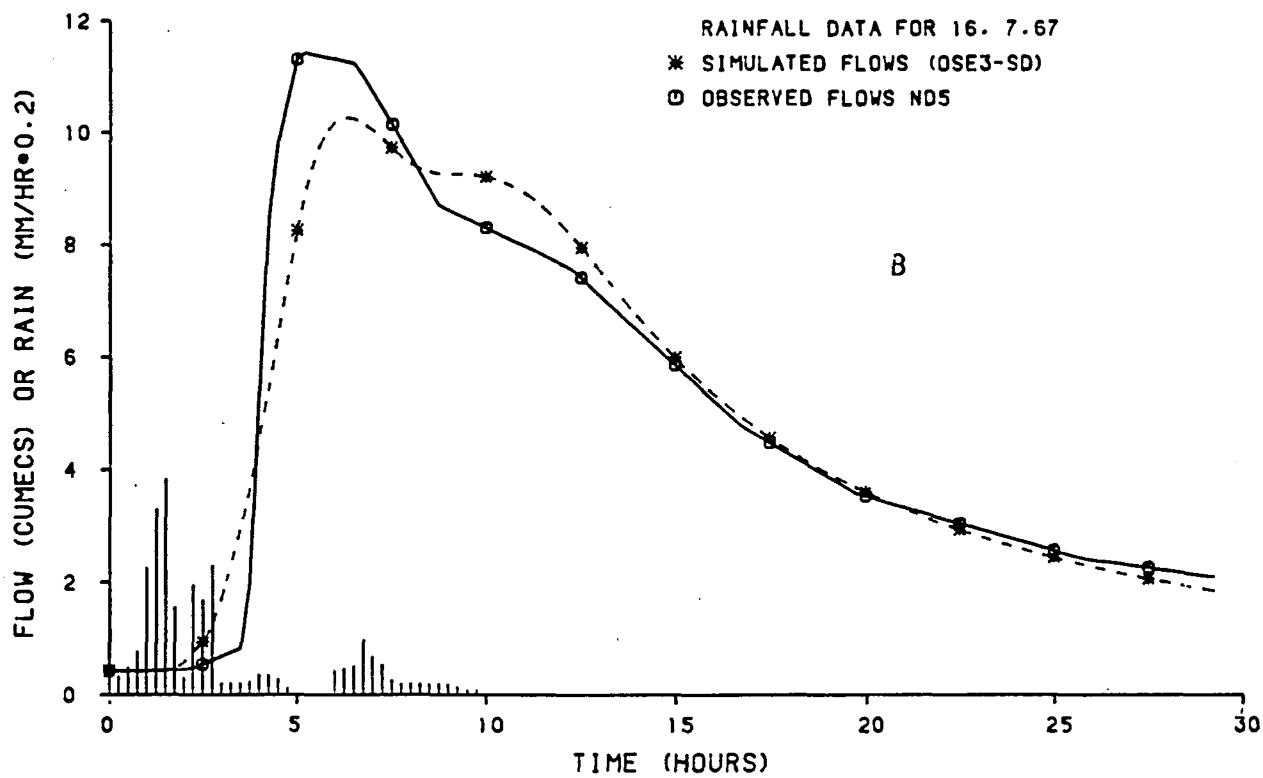


FIGURE B13 A-B N.Danville ND5

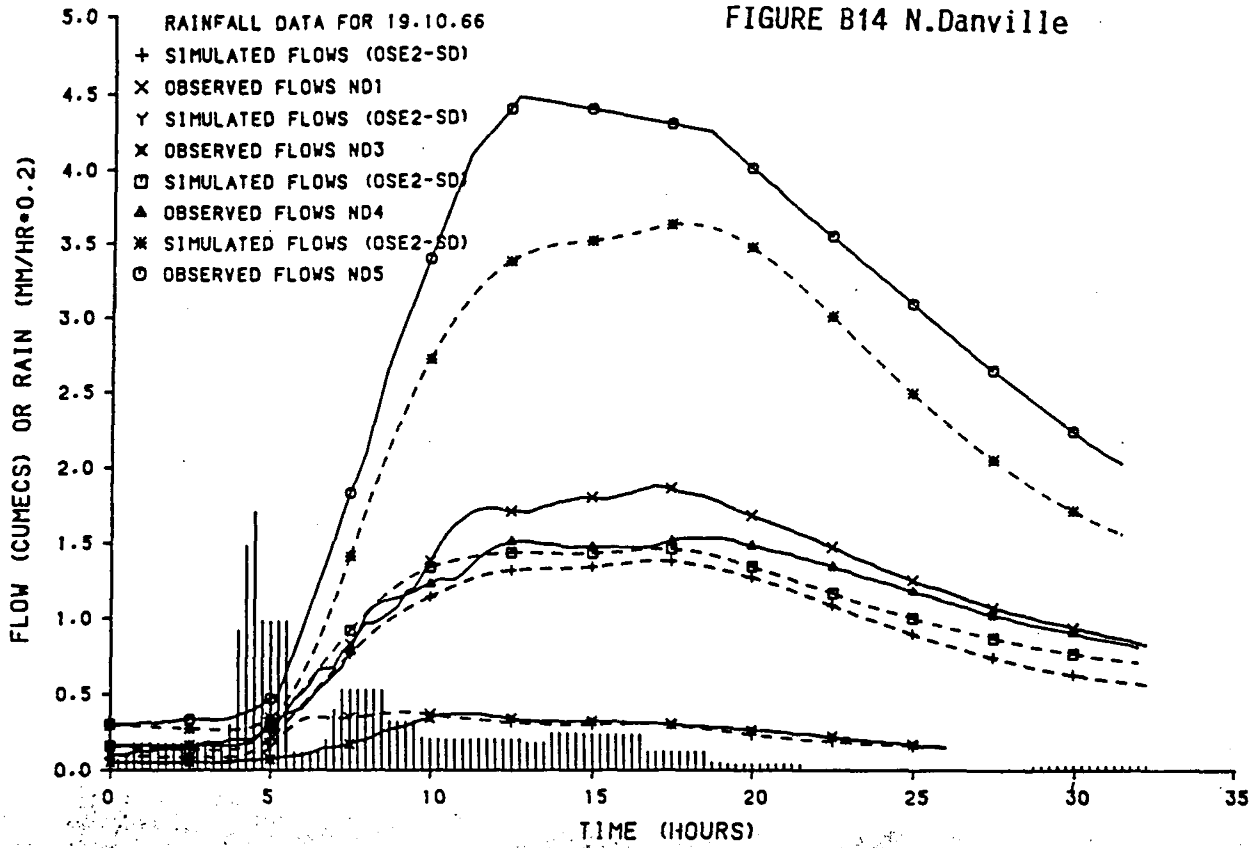


FIGURE B14 N.Danville
RAINFALL DATA FOR 19.10.66
+ SIMULATED FLOWS (OSE2-SD)
× OBSERVED FLOWS ND1
Y SIMULATED FLOWS (OSE2-SD)
✕ OBSERVED FLOWS ND3
□ SIMULATED FLOWS (OSE2-SD)
▲ OBSERVED FLOWS ND4
✱ SIMULATED FLOWS (OSE2-SD)
⊙ OBSERVED FLOWS ND5
FLOW (CUMECS) OR RAIN (MM/HR•0.2)
TIME (HOURS)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
5
10
15
20
25
30
35

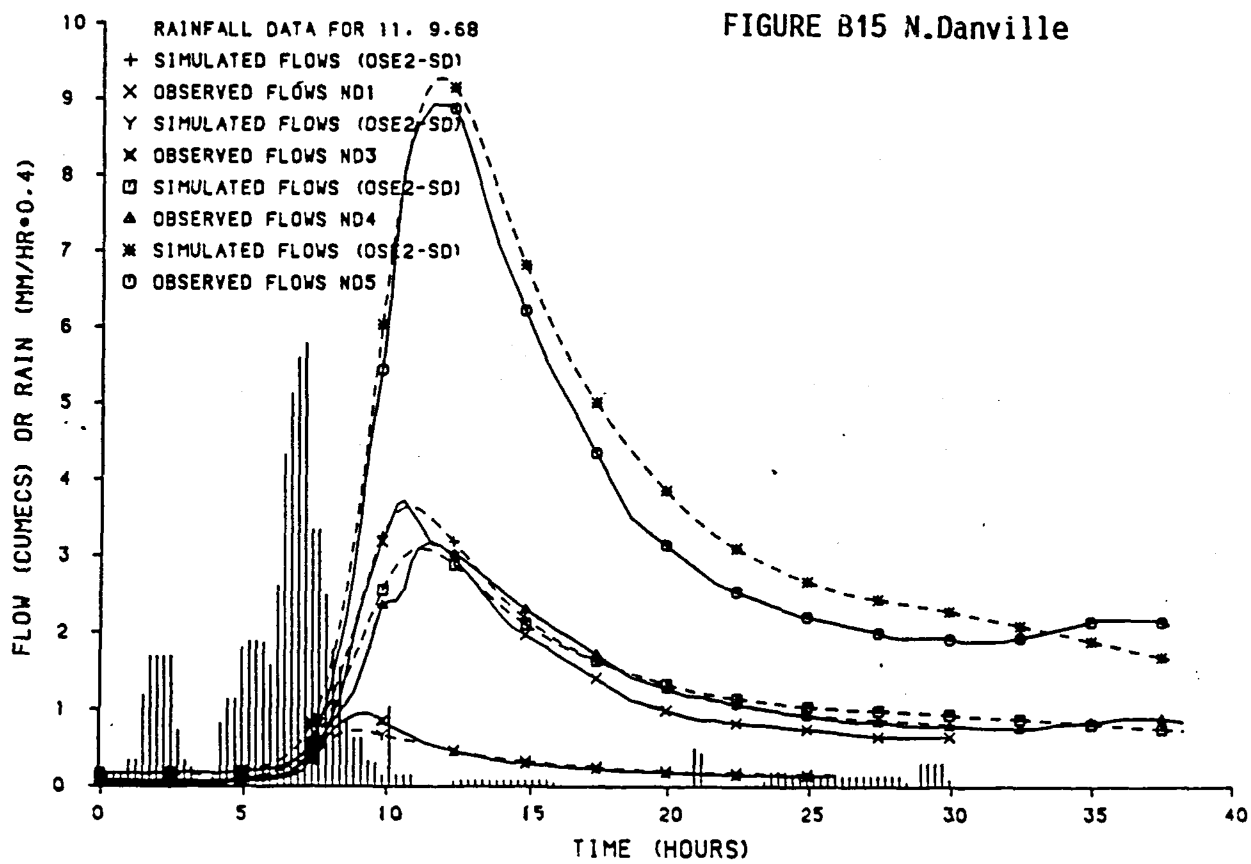


FIGURE B15 N.Danville
RAINFALL DATA FOR 11. 9.68
+ SIMULATED FLOWS (OSE2-SD)
× OBSERVED FLOWS ND1
Y SIMULATED FLOWS (OSE2-SD)
✕ OBSERVED FLOWS ND3
□ SIMULATED FLOWS (OSE2-SD)
▲ OBSERVED FLOWS ND4
✱ SIMULATED FLOWS (OSE2-SD)
⊙ OBSERVED FLOWS ND5
FLOW (CUMECS) OR RAIN (MM/HR•0.4)
TIME (HOURS)
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40

AN ASSESSMENT OF ISOLATED FLOOD EVENT CONCEPTUAL MODELS IN DIFFERENT CLIMATIC AND PHYSIOGRAPHIC AREAS - THE MODELS AND INITIAL RESULTS.

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FOREWORD

This report is the first preliminary report on the Water Research Commission project entitled 'Hydrological Research in catchments of the eastern and southern Cape'. The project has two major themes; one associated with isolated event deterministic models and the second with the use of stochastic models in semi-arid regions. This report addresses the former subject and is a continuation of preliminary work begun in an earlier project and reported by Hughes (1983).

The Hydrological Research Unit (HRU) at Rhodes University has been involved in the field of mathematical modelling of the rainfall-runoff process since its inception in 1974. It has established two areas where hydrological data are collected for research purposes. The first is in the semi-arid Ecca catchments of the eastern Cape while the second is in the sub-humid coastal area of the southern Cape Province.

Dr. Hughes has been a member of the HRU since 1980, and Ms Beater is a graduate student carrying out a research programme towards an MSc. degree. The research that has been completed in the past, as well as the continuation of this project, is only possible because of the funding from the Water Research Commission and due to the facilities provided by Rhodes University to my Department. My gratitude and appreciation is accordingly expressed to both organisations.

J.B.McI. Daniel
(Professor of Geography, Rhodes University).

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Professor Roland Schulze, of the Department of Agricultural Engineering of University of Natal, Pietermaritzburg provided the USDA publications from which the North Danville data were extracted.

The following people comprised the steering committee for this project. Any contributions made by them to this report, or the project in general, are gratefully acknowledged.

Mr J.M. Bosch : Department of Environment Affairs (alternate)
Mr H.C. Chapman : Water Research Commission
Mr D.W.H. Cousens : Water Research Commission (Chairman)
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Mr J. Myburgh : Department of Agriculture and Water Supply
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Mr P.W. Weideman : Water Research Commission (Committee secretary)

The second author gratefully acknowledges financial assistance from the Council for Scientific and Industrial Research through the provision of a graduate bursary.

ABSTRACT

The first chapters of this report review some aspects of the philosophy underlying deterministic approaches to modelling flood events. The discussion concentrates on isolated event modelling of non-urbanised catchment hydrological response. Consequently, some of the features specific to urban hydrological models (such as flow routing in stormwater drainage systems) are ignored. The introductory chapters are not meant as a full review of all modelling approaches but rather to define the context in which the models tested can be placed.

The four models investigated in this study are, a developed version of an implicit source area model, two simple constant runoff proportion models and a semi-distributed runoff-routing model. The first three models have been formulated as both lumped as well as semi-distributed models. The distribution system for all models is based upon sub-catchments. The structures of the four models are described and their parameters discussed with respect to perceived associations with physical characteristics of either the input rainfall or the catchment or both. Some of the models share common components but have essential differences in part of their structure. By comparing model results it was considered possible that some weaknesses might be identified and isolated.

The models have been calibrated on two physiographically and climatically different sets of catchments. Both represent nested gauging situations and one set (Ecca) is situated in the semi-arid eastern Cape of South Africa while the other (North Danville) is in the humid temperate north eastern United States. The ability of the four models to reproduce a range of observed storm hydrographs is examined from their curve fitting capabilities as well as the degree of parameter stability and acceptability. For each model, comparisons are made between the performance in the different regions and between the performance of the lumped and semi-distributed model versions. The North Danville catchments were generally modelled more successfully, although limitations in the available input data precluded firm conclusions from being made. Improved calibration results were obtained using the semi-distributed versions when the input rainfall was

spatially variable and adequately defined by the available data. Small events in the semi-arid catchments were not modelled successfully by any of the models. This is considered to be a consequence of a disparity between the scale of spatial variations of the real and modelled runoff generating processes during such low runoff response events. There are small differences in the overall ability of the four models to reproduce observed events. However, this was achieved with a more stable set of parameter values for the variable runoff proportion source area model, than for the other three. It is necessary to carry out further investigations to decide whether the variations in some parameter values between storms can be estimated from the storm input characteristics. Similarly, further work involving model testing on more catchments is necessary to examine more completely the physical relevance of the parameters of all the models. This work, as well as investigations into parameter sensitivity and model application forms part of a continuing project on single event modelling.

1. INTRODUCTION

Before discussing mathematical modelling approaches to the estimation of some or all of the characteristics of isolated or single flood events it is desirable to first of all define an 'event'. This is difficult in as much as the processes involved in the redistribution of water within the atmosphere/surface/subsurface system operate on a more or less continuous basis. Most hydrologists would agree that the processes predominantly operative during a 'flood event' differ only in degree from those during 'low flow' conditions. It is nevertheless impossible to define precisely a set of conditions that give rise to a 'flood event' as opposed to a 'non-flood event'. This can only be done in an arbitrary way by defining some peak discharge limit or perhaps a threshold rate of increase in discharge. An example would be the baseflow separation line of Hewlett and Hibbert (1967). A further example could be to choose only those events with peaks or volumes with recurrance intervals greater than a prescribed value. These arbitrary approaches to defining an event make no statements about any special set of conditions or processes that operate during the events. Consequently, it might be expected that modelling approaches to flood events would not be significantly different to modelling approaches to other periods in hydrological time series. However, this is not the case, and often flood models are designed as special case models. Such models ignore processes whichs are otherwise included, in some way, in models designed to simulate a range of hydrological occurrences. They may also concentrate more heavily on other processes deemed less important during lower flow situations.

The difference in approach to flood event modelling could be prompted by several factors. It may be prompted by the particular use for which the model is designed or related to the model designers' perception or understanding of the physical system being modelled. Perhaps the most common reason is an attempt to concentrate on those processes of the hydrological system that are most relevant to simulating flows at short time intervals (such as flow routing and neglect those deemed unimportant during storm rainfall. Event based models may therefore neglect the simulation of evapotranspiration and its effect on soil moisture (Loague and Freeze, 1985). This point is also related to the model designers' understanding of catchment hydrology. Ultimately, all hydrological models represent an attempt to simplify the physical system to a point where the model is operable for practical purposes but remains a sufficiently accurate simulation tool. The way in which a balance is achieved between the degree of simplification and the level of simulation accuracy has not been determined. It is, of course, a difficult problem and one that is inevitably related to the intended use of the model. A model designed to be used in a wide variety of catchments with different physiographic and climatic characteristics is expected to be more sophisticated than one intended for more limited purposes. At our current level of knowledge, hydrologists do not really know how much more complex such a model has to be. Nor do they know which components of the system have to be modelled in a more complex way. It is, admittedly, an enormous task to solve such a problem. A conclusive answer might only be achieved by testing a wide range of model types on an equally wide range of differing catchments (Sorooshian, 1983). The observed data from each catchment would also have to represent the variety of different streamflow responses that could occur from the catchment and be of good 'research' quality. Assuming that such data have been collected, the consolidation of such a test data set would alone be an enormous task.

It is inevitable that less extensive testing of flood event models has taken place and also that the confident use of models is often restricted to the area that they were developed in. The literature on hydrological models abounds with different approaches to model testing. Some contributions have concentrated on isolating the most important (or sensitive) components of models (Pickup, 1977; Mein and Brown, 1978; Bondelid et al., 1982; Sorooshian and Arfi, 1982; Rogers et al., 1985) often with the intention of isolating which model parameters should be most accurately evaluated. Others have concentrated on the application of models to situations or areas where a specific model (or models) has previously not been applied (Hope, 1983; Eyre and Crees, 1984; Devaurs and Gifford, 1986). Still others have investigated whether or not the sub-components of models (such as soil moisture levels or the extent of source areas) are simulated accurately (Manley, 1977; Beven and Kiekby, 1979; Ward, 1984; Bernier, 1985; Moore et al., 1986). Some contributions represent comparitive tests of different modelling approaches (Delleur et al., 1976; Singh and Buapeng, 1977; Lowing and Mein, 1981; Loague and Freeze, 1985) while others concentrate on single models (mein, et al., 1974; Foroud and Broughton, 1981; Diskin et al, 1984; Hughes, 1984; and many others). All such reports in the literature represent a large and still growing body of information related to the problem referred to in the previous paragraph. However, this problem still remains and until it is solved there will always be a measure of doubt about the successful use of models in practical, applied situations.

This report initially examines some of the principles underlying the different approaches to single event modelling (sections 2 and 3). It attempts to integrate some of the current attitudes to the deterministic modelling of flood events and discusses some of the problems of applying alternative modelling approaches. These sections of the report also place into context the models that have been selected for testing as well as the methods that are used to evaluate and compare the performance of the models. The remainder of the report describes the models under test, the initial test data and the results of calibrating the models on these data. The present report therefore provides the theoretical background to the complete study as well as establishing the authors' attitudes to the development, testing and application of single event models. The initial test data are drawn from two totally different regions. The calibration results reported herein have demonstrated that the models can be applied to simulating storm events in two different rainfall-runoff response situations. A future report (to be prepared in 1988) will discuss the results of further model calibration and verification on a wider range of catchments. This second report will also attempt to draw conclusions about the usefulness of the models for solving problems in applied situations.

It would be impossible to thoroughly test all the single event modelling approaches that have been reported in the literature. The models have therefore been selected to represent a range of approaches from very simple constant runoff proportion models to a more complex model which incorporates more than one runoff generation component. All the models selected represent non-linear approaches to modelling the response of runoff to rainfall. In order to investigate the desirability of using distributed approaches (section 2.3.1 of this report) it was decided to choose models that could be operated in either lumped or distributed format. This excludes some approaches that have been tested by other hydrologists working in this field (kinematic flow routing, for example). The models were also chosen on the basis of their perceived applicability to simulating floods from a relatively wide range of catchment sizes.

2. DETERMINISTIC MODELLING APPROACHES TO THE SIMULATION OF FLOOD EVENTS

In their introduction to a paper which discusses tests carried out on three models, Loague and Freeze (1985) suggest that comparisons should be made between different generic types of model. They consider that many earlier contributions have compared models of the same generic type. James and Hawkins (1981) presented a system of model classification based upon the needs of users and the approach to modelling. Their purpose was to evaluate the reliability of available models for meeting users' needs and to provide a taxonomic system for general model assessment. James and Hawkins (1981) covered a wide range of model types from catchment process models, through flood and drought frequency models to alluvial process models. There is very little reference to the detail of individual modelling approaches. When looking at a more restricted group of models it is difficult to construct a classification scheme that considers the detail of the complete range of approaches that have been adopted. There are a wide range of criteria which could be used to devise a scheme to group models. However, in some cases a model may fall into one group on the basis of one criterion but into a different group using another criterion. This chapter attempts to summarise and discuss the approaches that have been used by examining criteria related to the type of input data required, the detail of the output, the degree of spatial distribution used, and other factors. No attempt is made to define groups which individual models fall into uniquely.

2.1 Continuous or isolated event models

Continuous simulation models have been used to generate sequences of flood peaks or volumes but require long periods of short time interval input data. They may be useful to compare the probability structure of rainfall and resulting streamflow events (Packman and Kidd, 1980; Beaudoin et al., 1983) but long records of short period rainfall data are rarely available. They have also been used extensively for real time flood forecasting (Green, 1979; Anderson and Burt, 1985). One of the advantages is that moisture storages are modelled continuously, precluding the necessity to estimate initial conditions at the start of the storm. This is only an advantage if the model simulates the storages realistically.

An alternative approach is to model continuously but with a coarse time interval between events (Dunsmore, et.al. 1985). Given the condition of realistic simulation, such models have similar advantages to the first type without the stringent data requirements. If the model structure is essentially the same when dealing with event and non-event periods then the model has to be rigorous and flexible enough to operate under a wide variety of hydrological response situations. If, alternatively, the structure of the event model is different, then effectively the user is dealing with two models. He therefore has to establish two sets of parameter values by whatever technique is pertinant to the model or available to him. When the required output is only one isolated event it is necessary to know what length of period prior to the event that continuous simulation must begin. It may be difficult to assume a fixed period as it would still be necessary to set the initial model storage levels. One suggestion would be to begin at a point when the storages could be assumed full, such as the previous large rainfall event. In other cases, such as arid or semi-arid areas, it may be better to begin at the end of a prolonged dry period when storage levels could be assumed to be low.

It is difficult to draw a clear line of distinction between the second approach referred to above and some isolated or single event models (IEM's). IEM's have essentially three basic components: a method of determining initial conditions; a method of determining that proportion of rainfall that contributes to streamflow during the storm (excess rainfall or direct runoff); and some form of flow routing procedure. If a coarse time period model constitutes the first component then this is similar to continuous modelling with a differential time interval. A distinction could be made between those techniques that explicitly model initial storage conditions and those that rely upon some simple surrogate estimate (initial observed flow rate or antecedent precipitation indices, for example).

2.2 Model distinctions based upon intended application

Not all deterministic flood event models have been designed with the same intended application and often their structure is related in some way to the particular problem that they were initially designed to solve. This can lead to difficulties if a model is used for a purpose for which it was not originally intended. This is especially true if the new application is conceptually "in conflict" with the structure of the model. For example, a model that was originally designed to simulate flows from small catchments with little spatial variation in hydrological processes should not be used in relatively large catchments. Such an exercise is unlikely to be successful if the original model is not capable of accounting for either the spatial variation of processes or of rainfall input.

2.2.1 Design flood applications

Perhaps the classic application of single event flood models is for design purposes. In the past this has involved models with relatively simple formulations designed to predict the flood peak or the flood volume or both. Included in this group could be the Rational method, R-index (Hewlett et al., 1977; Hope, 1983; 1984), SCS formulae and various rainfall excess generating equations (Singh and Buapeng, 1977) attached to routing methods such as time-area diagrams, unit-hydrographs or others. One characteristic of some of these models is that they concentrate on estimating the peak flow rate and its timing and sometimes the flood volume. The unfortunate characteristic of most deterministic approaches to design floods is that they rely upon the equivalence of return period (or probability of exceedence) of the storm rainfall event and the resulting flood. Several authors have drawn attention to the inadequacy of such an assumption (Hiemstra, 1969; Cordery, 1970; Marsalek, 1978; Wenzel and Voorhees, 1978; Urbonas, 1979; Beaudoin et al 1983; Dunsmore et al., 1986; Hughes, 1986), identifying the importance of the role played by antecedent moisture as well as other characteristics of the rainfall event apart from simply its depth and duration. This problem is not necessarily model related, as even complex flood models suffer from this basic error in the concept of the design storm.

There is a further, perhaps more fundamental, problem that is inherent in most design flood approaches (deterministic and probabilistic). That is the concept that the probability of exceedance of a specified peak or volume is an adequate definition of the risk of flooding. This can only be true if the damage is directly associated with the single parameter of the flood specified in the probability statement (i.e. peak or volume), and that the other aspects of the event are irrelevant. Even when peak discharge is the dominant factor there may be other considerations that are important to the overall design problem. As long as the flood discharges remain below the design peak there is no problem. However, if it is exceeded, then the length of time it is exceeded and the volume of runoff occurring before the structure is capable of carrying the flow again could be relevant to the resulting amount of damage or inconvenience. Other design situations, although less common, may require information about the complete flood hydrograph. This would certainly be the case when the amount of storage available forms part of the design. The requirements for the effective planning of flood plain development or channel improvement works could involve the estimation of complete hydrographs with realistic shapes owing to the often complex relationships between discharge and overbank inundation (Hughes, 1980). Reference to the probability of peak or volume exceedance is then no longer adequate. Extending the probability statement to include several aspects of a hydrograph in a multivariate distribution approach is difficult although has been attempted in a limited way by Hiemstra and Francis (1979). The alternative of defining the exceedance probability of the event in terms of the important parameters of the causative rainstorm (for example, depth, duration and intensity variations) and antecedent conditions is also difficult to achieve (Hughes, 1986).

There are a large number of models with more complex structures than the relatively simple ones referred to above. Many are quite capable of simulating realistic hydrograph shapes resulting from complex temporal and spatial variations in rainfall intensity. However, the concept of the design event and associated probability statements have not been updated to allow the inclusion of such additional information about the characteristics of a flood. It is doubtful if it is mathematically possible to update the concept in the manner suggested in the previous paragraph. That the concept requires some form of updating and refinement cannot be in doubt, nevertheless the most effective way still remains to be determined.

2.2.2 Real time flood forecasting

A number of models have been designed to be used as flood forecasting models (Green, 1979; Serban, 1976; Beven, et. al. 1984) while others have been adapted for this use (Eyre and Crees, 1984). They are generally moisture accounting models and continuous, using either constant time intervals or reduced time intervals during potential floods. Some sophisticated forecasting systems exist whereby rainfall forecasts, from radar observations, are used as input to a model which continuously updates streamflow predictions (Green, 1979). Within larger catchments, monitored headwater rainfall inputs can be used to predict sub-catchment flows which are then routed to predict the flood levels further downstream. Such practices are only justified where the travel time of the flood wave is of sufficient length to allow adequate warning downstream. Efficient and accurate channel routing functions would form a major component of such models. Although channel routing methods are well developed, given certain basic data, overbank flooding and its attenuating effects can be difficult to model (James et al., 1981).

2.2.3 Land use change, sediment and chemical component models

These models have been grouped together as they are often perceived to require more realistic modelling of the physical processes involved in catchment hydrology (Beven and O'Connell, 1982; Roberts, 1983; Fleming, 1984; Hughes, 1985). With models designed to predict land use change effects on flooding it is essential that the parameters or coefficients of the model have at least quantifiable relationships with the physical characteristics of catchments. In most cases it would also be necessary to allow for spatial variation of parameter values over the catchment. Except in small catchments, it is unlikely that the whole area would be under one land use then change to another. A special case where changes in land use would need to be accommodated, would be those areas experiencing hydrologically significant seasonal differences in land use.

The need for models with a realistic representation of the physical system (physically-based) where chemical or sediment production components are to be included, can be illustrated by a simple example. The hydrological components of a model may simulate a greater proportion of overland flow in relation to rapid subsurface flow than actually occurs. If the majority of the chemical solution processes occur in the subsurface environment then the model is unlikely to predict chemical quantities adequately.

Complex, spatially distributed, physically-based models are often difficult to apply in many flood modelling situations. However, when the extra effort involved in determining the parameter values of such models is rewarded by greatly improved simulation results, then the use of such models is warranted. Although no conclusive tests have been reported in the literature, integrated simulation studies, requiring output of more than just streamflows should be more successful if truly physically-based models are used. Some further comments on the degree of model complexity will be made in later sections.

2.3 Model complexity

Differentiating models on the basis of their complexity can be useful. To a certain extent, it is a measure of the amount of input data required, or number of parameters needing evaluation, before storms can be simulated. However, while it is likely that models having a sound base in the physical hydrology of catchments will be complex, the reverse is not necessarily so. Complex models have a high number of "degrees of freedom", to borrow a statistical term. This statement can be liberally interpreted to mean that there is a lot of scope for errors to be made and for these errors to compound and not necessarily cancel. Simple models can be easier calibrate on individual events, but it is often not possible to find any physical relevence for their parameter values. Consequently, such models may be unreliable if applied to storms not included in the calibration data set.

This report identifies two aspects of model complexity which are discussed separately below. The first is based upon the spatial complexity accommodated in the model while the second addresses the complexity of the way in which the hydrological processes in each spatial element (or linking spatial elements) are treated.

2.3.1 Degree of spatial distribution

There are three possible reasons for incorporating some degree of spatial distribution into a model. The first is to allow for spatially variable input variables, mainly precipitation (Beven and Hornberger, 1982; Corradini and Singh, 1985; Schultz, 1985). The second is to allow for spatial variation in the hydrological response characteristics within catchments (Peck et al., 1977; Clark, 1980; Beven, 1983; Rajendran and Mein, 1986) The final reason could be related to the second and may be a direct consequence of the type of approach used in one or more components of the model. For example, if a kinematic flow routing approach is to be used then the model needs to be spatially distributed. It is not a simple task to suggest which of the first two reasons is most important. This is largely due to the fact that different dominant factors prevail in individual regions, or catchments, or even during individual storm events. For any storm occuring in a catchment it would be necessary to investigate whether any variaton in runoff amount or pattern from sub-areas is a consequence of variations in rainfall characteristics or runoff response characteristics or both. In some circumstances, part of the answer is obvious. Convective thunderstorms are known to have spatially variable intensity patterns even over small areas (Schultz, 1985). Similarly, in catchments with diverse physiographic or land use characteristics, spatial variation in hydrological response can be expected. However, the complete answer is likely to be elusive in many situations.

Having decided that a distributed model is the most applicable approach to a given problem, it is then necessary to provide the input and parameter information at an adequate level of accuracy to justify the distributed approach. In terms of rainfall input, this would mean a sufficient number of gauging locations, or rainfall estimation points, to represent the degree of heterogeneity in either intensity or total storm rainfall. With respect to spatially variable parameter values it would first of all be necessary for the relevent parameters to have at least some definable physical relevance, quantifiable from measurable characteristics of the catchment. Regression-type relationships, suitably tested for the area of application, may be adequate. Directly measurable parameters in physical equations should be the optimum if the physical accuracy of the model structure is the main criterion. However, it has to be remembered that in practice it is not always possible to obtain measurements of certain hydrological characteristics at a large number of locations within catchments. If the point raised earlier about 'degrees of freedom' is also considered, then complex, physically-based, distributed models lose much of their initial attractiveness for solving practical problems.

The importance of measurement techniques and scale corresponding to model structure and distribution scale has been emphasised by several authors (Beven and O'Connell, 1982; Dunne, 1983; Abbott et al., 1986). Loague and Freeze (1985) maintain that the primary barrier to the application of physically-based models lies in our inability to quantify the spatial variability of rainfall and soil hydraulic properties at a satisfactory scale.

There are many different approaches to sub-dividing the catchment area in fully distributed models. Distribution schemes based directly upon physiographic criteria have been used widely. Breaking the catchment down into individual slope elements (Jayawardena and White, 1977, 1979), or utilizing some aspect of the channel network (Lee and Delleur, 1976; Surkan, 1974) are common approaches. Indirect use of physiographic criteria have also been used by dividing catchment areas up into travel time elements (Krzysztofowicz and Diskin, 1978; Watson, 1981). An alternative is to base the network of sub-areas on a uniform grid pattern with an appropriate spacing for the size of the catchment (Gupta and Soloman, 1977). A compromise between lumped and fully distributed models is the semi-distributed approach where an essentially lumped model is applied to sub-catchments within the total area (Mein et al., 1974). Clearly, a channel routing component would be required to delay, attenuate and accumulate the runoff from each sub-catchment. Having developed such a component to add to one lumped model it is usually a simple matter to apply it to others.

2.3.2 Model component complexity

The word 'complexity' has been used in this sub-heading although it does not convey the real essence of the following discussion. The problem lies in the confusion that can be caused by equating model complexity with the model's ability to represent the 'real world' of hydrological response. A model with a complex structure may be based upon false premises or applied in an inappropriate way and therefore be no more representative of the physical system than a relatively simple model. Different names have been used to represent groups of models based upon their complexity or physical reality. Roberts (1979), amongst others, used the black, grey, white box scheme, which is useful as it correctly implies a continuum or spectrum of increasing physical reality. An alternative is to refer to empirical, conceptual and physical (or physically-based) models. However, this scheme immediately raises semantic problems as any model that relies upon calibration with observed data is an empirical model. In addition, many models have sound physically-based components coupled with simple empirical approximations as part of their structure. The following classification scheme is presented to define more accurately how the authors of this report perceive model distinctions.

a) Simple empirical models: This group consists of those models where little or no attempt is made to relate the model components to physical reality. They are essentially curve fitting methods. The most likely approach for predicting storms not used for calibration is through statistical relationships between model parameters and storm or catchment characteristics. It is unlikely that parameters will remain stable even within one catchment due to changing hydrological response characteristics between storms that are not accounted for in the model.

b) Conceptual models: Such models may also be fitted using empirical calibration procedures. However, they can be distinguished from those above by virtue of the fact that the structure of these models is based upon conceptualisations of the processes active during flood events. They may be viewed as an assemblage of empirical components, each representing individual or groups of processes. Their success will be partly dependent upon the accuracy of the model developer's perception of the physical system and the way in which this perception is translated into the mathematical components of a model. Some of the model components may be strongly physically-based. This group represents a wide range of modelling approaches, some being developed as generally applicable models while others are intentionally restricted to certain areas of application (i.e. urban, forested or agricultural catchments, small catchments or humid regions). Models which have a sound conceptual structure relative to their intended area of application, may have a totally unsound structure if used out of context. A distributed model utilizing infiltration equations to determine excess rainfall and a sound surface flow routing procedure (for example kinematic flow routing) could be considered a realistic conceptualisation for some areas. However, in catchments where subsurface flow is an important process during some events the model is no longer realistic. This does not mean that the model could not be calibrated in such catchments. It merely suggests that the parameters would not be evaluated correctly in terms of their original conceptual meaning.

c) Physically-based models: James and Hawkins (1981) state that the 'ultimate surface water model would be comprehensive in its cover-age of the physical factors influencing surface water movement and consequently reliable in its quantitative estimation of stream-flow'. The authors of this report would agree with the first part of the statement but consider the second to be misleading. The reliability of such a model would also depend to a great extent on the user's ability to supply the model with the necessary data requirements (Beven, 1983). It is difficult to conceive of a hydrological model that can be applied in practice and that is formulated from a set of highly physical equations. This is not necessarily so because our understanding of the movement of moisture through and over natural materials is lacking. It is mainly because the hydrological response system at a catchment scale is very complex. In addition it is not possible to measure all the physical characteristics of catchments (which vary temporally and spatially) necessary to evaluate such physical equations. The best that can be achieved is a model which has a sound conceptual structure with parameters demonstrated to have quantifiable physical significance, and which is sufficiently sophisticated to account for the spatial and temporal variation in hydrological processes. The point about the difficulties of applying complex, physically-based, distributed models has already been made in section 2.3.1 above and need not be repeated here. It is sufficient to conclude that a great deal of effort is involved if the parameters are to be evaluated correctly. If this effort is by-passed by estimating parameter values using incompletely substantiated assumptions, then the models can become a highly complex conceptual model. Abbott et al. (1986), in presenting the first readily available description of the SHE model, raise some very valid points about the use of physically-based, distributed models. By utilizing a physically-based structure and having an intimate knowledge of the sensitivity of the model to parameter value variations, the level of uncertainty associated with parameter estimation may be reduced. This uncertainty may also be quantified by carrying out simulations using parameters within a reasonable range of possible values. It is not possible to quantify the uncertainty when there exists no understanding of the physical significance of the parameters.

2.4 Approaches to modelling components

The previous sections have discussed several general aspects of the different approaches to modelling flood events. Reference to individual components of the hydrological response system has only been used to illustrate generalised points. This section looks more specifically at the different components of flood event models and the various ways in which processes have been conceptualised and simplified for use in mathematical models. Most flood event models can be reduced to three main components.

a) The estimation of the catchment moisture status prior to the start of the storm event.
b) A method or methods of converting gross rainfall into excess rainfall or more exactly, that proportion of gross rainfall that contributes to runoff. This will inevitably include procedures for up-dating the levels of any storages used in the model.
c) The routing of runoff across and/or below the land surface and in the network of channels to the catchment outlet.

2.4.1 Antecedent conditions

The different approaches to the estimation of initial conditions has already been partly discussed in section 2.1 Continuous models (with or without variable time intervals) do not require a separate component for these estimations as storages are updated continuously. Where data are available and where the model and its sub-components are physically realistic with respect to the catchment under consideration, such approaches should give the best results. However, the estimation of soil moisture storage levels is rarely tested using observed data and consequently it is often difficult to assess whether these levels are being modelled accurately. Other storages that can be included are interception and surface detention storage. The effects of different initial levels of these on hydrological response during floods is not well understood.

In isolated event models, estimates of initial moisture status have been based on simple decay functions of some number of previous days' rainfall, either modified or not for seasonal influences (Hughes, 1984). The level of catchment outflow at the beginning of the storm has also been used. In the UK, the Meteorological Office use moisture budgeting techniques to estimate soil moisture deficiencies continuously on a regional basis and such values have been used in several models (for example, Pirt and Bramley, 1985). The authors are not aware of any distributed, isolated event models that make use of distributed estimates of initial conditions. This could be a major drawback if it is assumed that antecedent conditions can play a major role in determining the degree of hydrological response and that such conditions could be spatially variable. Whatever method is used to estimate initial conditions it must be compatible with the structure of the rest of the model. The principle is particularly pertinent to the use of a short time interval isolated event model coupled to a longer time interval water balance model.

2.4.2 Estimation of excess rainfall

The term 'excess rainfall' is misleading and is a somewhat outmoded expression. However, even in its literal sense it is still applicable to many models in use today. It also remains a convenient term to refer to that proportion of the gross rainfall that eventually contributes to catchment outflow. The first point to consider is whether specific models are designed to estimate total outflows or stormflows. If stormflows only are modelled then no attempt is made to model the slower responding baseflow. The underlying reason for neglecting this flow component would be that it is considered negligible during the major part of a flood hydrograph. The difficulty is that some form of separation line between the flow components must be assumed. A commonly used method is that of Hewlett and Hibbert (1967) where stormflow begins when flow rises faster than a separation line of gradient 1,13mm $day^{-1}day^{-1}$ (5,47 x $10^{-4}m^{3}s.^{-1}km^{-2}.h^{-1}$). While this may be a useful generalisation it fails to account for the very big differences that may occur between catchments of different soils and physiography. If total flows constitute model output, then some attempt has to be made to estimate the amounts of baseflow occuring during the event. This may be negligible when antecedent moisture levels are relatively low and events shortlived.

Procedures used to estimate excess rainfall are difficult to group as they really represent a continuous spectrum from simple through to complex, more physically-based, methods. However, in broad terms it is possible to identify three loosely defined categories.

a) Simple methods utilize constant runoff ratios, (NERC, 1975) continuing constant loss rates (Laurenson and Mein, 1985) or infiltration curves (Singh and Buapeng, 1977). Some infiltration loss curves allow for variable losses during a storm and can be soundly based upon observations of the process. They have been included in this group of simple methods as they usually fail to account (either explicitly or implicitly) for the role of subsurface flow processes. However, used in a distributed model, (for example, the model of Huggins and Monke, 1966) infiltration equations could form one component of a strongly physically-based approach to excess rainfall determination. Models using constant runoff ratios or loss ratios can be modified to allow some degree of temporally variable response. Laurenson and Mein (1985) suggest that separate 'bursts' of rainfall within a storm could have different response levels. However, it is not apparent how such relative differences could be quantified.

b) Intermediate approaches include those attempts to vary runoff response as the storm progresses as well as with changes in rainfall intensity. More than one concept of runoff generation may be employed in the estimation of rainfall excess. Examples of this group could include several models that have attempted to use the variable source area concepts of runoff generation in either an implicit or explicit way (Lee and Delleur, 1976; Krzysztofowicz and Diskin, 1977; Hughes, 1984; Pirt and Bramley, 1985). One of the major problems with the first group (a) is that the parameter values of the excess rainfall component will inevitably change for different events even on the same catchment. Consequently, for prediction (not calibration) purposes it would be necessary to estimate loss rates or runoff proportions from a combination of catchment and storm characteristics. It is difficult enough to quantitatively characterise individual storms, let alone relate such measures to model parameters. Intermediate approaches often represent an attempt to allow parameters to remain fixed for any given catchment.

c) Physically-based equations of surface and subsurface flow processes represent the highest level of the spectrum. The authors have no experience of models which fit into this group and can be said to represent the hydrological response system of a wide range of catchments. However, there are models which claim to be physically-based with respect to a limited range of catchment response characteristics (Beven and Kirkby, 1979). The SHE model (Abbott, et al., 1986) may represent a major advance in this area of hydrological modelling.

2.4.3 Flow routing methods

Inevitably the approach to flow routing is closely allied to the other components and structural elements of any model. Simple methods can include linear (Bauer and Midgley, 1974; Ponce, 1979; Green, 1979;) or non-linear (Hughes and Murrell, 1986) storage-routing equations, instantaneous unit hydrograph methods, or time-area diagrams (O'Donnell, 1966; Dooge, 1973; Watson, 1981). They have been used in both lumped and semi-distributed models. Usually, land surface (or subsurface) and tributary channel routing are integrated in one estimation formula. Fully distributed, slope element or grid models often have more complex and physically-based routing approaches such as kinematic flow methods (Stephenson, 1980) or physical hydraulic equations (Danish Hydraulic Institute, 1985).

2.4.4 General

One general observation that may be made is that a model that is expected to have widespread applicability should have components that are compatible with each other. For example, there seems little point in using a physically-based routing method with a simple method for rainfall excess determination. It is likely that the weakensses of the rainfall excess method will have an effect on the routing parameters. Their values may then need to be different to the 'physically realistic' ones in order to account for poor estimation of the time distribution of rainfall excess. Model components should also be compatible with the level of spatial distribution used as well as the time interval used in the model. As these are not independent of the response characteristics of individual catchments it is difficult to make recommendations or define precise guidelines for model development or model application. It appears that more investigations are required to ascertain which approaches to flood event modelling will be most successful in different circumstances.

3. MODEL CALIBRATION, VERIFICATION AND TESTING

3.1 Calibration

Conventionally, the calibration of a deterministic model involves changing the values of the parameter set until a satisfactory correspondence between the simulated and observed data is achieved. The criteria chosen to determine whether a satisfactory fit has been achieved can have an influence on the final parameter values. The choice of fitting criteria has received a great deal of attention in the modelling literature (Diskin and Simon, 1977; Sefe and Brougton, 1982; Görgens, 1983; Sorooshian, 1983; Green and Stephenson, 1986). The selection of criteria depends to a large extent on the important characteristics of the data set relative to the specific aim of the modelling study. In flood event modelling, the following hydrograph characteristics can be considered to be important;

i) total volume of runoff;
ii) peak flow rate;
iii) timing of peak flow rate;
iv) time duration of rise to peak;
v) shape of recession curve.

It is often necessary to assess the degree of correspondence between observed and simulated flows using several statistics (Görgens, 1983; Green and Stephenson, 1980). The following measures should provide a satisfactory assessment:

i) coefficient of efficiency (Aitken, 1973), E;
ii) coefficient of determination, D;
iii) percentage error in total runoff volume, %V;
iv) percentage error in peak discharge, %P;
v) time difference between observed and simulated peak, TP.

Both the coefficients of efficiency and determination could be calculated using untransformed discharge values or using the natural logarithms of the values. The logarithmic transformation removes the bias towards the high values of runoff. Large differences between E and D is indicative of systematic error which may also be illustrated by high percentage errors in both peak and volume. Low percentage errors in peak and volume, low values of D and E and a large time difference between peak discharges is indicative of a time shift of the whole hydrograph.

Models may be calibrated manually, by modifying one or more parameter value, observing the effect on the fitting criteria and then repeating the exercise. This can be time consuming and confusing when there is a high degree of interaction between parameters. The alternative is to use a procedure whereby some or all of the parameters are evaluated using an automatic optimising technique (Rosenbrock, 1960; Ibbit and O'Donnell, 1971; Gupta and Sorooshian, 1985). Only one objective function can be used and it may be necessary to carry out some manual adjustments afterwards to achieve a better overall fit based on several criteria. Interaction between parameters can cause complications and result in sub-optimum results being produced. Similarly, beginning the optimisation with different starting values can result in different final solutions. Whichever method of calibration is used, a knowledge of the degree and patterns of interaction between parameters as well as the sensitivity of the fitting criterion to changes in parameter values is always useful. The definition of model sensitivity to changes in parameter values and plotting of response surfaces are essential if the uniqueness of a particular solution is to be assessed. Where complex interactions between different parameters occur it is not always straightforward to define the full array of response patterns. In addition, different individual events may have different model response patterns depending upon the characteristics of the input rainfall data.

When testing some models, it may be expected that parameter values should remain stable for all storms experienced on the same catchment. Two methods of calibration could be adopted to investigate whether this expectation is realistic. Individual storms may be calibrated separately and the stability of the parameters assessed later. Alternatively all available storms could be calibrated together as one data set but resetting the initial moisture status at the beginning of each storm. The latter approach has certain advantages particularly when it is possible to achieve similar fits with different parameter sets. In the former approach the non-uniqueness of results on individual storms could be confusing and lead to erroneous conclusions. It is important to note that a lack of uniqueness of solutions is not necessarily a weakness of a model. If the model is conceptually sound, with parameters that have some degree of physical interpretation then only one solution may be 'correct'. Other solutions may produce similar fits, but be achieved by setting certain parameter values at levels that do not correspond to the parameters physical interpretation on a specific catchment. Thus, in testing such models intuitive assumptions about the physical interpretation of parameters may play a major role during a calibration exercise. Only after a number of catchments, having different hydrological characteristics, have been modelled can the validity of these intuitive assumptions be assessed and perhaps modified.

Not all models can be expected to have stable parameter values for all storms on the same catchment. Simple models utilising constant loss coefficients are an example. Variations in total rainfall amount, temporal intensity patterns and antecedent conditions, amongst others, inevitably lead to variations in the proportion of rainfall that becomes streamflow. It is therefore not practical to calibrate a series of storms together. Part of the overall assessment of the models' applicability or validity would then include an investigation of the relationships between parameter values and relevant storm characteristics. Without a knowledge of such relationships and the way in which they vary between catchments it is difficult to imagine how such models may be applied.

Calibration of semi-distributed models is an extremely difficult task unless information about the differences in hydrological response between sub-areas is known. In addition this information should be able to be interpreted in terms of differences in parameter values. Without this background knowledge, changing the values of sub-area parameters to achieve improved fits becomes a dangerous and time consuming exercise. It is evident that the potential for reaching spurious conclusions is very high indeed. Despite these disadvantages, semi-distributed approaches should be more successful than lumped models when there is some degree of spatial variability in the rainfall input data. Improvements over lumped modelling approaches may be achieved simply by accounting for this spatial variability even if most model parameters are kept constant for all sub-areas.

In general terms, complete calibration of isolated event models involves three stages. Firstly, it is necessary to achieve a satisfactory correspondence between observed and simulated discharges for individual storm events. Secondly, it is necessary to establish if, and in what way, parameter values vary between storm events on the same catchment. Finally, before a model can be considered satisfactorily calibrated for the range of catchments it is intended to represent, the way in which parameters vary between catchments should be known. Admittedly, the latter represents an extension of the conventional use of the term calibration. However, this extension is warranted if deterministic model calibration is to be considered more than just a curve fitting procedure.

3.2 Verification

There is often a degree of confusion between the use of the words 'verification' and 'validation' and they have been used in the literature to mean the same thing. Sorooshian (1983) uses both terms to refer to a check or test that calibrated parameter values can be used to satisfactorily simulate events not used for calibration. Stedinger and Taylor (1982), referring to stochastic models, used the term 'validation' for this process and 'verification' for ensuring that the computer coding of the model represents the idealized model. Both terms refer to confirming the soundness or truth of a result and therefore could be used interchangeably. It therefore seems to be irrelevant which term is used as long as it is followed by a description of what aspect of the model is being verified or validated.

Verification of the computer model is necessary to ensure that moisture is not lost or gained due to the incorrect operation of a particular function. Solutions to functions should also be checked for stability within the range of parameters or variables over which the model is intended to operate (Hughes and Murrell, 1986). The remainder of this section discusses different aspects of verifying that the model, operated with an identified set of parameter values, can be satisfactorily applied to a specific catchment.

With reference to single event models, the first level of verification would be a check that the model formulation is adequate to simulate a range of storm responses. This stage is likely to occur concurrently with calibration. If the model cannot adequately simulate the hydrographs of the calibration data set, then there is little point in carrying out further model tests on a particular catchment. Having calibrated the model successfully it is then necessary to evaluate the meaningfulness of the resulting parameter values. If the model is a relatively sophisticated one then the parameters may be expected to remain stable for a variety of response characteristics from the same catchment. Thus verification will involve running the model with a series of observed storms not included in the calibration set and evaluating the simulation results. It is important that the storms reserved for verifying the calibration parameter set represent a relatively broad spectrum of the type of hydrological response that the model is designed to simulate. For models of the simpler, curve fitting type, an intermediate stage is necessary. The parameters of these models may be expected to vary with the characteristics of the storm rainfall or antecedent conditions. It would therefore be necessary to evaluate these relationships before any worthwhile verification could take place. The parameters of strongly physically-based models should be able to be evaluated from field based measurements of soil, vegetation or physiographic characteristics when these are available. Verification then consists of testing whether such values produce adequate simulation results.

Regardless of the models complexity and the user's expectations, the verification results may suggest further modification to the parameter values. This implies further calibration to investigate whether a modified parameter set can produce satisfactory results for all the available storm data. This must be considered a legitimate step in model testing as it makes use of the maximum amount of information available. However, the implication is that if additional data became available the parameter set may still require changes. Thus, no conclusive result about the representativeness of the model or the particular parameter set can be achieved. Perhaps the main problem lies in determining whether the available set of observed storm events is representative of the range of response types that can be expected from a specific catchment. This will inevitably depend upon the climate and land use regimes of the catchment. The problem is similar to determining the length of record that is adequate to achieve a stable calibration of a continuous model (Görgens, 1983).

The final level of verification relates to testing the transferability of parameters to other catchments (Hughes, 1985). In this context 'other catchments' also refers to the same catchment used for calibration, but under a different land use regime. The general lack of success associated with attempts at transferring parameters of relatively simple models has prompted many workers in this field to favour the use of physically-based models (Bevan and O'Connell, 1982; Roberts, 1984). However, there are few reports in the literature of physically-based models being tested over a range of different catchments. Perhaps this is because a large amount of fieldwork is necessary to evaluate the parameters of physically-based distributed models. Such fieldwork is obviously difficult and time consuming to undertake on a large scale.

3.3 Model testing

To summarise the points made in the previous two sections, model testing includes the whole range of procedures used to decide whether a specific model is efficient and hydrologically representative with respect to its intended use.

Thorough testing should incorporate the following :

i) Evaluations of calibration efficiency;
ii) Evaluation of the stability of calibration results;
iii) Analysis of the sensitivity of model results to changes in parameter values as well as input data errors;
iv) Assessment of the range of hydrological response types that can be satisfactorily modelled;
v) Assessment of the transferability of model parameters to other situations (storms or catchments) not represented in the calibration or development data sets;
vi) Testing of any hypothesized or perceived associations between model parameters and physical catchment or storm characteristics.

While there may be overlaps between the six points referred to above it is apparent that a complete evaluation of a model's capabilities represents a tremendous task. The amount of data required is difficult to determine and might not be obtainable. It is hardly surprising that many model tests are less than thorough and limited by available data, computer or manpower resources. Most tests that have been reported contribute to an overall understanding of what it is possible to achieve with deterministic hydrological models. However, as more and more new models are designed the amount of comparitive testing that is required grows rapidly.

4. S-CURVE MODEL (OSE2)

4.1 Background

The model described in this section is an extended version of the implicit source area model presented by Hughes (1983; 1984). The central concept of the original model is that the proportion of rainfall that contributes to streamflow varies throughout the storm in relation to the moisture status of the catchment. This relationship was defined in the model using an asymmetric S-curve described by a three parameter hyperbolic tangent (TANH) function (Hughes, 1984). The runoff-ratio in any particular time interval is calculated from the relative moisture status. The runoff-ratio is interpreted as the proportion of the catchment area that functions as a source area. All rain falling on this contributes to streamflow, while rain over the remainder of the catchment contributes to an increasing relative moisture level and an expanding source area. The initial moisture status at the start of the storm was estimated from a decay function of the previous 20 days rainfall. Excess rainfall routing was achieved using a non-linear storage-routing equation (Hughes and Murrell, 1986).

The original model was able to reproduce observed hydrograph shapes reasonably well after calibration in both semi-arid and sub-humid test catchments. However, the model parameters were found to vary quite considerably for different storms on the same catchment (Hughes, 1983; 1984). This was especially true for the semi-arid catchments which are characterised by variable storm producing mechanisms (Hughes, 1983). Only if the model parameters could be related to storm characteristics in some way could the model be used to estimate hydrographs when observed data are unavailable (to generate design hydrographs for example). An alternative is to develop the model further by identifying the conceptual weaknesses and incorporating additional components where necessary to improve the model's flexibility. The following sections discuss the way in which this model has been developed.

4.2 Conceptual weaknesses

One of the weaknesses of the original model is that intense rainfall at the beginning of a storm with low antecedent moisture conditions generates insignificant amounts of runoff. This is inevitable when the model formulation only implicitly incorporates one method of runoff generation and operates as a lumped model. To extend the generality of the model it would be necessary to conceptually incorporate other runoff generation processes that have been identified as being important in a wide range of catchments. Subsurface flow and infiltration-excess overland flow (Ward, 1985) are two processes that could be added using relatively simple model formulations.

The model operates in regular time intervals defined by the user. A large amount of rain falling in one time interval means that the differences between the moisture status at the start and end of the interval can be quite high. The original model used an iteration process to calculate average moisture status within the interval. Conceptually, rain that does not become runoff has to travel over or through the soils of the catchment before contributing to the expansion of source areas. The original model formulation does not allow for a variable amount of time for this to happen in different catchments. The soil depth, drainage characteristics and steepness of the slopes within different catchments must influence the rate at which rain falling on valley tops and sides reach the valley bottom.

The conceptual structure of the model is based upon a lumped formulation. However, a consideration of the spatial variability of both rainfall input and catchment characteristics within some catchments suggests that lumped models will not always perform adequately. Even when such characteristics are relatively uniform there are some processes that are difficult to incorporate in a lumped model, yet may be important in certain catchments. Semi-arid catchments with channels developed in alluvium may experience high degrees of channel losses from streamflow generated in headwater areas. Thus, not only is the amount of streamflow reduced, but the timing of the overall response at the outlet may also be affected. While it is difficult to imagine how this model could be developed into a fully distributed version, the alternative of adopting a semi-distributed approach based upon lumped modelling of sub-catchments is feasible. Such an approach has been used by Mein et al. (1974) and involves the addition of components to route streamflow along the channels connecting nodal points within sub-catchments.

A further potential weakness in the model lies in the simplified approach to the estimation of antecedent moisture status. To improve this part of the model would probably involve the addition of a coarse time interval moisture balance model which would be operated over a specified period prior to an event. Such models are available (for example the ACRU model of Schulze, 1984) but its parameter values would also need to be estimated (by calibration or other methods) for any specific catchment. Consequently, this acknowledged weakness of the model has not been attended to at this stage of the model development.

4.3 Conceptual structure of the developed model

The model can be divided into three major components; antecedent moisture status estimation, runoff generation estimation and runoff routing components. The model can be operated in either lumped or semi-distributed mode. The essential difference lies in the fact that the sub-catchment version allows for separate modelling of runoff generation from different areas and the use of a different routing function. Figure 4.1 illustrates the structure of the model.

4.3.1 Antecedent moisture

A decay function of the form :

$$API = \sum_{i=1}^{n} DR_i . APF^i$$

where DR_i = rainfall total i days before the event, is used to calculate an antecedent precipitation index (API) from n days of rainfall prior to the event and a model parameter APF ($\leq 1,0$). The number of days and the parameter APF can be varied between events to allow for seasonal effects. API then becomes the estimate of the initial moisture status of the catchment.

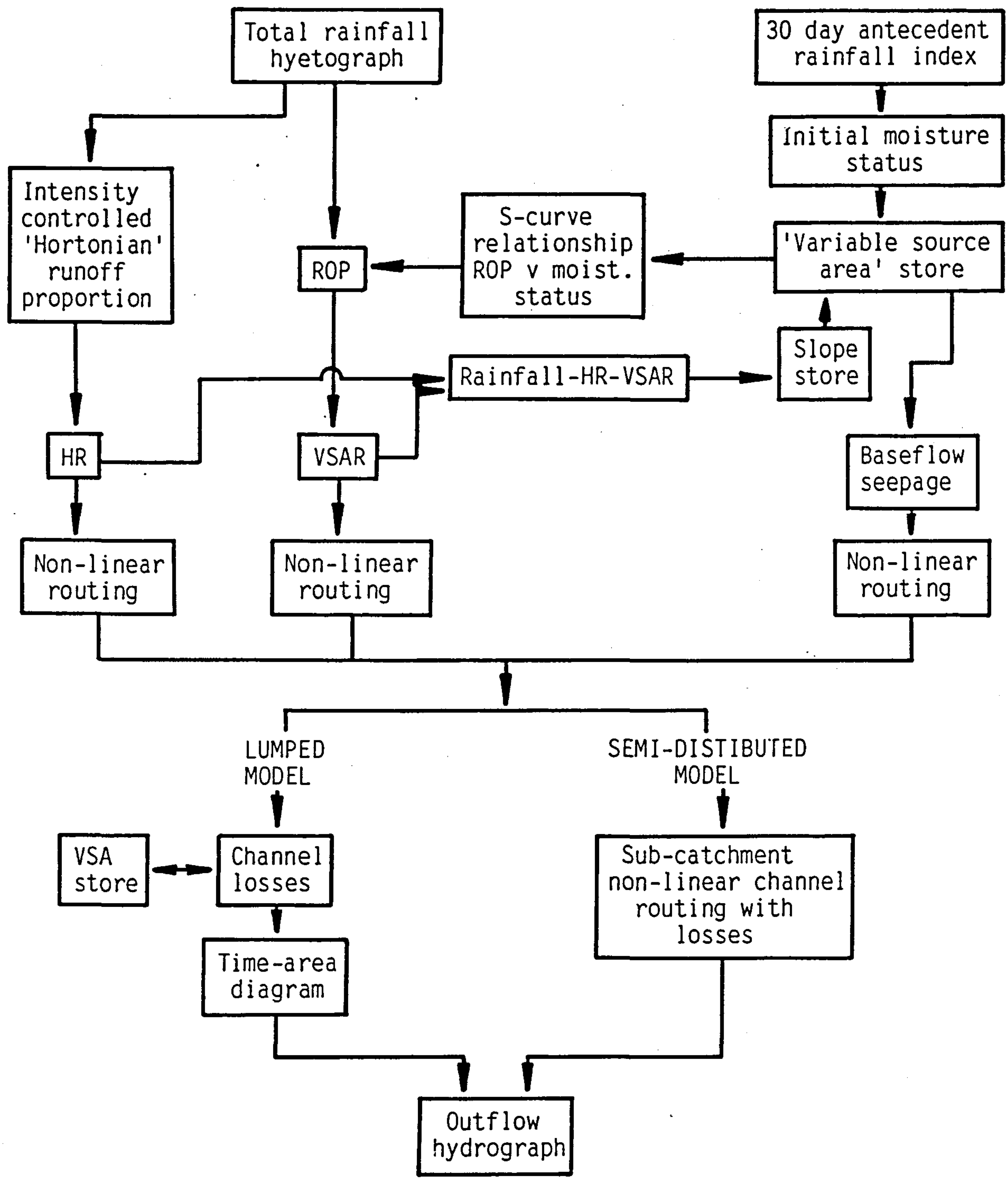

Figure 4.1 Structure of the S-curve model

4.3.2 Runoff generation

Runoff may be generated in any time interval by one or both of two methods. The first is dependent upon the intensity of the rainfall input, whilst the second on the intensity as well as the moisture status of the catchment. Both use a hyperbolic tangent function to estimate a runoff proportion value which is then multiplied by rainfall to produce the runoff amount. The intensity controlled runoff uses a symmetric S-curve function with intensity (mm. hr^{-1}) as a fraction of some maximum value (dependent on the time interval used in modelling) as the abscisa (figure 4.1a). The proportion of the catchment contributing through this mechanism at the maximum intensity is a model parameter (IAF). Conceptually, this element of runoff is viewed as originating from relatively impervious areas close to the channel. It may be thought of as infiltration-excess runoff away from saturated source areas but from zones close to channels such that re-infiltration of surface flow does not occur.

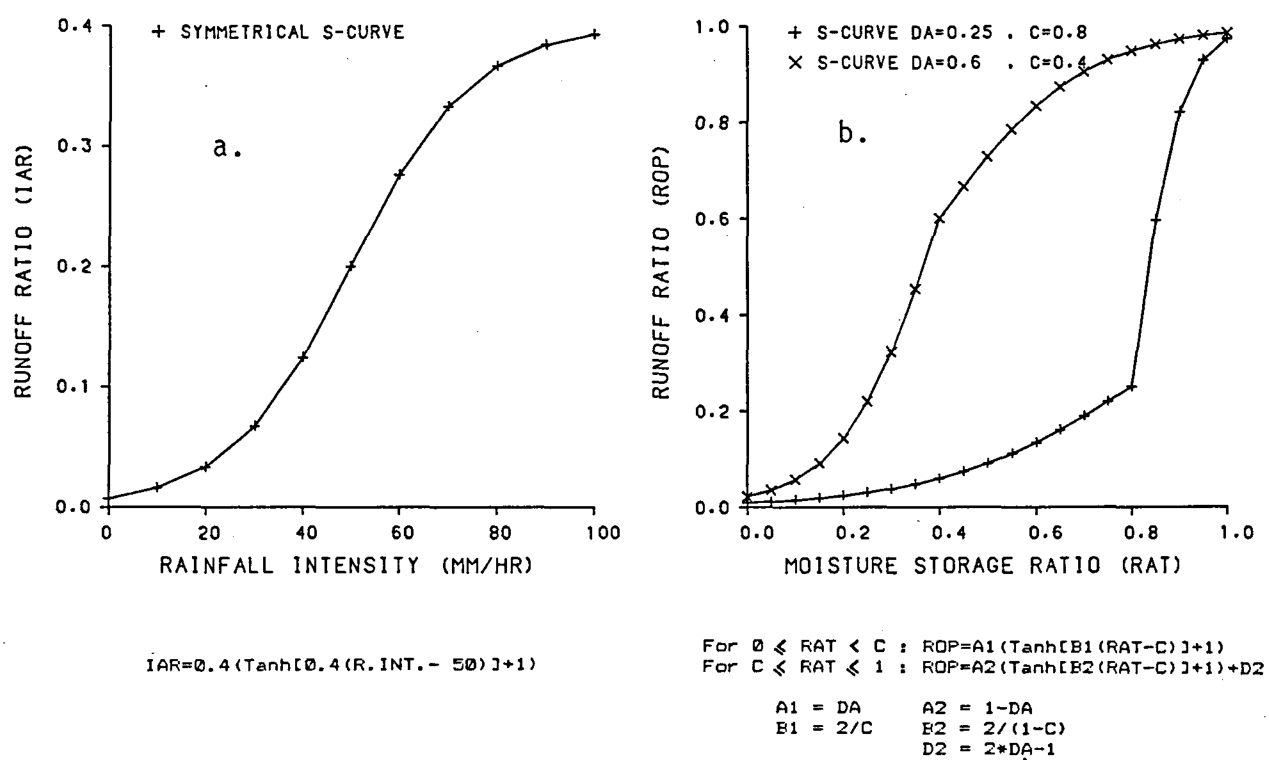

Figure 4.2 S-Curve relationships used in the S-Curve model
a) intensity controlled runoff, b) implicit variable source area runoff.

The moisture status of the catchment (RAT) is defined relative to some maximum value (SMAX). SMAX is conceived as the moisture level (mm) at which the complete catchment (or sub-catchment) is contributing directly to runoff (runoff proportion = 1,0). Thus the runoff proportion (ROP) at any time interval is defined by the relative moisture status and the shape of the assymmetrical S-curve function. As in the earlier model (Hughes, 1984) this function is constructed from two TANH functions having a common point at (DA,C). DA and C are model parameters and their influence on the S-curve shape is illustrated in figure 4.1b. As before, the runoff proportion (ROP) multiplied by the rainfall amount provides the unrouted runoff depth in one time interval. At high moisture levels there is a possibility that the runoff from this equation and the infiltration excess function add up to greater than unity. The model checks for this and adjusts accordingly.

The rainfall proportion that does not contribute to runoff is added to a store, having an infinite maximum value and which starts at zero level for convenience. In each interval a proportion of this conceptual slope storage drains into the conceptual variable source area (VSA) store and increments the moisture status of the catchment. Clearly, this gives rise to higher runoff proportions during later intervals. To account for slow subsurface drainage from the VSA store, a proportion of its absolute amount drains out per interval. For zero rainfall periods during the event, the balance between the drainage from the slope storage (into the VSA store) and the VSA storage determines whether the source area expands or contracts. The amount draining from the two storages are constant proportions of their levels (%. hr^{-1}) and defined by two model parameters (PCSLP and PCVSA). Drainage from the VSA is perceived as being able to flow into the channel or into deeper groundwater. While the former is likely to contribute to streamflow during the event, the latter is not. There is little information on which to base a quantitative differentation of these two components. For convenience, and to avoid adding further parameters, a fraction equal to the relative moisture status of the catchment is considered to flow into the channel during the event. The remainder is not accounted for during the storm duration.

Runoff can thus be generated by three separate components of the model. Two of them are considered to be relatively rapid flow elements, one determined by the rainfall intensity and one by the moisture status of the conceptual variable source area. The third element is the relatively slow drainage from the VSA store to the channel.

4.3.3 Runoff routing

Runoff routing is divided up into two components referred to as the 'land' and 'channel' phases. The land phase routing is the same for both lumped and semi-distributed model versions but for the channel phase different modelling approaches are used. The land phase routing makes use of a non-linear storage-routing relationship of the type $S=KQ^N$, where K and N are model parameters. This equation is combined with the continuity equation $dS/dt=I-Q$ and the solution achieved using the method developed by Hughes and Murrell (1986). In the lumped model this routing component represents the attenuation effects of flow over and below the surface as well as in minor tributaries. In the semi-distributed model, the routed flow is conceived to represent the outflow from a nodal point at the sub-catchment centre. The relatively rapid flow from the VSA and the intensity controlled runoff are combined and routed using parameters K and N. The slower flow component is routed using a higher value of K. This is determined by dividing K by the fractional loss from the VSA store per time interval and the moisture storage ratio. This is an arbitrary scaling factor but avoids incorporating additional parameters.

In the lumped model channel routing is carried out by means of a time-area triangle with an initial delay. Each unit of output from the non-linear land phase routing component is first of all delayed (parameter DEL) and then spread forward in time using an isosceles triangle with variable base length. The base length is calculated from a non-linear function of the output from the land phase routing (in $mm.hr^{-1}$). An inverse power function of the form $TA = A.Q^{-B}$ is used, where TA is the base length in hours, Q is discharge in $mm.hr^{-1}$ and A,B are parameters. As the discharge decreases, the triangle becomes more elongated, implying slower routing. As B increases, the triangle shape becomes relatively more variable .

After initial test results on a semi-arid catchment it was considered desirable to try and include a simple formulation to account for channel losses. The effects that were necessary to achieve were less runoff at low moisture levels than were being modelled, and a more rapid response of the remaining runoff. The latter effect is logical as the majority of the channel losses were considered to be occurring in the upstream reaches. Consequently, only the lower reaches with shorter travel times would be contributing. The effects can be achieved by reducing the runoff volume and the base of the time area triangle by a calculated amount. As this amount is likely to depend upon the moisture status of the catchment it has been made a function of this in the following equation:

$$CLOSS = 1/(RAT*ROP)^{CLP}$$

where RAT is the relative moisture status ($\leq$ 1,0), ROP the runoff proportion, CLP is a model parameter and CLOSS is the percentage runoff lost to the channel and the percentage decrease in the base length of the time area triangle. If CLP is greater than unity then losses vary at a lower rate than the moisture status and vice versa. To maintain a water balance, the amount of runoff absorbed by the channel is added to the VSA store to increment the moisture status of the catchment. In the semi-distributed form of the model it is merely necessary to reduce the output from each sub-catchment (by CLOSS percent) and route the remainder in the manner described below.

Semi-distributed routing is achieved by routing sub-catchment outflow through a conceptual channel reservoir to the next downstream sub-catchment node. The downstream sub-catchment outflow is added and then routed further downstream. Where the configuration of sub-catchments is such that more than one group of sequentially linked sub-areas exist then allowance is made for storing hydrograph elements and combining them at a confluence. The routing formulae used is the same as in the land phase but with different parameters. Land phase K is replaced with KC and N with a fixed value of 0,7. A further small difference exists in that the routing input for the land phase is the excess rainfall intensity during a specific time interval. For channel routing this becomes the average of the upstream inflows plus sub-catchment outflow (land routed excess rainfall) at the beginning and end of the time interval. As the non-linear routing function employed only incorporates attenuation, a further group of parameters is necessary to define the delays for each sub-catchment (CDEL).

4.3.4 Summary of parameters

The complete parameter set is given in table 4.1, which also lists the alphanumeric symbols and the parameters relevance to either the lumped or semi-distributed form of the model. Used as a lumped model, 13 parameters are involved. One is used in the antecedent moisture estimation component, six in the conversion of rainfall to runoff depths and six in the routing procedure.

Table 4.1 Summary of parameters used in the developed S-curve model

Description	Symbol	Lumped or Semi-distributed
1. Catchment routing constant	K	Both
2. Catchment routing power	N	Both
3. Channel delay time (hr)	CDEL	S.D.
4. Channel routing constant	KC	S.D.
5. Catchment delay time (hr)	DEL	L
6. Time area base constant (hr)	A	L
7. Time area relation power	B	L
8. Maximum soil moisture level (mm)	SMAX	Both
9. Ordinate S-curve parameter	DA	Both
10. Abscisa S-curve parameter	C	Both
11. Percent flow from slope to VSA store ($\%.hr^{-1}$)	PCSLP	Both
12. Percent flow from VSA store ($\%hr^{-1}$)	PCVSA	Both
13. Impervious area factor	IAF	Both
14. Antecedent precipitation factor	APF	Both
15. Channel losses power	CLP	Both

If the semi-distributed format is to be used then 12 parameters are involved and values must be assigned to these for each sub-catchment. If it is assumed that the runoff characteristics of the sub-areas can be considered uniform then only parameters 3 and 4 and 15 need to be estimated for separate areas. These are the only parameters that logically must be different. In the computer program the model accepts single values for each of the 12 parameters plus a matrix of sub-area factors, expanding the parameter space to 12 * number of sub-areas. This is a useful method of coding as it allows one or more parameters to be changed easily without changing the relative values for each sub-area. Equally, it allows one sub-area parameter to be changed without the others.

The model is not intended to represent a physically-based approach in the normally used sense. Consequently, few if any of the parameters can be evaluated directly from field measurements. However, the model has been designed such that the parameters should have relevance to some aspect of the physical response system of catchments. The likely physical association of the model parameters is discussed in the following section. An attempt is also made to identify those catchment characteristics that may be most important to consider when estimating parameter values. The value of such an approach can only be tested after a thorough assessment of the model on a range of different catchments.

4.4 Physical relevance of parameters and perceived association with catchment characteristics.

This model is designed to be a compromise between strongly physically-based approaches and simpler curve fitting methods. It has never been intended that the parameters should be measurable in the field. However, the model has been designed to include the major elements of runoff generation in some conceptual way. The intention was to build an adequate conceptualisation such that a variety of different storm responses on a single catchment could be represented by one set of parameter values. Thus, parameter values should not vary for different storms on the same catchment. There is inevitably a high degree of interaction between the parameters of this model. If used in semi-distributed format, there are a large number of possible parameter value permutations that could produce a similar hydrograph response to a single storm. Not all such permutations would produce a satisfactory response to another storm. Consequently, the calibration exercise largely consists of finding a unique permutation that is suitable for a wide range of storms. This can be an extremely difficult exercise and would be almost impossible without some kind of guidelines for setting initial parameter values and their relative level on different sub-catchments. This section of the report seeks to identify the physical relevance of the parameters with respect to catchment characteristics. At this stage these associations are of a qualitative nature. Part of the model testing procedure will be to confirm or reject such associations. Only when a range of catchments have been calibrated successfully will it be possible to investigate whether the qualitative associations could be extended into quantitative relationships. This may be considered to be the ultimate goal with respect to testing the usefulness of this particular model.

The antecedent precipitation factor (APF - parameter 14) determines the extent to which an amount of rainfall input, a number of days prior to the storm, has an effect upon the initial moisture status of the catchment. This is in turn dependent upon the proportion of that rainfall that drains out of the catchment and the amount that is lost due to evapotranspiration. There are a number of physical associations including soil drainage properties, land use and vegetation and topography. However, there are also climate factors and meteorological influences prevailing at the time of the rainfall input. It becomes apparent that there are no simple associations for this parameter and it must be recognised that this is a weak component of the model. The advantages and disadvantages of more complex approaches to the determination of initial catchment moisture status were discussed in section 2.4.1 of this report.

The impervious area factor (IAF - 13) determines how much runoff occurs in relation to rainfall intensity regardless of the moisture status of the catchment. It should be related to the area of the catchment close to channels that have low infiltration capacities. The inclusion of such a component is considered justified by the observed response of some catchments to intense rain falling on a dry catchment.

Parameters 11 and 12 (PCSLP and PCVSA) should be related to slope and valley bottom drainage characteristics. PCSLP determines how rapidly rain falling on the slopes drains to and increments a conceptual source area. This may be rapid on steep slopes with thin soils or with well drained upper soil horizons overlaying a relatively impervious layer. Lower values of PCSLP should occur if the valley slopes are gentler despite higher subsurface permeabilities. The length of slopes and hence the drainage density should also be important. PCVSA determines the rate at which moisture is removed from the source area due to drainage into the channel as well as deeper drainage. Consequently, the permeability and drainage characteristics of the valley bottom soils and the sub-stratum will be relevant to the value of this parameter.

Strictly, parameter SMAX (8) represents the amount of moisture in storage at the moment when the whole catchment is saturated. Consequently it should be evaluated as the moisture holding capacity of the catchment (or sub-area). The two parameters DA and C (9 and 10) define the relationship between moisture levels below SMAX and the proportion of the catchment that is saturated at the surface. The S-curve relationship is designed to represent the complex spatial interaction between the topography, and soil water retention capacity of the catchment or sub-area. Various authors have addressed the problem of defining source areas either by direct measurement (Kirkby et. al., 1976) or by estimation (Beven and Kirkby, 1979; O'Loughlin, 1986). It remains to be seen whether the progressive increase in the models conceptual source area is realistic and whether the form of its relationship with relative catchment moisture status can be estimated.

The catchment routing parameters, K and N (1 and 2) represent the attenuation effects of routing the so-called impervious area and variable source area runoff elements to the main channel system. It has been found by other authors who have used the same form of non-linear routing equation that it is better to hold N constant at some value between 0.6 and 0.8 (Mein et al., 1974). K should be related to the predominant mode of flow by which water collects in the stream channels. If this is overland flow then length of flow slope and surface roughness should also affect the value of K. If it is mainly saturated sub-surface flow then K may be higher (slower response) and affected by the lateral drainage characteristics of the soils and sub-stratum. If there exists a high degree of spatial variation in the rate of runoff response then it seems unlikely that a lumped approach will prove adequate even for individual storms.

The time area diagram used in the lumped version of the model has three parameters (DEL, A and B, - parameters 5 to 7). DEL merely represents the time delay before a significant response to any amount of rainfall is experienced at the catchment outlet. It is difficult to propose a physical association for this parameter as at least some response may be expected immediately, if only from rain falling on the channel surfaces close to the outlet. Hence, delay values are usually expected to be small and the parameter is of less importance than A and B which define the length of the symmetrical time area triangle for a given value of runoff in mm. hr^{-1}. B determines the extent to which this relationship is non-linear, lower values of B suggesting more similar triangles for all ranges of flows. The time area triangle should be related to the spatial pattern of the channel network and the channel slope variations within this network. Elongated catchment shapes are expected to have longer triangles than rounded shapes given similar areas and slopes. Higher slopes in channels more distant from the outlet may be expected to indicate shorter triangles. Channel roughness and flow resistance effects may also be important but subsidiary to the other factors already mentioned. Sub-catchment channel routing is controlled by two parameters for each sub-area. CDEL (3) represents the delay before a sub-area begins to contribute to flow at the catchment outlet, while KC represents the attenuation effects of routing the output from the node of one sub-area along the channel to the next. Channel length, dimensions, slope and flow resistance effects are expected to determine the relative values of both these parameters. Problems are likely to arise if strong attenuation effects result from overbank flows within a specific reach above certain flow thresholds. No account of floodplain inundation effects is allowed for in this model.

The final parameter CLP (15) determines the amount of flow that is lost through absorption by the channel and its banks. This parameter also affects the length of the time area triangle in the lumped model version.

The percentage of flow lost to the channel is determined by a power function of the size of the source area and relative moisture status. Channel losses should be related to the permeability of the bed and banks of the channel as well as the spatial positioning of the source area. If channels are developed on permeable materials (alluvium or permeable rock strata) and local groundwater levels are below the channel bed, then channel losses may be relatively high. As source areas can be predominantly surface features it is possible to have a saturated surface adjacent to a channel which has a capacity to absorb water through its bed. This may be a shortlived situation as vertical drainage from the upper soil horizons (and lateral drainage from higher slope areas) begins to reduce the lower zone moisture capacity. During short duration, high intensity events on dry catchments, channel losses may be high enough to absorb most of the runoff generated in upstream areas. It is possible that channel losses are the main reason why few flow events are recorded in some semi-arid areas despite thin soils and high intensity rainfall. Alternatively, channel losses may be insignificant or non-existent in catchments experiencing perennial streamflow. In such cases CLP would be set to a very low value.

It can be seen that it is easier to suggest associations with catchment characteristics for some parameters than others. The eventual usefulness of the model depends, to a certain degree, on the extent to which these associations can be confirmed after calibration and verification exercises have been performed on a number of catchments. It also depends upon whether the parameters to which the model is most sensitive have the highest levels of physical relevance. There is little point in determining quantitative relationships between relatively insensitive parameters and physical catchment characteristics if this is not possible for those parameters that affect runoff response the most.

5. SIMPLE ANTECEDENT MOISTURE MODEL (OSE1)

5.1 Background

The model described in this section is an extended version of the Isolated Event Model (IEM4), discussed in Eyre and Crees (1984), Mandeville (1983) and the Flood Studies Report (1975). The original IEM4 model used an exponential relationship between initial soil moisture deficit at the beginning of a storm and the proportion of gross rainfall that contributes to storm runoff. In OSE1 the exponential relationship is replaced by an assymmetrical S-curve function of the same type used in the S-curve model (OSE2) described in chapter 4 of this report. The model uses an antecedent moisture procedure determined by Hughes (1984), but unlike the S-curve model it applies a constant runoff proportion (ROP) throughout a storm event. A constant ROP has been retained for the purposes of comparing the performance of OSE1 with the Augmented Hydrograph model, which is described later in this report. The two models have similar major components but their order of operation is different (figure 6.3).

IEM4 has been widely tested (Mandeville,1983) and applied in the United Kingdom, not only for flood estimation (its orginal goal) but also for flood forecasting purposes (Eyre and Crees,1984). IEM4 has not been tested on ungauged catchments and it will be necessary to establish whether model parameters can be related to storm and or catchment characteristics in some way.

5.2 Conceptual structure of the model

As with the more complex S-curve model, OSE1 has three basic components; antecedent moisture status estimation, volume reduction and shape transformation and the model has been designed to run in lumped or semi-distributed format (figure 5.1). The method of estimating antecedent moisture status is to that used in the S-curve model and described in section 4.3.1.

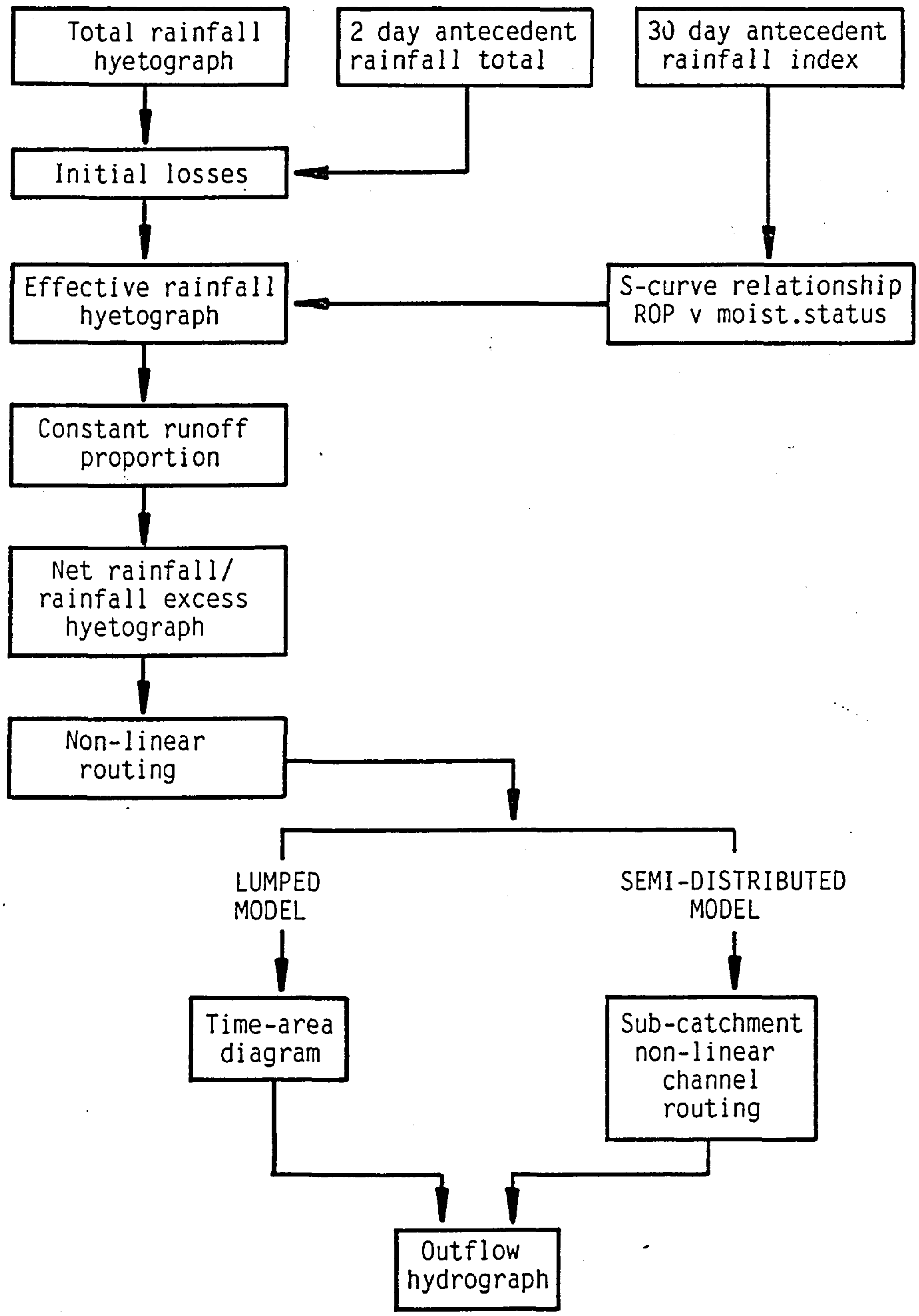

Figure 5.1 Structure of the simple antecedent moisture model (OSE1)

Table 5.1 Summary of parameters used in model OSE1

Description	Symbol	Lumped/semi-distributed
1. Catchment routing constant	K	Both
2. Catchment routing power	N	Both
3. Channel delay time (hr)	CDEL	S.D
4. Channel routing constant	KC	S.D
5. Catchment delay time (hr)	DEL	L
6. Time area base constant (hr)	A	L
7. Time area relation power	B	L
8. Maximum soil moisture level (mm)	SMAX	Both
9. Ordinate s-curve parameter	DA	Both
10. Abscisa S-curve parameter	C	Both
11. not applicable to OSE1		
12. not applicable to OSE1		
13. not applicable to OSE1		
14. Antecedent precipitation factor	APF	Both
15. Initial losses	IL	Both

The volume reduction component of the model begins with an estimation of initial losses (IL). Initial losses are first satisfied by the antecedent rainfall total for the two days prior to the storm event. Any remaining losses must then be satisfied by the rainfall in the early part of the storm. All remaining rainfall amounts are reduced by a fixed proportion (ROP) which is defined by the relative antecedent moisture status and the shape of the S-curve. This method of volume reduction is thus similar to the S-curve model, except that only one runoff proportion is calculated and remains fixed for the rainfall inputs at all time intervals. The moisture status (RAT) is defined relative to a maximum value (SMAX) when ROP is equal to 1,0 and the S-curve shape is fixed by parameters DA and C (table 5.1). The runoff routing or shape transformation components are identical to those described in section 4.3.3 except that the channel losses modification has not been included. OSE1 has fewer parameters than the S-curve model (10 for lumped and 9 for semi-distributed modelling) but where the parameters are shared between the two models they have the same basic meaning.

5.3 Physical relevance of parameters and perceived association with catchment characteristics

In a manner similar to the S-curve model (see section 4.4) this section attempts to identify the physical relevance of the model parameters with catchment and/or storm characteristics. The modelling of a wide range of catchments will be necessary to confirm or reject these associations and thus establish the usefulness of this particular model as a design tool.

Initial losses (IL-parameter 15) gives an indication of the amount of total rainfall which will not contribute to storm runoff. A wide range of factors are expected to be associated with initial losses and include the following:-

a) The catchment antecedent moisture status, that is the 'wetter' the catchment prior to an event, the lower the expected initial losses and vice versa. b) Topographical (depressions causing ponding), soil characteristics (infiltration rate), and vegetation (interception) are also expected to influence initial losses.

c) Loss of storm runoff due to channel losses, for example the infiltration of channel flow into an alluvial bed could result in significant losses.

d) Initial losses are also expected to be related to storm characteristics, in particular the amount, intensity and duration of an event.

It is apparent that there are no simple associations for this parameter as all of the above factors are likely to effect initial losses to varying degrees. It is likely that certain factors may be more dominant in different catchment types. In the semi-arid situation it is expected that the variability in initial losses will be greater than in the sub-humid situation which are thought generally to have more stable antecedent moisture conditions.

The expected physical relevance of parameter 14 (APF) and the parameters determining the ROP (parameters 8, 9 and 10 - SMAX, C and DA) are similar to those proposed in section 4.4 of the S-curve model. The catchment routing parameters, K and N (1 and 2) represent the 'land' phase routing of runoff to the main channel system and have similar expected physical associations as those described in section 4.4. The channel routing phase of the lumped version of the model is controlled by the time-area diagram which has 3 parameters (DEL, A and B, - parameters 5, 6 and 7). The parameters should be related to topographical elements of the channel system, such as the channel network pattern and channel slope variations within the catchment. The shape of the catchment is also expected to effect the shape of the time-area diagram (see section 4.4). The expected physical association of the sub-catchment routing parameters (CDEL and KC - 3 and 4) are identical to those described in section 4.4 of the S-curve model.

6. AUGMENTED HYDROGRAPH MODEL (OSE3)

6.1 Background

The model described in this section is a modified version of the Augmented Hydrograph model presented in Mandeville (1983). The central concept of the orginal model was developed by Mandeville while working on isolated event modelling at the Institute of Hydrology, Wallingford, and represents a novel approach to modelling the rainfall-runoff process. In conceptual modelling the usual procedure is to seperate the rainfall-runoff process into two major components, which are independent of each other (Tennesse Valley Authority, 1965; Rajendran and Mein, 1986; Murray and Görgens, 1981). The first step, traditionally, is to estimate volume reduction (figure 6.1), that is the transformation of rainfall into storm runoff (often referred to as net or excess rainfall). This step generally includes the catchment antecedent moisture status estimation. The volume reduction procedure produces a an excess rainfall hyetograph, which is then applied to the shape transformation component which routes the excess rainfall across and or beneath the land surface and along the channel network to produce delayed and attenuated streamflow at the outlet.

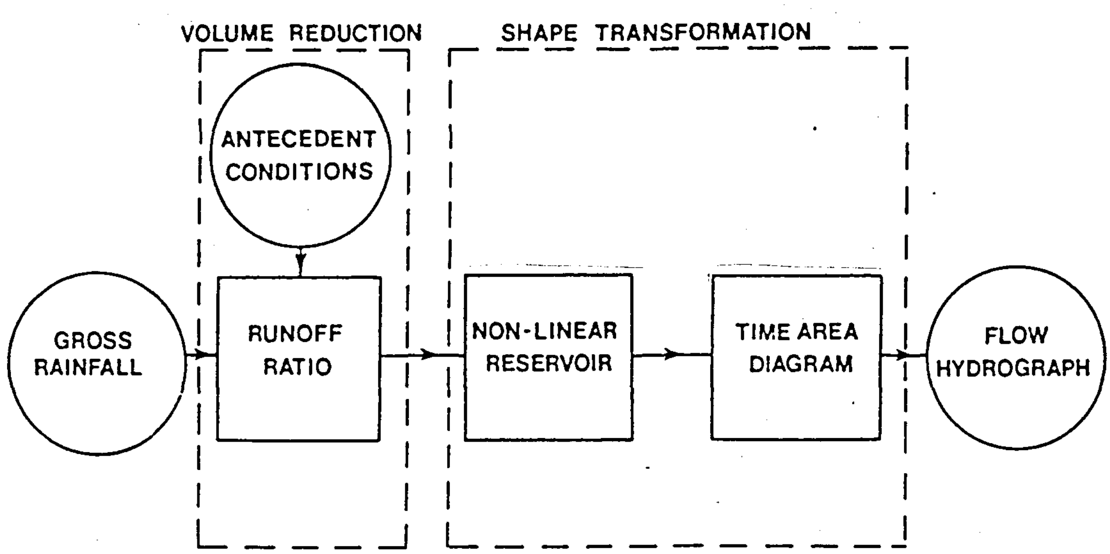

Figure 6.1 Traditional order of model components (from Mandeville,1983)

The Isolated Event Model (IEM4), referred to in chapter 5 is a traditional rainfall-runoff model. Analysis of this model by Mandeville (1983) revealed that the major components were not independent of each other. He therefore proposed a new form of model in which the major components are the same as the IEM4, but their order is changed (figure 6.2). In the new model the parameters of the shape transformation component do not depend in any way on the volume reduction component.

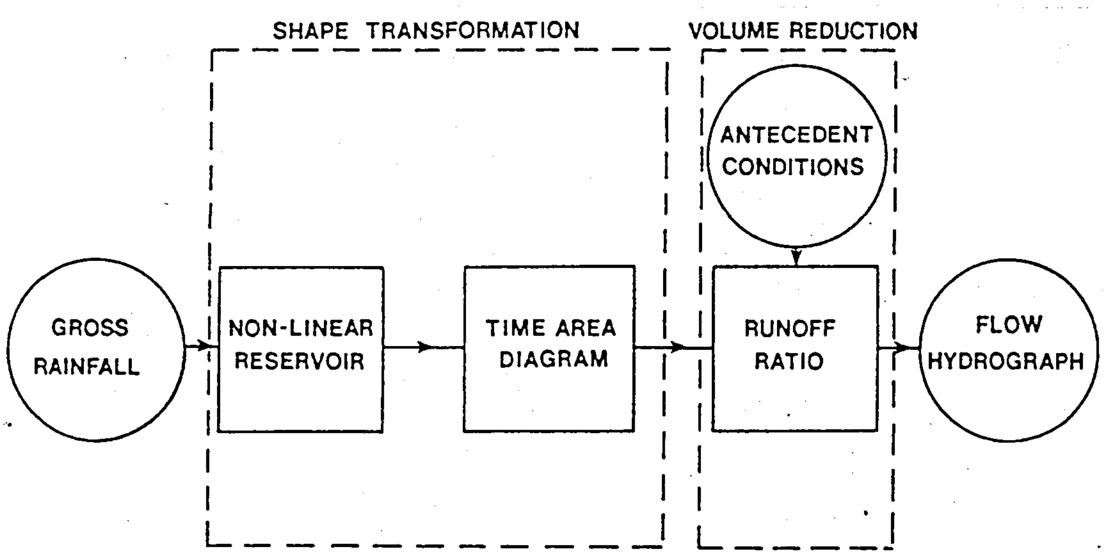

Figure 6.2 Augmented hydrograph model : component order (from Mandeville, 1983)

In the Augmented Hydrograph model, the gross rainfall hyetograph is applied as input to the shape transformation component, the output is a hydrograph with the same volume as that under the gross rainfall hyetograph, but a different shape (Figure 6.3). This intermediate hydrograph is termed the augmented hydrograph. The augmented hydrograph is then applied as input to the volume reduction component of the model to produce the flow hydrograph. The augmented hydrograph has the same shape as the flow hydrograph but a larger volume.

The advantages of this approach include:-

a) By reversing the order of the two subsystems, so that the non-linear reservoir precedes the runoff ratio, the large variations in the size of the non-linear reservoir obtained when fitting the IEM4 model will be reduced (Mandeville, 1983). The new model contains the non-linear reservoir which is fixed for all events followed by the application of a variable runoff ratio appropriate to any one event.

b) The new model has the advantage, if it works, of being able to check routing parameters against shape and then reducing the volume to fit the output hydrograph.

c) There is no seperation of runoff into stormflow and baseflow; another determination which is difficult to physically measure.

The model proposed by Mandeville is based mainly on the results from a detailed study of one catchment and while preliminary tests are promising (Mandeville, 1983) the model hypothesis has not been widely tested and applied. For the model to be of value as a hydrological tool it will be necessary to establish whether model parameters can be related to storm characteristics in some way. Only if this were successful could the model be used to estimate hydrographs in the ungauged or design situation. It might be necessary therefore to develop the model futher without changing its basic structure. This can be done by identifying conceptual weaknesses within the model and incorporating additional components where necessary to improve the models flexibility.

6.2 Conceptual structure of the developed model

The form of the Augmented Hydrograph that is being tested can be divided up into three major components. Initial losses are first removed from the input rainfall, the remainder is then routed, then reduced to equal the runoff volume. As with the models discussed in the previous chapters, the model has been designed to run in lumped and semi-distributed format. On the basis of some preliminary model runs on events from different catchments, the initial losses component was added to account for antecedent rainfall immediately prior to the event. The initial losses component operates the same way as in model OSE1 and has one parameter (IL, table 6.1).

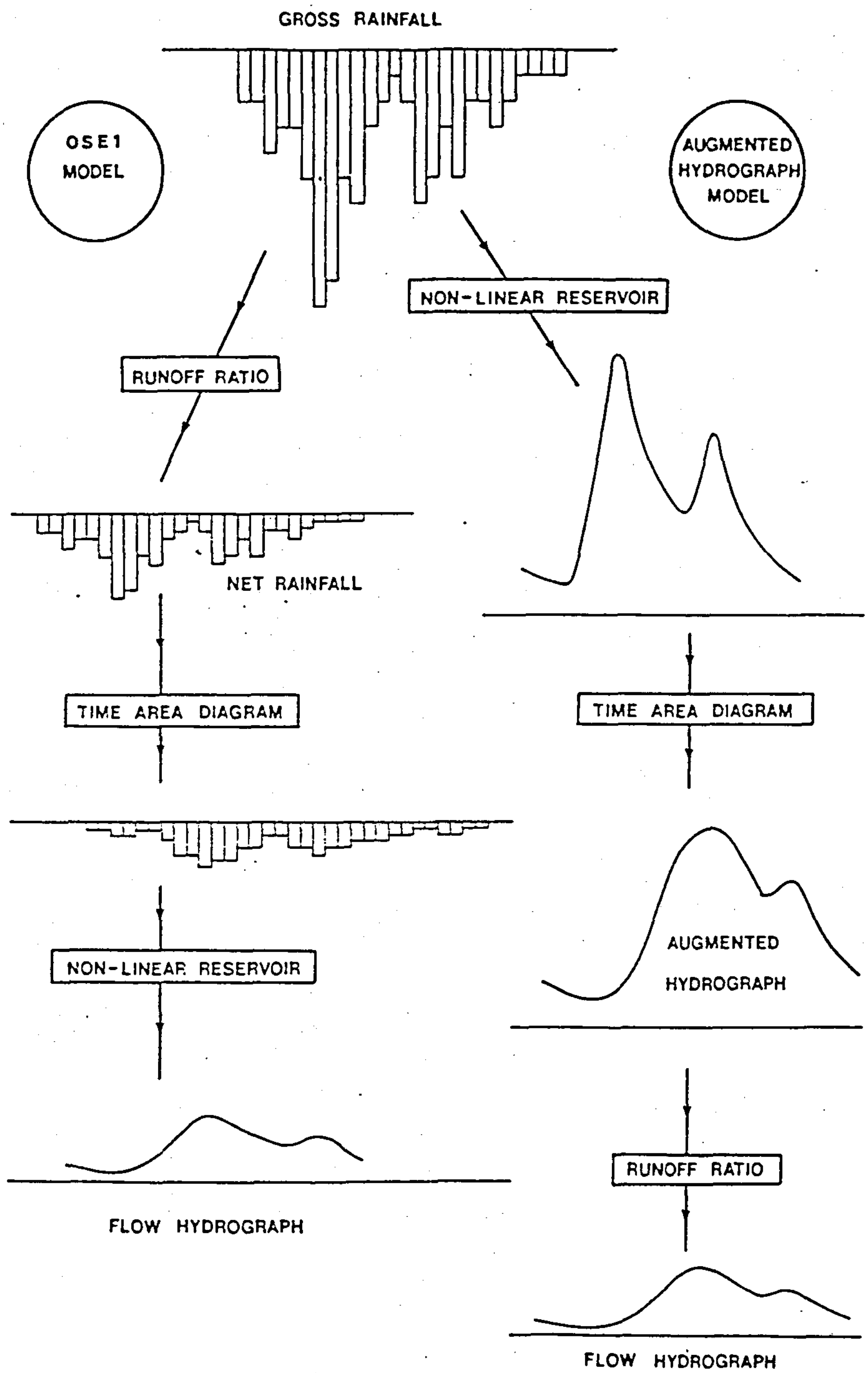

Figure 6.3 Comparison between component responses of OSE1 and augmented hydrograph models (from Mandeville, 1983)

The shape transformation or runoff routing component involves applying the rainfall hyetograph (minus initial losses) to the routing subsystems to give output as a hydrograph with the same volume as the rainfall input but with a different shape. Runoff routing is divided into two subsystems referred to as the 'land' and 'channel' phases in a similar way to that described in section 4.3.3 for model OSE2. The 'land' phase routing makes use of the non-linear storage-routing relationship $S=KQ^N$. In the lumped version, the 'channel' phase routing, uses an isosceles triangle defined by the parameters A, B and DEL (table 6.1). The semi-distributed 'channel' phase routing uses the storage-routing equation to attenuate sub-catchment flows as they pass through downstream sub-areas.

The intermediate hydrograph produced by the routing subsystems is applied as input to the volume reduction component of the model, in which each of its individual ordinates is reduced by multiplying by the runoff ratio (ROP) to give the flow hydrograph as output. The initial value of ROP is estimated as follows (Mandeville, 1983):-

$$ROP = \frac{\text{observed runoff volume}}{\text{observed gross rainfall volume (minus initial losses)}}$$

The complete parameter set is given in table 6.1, which also lists the alphanumeric symbols and the parameters relevance to either the lumped or semi-distributed form of the model. In the lumped format, 7 parameters are involved. One is used to estimate initial losses, five in the shape transformation procedure to produce the intermediate hydrograph and one to effect volume reduction and produce the output hydrograph. If the semi-distributed format is used then 6 parameters are involved and values must be assigned to these for each sub-catchment. If it is assumed that the runoff characteristics of the sub-areas can be considered uniform then only parameters 1 and 2 need to be separately calculated for individual sub-areas.

Table 6.1 Summary of parameters used in the Augmented Hydrograph Model

Description	Symbol	Lumped/semi-distributed
1. Channel delay time (hr)	CDEL	S.D.
2. Channel routing constant	KC	S.D.
3. Runoff Coefficeent	ROP	both
4. Catchment routing power	N	both
5. Catchment delay time (hr)	DEL	L
6. Time area base constant (hr)	A	L
7. Time area relation power	B	L
8. Catchment routing constant	K	both
9. Initial losses (mm)	IL	both

6.3 Physical relevance of parameters and perceived association with catchment characteristics.

Ideally the parameters of a simulation model should be determined objectively and should be closely related to measurable physical catchment characteristics. Differences in parameter values may then be examined in light of physical changes on a catchment or changes in catchment characteristics from one catchment to another (Dickenson and Douglas, 1972).

The expected physical relevance of the initial losses parameter and the shape transformation or routing parameters of this model are identical to those discussed in section 4.3 and 3.3. This section of the report will concentrate on the perceived physical relevance of the volume reduction parameter (ROP - parameter 3). According to Mandeville (1983), by changing the order of the major components of the model, so that runoff routing precedes the volume reduction component, the parameters of the two components should be independent of each other. Therefore the routing parameters should remain constant between events on the same catchment and should not be influenced by the volume reduction parameter (ROP). The routing parameters are expected to be related to topographical catchment characteristics such as slope, slope length, drainage pattern etc, which do not change. It is expected that the volume of runoff (ROP) will be related to storm characteristics and the catchment antecedent moisture status, (which do change between events), as well as soil characteristics (more stable). Rainfall characteristics such as rainfall volume, duration and intensity are expected to influence the runoff proportion. Soil characteristics such as depth of soil, permeability and organic content are expected to influence the volume of runoff. For example, if a long duration, low intensity event occurs on a 'wet' catchment which has deep, permeable soils, the ROP is likely to be fairly high. For the same event on a 'dry' catchment the volume of runoff is expected to be lower because a larger proportion of the rainfall will be required to satisfy the catchment moisture status before runoff can occur. Likewise, if the same event occurred on catchments with similar antecedent moisture conditions but with different soil characteristics the proportion of runoff is expected to be different. For example, the runoff response of shallow, impermeable soils to rainfall is expected to different to the response of deep, permeable soils.

7. RUNOFF-ROUTING MODEL (RORB) (OSE4)

The basic conceptual structure of the rainfall-runoff routing model developed at Monash University, Department of Civil Engineering has been described by Mein et al. (1974). The relatively brief description given in this section is drawn from the User Manual supplied with the computer program by Monash University (Laurenson and Mein, 1985). RORB version 3 is a general rainfall-runoff and streamflow routing model that can take into account amongst others, the effects of retarding basins, storage reservoirs, lakes or flood plain storages. The model program is run interactively from a terminal and operates in different modes depending upon whether the user wishes to FIT the model to observed data; TEST a parameter set or calculate DESIGN hydrographs. The model is arealy distributed and the authors of the manual claim that it is applicable to both urban and rural catchments. The description provided below concentrates on the rainfall-runoff modelling components of the model. For those readers who require more information about the complete range of options that are available reference should be made to the User Manual (Laurenson and Mein, 1985).

7.1 Distribution system and routing method

RORB is a semi-distributed model that operates on a sub-catchment basis by defining nodes to represent the sub-area inflow points or junctions of sub-areas. Between nodes are placed conceptual storages through which sub-area inflows.plus upstream flow is routed to the next node downstream. Several types of inflow to, and outflow from the channel network are possible. Sub-area inflow represents the input of excess rainfall from a specific sub-catchment and it is assumed to enter the network at a point close to the sub-area centroid. Concentrated channel inflow allows for the input of streamflow from a source (off-channel storage, tributary or diversion) not being modelled. Distributed inflow can be included over a specified number of reaches and can be used to represent lateral inflow of base flow for example. Concentrated outflow may be required if a diversion channel or effluent stream forms part of the system being modelled. Finally, the reverse of distributed inflow is also possible to represent lateral outflow or channel loss processes.

The model is conceptually an overland flow model and the storage effects of minor channels and overland flow are included in the storage effects of the major channels. Unlike the other models discussed, the land surface and channel routing components are lumped together. However, the model can be adapted to consider these two storages separately. Usually the storage parameters of each reach are assumed to be related to the properties of the reach and not the sub-area. Streamflow routing is based upon a storage-discharge relation of type $S = 3600\ k.Q^m$. Where k is the product of two parameters k_c and k_r. k_c is a parameter applicable to the complete catchment whereas k_r is applicable to individual reach storages. k_r values are calculated in the program from input data of channel reach lengths and type of channel (natural, lined or drowned by a reservoir). The assumption is made that delay time is proportional to flow distance. However, if this assumption is considered inadequate then a user may substitute other values to represent delay times in place of reach lengths. The User Manual (Laurenson and Mein, 1985) suggest that the variable $L/\ S_c$ (L = reach length; S_c = reach slope) may be more appropriate when catchments have extreme slope variations. k_c is a parameter of the model when operating in calibration mode and Laurenson and Mein (1985) offer suggestions for estimating its value. The power m of the storage-discharge equation is also a parameter but has found to be of subsidiary influence to k and a value of 0,8 is recommended.

The program allows a user to specify where observed streamflow data are to be used to compare with simulated flows. This feature can be very useful where streamflow gauging networks are nested. The model then only needs to be run once to allow comparison of results with observed data to be effected at several points within the total catchment.

7.2 Modelling of excess rainfall

RORB is an isolated event model that does not account for evapotranspiration, soil moisture or groundwater redistribution. The latter can only be accounted for through independently determined component inputs to the model. The calculation of rainfall excess is based upon two alternative loss models. In both models an initial loss is assumed and must be satisfied before any rainfall excess can occur. In the first model option the initial loss is followed by a constant runoff coefficient; that is the proportion of rainfall that becomes runoff ramains constant. The second model assumes that the initial loss is followed by a constant, continuing loss rate. Only rainfall inputs higher than this rate can contribute to streamflow.

Variability of losses between sub-areas can be accommodated through a sub-area input parameter referred to as the fraction imperviousness. If the fraction imperviousness is set to anything but zero then the values input for initial loss, runoff coefficient or loss rate are applicable to the most pervious area. The loss parameters for each sub-area are calculated in the model in the following way :

$$IL_i + (1-F_i)\ IL_{perv}$$

if $IL_{perv} >$ Sub-area rainfall then IL_{perv} = sub-area rainfall

$$C_i = F_i C_{imp} + (1-F_i) C_{perv} \quad \text{for } C_{perv} \leq C_{imp}$$
$$C_i = C_{imp} \quad \text{for } C_{perv} > C_{imp}$$

$$CL_i = (1-F_i) CL_{perv}$$

where IL = initial losses
C = runoff coefficient
CL = continuing loss rate
F = fraction imperviousness
i = sub-catchment subscript
imp = impervious subscript
perv = pervious or most pervious subscript

The parameters subscripted perv are those input (IL_{perv}) or calculated by the program (C_{perv} or CL_{perv}). C_{imp} is set by the program to a value of 0,9. In FIT and TEST runs the constant runoff coefficient or loss rate is determined by an iterative procedure in the model to ensure that the correct volume of runoff is predicted. If more than one set of observed streamflow data are input to the program, then separate loss parameters are calculated for the areas upstream of or between gauging points.

7.3 Input of rainfall data

A number of separate rainfall profiles may be input to the program. Any one of such profiles may then be assigned to each sub-area of the distribution system. The total amount of storm rainfall for each sub-area is also input. Two or more sub-areas may therefore experience the same time distribution of rainfall but different total rainfall depths.

The model makes allowance for total rainfall amount to be entered as a series of separate bursts defined by their start and finishing times. Different loss parameters can then be calculated for different bursts. The streamflow is then assumed to occur in separate "rises" associated with each burst and the proportions of the total streamflow corresponding to each 'rise' must be input. Loss parameters are then calculated from the amounts of rainfall and the proportional amount of resulting streamflow from each burst. This is clearly quite restrictive as it assumes that the user has some knowledge of the relative runoff responses of the different bursts.

8. TEST CATCHMENTS AND AVAILABLE DATA

8.1 Catchment Description

For this preliminary report on the evaluations of the four models two different catchment areas have been used. Both represent nested gauging situations such that observed flow data are available at more than just the total catchment outlet. One of the catchments (Ecca) is situated in the semi-arid eastern Cape Province of South Africa while the other (North Danville) is in the temperate, northeastern American state of Vermont.

8.1.1 Ecca catchments

This set of five nested research catchments (fig. 8.1) were established in 1974 by the Hydrological Research Unit of Rhodes University and funded by the Water Research Commission. Unfortunately, the two smaller sub-catchments have not produced flow data of an acceptable quality due to inadequacies in the design of the flow gauging structures. Both Roberts (1978) and Görgens (1983) provide descriptions of the physical characteristics of the area and consequently only summary information is given in this report. Figure 8.1 shows the boundaries of the gauged catchments and the positions of the 10 autographic raingauges established in 1975. The gauge indicated as BP01 was removed in 1981 and relocated at position CP01. In 1983 a further five continuously recording raingauges were established in a small area close to the position of BP01.

The values given in table 8.1 illustrate the semi-arid nature of the climate with relatively low rainfall amounts and high potential evapotranspiration losses. The area experiences two different rainfall producing mechanisms. Long duration storms with relatively low intensities are caused by large-scale frontal or advection systems. These storms have produced the highest flows in the catchment during the period of gauging. Spatial variation in rainfall amounts during such storms is usually quite low but indicates an orographic effect with higher rainfalls being observed on the southern and eastern borders of the catchment. Although this type of storm is more common during the winter months they have also occurred in summer. However, the main storm type in summer is caused by convectional or convergence uplift resulting in short duration and often high intensity thunderstorms. During convectional thunderstorms the rainfall amounts and intensities can be spatially highly variable. Characteristically, the valley bottoms receive most rain during these storms. The distinct differences between the two types of rainfall event will inevitably be reflected in the characteristics of the resulting runoff response. These catchments should therefore provide a fairly rigorous test of the calibration capabilities of the models.

Table 8.1 Ecca catchments : physical details

Mean annual rainfall (MAP)	487 mm
Standard deviation of annual rainfalls	99 mm
Mean annual number of raindays	101 days
Mean annual free water surface evaporation	1364 mm

	Q9M20	Q9M21	Q9M24
Area (Km^2)	73,1	9,1	23,1
slopes (%area)			
less than 20%	69	52	79
20 - 40%	19	29	13
more than 40%	12	19	8
Geology (% area)			
shales	49	70	55
others	51	30	45
Vegetation density (% area) ground and canopy cover			
Dense	18	15	31
Medium	42	45	34
Sparse	40	40	35

The catchment is underlain by interbedded shales and sandstones dipping at approximately 40°N in the south and almost horizontally bedded in the north. Part of the southern catchment boundary consists of harder formations of quartzite and tillite. Figure 8.1 illustrates the drainage pattern of the area with two dominant channel directions. One follows the strike of the rock formations and the other occurs at right angles to this in highly dissected valleys. Figure 8.2 (taken from Roberts, 1978) shows the distribution of slopes within the catchment. The most noticeable characteristics are the flat headwater areas and main valley bottom separated by very steep slopes in the central parts of most tributary catchments. Soil depth is quite strongly related to slope, being thin and stoney on the steep slopes as well as some hilltops. Alluvial and colluvial deposits are unevenly spread throughout the valley bottoms, and where they exist, associated soils can be up to 2m deep. In some tributaries there is evidence that deeper soils occur on slopes where the geological dip is parallel to the slope. However, this does not appear to be consistant throughout the catchment. Vegetation consists of succulent to sub-succulent bush with a variable density (table 8.1). Ground cover was identified by Roberts (1978) as being relatively sparse over large parts of the catchment. Observations over a number of years have suggested that ground cover is temporaly variable depending upon the previous history of rainfall. During prolonged dry periods ground cover may disappear from large parts of the catchment only to reappear at the end of such a drought. This change appears to constitute the major temporal variation in the vegetation cover rather than any differences related to seasonal influences.

Figure 8.3 shows the way in which the catchment has been divided up into 12 sub-areas for sub-catchment modelling. Sub-catchment modes and conceptual storages for routing modelled flows through the channel network are also indicated. Where relevant, sub-area outlets correspond to gauging locations (Q9M21 and Q9M24) within the total catchment area.

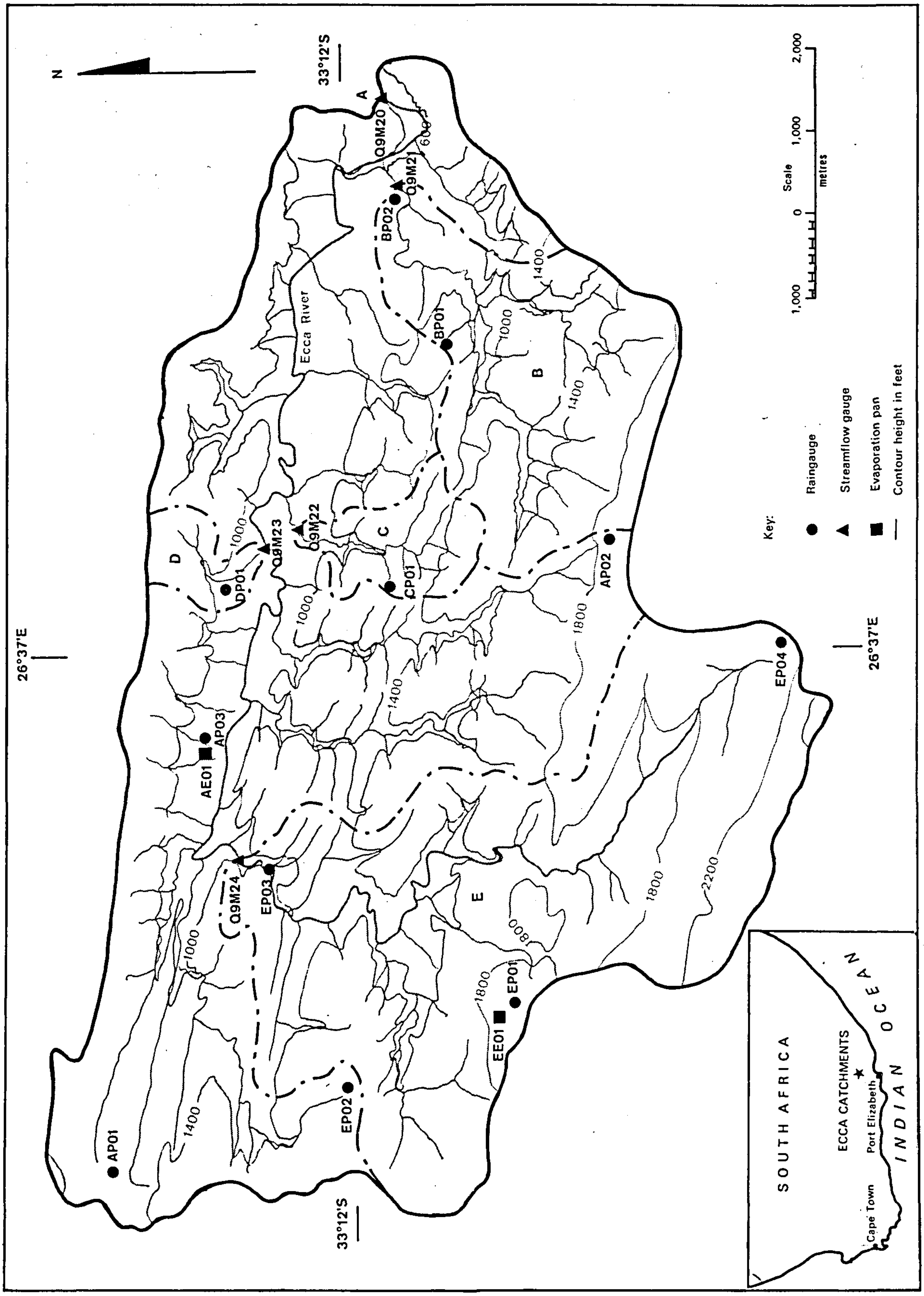

Figure 8.1 The Ecca catchments and gauging network (from Görgens, 1983).

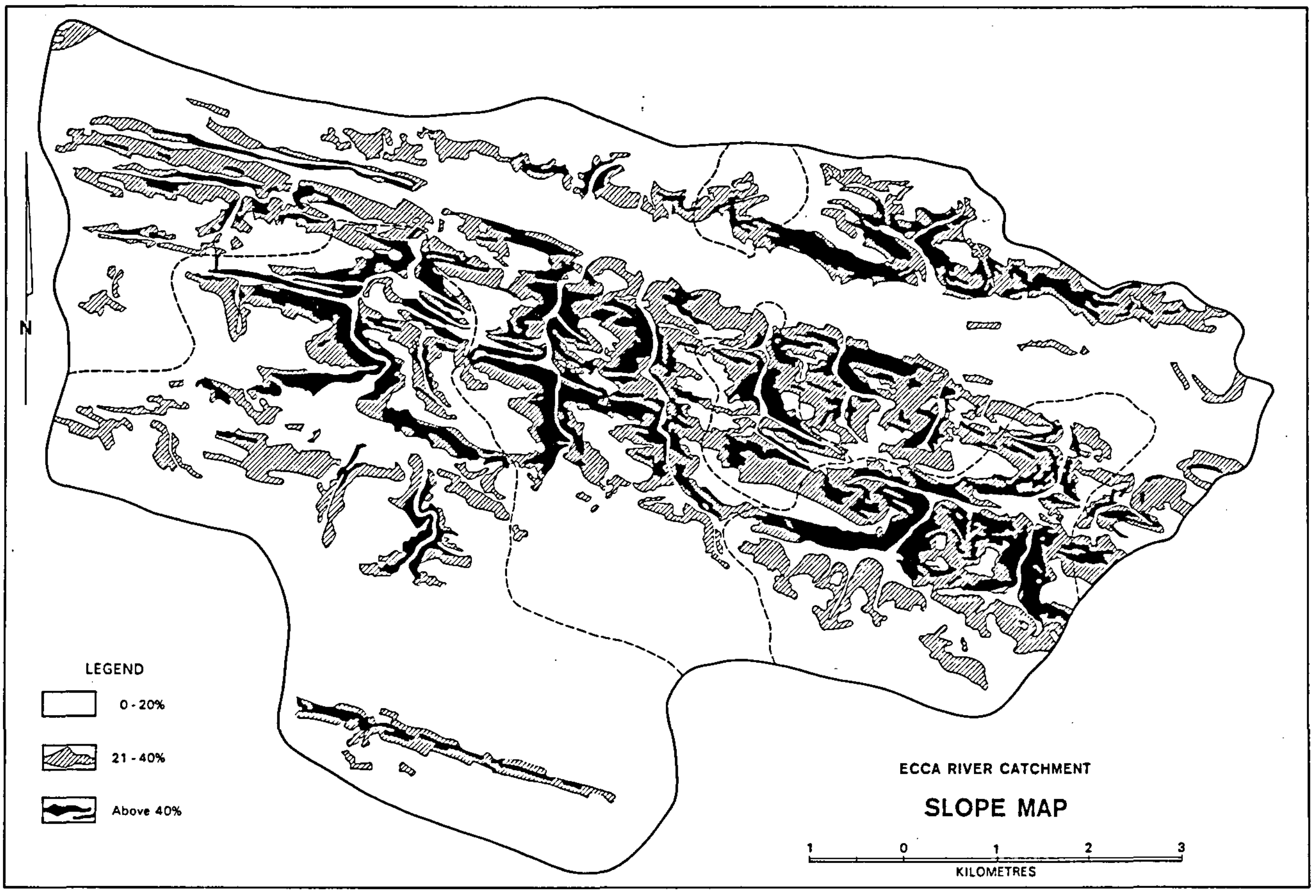

Figure 8.2 The distribution of slope steepness within the Ecca catchments (from Roberts, 1978).

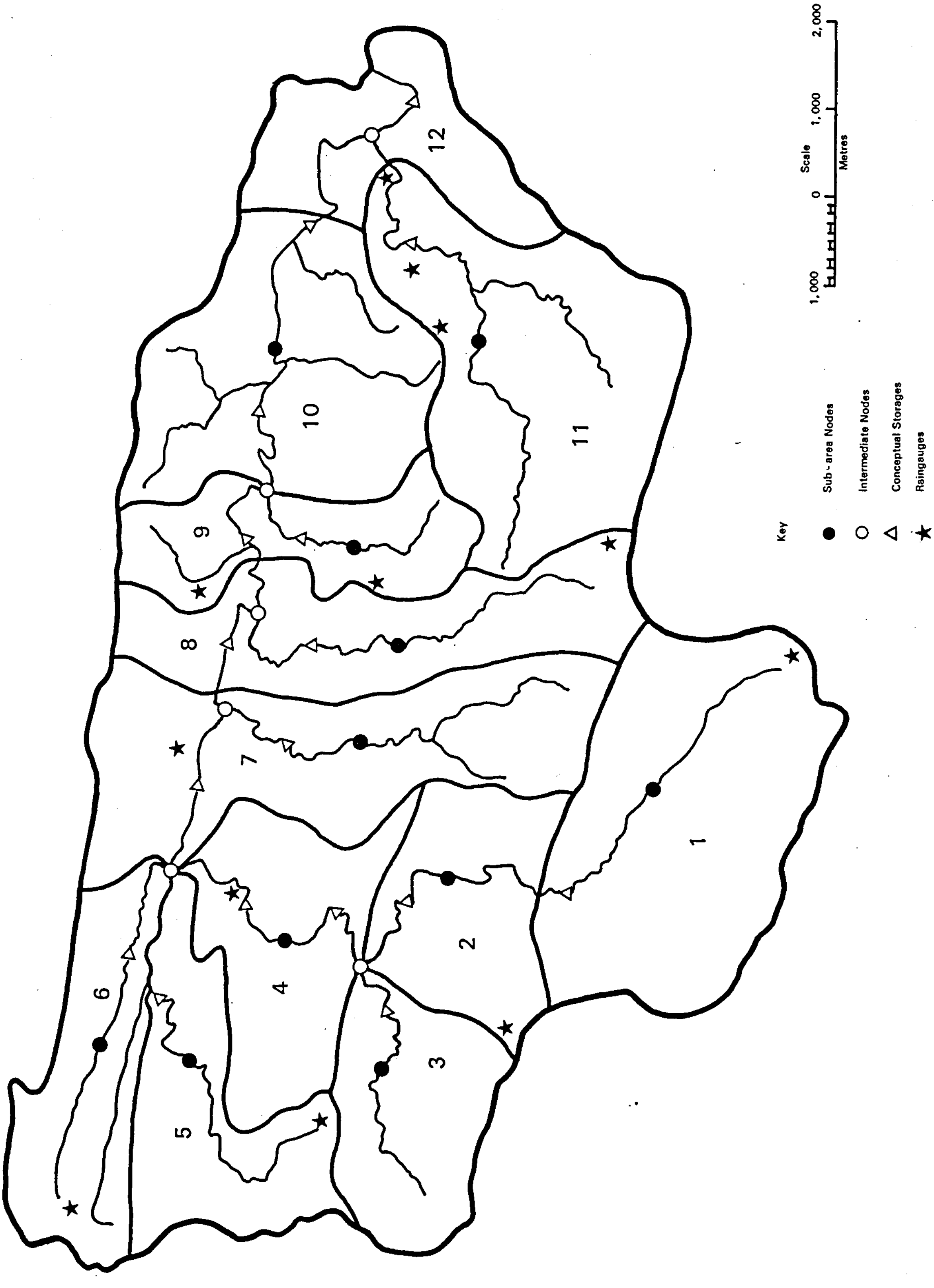

Figure 8.3 Sub-area boundaries in the Ecca catchments.

8.1.2 North Danville Catchments.

The North Danville catchments are situated in Caledonia County, Vermont State in the northeastern USA. They form part of the Connecticut River basin and cover a total area of 111,6km² (figure 8.4 and table 8.2). The information on their physical characteristics and the single event storm data has been drawn from various miscellaneous publications of the United States Department of Agriculture, Agricultural Research Service. (UDSA, 1960 to 1973). These volumes were kindly loaned to the HRU at Rhodes University by Professor R.E.Schulze of the Department of Agricultural Engineering, Natal University, Pietermaritzburg.

Within the largest catchment (ND5) there exist a further 10 streamflow gauging points of which 3 (ND1, ND3 and ND4) have been used in this study. There are 28 recording raingauges within the area but the records for only a few of these are printed in the publications (USDA, 1960 to 1973). Records suggest that five months of the year experience sub-zero temperatures and there appears to be a spring snowmelt period in April and May. Surface drainage is in well defined perennial channels.

The catchment is underlain by calcareous schists and cal-silicate rocks interbedded with quartz-mica schists and micaeous quartzite. Overlaying these formations is an impervious glacial till or boulder clay which ranges in depth from 0 to 27m. Soils vary from rocky, fine sandy loams with rapid permeabilities to silty loams with moderate to slow permeabilities (table 8.2). Soil depths to the substratum varies from 0,3m to 0,8m. While no soil distribution maps are included in the publications used (USDA, 1960-1973) there is little variation in soil characteristics between the gauged catchments. The steepest slopes are on the western catchment boundary and in the northeastern part of ND4 (figure 8.3) where the channels appear to be slightly more incised. The area is predominantly covered by hardwood forest with some softwoods. Similar proportions of the catchment are under cultivation and pasture (table 8.2) while buildings and roads occupy only about 1% of the area.

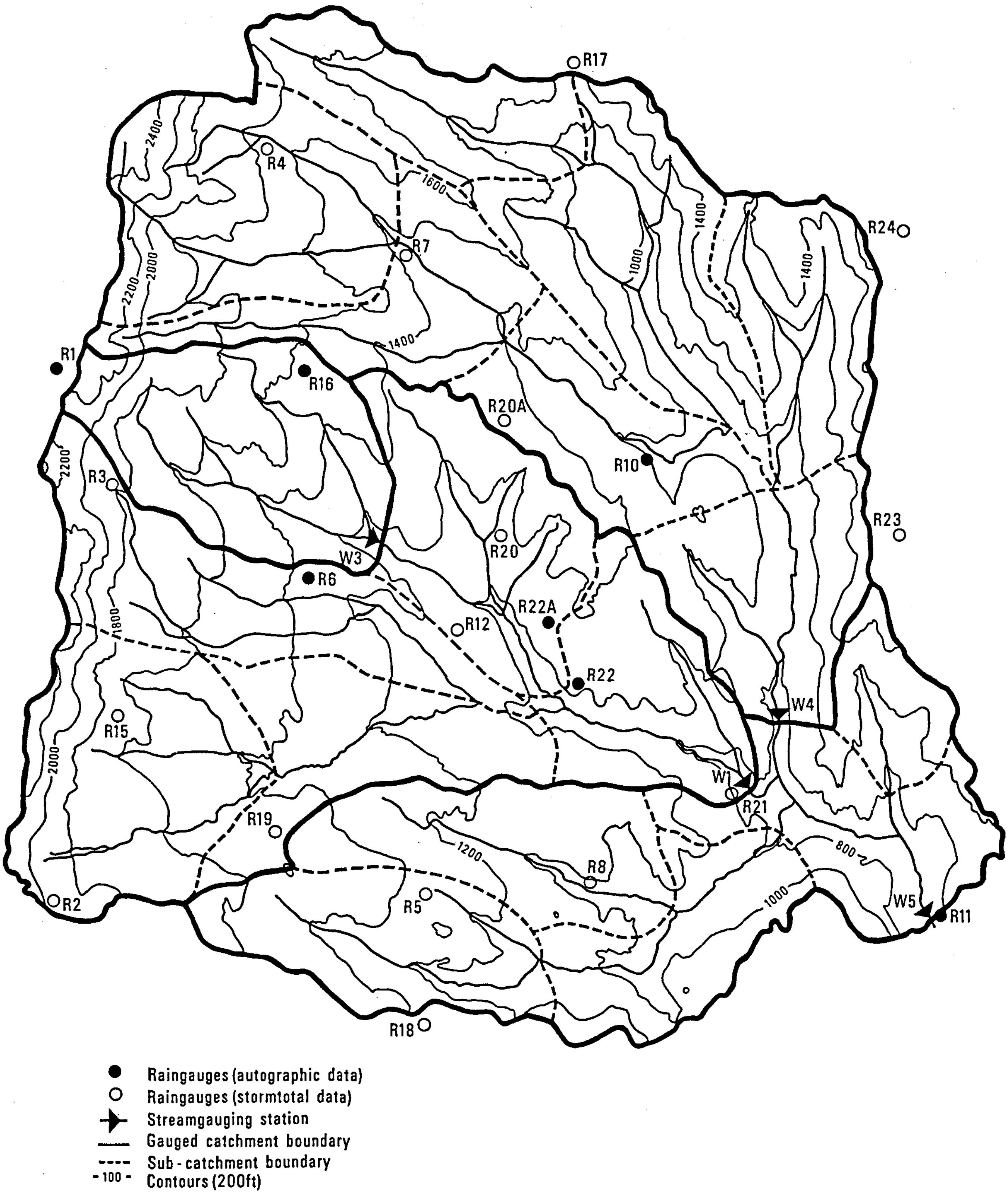

Figure 8.4 The North Danville catchments, gauging network and sub-area boundaries

Figure 8.4 shows the boundaries for the 18 sub-areas that the complete catchment has been divided up into for the purposes of sub-area modelling. As with the Ecca, sub-area outlets correspond where necessary to the gauged sub-catchments (ND1, ND3 and ND4) within ND5. Within ND1 there are 6 sub-areas and 7 within ND4. ND3 constitutes a sub-area on its own.

Table 8.2 North Danville : physical details
Mean annual precipitation (MAP) 1000mm

	ND5	ND1	ND3	ND4
Area (km^2)	111,6	42,9	8,4	43,5
Slopes (% area)				
0-15%	64	74	66	-
15-25%	23	17	22	-
more than 25%	13	9	12	-
Average soil depth (m)				
Top soil	0,2	0,2	0,2	-
Depth to substratum	0,6	0,6	0,6	-
Soil permeabilities (% area)				
Rapid	44	33	36	-
Moderate	53	65	63	-
Slow	3	2	1	-
Land Use (% area)				
Forest	67	64	67	-
Cultivated	17	17	11	-
Pasture	13	15	19	-
Other	3	4	3	-

8.2 Storm data

The storm data for all the catchments modelled are summarised in the tables at the end of this chapter (tables 8.3 to 8.9). Each table is divided into three components. The first summarises the characteristics of the storm rainfall and the antecedent rainfall. The second lists the volumes, discharges and timing of total streamflows while the third concentrates on the streamflows above a separation line of 1,13mm. day $^{-1}$. day $^{-1}$ (5,47 x $10^{-4} M^3.s.^{-1} km.^2 h.^{-1}$, Hewlett and Hibbert, 1967). Each table component includes the storm number and the date and time of the beginning of the storms. The catchment name, code, area and data time interval are given at the top of each table.

The tables illustrate that there is a great variety in the amount of rainfall data available for the different storms. The number of rain profiles given in the tables represent the number of separate rainfall time distributions that were used for modelling and do not necessarily reflect the total amount of information available. Total storm rainfall at additional gauge sites has also been used to determine weighting factors for individual sub-areas. For all the storms the maximum amount of information available has been used to decide the weighting factor and profile to use for any sub-area. For some storms there is relatively little information and it is essential to consider this during the interpretation of the results. Isohyetal diagrams of storm total rainfall have been used to obtain estimates of sub-area storm totals. Sub-area weighting factors can then be calculated using the ratio of these estimates to the storm total at the gauge selected to describe the time distribution.

8.2.1 Ecca catchments.

15 events were extracted from the breakpoint data files for the period 1976 to 1986 and vary between short duration, high intensity convectional storms to long duration, low intensity storms. A wide range of antecedent moisture conditions are also represented by the 15 events. The number of rainfall profiles available for each is different due to variations in the number of gauges that operated successfully at the time. Each profile represents a weighted average of the group of possible gauges most relevant to one or more of the sub-areas. Although not apparent from tables 8.3 to 8.5, the degree of spatial variation in rainfall amounts is different for some storms. Storms 6 to 8 represent relatively uniform rainfall examples while the low total rainfall amount on storm 2 is partly due to the fact that 5 of the sub-areas experienced no rainfall for this event.

The discharge components of tables 8.3 to 8.5 suggest that the resulting flow events range from very small and short duration hydrographs (peaks 1,0$m^3 s^{-1}$) to the largest events recorded. During many of the smaller events no flow was recorded at Q9M24 and consequently the data set for this area is made up of only the five large events in 1979 and 1985. The overall runoff coefficients (total storm runoff/total storm rainfall) vary from more than 0,33 to less than 0,01. It is apparent that this data set represents a wide range of storm types both in terms of the type of rainstorm and the antecedent conditions. Many of the events are very small and would certainly not warrent being referred to as floods. However, they have been included as the amount of data on 'real floods' is extremely limited for this semi-arid catchment. It is possible that their inclusion will indicate deficiencies in certain components of the models being tested.

8.2.2 North Danville Catchments

Between 9 and 15 storm events are tabulated in the USDA publications for 1960 to 1973 for the four streamflow gauges used in the North Danville Catchments. The amount of rainfall data available for each storm is highly variable. For some storms the data consist of profiles for several gauges, plus totals for additional gauges and isohyetal maps of the total storm rainfall. However, for the majority of storms, autographic records. for gauges 1 and 10 or 16 and 22 (figure 8.4) only are available. For the storms prior to 1965, totals for some other gauges are given (USDA, 1960 to 1973) and these have been used to estimate weighting factors for sub-area rainfall input. The lack of more rainfall data is bound to have an effect on the interpretation of the modelling results, particularly where the spatial variation in input rainfall is high. The available records do indicate that this variation is important for some events, with gauge totals varying quite considerably (Gauge 1 = 35,0mm, 10 = 17,7mm for storm 11 on ND1 for example). It has been necessary to place greater emphasis during interpretation of the results on those storms with more complete rainfall input information.

As with the Ecca the available storms seem to represent a reasonably wide variation of rainfall input type as well as streamflow response and antecedent conditions type. It is difficult to suggest whether the range of storm types is representative of all storms experienced on these catchments as the full record is not available to the authors. There are two aspects of the flow regime of this area that the data set certainly does not represent. These are precipitation events during winter on frozen catchments and spring snowmelt events. None of the models being tested have components to represent these processes and therefore the exclusions are justified.

SUMMARY TABLES (8.3 to 8.9) OF STORM DATA FOR :

Ecca - Q9M20, Q9M21, Q9M24
North Danville - ND1, ND3, ND4, ND5

Explanatory notes :

a) The rainfall duration includes zero rain periods within the rainstorm.
b) The 30 day API is calculated from the following equation :

$$API = \sum_{i=1}^{30} DR_i . 0,9^i$$

where DR_i = rainfall total i days before the event.

c) The rainfall totals and intensities are derived from catchment averages.
d) For multipeaked events the rising limb refers to flows before the highest peak.
e) In some cases storms with erroneous data have been included in the tables and are clearly marked with aline through the data.

Table 8.3 Summary of storm data : Ecca, Q9M20

SUMMARY OF STORM DATA FOR ECCA AT Q9M20 CATCHMENT AREA (SQ.KM) 73.94 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	28. 2.77	15.00	8	24.61	13.75	14.05	1.79	55.50	91.95	99.77	100.00	46.45
2	6. 3.77	10.00	10	8.05	4.50	16.65	1.79	15.35	29.19	90.50	100.00	48.52
3	7. 5.77	4.00	10	45.53	20.25	28.13	2.25	29.13	55.20	70.81	100.00	16.46
4	19. 4.78	13.00	10	44.87	24.50	8.02	1.83	15.26	29.83	79.29	100.00	10.53
5	21. 4.78	6.00	10	35.50	18.25	15.29	1.95	80.25	98.81	98.81	100.00	43.59
6	20. 7.79	2.00	10	164.86	49.50	20.70	3.33	13.27	37.18	78.35	100.00	1.30
7	23. 7.79	22.00	8	29.07	26.75	5.48	1.09	57.71	94.04	99.24	100.00	100.43
8	19. 8.79	20.00	10	113.91	66.50	8.22	1.71	40.10	83.19	88.57	100.00	16.59
9	26. 3.81	8.00	8	23.45	12.50	6.64	1.88	27.24	87.12	99.59	100.00	51.97
10	22.10.81	13.00	10	48.13	12.50	52.06	3.85	64.06	82.72	99.53	100.00	8.21
11	23.12.81	14.00	10	35.22	13.00	60.11	2.71	35.89	37.42	99.89	100.00	5.86
12	2.11.85	7.00	5	50.80	28.00	11.16	1.81	64.83	86.71	97.73	100.00	60.23
13	25.11.85	19.00	6	65.54	38.25	32.93	1.71	76.82	99.63	99.92	100.00	12.66
14	1.12.85	16.00	10	24.16	24.75	30.48	.98	87.05	99.30	99.33	100.00	44.37
15	3.12.85	8.00	5	30.66	26.50	11.61	1.16	63.06	85.26	94.62	100.00	49.72

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	INITIAL FLOW (M¢3/S)	FINAL FLOW (M¢3/S)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)
1	28. 2.77	15.00	.11	.35	.45	33.31	.021	.516	1.066	6.00
2	6. 3.77	10.00	.10	.56	.66	48.63	.004	.477	3.227	4.00
3	7. 5.77	4.00	.10	.37	.47	34.47	.001	.614	1.158	20.00
4	19. 4.78	13.00	.05	.05	.09	6.76	.000	.248	.411	21.50
5	21. 4.78	6.00	.21	1.19	1.39	103.07	.053	.859	2.586	5.25
6	20. 7.79	2.00	16.79	11.54	28.33	2094.63	.000	2.269	31.582	49.25
7	23. 7.79	22.00	3.68	6.72	10.40	769.11	1.650	2.987	12.238	14.50
8	19. 8.79	20.00	12.69	33.13	45.82	3387.75	.039	3.507	35.678	34.75
9	26. 3.81	8.00	.04	.09	.13	9.32	.020	.300	.550	8.00
10	22.10.81	13.00	.22	.78	1.00	74.06	.000	.636	1.923	5.50
11	23.12.81	14.00	.05	.05	.10	7.56	.000	.278	.667	10.75
12	2.11.85	7.00	3.65	11.24	14.89	1100.92	1.380	2.930	15.342	12.25
13	25.11.85	19.00	.91	11.38	12.29	908.67	.004	1.761	15.172	5.75
14	1.12.85	16.00	.37	1.88	2.25	166.00	.295	1.236	5.979	5.25
15	3.12.85	8.00	7.56	5.98	13.55	1001.59	1.610	3.342	7.007	26.50

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	28. 2.77	15.00	.09	.19	.28	20.81	.927	3.00	3.00	12.25
2	6. 3.77	10.00	.10	.41	.51	37.55	3.176	1.00	3.00	11.75
3	7. 5.77	4.00	.07	.15	.22	16.61	.983	2.75	17.25	13.50
4	19. 4.78	13.00	.02	.03	.05	3.44	.287	2.25	18.50	5.50
5	21. 4.78	6.00	.18	.74	.92	67.69	2.396	3.25	2.00	20.25
6	20. 7.79	2.00	16.12	9.02	25.14	1858.81	30.537	26.00	23.25	56.75
7	23. 7.79	22.00	2.40	3.92	6.32	467.42	10.141	12.50	2.00	34.75
8	19. 8.79	20.00	11.86	26.37	38.23	2826.48	34.524	26.25	8.50	85.25
9	26. 3.81	8.00	.02	.04	.06	4.39	.415	2.50	5.50	6.75
10	22.10.81	13.00	.21	.52	.73	54.13	1.772	3.50	2.00	16.00
11	23.12.81	14.00	.04	.02	.06	4.40	.487	1.75	9.00	4.00
12	2.11.85	7.00	2.73	7.91	10.63	786.17	13.564	10.50	1.75	39.25
13	25.11.85	19.00	.89	9.46	10.36	765.73	15.005	3.50	2.25	43.50
14	1.12.85	16.00	.28	1.07	1.34	99.26	5.521	4.00	1.25	23.25
15	3.12.85	8.00	2.86	4.89	7.75	573.23	4.911	16.50	.25	49.50

Table 8.4 Summary of storm data : Ecca, Q9M21

SUMMARY OF STORM DATA FOR ECCA B AT Q9M21 CATCHMENT AREA (SQ.KM) 9.10 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	28. 2.77	15.00	1	29.82	5.50	40.56	5.42	4.36	62.89	91.85	100.00	46.45
2	6. 3.77	10.00	1	15.91	4.25	40.20	3.74	23.26	30.17	98.55	100.00	48.52
3	7. 5.77	4.00	1	49.48	18.75	32.00	2.64	28.15	51.84	78.17	100.00	16.46
4	19. 4.78	13.00	1	45.71	24.25	10.04	1.88	25.01	39.66	81.05	100.00	10.53
5	21. 4.78	6.00	1	38.17	17.25	25.48	2.21	71.71	98.56	98.56	100.00	43.59
6	20. 7.79	2.00	1	157.47	48.00	20.56	3.28	12.62	33.68	77.30	100.00	1.30
7	23. 7.79	22.00	1	28.83	26.75	7.00	1.08	59.35	92.47	98.92	100.00	100.43
8	19. 8.79	20.00	1	108.83	66.25	8.04	1.64	37.28	78.94	86.68	100.00	16.59
9	26. 3.81	8.00	1	24.61	12.50	8.52	1.97	20.20	88.95	99.39	100.00	51.97
10	22.10.81	13.00	1	59.30	10.00	49.32	5.93	42.06	77.93	82.68	100.00	8.21
11	23.12.81	14.00	1	33.24	11.00	54.80	3.02	40.94	42.54	97.92	100.00	5.86
12	2.11.85	7.00	1	58.35	26.00	15.84	2.24	53.71	79.54	97.24	100.00	60.23
13	25.11.85	19.00	1	75.91	38.25	42.24	1.98	86.04	99.83	99.91	100.00	12.66
14	1.12.85	16.00	1	9.36	4.25	24.24	2.20	92.09	95.73	98.40	100.00	44.37
15	3.12.85	8.00	1	30.75	26.50	14.32	1.16	73.76	92.20	96.68	100.00	49.72

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	INITIAL FLOW (M¢3/S)	FINAL FLOW (M¢3/S)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)
1	28. 2.77	15.00	.08	.32	.40	3.64	.000	.236	.811	3.00
2	6. 3.77	10.00	.21	.20	.41	3.74	.000	.107	1.156	3.25
3	7. 5.77	4.00	.35	1.58	1.94	17.62	.000	.117	1.213	18.50
4	19. 4.78	13.00	.00	.01	.01	.12	.000	.000	.003	7.75
5	21. 4.78	6.00	.29	.92	1.21	10.97	.000	.082	.433	5.00
6	20. 7.79	2.00	14.18	15.22	29.40	267.56	.000	.300	4.621	45.50
7	23. 7.79	22.00	3.43	8.22	11.65	105.97	.217	.384	1.809	10.75
8	19. 8.79	20.00	13.65	21.76	35.41	322.26	.007	.439	2.501	38.00
9	26. 3.81	8.00	.09	.20	.29	2.67	.001	.054	.187	6.50
10	22.10.81	13.00	.00	.01	.01	.07	.002	.001	.002	.25
11	23.12.81	14.00	.16	.17	.33	3.02	.000	.047	.458	9.25
12	2.11.85	7.00	4.54	11.82	16.36	148.86	.039	.285	1.733	13.00
13	25.11.85	19.00	.01	1.27	1.28	11.67	.089	.059	.089	.25
14	1.12.85	16.00	.10	.17	.27	2.48	.058	.087	.129	3.00
15	3.12.85	8.00	.99	9.63	10.63	96.70	.209	.399	1.115	6.25

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	28. 2.77	15.00	.01	.02	.02	.21	.069	.00	4.25	1.00
2	6. 3.77	10.00	.19	.11	.30	2.71	1.045	.25	3.00	2.00
3	7. 5.77	4.00	.32	1.10	1.42	12.92	1.173	7.75	10.75	23.00
4	19. 4.78	13.00	.12	.60	.72	6.58	.370	14.00	7.75	26.00
5	21. 4.78	6.00	.28	.65	.93	8.44	.419	2.50	2.50	16.25
6	20. 7.79	2.00	13.59	12.22	25.81	234.85	4.500	24.25	21.25	60.00
7	23. 7.79	22.00	2.48	4.70	7.17	65.28	1.562	8.25	2.50	36.00
8	19. 8.79	20.00	6.56	21.12	27.68	251.91	2.329	25.25	5.75	85.25
9	26. 3.81	8.00	.07	.11	.18	1.60	.162	4.50	2.00	10.75
10	22.10.81	13.00	.00	.00	.00	.00	.000	6.50	.00	12.75
11	23.12.81	14.00	.19	.12	.31	2.83	.418	8.00	1.25	10.50
12	2.11.85	7.00	4.21	8.90	13.10	119.25	1.637	11.75	1.25	50.00
13	25.11.85	19.00	.00	.00	.00	.00	.000	13.00	.00	51.25
14	1.12.85	16.00	.02	.05	.07	.62	.062	1.00	1.75	5.25
15	3.12.85	8.00	.50	5.03	5.53	50.34	.902	5.00	1.25	42.50

Table 8.5 Summary of storm data : Ecca, Q9M24

SUMMARY OF STORM DATA FOR ECCA AT Q9M24 CATCHMENT AREA (SQ.KM) 23.30 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	20. 7.79	2.00	1	168.82	48.00	19.76	3.52	11.63	32.69	75.42	100.00	1.30
2	23. 7.79	22.00	1	31.35	25.50	6.92	1.23	58.21	92.44	98.53	100.00	100.43
3	19. 8.79	20.00	1	119.67	59.25	10.80	2.02	38.45	77.51	88.45	100.00	16.59
4	2.11.85	7.00	1	50.81	28.00	17.32	1.81	62.70	84.96	96.24	100.00	60.23
5	25.11.85	19.00	1	40.17	7.00	32.28	5.74	2.44	15.09	58.05	100.00	12.66

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	INITIAL FLOW (M¢3/S)	FINAL FLOW (M¢3/S)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)
1	20. 7.79	2.00	8.37	8.67	17.04	397.01	.000	.579	9.581	46.00
2	23. 7.79	22.00	2.53	5.95	8.48	197.57	.351	.776	3.910	10.75
3	19. 8.79	20.00	6.29	18.28	24.57	572.49	.000	1.064	5.908	31.25
4	2.11.85	7.00	3.38	4.07	7.46	173.73	.135	.583	2.517	16.50
5	25.11.85	19.00	.05	.05	.10	2.27	.001	.046	.301	5.50

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M¢3*1000)	PEAK FLOW (M¢3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	20. 7.79	2.00	8.07	6.88	14.94	348.21	9.357	17.25	28.75	45.25
2	23. 7.79	22.00	1.87	3.58	5.45	127.02	3.450	9.00	1.75	33.50
3	19. 8.79	20.00	5.65	11.96	17.61	410.33	5.584	25.25	6.00	83.50
4	2.11.85	7.00	2.84	2.57	5.41	126.09	2.203	14.25	2.25	35.50
5	25.11.85	19.00	.05	.03	.08	1.84	.283	1.25	4.25	3.75

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Table 8.6 Summary of storm data : N. Danville, ND5

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND5   CATCHMENT AREA (SQ.KM) 111.60 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	30. 7.60	12.00	3	43.98	12.00	14.95	3.66	24.06	61.54	84.59	100.00	11.45
2	2. 6.61	2.00	3	23.09	6.75	12.29	3.42	30.06	41.70	93.54	100.00	15.53
3	31. 7.62	4.00	3	48.55	9.25	34.21	5.25	33.53	63.50	72.16	100.00	24.01
4	30. 7.63	2.00	8	22.61	4.00	14.36	5.65	39.45	49.30	84.44	100.00	9.41
5	22. 7.64	17.00	8	21.78	1.50	43.13	14.52	8.89	30.03	100.00	100.00	27.20
6	7. 6.65	15.15	3	37.48	8.75	29.02	4.28	50.71	76.75	94.88	100.00	9.79
7	19.10.66	20.15	3	29.86	31.75	9.30	.94	58.23	90.98	98.93	100.00	15.15
8	16. 7.67	4.00	3	32.22	10.25	19.08	3.14	63.56	79.77	95.94	100.00	26.67
9	11. 9.68	5.00	3	43.27	30.50	13.75	1.42	70.47	91.53	93.42	100.00	14.02
10	7. 9.69	17.00	3	22.03	12.00	38.40	1.84	96.91	99.28	99.52	100.00	27.33
11	23. 8.71	1.00	3	31.26	23.00	19.44	1.36	77.37	94.66	97.84	100.00	36.39
12	10. 7.72	10.45	3	30.13	13.75	19.74	2.19	7.93	86.53	92.52	100.00	30.50
13	20. 7.72	24.00	1	38.97	25.75	31.79	1.51	14.53	93.79	98.15	100.00	35.49
14	14. 7.73	1.00	1	25.20	6.50	13.85	3.88	22.23	65.11	92.63	100.00	50.07
15	17. 9.73	24.00	3	38.02	16.25	7.62	2.34	11.50	53.33	91.92	100.00	29.97

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	30. 7.60	12.00	.86	2.23	3.09	344.52	.160	1.700	10.200	12.75
2	2. 6.61	2.00	1.27	5.19	6.46	721.18	1.180	3.070	15.690	7.75
3	31. 7.62	4.00	3.03	4.96	7.99	891.96	.230	2.170	21.230	11.25
4	30. 7.63	2.00	.10	.02	.12	13.91	.060	.610	.640	10.50
5	22. 7.64	17.00	.46	1.05	1.51	168.59	.330	1.320	5.070	5.75
6	7. 6.65	15.15	1.03	2.42	3.45	384.85	.330	1.990	8.610	10.00
7	19.10.66	20.15	.73	2.10	2.83	315.37	.300	2.030	4.460	13.00
8	16. 7.67	4.00	.54	4.20	4.74	528.56	.420	2.100	11.430	5.50
9	11. 9.68	5.00	.74	2.76	3.50	390.56	.170	2.120	8.920	12.00
10	7. 9.69	17.00	.49	.83	1.32	147.54	.910	1.880	4.100	7.25
11	23. 8.71	1.00	.91	2.27	3.18	354.63	.700	2.180	7.830	10.50
12	10. 7.72	10.45	.72	3.57	4.29	478.55	.650	2.350	11.590	10.25
13	20. 7.72	24.00	1.71	5.74	7.46	832.26	.750	2.820	20.030	14.75
14	14. 7.73	1.00	1.51	3.52	5.03	561.09	2.020	3.370	14.850	7.50
15	17. 9.73	24.00	1.31	4.14	5.45	608.42	.520	2.280	13.800	13.75

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	30. 7.60	12.00	.70	1.58	2.28	254.27	9.450	7.75	5.00	23.50
2	2. 6.61	2.00	.92	3.34	4.26	475.35	14.070	7.00	.75	30.75
3	31. 7.62	4.00	2.86	3.83	6.69	746.36	20.440	8.75	2.50	31.50
4	30. 7.63	2.00	.00	.01	.02	1.68	.130	2.00	3.25	8.00
5	22. 7.64	17.00	.37	.67	1.04	115.61	4.420	5.00	.75	16.50
6	7. 6.65	15.15	.83	1.58	2.41	269.06	7.700	8.75	1.25	26.25
7	19.10.66	20.15	.51	1.21	1.72	191.43	3.570	8.50	4.50	27.00
8	16. 7.67	4.00	.45	3.12	3.57	398.59	10.780	2.75	2.75	26.50
9	11. 9.68	5.00	.62	1.61	2.23	249.06	8.340	5.25	6.75	30.75
10	7. 9.69	17.00	.23	.35	.58	64.91	2.780	6.25	1.00	15.25
11	23. 8.71	1.00	.62	1.33	1.95	217.44	6.700	6.75	3.75	24.00
12	10. 7.72	10.45	.46	2.43	2.89	322.52	10.530	4.75	5.50	25.50
13	20. 7.72	24.00	1.25	4.07	5.32	594.21	18.670	8.00	6.75	32.25
14	14. 7.73	1.00	.97	2.06	3.04	338.81	12.420	6.50	1.00	21.75
15	17. 9.73	24.00	1.02	2.98	4.00	446.11	12.810	6.75	7.00	28.25

Table 8.7 Summary of storm data : N. Danville, ND1.

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND1   CATCHMENT AREA (SQ.KM)   42.94   DATA TIME INTERVAL (HRS)   .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	24.10.59	5.00	1	74.30	17.00	20.83	4.37	44.32	49.49	92.77	100.00	40.89
2	30. 7.60	12.00	3	45.35	12.00	14.77	3.78	24.00	61.52	85.08	100.00	11.37
3	2. 6.61	2.00	3	22.76	6.75	11.98	3.37	30.19	41.95	93.62	100.00	15.53
4	31. 7.62	4.00	3	51.66	9.25	35.60	5.59	32.83	62.97	71.92	100.00	24.01
5	30. 7.63	2.00	8	23.30	4.00	18.25	5.82	42.59	51.15	85.87	100.00	15.63
6	22. 7.64	17.00	8	19.52	1.50	35.98	13.02	8.26	36.50	100.00	100.00	28.42
7	7. 6.65	15.25	3	39.49	8.75	32.51	4.51	53.82	75.52	94.38	100.00	9.79
8	19.10.66	20.15	3	30.05	32.50	8.51	.92	57.52	91.41	98.36	100.00	16.73
9	16. 7.67	4.00	3	33.78	10.25	20.63	3.30	65.02	81.28	96.23	100.00	26.67
10	11. 9.68	4.00	3	43.24	31.25	14.45	1.38	50.33	92.24	94.11	100.00	14.41
11	7. 9.69	17.00	3	20.65	12.00	36.28	1.72	96.74	99.28	99.55	100.00	27.48
12	23. 8.71	3.00	3	30.61	21.00	18.88	1.46	84.33	94.87	98.00	100.00	36.39
13	3. 7.72	11.00	1	26.23	5.50	23.22	4.77	4.45	45.08	92.91	100.00	43.69
14	10. 7.72	10.45	3	34.93	13.75	23.99	2.54	6.99	83.39	86.74	100.00	34.87
15	17. 9.73	24.00	3	37.76	16.25	7.75	2.32	11.49	52.72	92.14	100.00	36.26

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	24.10.59	5.00	15.38	14.90	30.28	1300.19	1.820	4.480	31.180	14.25
2	30. 7.60	12.00	.82	1.83	2.65	113.86	.040	.540	3.970	11.75
3	2. 6.61	2.00	1.52	4.90	6.42	275.74	.370	1.130	6.270	8.00
4	31. 7.62	4.00	3.27	6.24	9.51	408.29	.080	.830	12.410	10.25
5	30. 7.63	2.00	.10	.07	.16	7.00	.050	.240	.320	8.75
6	22. 7.64	17.00	.38	.78	1.16	49.76	.140	.490	1.700	4.75
7	7. 6.65	15.25	1.58	4.05	5.63	241.93	.110	.500	5.520	9.00
8	19.10.66	20.15	1.45	1.68	3.13	134.20	.100	.830	1.880	17.25
9	16. 7.67	4.00	.41	4.26	4.66	200.30	.140	.780	4.100	4.25
10	11. 9.68	4.00	.68	2.19	2.87	123.28	.070	.650	3.730	12.00
11	7. 9.69	17.00	.35	.61	.96	41.41	.250	.560	1.270	6.50
12	23. 8.71	3.00	.51	1.79	2.30	98.97	.180	.670	2.680	6.75
13	3. 7.72	11.00	.56	3.76	4.32	185.63	.270	.870	5.180	7.25
14	10. 7.72	10.45	.74	3.67	4.42	189.62	.230	.850	5.180	9.25
15	17. 9.73	24.00	1.34	3.60	4.94	211.98	.170	.830	5.000	13.25

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	24.10.59	5.00	13.05	12.08	25.13	1079.09	29.070	12.00	2.25	26.75
2	30. 7.60	12.00	.71	1.39	2.10	90.00	3.740	8.00	3.75	21.25
3	2. 6.61	2.00	1.21	3.12	4.33	186.10	5.720	7.25	.75	32.00
4	31. 7.62	4.00	3.14	5.10	8.24	353.98	12.150	7.50	2.75	31.75
5	30. 7.63	2.00	.02	.01	.04	1.61	.130	5.75	3.00	8.00
6	22. 7.64	17.00	.30	.46	.76	32.84	1.450	4.00	.75	14.00
7	7. 6.65	15.25	1.44	4.11	5.55	238.25	5.230	8.75	.25	37.25
8	19.10.66	20.15	1.03	.82	1.85	79.56	1.390	16.25	1.00	31.00
9	16. 7.67	4.00	.35	3.22	3.56	152.96	3.880	2.75	1.50	26.75
10	11. 9.68	4.00	.58	1.50	2.08	89.24	3.530	5.25	6.75	24.00
11	7. 9.69	17.00	.18	.27	.45	19.40	.880	5.75	.75	13.75
12	23. 8.71	3.00	.39	1.14	1.52	65.08	2.370	5.25	1.50	20.75
13	3. 7.72	11.00	.38	2.62	3.00	128.84	4.800	4.25	3.00	25.50
14	10. 7.72	10.45	.53	2.57	3.10	133.27	4.810	5.50	3.75	26.50
15	17. 9.73	24.00	1.00	2.58	3.67	157.44	4.640	7.75	5.50	27.75

Table 8.8 Summary of storm data : N. Danville, ND3.

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND3 CATCHMENT AREA (SQ.KM) 8.37 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	30. 7.60	12.00	3	47.50	12.00	14.11	3.96	23.63	61.16	86.65	100.00	11.37
2	2. 6.61	2.00	3	21.96	6.75	13.90	3.25	33.84	45.82	95.28	100.00	15.53
3	31. 7.62	4.00	3	48.77	9.25	34.68	5.27	33.81	63.71	72.24	100.00	24.01
4	30. 7.63	2.00	8	22.49	4.00	13.80	5.62	38.59	49.13	84.08	100.00	15.63
5	22. 7.64	17.00	8	10.46	1.50	23.84	6.97	3.81	66.19	100.00	100.00	28.42
6	7. 6.65	15.25	3	43.20	8.75	42.32	4.94	58.77	73.52	93.52	100.00	9.79
7	19.10.66	20.25	3	29.84	19.25	12.56	1.55	44.03	77.45	92.02	100.00	16.73
8	16. 7.67	4.00	3	17.50	10.25	6.32	1.71	36.69	52.00	90.63	100.00	26.67
9	11. 9.68	4.00	3	41.78	27.25	14.08	1.53	31.31	94.35	95.86	100.00	14.41
10	7. 9.69	17.00	3	23.38	12.00	40.64	1.95	97.01	99.23	99.49	100.00	27.48
11	23. 8.71	3.00	3	26.32	19.00	15.24	1.39	91.60	96.58	96.58	100.00	36.39
12	10. 7.72	10.45	3	39.89	13.75	31.96	2.90	6.39	87.24	87.24	100.00	34.87
13	17. 9.73	24.00	3	40.40	16.25	10.16	2.49	11.58	59.06	90.35	100.00	36.26

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	30. 7.60	12.00	.49	3.48	3.97	33.24	.020	.130	1.030	10.50
2	2. 6.61	2.00	1.00	3.82	4.82	40.35	.120	.230	1.060	6.00
3	31. 7.62	4.00	2.58	4.45	7.04	58.89	.030	.150	2.050	9.00
4	30. 7.63	2.00	.21	.29	.50	4.19	.030	.070	.210	5.75
5	22. 7.64	17.00	.17	.28	.45	3.79	.160	.180	.210	2.25
6	7. 6.65	15.25	2.84	3.69	6.53	54.63	.070	.170	1.860	7.50
7	19.10.66	20.25	.62	1.82	2.45	20.47	.050	.150	.370	10.75
8	16. 7.67	4.00	1.01	1.20	2.21	18.53	.060	.140	.470	10.25
9	11. 9.68	4.00	.83	2.22	3.05	25.54	.040	.130	.950	10.50
10	7. 9.69	17.00	.19	1.33	1.51	12.67	.080	.140	.620	2.25
11	23. 8.71	3.00	.50	1.95	2.45	20.52	.070	.150	.760	5.00
12	10. 7.72	10.45	1.17	4.79	5.96	49.90	.100	.210	2.630	8.00
13	17. 9.73	24.00	1.24	4.01	5.24	43.87	.060	.180	1.310	10.50

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	30. 7.60	12.00	.38	2.68	3.06	25.62	.990	5.00	5.50	24.75
2	2. 6.61	2.00	.68	2.20	2.88	24.11	.920	3.75	2.25	23.25
3	31. 7.62	4.00	2.42	3.47	5.89	49.28	1.990	6.75	2.25	27.00
4	30. 7.63	2.00	.11	.13	.24	2.01	.160	5.00	.75	9.50
5	22. 7.64	17.00	.01	.04	.05	.45	.040	.75	1.25	3.75
6	7. 6.65	15.25	2.56	2.76	5.32	44.53	1.760	7.00	.50	22.25
7	19.10.66	20.25	.34	1.04	1.38	11.53	.290	6.75	4.00	22.00
8	16. 7.67	4.00	.67	.69	1.36	11.37	.370	8.50	1.75	18.00
9	11. 9.68	4.00	.63	1.49	2.12	17.78	.890	4.50	6.00	20.25
10	7. 9.69	17.00	.11	.75	.86	7.17	.530	1.25	1.00	11.75
11	23. 8.71	3.00	.33	1.24	1.57	13.18	.670	3.25	1.75	16.75
12	10. 7.72	10.45	.81	3.30	4.10	34.35	2.510	4.50	3.50	24.75
13	17. 9.73	24.00	.90	2.89	3.79	31.71	1.210	7.50	3.00	26.00

Table 8.9 Summary of storm data : N. Danville, ND4.

SUMMARY OF STORM DATA FOR N.DANVILLE AT ND4 CATCHMENT AREA (SQ.KM) 43.51 DATA TIME INTERVAL (HRS) .25

SUMMARY TABLE OF RAINFALL DETAILS

STORM	DATE	START TIME	NO.OF RAIN PROFILES	TOTAL RAIN(MM)	DURATION (HRS)	MAX.INT. (MM/HR)	MN.INT. (MM/HR)	QUARTILE RAIN OVER DURATION (CUM%) 1	2	3	4	30 DAY API (FACTOR=0.9)
1	7. 6.65	15.25	3	34.54	8.75	37.64	3.95	45.57	78.86	95.81	100.00	9.79
2	19.10.66	20.25	3	29.88	31.75	10.31	.94	61.49	92.55	99.26	100.00	15.15
3	16. 7.67	4.00	3	35.85	10.25	22.68	3.50	66.75	83.07	96.56	100.00	26.67
4	11. 9.68	5.00	3	43.26	30.50	13.79	1.42	70.64	91.66	93.51	100.00	14.02
5	7. 9.69	17.00	3	18.84	12.00	33.36	1.57	96.48	99.29	99.61	100.00	27.33
6	23. 8.71	1.00	3	29.74	23.00	18.14	1.29	79.84	95.17	97.62	100.00	36.39
7	10. 7.72	10.75	3	31.50	13.75	21.46	2.29	7.64	86.66	91.58	100.00	30.50
8	14. 7.73	1.00	1	25.93	6.50	14.25	3.99	22.23	65.11	92.63	100.00	50.07
9	17. 9.73	24.00	3	38.34	16.25	7.45	2.36	11.51	54.25	91.76	100.00	29.97

SUMMARY TABLE OF TOTAL FLOWS

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	INITIAL FLOW (M^3/S)	FINAL FLOW (M^3/S)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)
1	7. 6.65	15.25	.88	1.28	2.16	93.83	.170	.750	1.770	11.75
2	19.10.66	20.25	1.34	1.40	2.74	119.18	.160	.810	1.530	18.00
3	16. 7.67	4.00	.55	3.84	4.39	190.96	.200	.840	5.140	4.50
4	11. 9.68	5.00	.76	2.80	3.55	154.63	.080	.850	3.190	12.00
5	7. 9.69	17.00	.59	1.36	1.95	84.85	.480	.890	2.330	6.25
6	23. 8.71	1.00	.70	1.77	2.47	107.32	.210	.730	2.570	9.75
7	10. 7.72	10.75	1.19	3.84	5.03	218.92	.290	.970	5.000	10.75
8	14. 7.73	1.00	1.39	3.68	5.06	220.34	.810	1.320	5.590	7.00
9	17. 9.73	24.00	1.68	4.35	6.03	262.40	.260	.990	5.400	13.25

SUMMARY TABLE OF STORM FLOWS (SEP.LINE=1.13MM/DAY/DAY)

STORM	DATE	START TIME	FLOW DEPTH (MM) RISING LIMB	FALLING LIMB	TOTAL	FLOW VOLUME (M^3*1000)	PEAK FLOW (M^3/S)	TIME TO PEAK (HRS)	TIME TO STORMFLOW START(HR)	DURATION OF STORMFLOW (HRS)
1	7. 6.65	15.25	.58	.60	1.18	51.35	1.330	11.25	.50	24.25
2	19.10.66	20.25	.46	1.08	1.53	66.74	1.150	8.25	4.50	27.50
3	16. 7.67	4.00	.46	2.73	3.19	138.71	4.050	3.25	1.25	26.50
4	11. 9.68	5.00	.63	1.57	2.20	95.84	2.950	6.50	5.50	32.50
5	7. 9.69	17.00	.30	.66	.96	41.69	1.710	5.75	.50	16.75
6	23. 8.71	1.00	.48	1.06	1.55	67.26	2.210	6.25	3.50	21.50
7	10. 7.72	10.75	.88	2.56	3.44	149.54	4.540	7.00	3.75	28.25
8	14. 7.73	1.00	.89	2.17	3.06	133.24	4.650	5.25	1.75	21.00
9	17. 9.73	24.00	1.32	3.02	4.33	188.57	4.930	8.50	4.75	30.25

9. COMPUTER PROGRAMMING CONSIDERATIONS

In order to facilitate the simple application of all models to each data set, the computer coding of three of the models has been included as a subroutine in a larger program. This was not easily possible with RORB model as it was received as an already coded program on magnetic tape. However, the RORB model was modified slightly to accept the input data in the same format as the other models.

The data for the Ecca catchment is drawn from the breakpoint data bank of the Rhodes HRU while the North Danville data was available as breakpoint data from the volumes of the US Department of Agriculture (USDA 1960 to 1973). Additional data are available from several other sources within South Africa. A suite of FORTRAN programs has been established to reduce or extract from the original data a set of fixed time interval values of rainfall depth and instantaneous flow. Stormflows, based on the separation line method of Hewlett and Hibbert (1967) are also calculated and the storm is considered to terminate when such stormflows become zero. The programs allow the extraction of different combinations of raingauges to produce any number of storm profiles for sub-catchment rainfall input. An example of the resulting rainfall and observed streamflow data input file is given in table 9.1. Although a time interval of 15 minutes was used throughout this study all the data extraction programs are flexible and any time interval can be set. The input data files for any one catchment contain all the storm data for that catchment and the model programs select which storm or combinations of storms are to be modelled in any single model run.

Where relevant, the antecedent rainfall data are stored on a separate file. Information about the way in which the model should run (lumped or semi-distributed, optimization or not, etc.) plus the essential information about the parameters and the definition of the sub-catchments is contained within control data files. An example of a control file for the S-curve model is given in table 9.2. These control files are reasonably well labelled to make it simpler to edit them between model runs. The control file for the RORB model has a different format (table 9.3) and closely corresponds to the standard input file for this model (Laurenson and Mein, 1985). The only difference is that the rainfall and streamflow data are read in separately and some of the sub-catchment data are read in interactively during execution of the program.

It is apparent from the format of the control files (table 9.2) that the models (except RORB) can be operated in lumped or semi-distributed format, single run or optimisation and single storm or multiple storm, using the same program. This method of operation makes it very easy to change from one mode to another without having to deal with a large number of different programs and data files. It should also be noted that there is always only one set of parameter values. For the semi-distributed models, sub-area changes in parameter values are determined by the sub-catchment parameter factor values. When running in optimization mode it is more or less impossible to expect sensible results if the parameter values on each sub-catchment were to be included in the optimization exercise. There is simply too much interaction between the different values being optimized. Consequently, the relative values of each parameter for the different sub-catchments must first be determined (or estimated) before optimization of the nominal parameter value can take place. The upper and lower limits associated with each parameter value are used to control the automatic optimization procedure. If these are equal to the actual parameter value then that parameter is excluded from the optimization.

For the first three models (not RORB) any number of the available storms may be run together using the same set of parameter values. This mode of operation allows a single set of parameters to be optimized for a group of storms using an objective function calculated over the whole data set as a fitting criterion. Initial moisture conditions and the internal counters for individual storm fit statistics are reset at the beginning of each storm.

Output from the common model program consists of a summary of the control data, individual and combined storm statistics describing the degree of correspondence between observed and simulated streamflows as well as a lineprinter plot of rainfall and flow data (figure 9.1). In the semi-distributed models the plotted rainfall data represent a single catchment average. Options are also available to output details of the values of different variables at each time interval and the flow from each sub-catchment. If these options are selected when operating in sub-catchment mode the output file can become quite large. However, these options are extremely useful when trying to evaluate the effects of changes in model parameter values or the relative contribution of individual sub-areas to total catchment streamflow. A further option is also possible to output rainfall, observed and simulated flows in a format compatible with a general graph plotting program (GENPLOT) developed by the senior author for use with the Rhodes University CALCOMP plotter.

9.1 Verification of the computer programs

This aspect of model verification (section 3.2) entails ensuring that the computer coding of the model adequately represents the conceptual structure of the model. In this study it was necessary to check the computer coding of models OSE1, 2 and 3 as these were written by the authors. OSE4 was received as an already coded model with accompanying test data and therefore did not require extensive checking. The detailed output option referred to earlier is used to ensure that model storages and outputs are calculated and updated correctly. Examination of the detailed output also ensures that moisture is not unintentionally lost and that changes in modelling time interval do not affect the operation of the computer algorithms.

Table 9.1 Example of rainfall and streamflow input data file.

```
15 ECCA A   09M20    73.1
 1 28. 2.77    15.00    .25 HRS INTERVAL
  62
RAINFALL  FOR 28. 2.77 15.00    62  .25 HR PERIODS  MULT= 1.000   CATCH           8
RAINFALL   1.000     610
     .00     .00     .00     .00     .00    1.57    1.57    1.53     .03     .00    1.02    1.02     .14     .99    1.44
    1.44    1.44    1.44     .59     .38     .38     .38     .05     .00     .09     .78     .78     .78     .78     .42
     .00     .00     .00     .00     .35     .48     .48     .48     .48     .48     .35     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .09     .09     .09     .05     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     60
     .00    1.16     .44     .00     .24     .44     .45    1.20    1.42     .22     .81     .81     .11     .69    1.38
    1.38    1.38    1.15    1.05     .63     .00     .38     .00     .00     .04     .66     .66     .66     .66     .53
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     63 8
     .00    1.00     .49     .11     .47     .29     .38    1.39    1.38    2.48    3.35    1.13     .26     .79    1.01
    1.46    1.46    1.38    1.19     .94     .04     .26     .03     .02     .02     .42     .49     .49     .66     .54
     .07     .01     .01     .01     .21     .15     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     61 8
     .00    1.27     .57     .47     .37     .45     .67     .93     .74     .36     .91     .91     .18    1.06    1.36
    1.36    1.36    1.18    1.18     .64     .03     .35     .00     .00     .02     .53     .58     .58     .58     .48
     .00     .00     .00     .00     .11     .14     .09     .23     .23     .23     .23     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     62 3
     .00     .78     .34     .15     .44     .39     .68    2.47    1.65    2.99    3.80    1.14     .55     .65     .75
    1.38    1.35    1.25    1.19     .98     .09     .24     .04     .02     .02     .33     .43     .43     .63     .44
     .09     .01     .01     .01     .01     .18     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     64
     .00     .31     .59     .00     .40     .00     .70     .88    1.12    2.55   10.14    2.06    1.44    1.44    1.44
    1.44    1.44    1.44    1.02     .95     .13     .33     .07     .00     .00     .17     .51     .51     .51     .51
     .07     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     62 4 5
     .00     .51     .50     .02     .22     .21     .70    1.71    1.44    1.63    7.74    2.13    1.64    1.24    1.24
    1.25    1.28    1.28    1.04     .89     .21     .29     .06     .02     .03     .27     .58     .51     .51     .43
     .10     .00     .00     .00     .00     .05     .01     .06     .08     .08     .08     .02     .00     .00     .00
     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
     .00     .00
RAINFALL   1.000     6 ALL
     .00     .67     .44     .13     .33     .47     .67    1.59    1.24    1.69    4.18    1.49     .74     .98    1.13
    1.37    1.38    1.29    1.07     .84     .16     .28     .04     .02     .04     .41     .51     .52     .61     .46
     .08     .01     .01     .01     .07     .19     .08     .12     .14     .14     .12     .01     .00     .00     .00
     .00     .00     .00     .00     .00     .01     .01     .01     .01     .01     .00     .00     .00     .00     .00
     .00     .00
TOTALFLOW  0.021
    .021    .021    .020    .020    .020    .019    .019    .018    .018    .018    .017    .023    .064    .105    .167
    .650    .764    .878    .902    .983    .923    .971   1.018   1.066   1.044   1.005    .966    .945    .938    .915
    .900    .885    .870    .856    .841    .826    .811    .796    .781    .768    .759    .751    .742    .734    .725
    .716    .708    .697    .684    .671    .658    .645    .632    .619    .606    .593    .580    .568    .555    .542
    .529    .516
STORMFLOW  0.000
    .000    .000    .000    .000    .000    .000    .000    .000    .000    .000    .000    .004    .036    .067    .119
    .592    .696    .800    .814    .805    .815    .852    .890    .927    .896    .847    .798    .767    .742    .717
    .692    .667    .642    .617    .592    .567    .543    .518    .493    .470    .451    .433    .414    .395    .377
    .358    .339    .319    .296    .273    .250    .227    .204    .181    .158    .135    .112    .089    .066    .043
    .021    .000
 2  6. 3.77    10.00    .25 HRS INTERVAL
  60
RAINFALL  FOR  6. 3.77 10.00    60  .25 HR PERIODS  MULT= 1.000   CATCH           10
```

Table 9.2 Example of S-curve model input control file.

```
ECCA                      NAME OF CATCHMENT
Q9M20                     CATCHMENT CODE
  73.94                   CATCHMENT AREA
ECCA                      CDC FILENAME HOLDING DATA SOURCE
ECCAA                     CDC FILENAME HOLDING AMI DATA
 1                        TOTALFLOWS ON FILE (1 IF YES)
 1                        STORMFLOWS ON FILE (1 IF YES)
 1                        DATA FOR USE (1=TOTAL,2=STORM)
 1                        HEMISPHERE (1=SOUTH,0=NORTH)
 1.0000                   CONVERSION FACTOR - FLOWS TO CUMECS
 1.0000                   CONVERSION FACTOR - RAINS TO MM
 0.25                     DATA INTERVAL (HOURS)
 15                       NUMBER OF STORMS ON FILE
INCLUSION ARRAY FOR INDIVIDUAL STORMS (1=YES,0=NO)
 1  2  3  4  5  6  7  8  9 10 11 12 13 14 15
 1  0  0  0  0  1  0  0  0  0  0  1  0  0  0
S-CURVE (S.D)             MODEL TYPE
15                        NUMBER OF PARAMETERS
 VALUE   UPPER   LOWER             DESCRIPTION
   1.000   1.000   1.000   1 CHANNEL TIME DELAY
   0.500   0.500   0.500   2 CHANNEL ROUTING K
   0.500   0.500   0.500   3 BASIN TIME DELAY
   6.000   6.000   6.000   4 BASIN ROUTING K
   0.600   0.600   0.600   5 BASIN ROUTING N
   2.700   3.000   0.500   6 CHANNEL LOSS PARAM
   0.150   0.150   0.150   7 TIME AREA B
 200.000 250.000 100.000   8 MAX STORE
   0.250   0.600   0.050   9 DA IN TANH.
   0.695   0.900   0.300  10 C IN TANH
 400.000 400.000 400.000  11 % FLOW FROM SLOPE
   0.600   0.600   0.600  12 % FLOW FROM VSA
   0.960   0.990   0.900  13 WINTER API FACT.
   0.600   0.990   0.600  14 MAX. IAR
   1.000   1.000   1.000  15 A IN TANH
 1                        LUMPED OR SEMI-DIST. (0 OR 1)
12                        NUMBER OF SUBCATCHMENTS
         SUBCATCHMENT PARAMETER FACTORS
SUB-CATCH    1    2    3    4    5    6    7    8    9   10   11   12
AREA %    13.0  5.9  5.6  7.0  6.4  7.0 11.4  7.9  6.0  9.7 12.9  7.4
PARAMETER 1 5.25 4.50 4.50 4.00 4.00 4.00 3.00 2.75 2.25 1.25 0.75 0.25
PARAMETER 2 0.80 0.90 0.90 1.00 0.75 0.75 0.50 0.60 0.96 1.40 1.00 0.60
PARAMETER 3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 0.00 1.00 1.00
PARAMETER 4 1.00 0.92 0.92 0.92 0.90 0.90 0.85 0.80 0.65 0.95 1.05 0.80
PARAMETER 5 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
PARAMETER 6 1.00 0.89 0.89 0.94 0.85 0.85 0.75 0.75 0.75 0.88 0.85 0.60
PARAMETER 7 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
PARAMETER 8 1.10 0.95 0.95 0.90 0.82 0.82 0.78 0.78 0.78 0.90 0.80 0.90
PARAMETER 9 0.72 0.84 0.84 0.92 1.05 1.05 1.15 1.15 1.15 1.07 0.99 1.07
PARAMETER10 0.83 0.93 0.93 0.95 0.95 0.95 0.95 0.95 0.95 0.92 0.99 0.92
PARAMETER11 0.75 0.82 0.82 0.90 0.90 0.90 0.92 0.92 0.92 0.90 0.92 0.90
PARAMETER12 1.00 0.83 0.83 0.83 0.83 0.83 0.83 0.90 0.90 1.00 0.83 1.00
PARAMETER13 1.00 1.00 1.00 0.99 1.00 1.00 1.00 1.00 1.00 1.01 0.99 1.01
PARAMETER14 0.92 1.03 1.03 1.05 1.10 1.10 1.30 1.30 1.30 1.20 1.40 1.20
PARAMETER15 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
NUMBER OF STORM PROFILES FOR EACH STORM
STORM NO.     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15
N.OF PROFS.   0  10  10  10  10  10   8  10   8  10  10   5   6  10   5
```

continued

```
STORM PROFILE AND MULTIPLIER FOR USE IN EACH SUBCATCHMENT
SUB-CATCH   1    2    3    4    5    6    7    8    9   10   11   12
ST. 1       1    2    2    3    4    4    5    5    5    8    7    7
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 2       1    2    2    3    4    4    5    6    7    9    9    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 3       3    3    3    3    3    3    5    7    7    7    8    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 4       1    2    2    3    4    4    5    6    6    7    8    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 5       1    2    2    3    4    4    5    6    6    7    8    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 6       1    2    2    3    4    4    5    6    6    7    8    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 7       1    2    2    3    4    4    5    5    6    6    6    6
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 8       1    2    2    3    4    4    5    5    6    7    8    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST. 9       1    3    3    3    3    3    3    3    6    6    1    4
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.10       1    2    2    3    5    5    8    8    8    9    8    8
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.11       1    2    2    3    4    4    5    6    6    7    8    9
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.12       2    2    2    2    2    2    3    3    4    4    4    4
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.13       1    1    1    1    2    2    3    3    3    3    4    5
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.14       1    2    2    3    4    4    5    5    5    5    9    8
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
ST.15       1    2    2    3    3    3    2    2    4    4    4    4
         1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
RUN INFORMATION CONTROL
 0                        OPTIMISATION OR NOT (1=YES)
  5                       NUMBER OF OPTIMISATIONS
 1                        COEFF. OF EFFICIENCY (NO TRANS.)
 0                        COEFF. OF EFFICIENCY (LN TRANS.)
 0                        ABS.FRACTION ERROR IN PEAK AND VOL.
OS*I-                     LINEPRINTER PLOTTING SYMBOLS
  1.000   1.000           LINEPRINTER PLOT SCALES
 0                        OUTPUT TABLE (0=NO ,1=YES ,2=NODAL FLOWS)
   SUBCATCHMENT SEQUENCE CODES
 22
 99  1  2 99  3 88  4 99  5 99  6 88 88  7  8  9 10 99 11 88 12 77
 0                        MOVING STORM CODE (0=STATIC,1=MOVING)
```

Table 9.3 Example of RORB model input control file.

```
ECCA 09M20
 1 ,     NATURAL REACH
 1, 3.42,-99,     SUB-AREA A
 8, 3,-99
 2, 2.02,-99,     SUB-AREA B
8, 2,-99
 3,     STORE H/G
 1, 1.95,-99,     SUB-AREA C
8, 2,-99
 4,     ADD UP H/G'S
 5, 1.95,-99,     ROUTE TO TO D
 8, 2,-99
 2, 1.93,-99,     SUB-AREA D
 8, 2,-99
 7,     P/O FOR 09M24
P/O FOR 09M24
 3,     STORE H/G
 1, 3.12,-99,     SUB-AREA E
8, 3,-99
 3,     STORE H/G
 1, 2.18,-99,     SUB-AREA F
8, 2,-99
 4,     ADD UP H/G'S
 4,     ADD UP H/G'S
 5, 2.41,-99,     ROUTE TO G
 8, 3,-99
 3,     STORE H/G
 1, 2.58,-99,     SUB-AREA G
8, 3,-99
 4,     ADD UP H/G'S
 5, 1.31,-99,     ROUTE TO H
 8, 1,-99
 3,     STORE H/G
 1, 3.07,-99,     SUB-AREA H
8, 3,-99
 4,     ADD UP H/G'S
 5, 2.06,-99,     ROUTE TO I
 8, 2,-99
 3,     STORE H/G
 1, 1.31,-99,     SUB-AREA I
8, 1,-99
 4,     ADD UP H/G'S
 5, 1.8,-99,     ROUTE TO J
 8, 2,-99
 2, 4.05,-99,     SUB-AREA J
 8, 4,-99
 3,     STORE H/G
 1, 3.01,-99,     SUB-AREA K
 8, 3,-99
 7,     P/O FOR 09M21
P/O FOR 09M21
 4,     ADD UP H/G'S
 2, 1.21,-99,     SUB-AREA L
 8, 1,-99
 7.1,     P/O FOR 09M20
 0 ,     END OF CONTROL VECTOR
 9.609999, 4.38, 4.13, 5.19, 4.74, 5.16, 8.390001, 5.83, 4.42, 7.14, 9.5, 5.45,-99     SUB-AREA AREAS (KM**2)
1,0.02,0.02,0.02,0.02,0.10,0.10,0.20,0.20,0.20,0.15,0.08,0.10,-99
12.00
FIT
```

continued

```
 .25, 90, 1, 10, 1,-99,     STORM DATA DETAILS
 0, 90
GAUGE 1
GAUGE 2
GAUGE 3
GAUGE 4
GAUGE5
GAUGE 6
GAUGE 7
GAUGE 8
GAUGE 9
GAUGE 10
 1 1 1  23.0  18.2  18.2  24.0  20.1  20.1  26.0  26.0  26.0  25.7  27.6  27.6
 2 1 1   0.0   0.0   0.0   2.2   1.2   1.2   8.1  12.1  18.0  15.9  15.9  15.9
 3 1 1  44.9  44.9  44.9  44.9  44.9  44.9  54.6  40.8  40.8  40.8  55.5  42.6
 4 1 1  46.1  34.0  34.0  45.5  36.1  36.1  44.9  49.4  49.4  53.9  45.7  51.8
 5 1 1  39.1  34.3  34.3  29.7  31.0  31.0  31.6  37.1  37.1  37.9  38.2  38.9
 6 2 1 135.7 133.3 133.3 131.4 130.7 130.7 132.1 133.1 133.1 125.7 124.4 118.4
 6 2 2  36.1  35.5  35.5  34.9  34.7  34.7  35.1  35.4  35.4  33.4  33.1  31.5
 7 1 1  32.0  31.1  31.1  27.8  27.7  27.7  28.4  28.4  28.0  28.0  28.8  28.8
 8 1 1 122.5 119.7 119.7 115.1 114.4 114.4 115.6 115.6 113.9 106.0 108.8  99.5
 9 1 1  24.6  22.9  22.9  22.9  22.9  22.9  22.9  22.9  23.6  23.6  24.6  22.1
10 1 1  30.1  43.4  43.4  26.5  44.4  44.4  59.3  59.3  59.3  59.3  59.3  59.3
11 1 1  29.8  36.7  36.7  39.7  42.6  42.6  34.3  33.1  33.1  33.6  33.2  34.7
12 1 1  50.8  50.8  50.8  50.8  50.8  50.8  46.1  46.1  58.4  58.4  58.4  58.4
13 1 1  58.5  58.5  58.5  58.5  51.6  51.6  70.6  70.6  70.6  70.6  75.9  76.8
14 1 1  28.6  41.6  41.6  30.7  33.9  33.9  17.7  17.2  17.2  17.2  16.9   7.8
15 1 1  28.0  30.2  30.2  32.6  32.6  32.6  30.2  30.2  30.8  30.8  30.8  30.8
 0, 90,-99
09M20
```

INDIVIDUAL STORM FITS

STORM	RAIN(MM)	FLOW(MM)	%ERROR	PEAK	%ERROR	C.EFF	C.EFF(LN)	R**2
3 OBS	48.6	7.99		21.230				
SIM		7.56	-5.34	18.749	-11.69	.9639	.9475	.9679

STATISTICS FOR ALL STORMS

	FLOW(MM)	%ERROR	C.EFF	C.EFF(LN)	R**2
OBS	7.992				
SIM	7.565	-5.343	.9639	.9475	.9679

STORM PLOTTED - DATE 31. 7.62 FLOW SCALING FACTOR- 1 PLOT UNIT = .0685 MM/HR
RAIN SCALING FACTOR- 1 PLOT UNIT = 10.0000 MM/HR

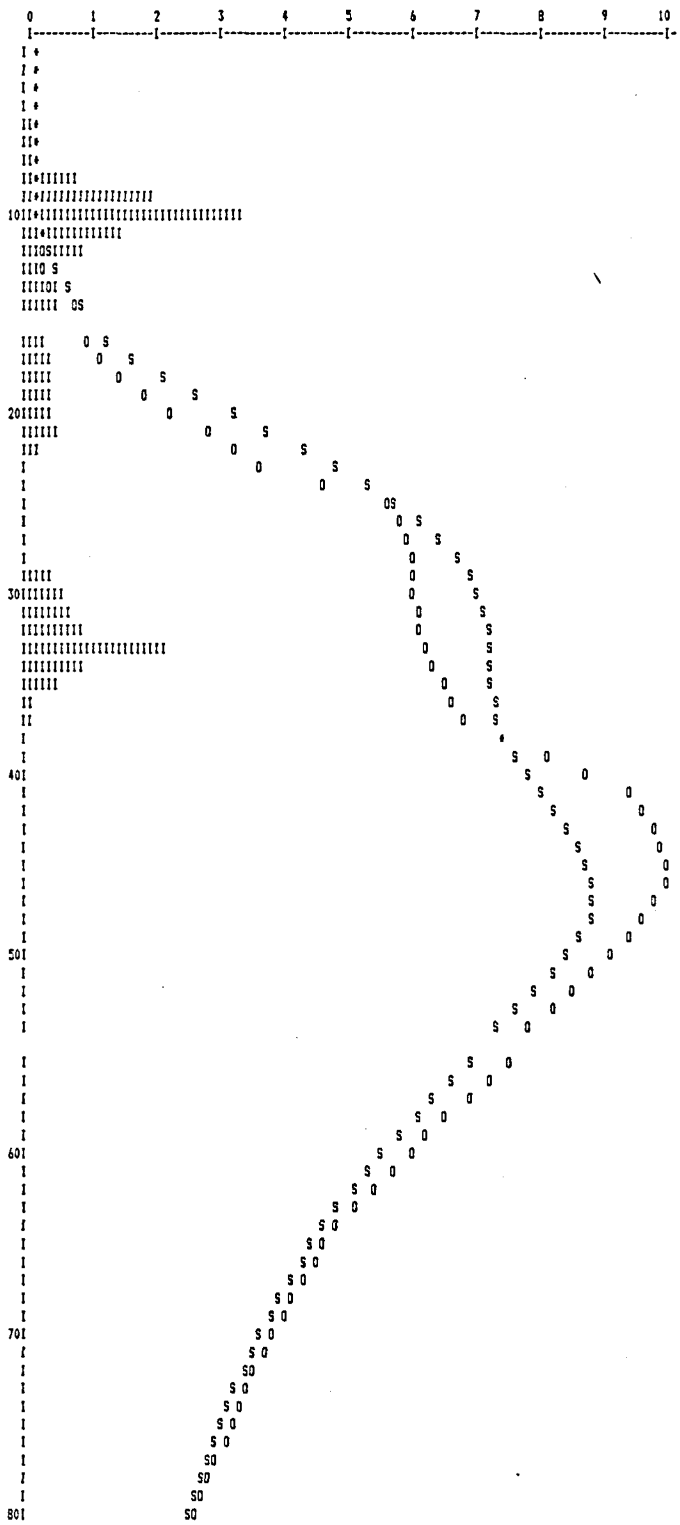


Figure 9.1 Output from the model program for OSE1, 2 and 3

10. MODEL FITTING RESULTS

This chapter discusses the results and the degree of success with which the four models have been able to reproduce the observed hydrographs. Comparisons between the individual model results are also discussed. To avoid breaking the text up with a large number of tables and diagrams most of the numerical and graphical results are contained in appendices A and B respectively. Appendix A consists of tables containing the parameter values and some statistics of fit for all the models in both lumped and semi-distributed format where applicable. Appendix B contains a number of graphical plots of storms that have been selected to illustrate a range of different results. There are several aspects associated with the results of fitting conceptual models to observed storm data. The following topics are discussed under separate headings for each of the models.

a) Ability of the models tc reproduce a range of hydrograph responses to a range of input rainfall types. This may be thought of as the models curve fitting capabilities.

b) The extent to which a) can be achieved with a reasonable degree of parameter stability and with parameter values that are intuitively acceptable. It may not always be easy to determine what is an intuitively acceptable value. To a large extent this depends upon the type of model and whether it is being operated in lumped or semi-distributed mode. Semi-distributed models have an extremely large parameter 'space' and there are consequently a large number of values that could be changed to vary the simulation result. For all the models, intuitive ideas about the sub-catchments variation in response have been used to determine the sub-catchment parameter factors. In some cases sub-catchment factors have been calculated from relative differences in measurable physiographic factors. To a certain extent the calibration results constitute a test of the applicability of these relationships. The factors have only been changed during calibration runs when changes in global parameter values have not been able to achieve a satisfactory result. In such cases, the characteristics of the sub-areas have been re-examined to try and rationalise such changes to the original intuitive reasoning.

c) The ease or difficulty of achieving acceptable fits to the observed data. This is an important consideration if a model is to have a future practical value.

During the discussions of these three topics comparisons are made between the temperate and semi-arid catchments. Comparisons are also made between the lumped and semi-distributed versions of the models to investigate whether or not the more complex semi-distributed approach is warrented. In the following sections reference is often made to 'acceptable' fits. This is of course a very difficult description to define. For the purposes of this report an 'acceptable' fit is one where the peak and volume estimations are within approximately 20% of the observed values and where the overall shape of the hydrograph is well simulated. This rather loose definition is considered adequate at this stage of the model evaluations especially if the term 'acceptable' is qualified by reference to specific features or statistics of the fits.

10.1 OSE2 - S-Curve model.

Before discussing the aspects of this model's results, it is essential to re-state the point that the model has been designed with a number of sub-components to account for differences in runoff response characteristics between storms on the same catchment. Part of the model evaluation has been to determine whether or not this is achieved successfully. Whereas the other models have been calibrated for each storm individually, the calibration of this model has been based on the assumption that the model parameters will remain the same for all storms in the same catchment. Therefore the exercise really consists of calibrating the model for the catchment not for individual storms.

10.1.1 Curve fitting capabilities

The curve fitting capability of a model refers to its ability to fit a range of disparate rainfall-runoff responses regardless of the values that the parameters have to assume to achieve this. With respect to the lumped model there are some situations where acceptable fits cannot be obtained. These are exclusively associated with storms having a high degree of spatial variability in the rainfall input (Q9M20 storm 2 - table A1, storms 30.07.63 and 22.07.64 on ND1, ND3, ND5 - tables A4, 5 and 7). The observation does not apply to all spatially variable storms and in some cases the smoothing effect of the catchment is such that the lumped model simulates the result satisfactorily.

The semi-distributed model produces better results for spatially variable storms when the space/time pattern of input is well defined. Examples are illustrated in figures B1A (Q9M20) and B10 to 12 (ND1, 4 and 5). However, little improvement is experienced for storm 22.07.64 on the North Danville catchments (fig. B8A). The information available for this storm consists of 4 rainfall profiles (gauges 1, 11, 16 and 22 - fig. 8.4) plus storm totals for most of the other gauges in the catchment. Storm totals as well as intensities are extremely variable and one possible reason for the unsatisfactory results is the inadequate definition of the time distribution of rainfall over some sub-areas. Even less information is available about the spatial variation during two other events (1963 and 1969). There is enough to demonstrate a high degree of spatial variation but not enough to define it. Where the rainfall is more uniformly distributed in space there is little difference in the modelling capabilities of the lumped and semi-distributed versions of the model.

Figure B3A illustrates an intense storm (maximum intensity 25.5mm/hr) on Q9M21 where the response was relatively low. The first peak of the storm is apparently a rapid response to the high intensity rain period from the lower parts of this small catchment. A much finer distribution system would have to be used to accommodate this degree of response sensitivity. Even then the model would be unlikely to reproduce the three clear peaks of this hydrograph. Comparison with figures B2A and B illustrates that the effects of time differentiated runoff generation are smoothed in the larger catchment (Q9M20). The hydrograph shape and peak are reasonably well reproduced although the timing of the response is still too late, especially using the lumped version.

The response characteristics of the small storms on the semi-arid Ecca prompted the inclusion of the channel losses function. The volume of runoff from any sub-area is reduced as a non-linear function of the product of the moisture status (RAT) and contributing area (ROP). In the lumped version the base of the time area triangle is reduced by the same proportion. These functi ns have the desired general effect of reducing the runoff more so from the upper catchment areas and hence simulating the smaller but more rapid response. However, it is pe haps naive to expect the same proportional decrease to apply to the volume and timing. This point will be considered further in the next section.

10.1.2 Parameter stability and acceptability.

The calibration results for this model on all catchments are given in tables A1 to A17 in appendix A. As well as listing the storm fit statistics for each storm, the values of the parameters are given when they differ between storms. The values of those parameters that are constant for all storms are given at the bottom of the tables. In the model the antecedent rainfall factor entered through the control file is considered to apply to all winter season storms (October to March in the northern hemisphere, April to September in the southern hemisphere). The summer season APF is set at 0,05 lower than the winter value. This facility was included in the model to allow storms from different seasons to be calibrated together in a single model run. However, it is recognised that the simple seasonal differential is likely to be inadequate. It is designed to account for lower evaporation rates and shorter day lengths in the winter period but APF may be more correctly expected to vary more smoot ly between the hottest month and the coldest. The tables as well as some of the figures (B9A and B14) illustrate that in some cases poor fits are due to systematic errors indicated by large differences between the coefficients of efficiency and determination. Examples are storms 2, 7, 8 and 12 on ND1 (tables A4 and A12 and 1, 7, 12, 13, 14 on ND5 (tables A7 and A16). The fits can be easily improved by making adjustments to the APF parameter (increase for negative errors, decrease for positive). The degree of change in APF necessary depends on the percentage errors as well as the history of rainfall in the previous 30 days.

The values for APF given in the tables for the Ecca results represent attempts to improve the fits by initially varying this parameter only. In some cases this was possible but in others additional parameters had to be changed to achieve, or come closer, to an acceptable fit. In table A1 it can be seen that for most storms parameters 6 (time area A) and 15 (channel losses parameter) have values of 5,38 and 2,32 respectively. It was found necessary to change these values on some of the small storms to achieve a satisfactory reproduction of the timing of the observed flows. It was mentioned at the end of the previous section that the channel losses parameter adjusts the volume and timing of flow in the same proportion. The changes in the values of parameter 6 (A) are thought to reflect the inadequacy of this simple relationship when trying to model a variety of very s...all responses to different rainfall input patterns.

Of the four large runoff events in the Ecca data set (20.07.79, 23.07.79, 19.08.79 and 2.11.85) only the August 1979 event requires a different APF value to produce an acceptable fit. This event occurs one month after the earlier events in July and the most suitable APF value for the other storms appears to overestimate the degree of catchment drying that actually takes place. However, it should also be noted that the 1985 event occurs in summer when the model would normally assume that the APF should be 0,05 lower. This November event occurred after a month long period of intermittant rain and cloudy cool conditions. Such conditions are more characteristic of the winter months in the Ecca and would therefore seem to justify the higher APF value. The APF values for the small events on the Ecca are highly variable and do not demonstrate any clear pattern. These va iations are far greater than the adjustments that were neces ary in the North Danville catchments to remove the systematic errors referred to e rlier. This may be a reflection of the greater variability of catchment drying out processes in the semi-arid Ecca. Alternatively, the variability in this parameter value may be accounting for other deficiencies in the model when it is applied to a semi-arid area. No final conclusion can be r ached on the basis of the limited number of catchments calibrated so far.

The tables in appendix A indicate that the other parameters not referred to above can remain constant for individual catchments. In the North Danville catchments this results in good fits over most of the storms (assuming systematic errors are removed by adjusting APF). For the Ecca catchments, the same can be said for the large storms but there are still several of the smaller storms which are relatively poorly reproduced. This model is conceived as being a flood model and many of the smaller events can hardly be defined as flood. It may be concluded that the results are better than is initially apparent and that most of the parameters can be considered stable for the range of 'flood' events modelled.

Table 10.1 lists comparitive parameter values for ND5 and Q9M20 for both the lumped and semi-distributed model versions. It is apparent that a greater degree of delay and attenuation occurs in the Ecca catchments than in ND5. For the lumped model the basin routing parameter. K and the time area base A are both higher for Q9M20. Although the semi-distributed K and KC values are lower for the Ecca. the channel delays for the remote sub-areas are greater than for ND5. The semi-distributed values correspond reasonably well with intuitive expectations. Valley side slopes are steeper with thinner soils in the Ecca suggesting more rapid runoff to the channel system than from the more gentle slopes and deeper soils of the North Danville valley sides. In fact, experience of the North Danville catchments (R. Schulze. pers. c mm.) suggests that the predominant runoff generation processes is sub-surface flow. If this sub-surface flow is relatively rapid and the valley bottom alluvium in the Ecca plays an attenuating role then it might be expected that the two catchments would have sim_lar basin routing characteristics. With respect to channel routing, the Ecca is more elongated and has fewer main channel segments per unit catchment area. The runoff generated in some of the upstream areas therefore has a greater distance to travel than in ND5.

The SMAX values for the two catchments are not very different but the shape of the S-curves are. The ND5 S-curve implies greater runoff proportions at lower moisture values than Q9M20. This is logical in view of the fact that the main moisture storage in the Ecca is in the valley bottom alluvial soils and on some of the flatter hilltops. A greater proportion of the total storage must therefore be satisfied before relatively high runoff proportions can be achieved. The soil depth distribu ion in ND5 is more uniform suggesting that valley bottom soils will become saturated more quickly and hence generate runoff at lower catchment moisture values. These characteristics of the two catchments seem to be reflected in the PCSLP parameters as well. The steep slopes and low moisture storage of the Ecca valley sides suggest little slope storage and high PCSLP values. The lower permeabilities (particularly lateral permeabilities) observed in the soils of the Ecca (Moolman. 1984) compared with those indicated in the USDA (1960-1973) volumes support the relative differences in the values of PCVSA (table 10.1).

Table 10.1 Comparison between parameter values for OSE2 on ND5 and Q9M20

Parameter	ND5		Q9M20	
	lumped	Semi-Dist.	lumped	Semi-Dist.
1. K	5,75	4,3 - 9,8	10,0	3,9 - 6,3
2. N	0.7	0,7	0.6	0,6
3. CDEL	-	0,0 - 2,25	-	0,25 - 5,25
4. KC	-	0,3 - 1,15	-	0,25 - 0,7
5. DEL	0.5	-	0,25	-
6. A	2,68	-	5,38	-
7. B	0,15	-	0,10	-
8. SMAX	218,0	196,2 - 239,8	175,1	156,0 - 220,0
9. DA	0,451	0,451	0,282	0,180 - 0,287
10. C	0.245	0,245	0,672	0,576 - 0,688
11. PCSLP	131,0	105,0 - 143,0	340,0	300,0 - 368,0
12. PCVSA	3,87	3,1 - 4,2	0.43	0,50 - 0,60
13. IAF	0,3	0,27 - 0,34	0.67	0,55 - 0,84
14. APF	0,898	0,889 - 0,907	0,963	0,95 - 0.97
15. CLP	0,0	0,0	2,32	2,16 - 2.70

The values listed under semi-distributed represent the range over the sub-catchments.

There are a number of areas in the Ecca where virtually bare slopes are adjacent to channels. Coupled with the fact that infiltration rates are expected to be lower in the Ecca it is not surprising that parameter IAF is a great deal higher for Q9M20 than ND5. The values given for APF in table 10.1 represent the winter values and suggest that the Ecca dries out more slowly for a given antecedent rain input than North Danville. This parameter has to represent the combined effects of evapotranspiration and drainage. The Ecca however experiences higher potential evaporation effects due to higher temperatures. Higher unsaturated lateral permeabilities and more dense vegetation cover in ND5 may be accounting for the greater drying effect. As mentioned earlier the component of the model controlled by this parameter has many weaknesses and this parameter is less stable than the others.

The channel losses component was incorporated after the North Danville modelling exercise had been completed and is therefore assumed to be 0,0. This parameter also has a minor effect on the large storms experienced in the Ecca. Its effect is to remove very s all flows generated by some of the rainfall that serves to wet the catchment before widespread streamflow occurs. This is illustrated in figure B4A. Because small amounts of runoff are generated by the S-curve even at a low moisture status. without the CLP parameter there would be low flow in the 5-25 hour period of storm 20.7.79. An alternative would be to begin modelling at approximately 20 hours and include the earlier rain as antecedent conditions.

The method used to set initial values for the sub-catchment parameter factors was largely intuitive and based upon the ideas expressed in section 4.4. During calibration these were only modified if an improved fit could not be obtained by changing the global parameter values or if the characteristics of the generated flow from gauged sub-areas did not approximately match the observed data. It was generally found necessary to adjust the channel delays on both catchments but few other adjustments were necessary for the North Danville catchments.

The basin routing parameter (K) factors for the North Danville sub-areas were determined by calculating the time of concentration (Tc) based on the equation :

$$Tc = 0.00025 * \frac{(L * 1000)^{0.8}}{(S)^{0.5}}$$

where L = sub-catchment area (km^2)/total channel length (km)
S = Average sub-catchment slope (mm^{-1}).

An area weighted average Tc for the whole catchment was calculated and all individual Tc values divided by this average to give the sub-area factors. The sub-area CDEL factors were initially calculated from Tc values using the length (L) from the outlet to the sub-area centre and the average slope (S) over that length. It was then found necessary to reduce these values by approximately 0,75 to obtain CDEL values (table A17) that produced acceptable fits. KC factor values were fixed by relative channel distances from the sub-area node to the next downstream node. Maximum storage (SMAX) parameter factors were subjectively related to the soils information given in the USDA (1960-1973) reports. PCSLP and PCVSA factors were estimated from relative values of average sub-catchment slopes and rounded up or down to the nearest 0.05 according to slope alignment. Thus, if the slopes are predominantly aligned toward the channel (incised situation) the values were rounded upwards. If slopes are predominantly aligned in a downstream direction then factor-values were rounded downwards, implying slower drainage from the slopes (or VSA) to the VSA (or channel). Similarly, those sub-catchments with higher slopes were assigned slightly higher IAF parameter factors.

A similar procedure was followed for determining the initial values of the sub-area factors for running the semi-distributed model in the Ecca c tchments. There is less formal information on the soil depth variations in this area than North Danville. Personal observations and experience have consequently played a greater role. The first comment that can be made is that more changes to the sub-area factors were made during the Ecca calibrations. The K parameter factors were determined largely through a consideration of both sub-catchment areas and slopes. Thus the relatively small (6% of total) and steep sub-area 9 has the lowest value, while the larger, more rounded or flatter sub-areas 1 and 11 have the highest values (figures 8.2 and 8.3). An indication of the CDEL factors is given by the calibrated value of the time area triangle used in the lumped model but these and the KC values were largely determined by consideration of the timing of observed flows at the three gauging points within Q9M20.

Factors for SMAX, DA, C and CLP, were found to be very difficult to fix. While some consideration was given to the distribution of soil depth within sub-areas (from observation, not formal measurement), the response characteristics of various observed events also helped to determine the factor values given in table A9. Q9M24 has failed to produce runoff for many of the smaller events included in the test data set. This could imply greater storage or higher channel losses or a combination of both. The latter implication has been used to fix the values given in table A9. The generally lower runoff response (c.f. tables 8.5 to 8.7) from Q9M24 relative to Q9M20 and Q9M21 is also reflected in the values of parameter factors for DA, C and IAF. While the North Danville storms could be modelled with uniform sub-area factors for DA and C, this was not the case for the Ecca storms. The authors have insufficient experience of this model to suggest how the detail of the S-curve shape changes with physiography. This will require further investigation after more catchments have been calibrated.

The model was re-run for three of the ND5 storms, setting the sub-catchment factors equal to the area weighted average for all sub-areas. This exercise was carried out for individual parameters (except CDEL) and then for all parameters combined. The largest deterioration in fit occurs when the K and SMAX factors are set equal. Errors change by only a few percent at the most and coefficients of efficiency decrease by a maximum of 6%. Setting all the factors for PCSLP, PCVSA and IAR constant has little effect on the overall fit. If all factors except CDEL and KC are set to be equal then the largest decrease in coefficient of efficiency is 8%, % volume errors remain similar and the % peak error for one storm changed from -11% to -18%. The equivalent results for 3 storms in Q9M20 (storms 1,6 and 12) are less clear. For some parameters the volume errors improve, while the peak errors deteriorate and vice versa. The largest effects occur on storm 1 and are caused by setting the main volume parameter factors equal (SMAX, DA and C). Changes to the other parameter factors cause negligible effects. If all factors (except CDEL and KC) are set equal then the coefficients of efficiency change from 0,70 to 0,46 (storm 1), 0.97 to 0,93 (storm 6) and 0.67 to 0.85 (storm 12). It is interesting to note that the one to one fit for storm 12 improves.

10.1.3 Ease of calibration

In some respects the model was easier to calibrate on the North Danville storms than the Ecca. However. it should be noted that calibration was stopped for some North Danville events when a high value for the coefficient of determination was achieved despite relatively high percent errors in peak and volume. These situations suggest systematic error and usually occurred on storms where there is a lack of information about the spatial variation in rainfall. For some of the storms, information is only available for rainfall input at gauges 1 and 10 (figure 8.4). Sometimes the storm profiles for these gauges are very different. implying a high degree of spatial variability. At other times they are similar. but unfortunately this does not necessarily imply low spatial variability. Figure B14 illustrates an example where profiles 1 and 10 are similar. The fits for ND3 and ND4 are good while those for ND1 and ND5 are systematically in error. Best fit APF values for the full range of storms on ND3 and 4 are higher (more moist antecedent conditions) than ND1 and 5. If the APF values for this storm on ND1 and 5 were adjusted to be more in line with those on ND3 and 4 the fits would be much better. In contrast, figure B15 indicates that the APF values are satisfactory over the four catchments. It is possible that errors in input data and antecedent moisture status are cancelling each other out. Where insufficient information is available about the storm rainfall input and where one (or more) component of the model is considered to be weak. it is difficult to attribute reasons for poor simulations.

A great deal of effort was required to achieve the fits on the Ecca catchment storms. This was especially true when attempting to obtain acceptable results for both the large and small events using a stable parameter set. As the tables in appendix A illustrate, this was not actually achieved. However, it was also true when attempting to simulate just the large events with one parameter set. This semi-arid catchment appears to have more complex response characteristics than the North Danville area. A closer inspection of the various sub-area outputs (with respect to relative timing and volumes) as well as the outputs of different model components was necessary in order to reach decisions about how to modify global parameter or sub-area factor values for the Ecca. Automatic optimisation techniques were useful in the lumped model version. but rerely provided the best overall fit without further manual parameter modification. Automatic optimization of the semi-distributed model took a great deal of time to run on the computer. If the sub-set of storms being optimised were of long duration then the program often ran into job step limits on the Rhodes Cyber computer before an optimal fit was reached.

It was originally intended to calibrate the semi-distributed model on Q9M20 and subsequently evaluate the results for Q9M21 and Q9M24 using the equivalent parameter values. However, after repeated attempts this procedure was abandoned and the smaller gauged catchments calibrated first. Acceptable calibrations were achieved in a shorter period of time, illustrating the advantage of some knowledge about sub-catchment response characteristics for calibrating a larger catchment.

10.1.4 Summary observations

In general, the results of calibrating model OSE2 were satisfactory for both areas. The main weakness of the model appears to be in the estimation of the initial moisture status of the catchment using an index of the previous 30 days of rainfall. With the exception of the antecedent moisture parameter a high degree of stability is evident in parameter values when calibrating a group of storms on the same catchment. In general the differences in parameter values both between catchments and within catchments (between sub-areas) are explicable in terms of physiographic differences. It is considered to be too soon to attempt to derive more definite. quantitative relationships. Further catchments need to be calibrated to obtain a better understanding of the model operation under different hydrological response characteristics. It will also be necessary to examine whether the relative insensitivity of the model to averaging sub-catchment factors found in the North Danville catchments is also found elsewhere.

10.2 OSE1 - Simple antecedent moisture model

10.2.1 Curve fitting capabilities

The curve fitting capability of the model for the North Danville catchments, over the range of storms, appears adequate (figure B6B, for example). However, an acceptable fit was not obtained for some storms with a high degree of spatial variability in the rainfall input (storms 2.06.61, 30.07.63, 22.07.64 for ND1 and storms 30.07.73, 14.07.73 for ND5). The curve fitting capabilities for storms on ND5 are better, implying perhaps that the larger catchment has a smoothing effect on spatially variable rainfall events. Individual storm simulations may be significantly better in the different formats of the model but there is little difference in the overall fitting capabilities of the lumped or semi-distributed versions. For the event of 1967 on the North Danville catchments, a significantly better result is obtained using the semi-distributed format (tables A21 and A26). However, the 1969 event, which is adequately reproduced using the lumped model, cannot be reproduced by the semi-distributed version. The curve fitting capabilities for the Ecca storms are less satisfactory. Without the incorporation of initial losses the fits would have been even worse. Simulation of the 'large' events is generally adequate, although neither version of the model can reproduce the large, twin peaked event (20.7.79), suggesting the need for a variable ROP. As is the case with North Danville, spatially variable rainfall events were difficult to simulate satisfactorily (storm 6.03.77, fig. B1B). It was also found that simulations were generally better for the larger catchment (table A18 and A19). The overall curve fitting capabilities of the lumped and semi-distributed model formats are not significantly different, however on an individual storm basis there are differences (figure B1 B and C). The model has distinctly poorer fitting capabilities on the 'small' events.

10.2.2 Parameter stability and acceptability

The lumped and semi-distributed calibration results for OSE1 are given in tables A18 - A27 in appendix A. For the North Danville catchments it was possible to use constant non-linear routing and initial loss parameters. Basin delay is the only routing parameter which needed to be varied in the lumped and semi-distributed version of the model. SMAX was held constant but the shape of the S-curve had to be varied to get adequate fits. The APF parameter was varied according to the season in which the event occurred. The APF for winter (Oct-Mar) was set 0.10 higher then the APF for summer (Apr-Sept). Generally this simple separation produced acceptable results, indicating that in summer there is higher evaporation and therefore a greater drying effect, while in winter the evaporation is lower and the catchment is more moist for the same amount of antecedent rainfall. The calibration results for the Ecca (table A18, A22) indicate how difficult it was to establish constant parameter values for the set of events. In particular, the results for the so-called 'small' events are very variable, due possibly to the fact that these 'small' events can hardly be classed as floods. The four 'larger' floods (20.07.79, 23.07.79, 19.08.79 and 2.11.85). indicate less variation in parameters, particularly the semi-distributed model parameters. The problem with modelling the 'small' events is that only a limited area near the catchment outlet appears to be generating the runoff. Evidence for this feature is that the response of the catchment to the low flows is very quick. The result is that the model needs low A and K values to simulate the rapid response (tables A18. A19 and A22).

Table 10.2 lists comparative parameter values for ND1, ND5 and Q9M20. for both versions of the model. Parameters for ND1 and ND5 are similar and as would be expected the channel delay on ND1 is generally less than ND5. The lumped results indicate that a greater degree of delay and attenuation occurs in the semi-arid Ecca catchment. This is also the case for the semi-distributed version which in addition has initial losses a kind of delay). far greater than those applied to ND5.

Table 10.2 Comparison between parameter values for OSE1 on ND1. ND5 & Q9M20

Parameter	ND1		ND5		Q9M20*	
	lumped	Semi-Dist.	lumped	Semi-Dist.	lumped	Semi-Dist.
1. K	5,5	6,0	6,0	6,0	9,0-11,5	5,40-11,5
2. N	0.7	0,7	0,7	0,7	0.7	0,7
3. CDEL	_	0,0-1,25	_	0.0-2,25	_	0,75-5,25
4. KC	_	0,4-0,8	_	0,31-1,15	_	0,40-1,04
5. DEL	0,0-1.50	_	0,0-3,0	_	1,5	
6. A	4,0	_	5,5	_	4,5-7,0	_
7. B	0,15	_	0,15	_	0,15	_
8. SMAX	150	150	150	150	200	200
9. DA	0.42-0,88	0,43-0,68	0,50-0,60	0,55-0,63	0,26-0,94	0.20-0,90
10. C	0,10-0.75	0,056-0,32	0.06-0,42	0.05-0,26	0,03-0,58	0,03-0,58
14. APF	0.80/0.90	0,80/0,90	0,80/0,90	0,85/0,90	0,85/0,95	0,85/0,95
15. IL	0,0	0,0	0,0	0,0	1,0-50,0	1,0-45,0

The values listed under semi-distributed represent the range over the sub-catchments.
* Parameters for 'large' events only.

SMAX values for the two catchments are different as is the general shape of the S-curves (see section 10.1.2 for an explanation for the different S-curves). There is a great deal of variation in the S-curve parameters which is not easily explicable in terms of physical storm or catchment characteristics. The parameter APF differs between catchments and is generally higher on the Ecca. However, the effect of changing this parameter is closely associated with changes in the S-curve parameters. These associations require further investigation specifically to find out whether a stable set of S-curve parameters can be used together with more variable APF values. The initial losses parameter was included once modelling on North Danville had been completed and has been assumed to be 0,0. On the Ecca. initial losses improved the calibration results quite significantly, especially for events with 'dry' antecedent conditions. The improvement occurs because even at a low moisture status, the S-curve generates runoff. Without the IL parameter, flow would occur in the period prior to actual catchment response (e.g. storm 20.07.79). The initial losses parameter allows catchment moisture requirements to be satisfied prior to producing runoff.

10.2.3 Ease of calibration

Although OSE1 was found to be more difficult to calibrate than OSE3, it was easier to calibrate on the temperate North Danville catchments than the semi-arid Ecca catchments. OSE1 has more parameters than OSE3, which makes it more difficult to operate. It was often felt that the best result was rarely achieved with OSE1, whereas with OSE3 it was generally possible to recognise the best result. In particular, problems were encountered with the volume reduction stage of the model, which in OSE1 has 3 parameters, all of which were difficult to stabilize. It was also more difficult to combine the effects of the APF and IL parameters, as both reflect antecedent moisture conditions. Calibration would be made a great deal easier if the S-curve parameters could be stabilised and response variations between storms accounted for using other parameters.

10.2.4 Summary observations

The fact that OSE1 uses a constant runoff proportion precludes adequate reproduction of complex, multi-peaked events. Storm events on the larger catchments were modelled more successfully. Apart from some events with a high level of spatial variability in rainfall input, there seems to be l ttle difference between the lumped and semi-distributed versions. One of the main proble s with calibrating this model is in the determination of the S-curve parameters. It is extremely difficult to fix the shape of the S-curve when modelling the storms separately. Some pre-calibration investigations of the variation in storm response characteristics may help and ways of doing this effectively are being studied.

10.3 OSE3 - Augmented hydrograph model

10.3.1 Curve fitting capabilities

The curve-fitting capabilities of the model on the North Danville catchments are considered to be adequate in both the lumped and semi-distributed formats, for the range of storms used (tables A30, A31, A34, A35 and figures B7A and B9B). However, with respect to the lumped model and particularly the smaller catchment (ND1), there are several situations where acceptable fits are not possible. As with the previous two models this feature is associated with the degree of spatial variability in the rainfall input.

The semi-distributed format of the model did not produce significantly better results for the spatially variable events, the exception being storm 10 (7.09.69) on ND5. For the storms of 1963 (ND1 and ND5) and 1969 (ND1) there was not sufficient information to define the distribution of rainfall over the sub-areas, therefore adequate simulation was not possible. However, it is likely that the flexibility of the semi-distributed format of the model has not been adequately exploited. Figures B13A and B, illustrate a situation where the semi-distributed fit is an improvement on the fit obtained using the lumped format. The curve fitting capabilities of OSE3 on the Ecca catchment, are generally less adequate and without the inclusion of initial losses would have been worse (figure B4B). To facilitate modelling, the storm events on the Ecca were divided into 'large' and 'small' runoff events. With the exception of storm 13 (25.11.85), the 'larger' events are reproduced adequately, especially those events with 'wet' antecedent moisture conditions (storms: 23.07.79 amd 2.11.85, figure B5B). The smaller storms were generally less satisfactorily reproduced as were events with a high degree of spatial variation of rainfall input (storm 2, 6.03.77). For most events the curve fitting capabilities of the semi-distributed format were better than the lumped model. The sub-catchment factors determined for initial losses improved the response of the model (table A33). However, even in semi-distributed format the model was not capable of reproducing double peaked events on the Ecca catchments (figure B4B), suggesting that a constant ROP is inadequate in this semi-arid area.

10.3.2 Parameter stability and acceptability

Both lumped and semi-distributed calibration results for OSE3 are given in tables A28-A37. For the temperate North Danville catchments it was possible to simulate observed flows acceptably with constant routing and initial loss parameters (see tables A30, A31, A34, A36). Although the catchment delay of the time-area routing function was allowed to vary, this is not considered a serious problem and only effects the timing of the hydrographs to a limited extent. As expected, the volume reduction parameter (ROP), does vary between events (see Section 6.3). The variation of the ROP parameter is much the same for storm events on ND1 and ND5. At present it is difficult to evaluate the suitability of the ROP's achieved, although it is possible to establish intuitively a degree of acceptability. For example the 24.10.59 storm is a large event, the rainfall is fairly intense and the catchment is 'wet' prior to the event, therefore a high ROP is not u expected (ROP=0.420). The 30.07.60 storm is a long duration, low intensity rainfall event with 'dry' antecedent conditions, therefore a low ROP is expected. The general stability of parameters on North Danville appears to suggest that catchment charactersitics are not very variable, thus making it possible to model events with reasonable success even in lumped format.

For the semi-arid Ecca catchments, parameter stability appears to be dependent on the size of the event and the format of the model. There is little stability when the model is in lumped format (table A28, A29) and when small events are calibrated (table A28, A29 and A32). In the semi-distributed version, the channel routing parameters are constant (table A32) and the range of the basin routing parameter (K) for the large storms is small. The poor results achieved for the 'small' storms is possibly due to the fact that these events can hardly be classed as floods and that the 'large' events reflect true flood conditions for the semi-arid Ecca. The general lack of stability of parameters in the lumped format suggests that, in the semi-arid situation, catchment and storm characteristics are very variable. It is extremely difficult to determine a single value for a parameter that is suitable for all events.

Table 10.3 lists comparative values for ND1, ND5 and Q9M20 (large events only), for both versions of the model. As intuitively expected, ND1 (smaller catchment) has lower delays then ND5 in the semi-distributed format and a smaller time-area base (A) in the lumped version of the model. For ND5 and Q9M20 the table indicates that a greater degree of delay and attentuation occurs in the Ecca catchment. For the lumped version, basin routing K and A are generally higher for Q9M20. In the semi-distributed version of the model, K can be lower (less attenuation on some sub-catchments) for Q9M20, but initial losses (which can include channel losses) for the Ecca are higher than for ND5. The methods used to set initial values for the sub-catchment parameter factors are similar to those described in section 10.1.2 for the S-curve model.

Table 10.3 Comparison between parameter values for OSE3 on ND1, ND5 & Q9M20

Parameter	ND1		ND5		Q9M20*	
	lumped	Semi-Dist.	lumped	Semi-Dist.	lumped	Semi-Dist.
1. CDEL	_	0,0-1,25	_	0,0-2,25	_	0,75-5,25
2. KC	_	0,4-0,8	_	0,13-0,85	_	0,43-1,10
3. ROP	0,09-0,43	0,09-0,44	0,10-0.37	0.10-0,38	0,19-0,54	0,31-0,58
4. N	0,5	0,5	0,5	0,5	0,5	0,5
5. DEL	0,0-1,75	_	0,0-1,75	_	0,0-1,50	_
6. A	4.0	_	5,0	_	4.5-8,0	_
7. B	0,15	_	0,15	_	0,15	_
8. K	15	15	15	15	15-24	9,7-25,2
9. IL	2.5	2,5	2,5	2,5	0-65	0-98

The values listed under semi-distributed represent the range over the sub-catchments.

* Only 'large' events considered.

10.3.3 Ease of calibration

It was generally easier to calibrate both forms of the Augmented Hydrograph on the North Danville catcments. This is possibly due to the greater degree of parameter stability obtained on the North Danville catchments.

In most cases it was easier to establish when the best possible result had been achieved. when the model was in the lumped version. This was due in part to inexperience with semi-distributed modelling and because of the fewer parameters involved in the lumped version. Therefore the sub-catchment parameter factor values need to be investigated futher to improve the understanding of the semi-distributed version of the model.

10.3.4 Summary observations

This model was found to be easier to calibrate than the previous constant runoff proportion model, OSE1. This is largely because the volume reduction component is simpler than in OSE1. With respect to the North Danville catchments the semi-distributed version does not achieve better results than the lumped model. However, the semi-distributed model is better able to reproduce storm hydrographs in the Ecca catchment. As with OSE1, multi-peaked and spatially variable rainfall events are not well modelled.

10.4 OSE4 - RORB model

Before discussing the results of calibrating this model it should be emphasised that OSE4 has been applied in its basic form only. Few of the options that are available to refine the model beyond its basic structure have been tested. Thus, the sub-area routing factors have been calculated on the basis of the channel length between nodes and no attempt has been made to incorporate a sub-area routing component as suggested in Laurensen and Mein (1985). A further component could also be incorporated to include distributed channel losses. The observed flows for this model refer to s ormflows and not totalflows as in the other models. There is unfortunately no simple or direct way of allowing for the decay of an initial observed flow at the beginning of the storm. An additional difference is that the OSE4 program does not calculate coefficients of efficiency or determination but rather a statistic referred to as the 'average absolute ordinate error' (AAOE in tables A38 to A40). The percentage errors for volume and peak are included in the program printout and are comparible with the other models.

10.4.1 Curve fitting capabilities

Although only the results for the constant runoff coefficient version of the model are reported in appendices A and B, the continuing losses model was also tested. The latter proved to be inadequate especially for the Ecca storms and generally for those storms with large intensity variations during the rainfall input. Some events begin with relatively high intensity rainfall which initiates runoff, followed by lower intensity rainfall which sustains flow. The continuing losses model ignores the later rainfall as it lies below the continuing loss level. This situation is exacerbated for the small storms on the Ecca where the runoff proportion is extremely low and is therefore derived from the highest 15 minute intensity fall occuring after the period of initial losses.

The runoff proportion model is more flexible in its fitting capabilities but nevertheless it is still difficult to fit to some situations. Figure B2D illustrates that the model assumes that some of the flow is derived from upper catchment areas when in fact no flow was observed at Q9M24. To decrease the amount of flow derived from upstream areas it would be necessary to include a spatially variable channel losses component. The alternative method of introducing spatial variability in runoff amount is to allow some proportion of the sub-areas to be impervious to rainfall. However, when the runoff response is very low (5%) this usually means that more runoff is generated from these impervious areas than was observed. The model will therefore not run. Figure B4C illustrates that despite dividing this twin peaked event into two bursts (table A38 - storm 6) the first peak is still underestimated. The latter fit could be improved by adjusting the proportion of flow resulting from each rainfall burst. However, this example serves to illustrate the difficulty of defining these proportions. It is of interest to note that the twin peaked event on ND1 (figure B7B) was reproduced satisfactorily without resorting to seperated rainfall bursts.

The model calculates the runoff coefficient from the rainfall (after removing initial losses and the observed flow volume. The large volume errors result when some of the simulated flow volume has not been routed out at the end of the observed duration. The mean and standard deviations for the three fit statistics given in Tables A38 to 40 suggest that OSE4 is more successful in modelling the North Danville catchments than the Ecca. While Q9M20 was the only Ecca catchment calibrated with this model, summary data for output from Q9M21 and Q9M24 was examined during each run. Only during the larger events did the volumes, peaks and timing of flows from these gauged sub-catchments come close to matching the observed data.

10.4.2 Parameter stability and acceptability

As with models OSE1 and OSE3, the parameters of OSE4 were not necessarily expected to be constant for all storms. However, it was expected (or hoped) to find greater stability in the routing parameter KC than is indicated by the results given in tables A38 to 40. These values are extremely variable for the Ecca ranging from 0,8 for the smallest storm to 15,0 for the largest. The variation is much less for the North Danville storms (ND1 and ND5) and could possibly be reduced by adopting a different N value.

No attempt has been made in this preliminary study to examine in detail any relationships between initial losses or the runoff coefficient and antecedent moisture status and storm parameters. However, a casual comparison of the model parameters with storm characteristics does not reveal any obvious structure. Further investigations into this matter will follow after more catchments have been calibrated and will closely parallel similar studies involving models OSE1 and OSE3.

10.4.3 Ease of calibration

The simple version of the model used in this study (that is without attempting to use some of the optional components) is relatively straightforward to calibrate. There is commonly only one combination of KC and initial losses that produces the best fit to a single storm. After only a few test runs it becomes quite simple to roughly estimate the effects of changing KC or I.Loss values. For those storms where an acceptable fit is not possible it becomes apparent after several parameter changes that further improvement is beyond the models capabilities. Increasing initial losses inevitably delays the start of runoff as well as increasing the proportion of later rainfall amounts that contribute to runoff. The effect of such a parameter change on the hydrograph shape is dependent upon the shape of the rainfall profile particularly at that point where initial losses are satisfied. The rainfall profile shape also has a strong influence on how sensitive the model is to changes in initial loss.

10.4.4 Summary observations

The use of the continuing losses model was not successful for both catchment areas. The runoff proportion model was relatively easy and rapid to calibrate but little stability exists in the parameter values. This is especially true over the range of events from the Ecca catchments. Sub-catchment outflows at Q9M21 and Q9M24 were not simulated satisfactorily even when the results for Q9M20 were good.

10.5 Discussion of model comparisons

The mean values for the fitting criterion are compared in table 10.4. Comparisons are made between model types as well as between the two groups of catchments. The table suggests that model OSE3 most accurately reproduces the observed hydrographs with model OSE2 performing least successfully. The relatively higher values for the percentage volume and peak errors associated with OSE2, appear to be largely due to systematic error. This feature is illustrated by the larger differences between the two coefficients for OSE2 (lumped and semi-distributed). The figures in table 10.4 do not provide a complete impression of the comparitive success of the models. OSE2 has a far more stable set of parameter values which can. to a large extent, be intuitively justified on the basis of known differences between catchments or sub-areas within catchments. The other models have a greater amount of parameter variability which has no immediately apparent relationship with storm characteristics. This is particularly true when modelling the Ecca storms. Model OSE1 has more parameters than OSE3 and OSE4 due to the S-curve component designed to estimate the constant runoff proportion from antecedent conditions. The parameters of this component are extremely variable but this could be a consequence of the way in which the model was calibrated. More emphasis was placed on stabilising the routing and APF parameters than the S-curve parameters. The alternative, of trying to fix DA and C and modify other parameters to achieve a satisfactory fit, requires investigation. It might then be simpler to find reasons for variations in the other parameters than it is to find reasons for differences in the S-curve parameters. The results obtained so far suggest that the additional component in OSE1 for estimating the runoff proportion is not justified and merely makes the calibration procedure more complex.

Table 10.4 Comparison of model fit statistics

		Mean values			
	% Vol.	% Peak	C. Eff.	C. Det.	AAOE %
All catchments					
OSE2 lumped	12,6	15,6	0,700	0,844	
semi-dist.	16,5	15,4	0,633	0,862	
OSE1 lumped	6,4	7,9	0,857	0,885	
semi-dist.	6,4	7,9	0,879	0,916	
OSE3 lumped	4,4	4,5	0,875	0,903	
semi-dist.	3,9	5,1	0,904	0,916	
OSE4 lumped	6,0	7,0			25,0
All models					
Ecca	8,5	9,1	0,754	0,832	36,2
North Danville	9,4	10,9	0,812	0,915	19,5

AAOE - Average absolute ordinate error.

The tables in appendix A present a relatively confusing impression of the differences between lumped and semi-distributed modelling. The patterns are similar regardless of the actual model type (OSE1, 2 or 3). Some of the storms are modelled more successfully with the lumped versions while others favour the semi-distributed approach. Figures B10 to B13 illustrate a situation where, given well defined spatial variation of rainfall input, the semi-distributed versions of the models produce improved overall fits. This is not always the situation and figure B8 illustrates that the semi-distributed versions are not always successful. For this particular event OSE4 appears to come closest to the observed hydrograph (figure B8C). It is difficult to draw firm conclusions at this stage but it would appear that inadequate definition of the spatial variation in rainfall input contributes to some of the poor modelling results in the North Danville catchments. This factor certainly makes it difficult to compare the relative success of the lumped and semi-distributed approaches. Further model tests, in catchments with more complete data, are required to investigate this problem further.

The small storms on the Ecca catchments are difficult to simulate with all the models. The authors believe that the scale of operation of the hydrological processes during these storms is much smaller than the distribution scale of the models. It is suggested that the streamflow during these events is generated in the lower parts of the catchment and only in areas close to river channels. The rapid and very small responses of the observed hydrographs support this view and suggest that surface runoff generated elsewhere in the catchment is re-absorbed into the soils or valley bottom alluvium. The incorporation of a channel losses parameter into both versions of OSE2 proved to be useful with respect to modelling the small Ecca storms. However, table A1 illustrates that it was still necessary to reduce the time area base parameter (A) to achieve the faster response in the lumped model. The values for the basin routing parameter (K) are lower for models OSE1 and 2 than for OSE3. This might be expected as gross rainfall is being routed in OSE3 while only excess rainfall is routed in the other models. The other routing parameters (KC, A, B and CDEL) have very similar values for models OSE1 and 3.

Only model OSE2 could satisfactorily reproduce the two peaks of storm 20.07.79 on the Ecca catchments (figure B4) although OSE4 could produce a better fit if the proportions of flow from the two rainfall bursts were adjusted. It is therefore apparent that a model having some way of accounting for a variable runoff proportion during a storm is necessary for the semi-arid catchments. Figures B6 and B7 suggest that the same is not true for the North Danville catchments. All the models are capable of reproducing the two peaks of the 24.10.59 event on ND1.

With respect to ease of calibration, OSE3 and OSE4 are more straightforward to calibrate than the other models. However. this conclusion does not take into account the additional work that will have to be done in the future to obtain a better understanding of the variation in model parameter values. The semi-distributed version of OSE2 is the most difficult model to calibrate while the results obtained so far indicate that this more complex approach is not justified for most storms. After a larger number of catchments have been calibrated, the physical relevence of the parameters of OSE2 may become better defined. If this is possible then some of the difficulties of calibrating OSE2 will be removed.

11. CONCLUSIONS AND FUTURE INVESTIGATIONS

There are very few clear guidelines in the hydrological modelling literature to suggest what degree of si…plification is permissable to produce acceptable simulation results in different situations. Simplification can refer to many different things. The whole structure of a model may be a simplified concept of the real physical system. Alternatively the model may have a complex, spatially distributed structure but be applied in a simplified way because of the users inability to accurately evaluate certain physically-based parameters. Such simplifications may imply the evaluation of parameters through indirect methods (Bathurst, 1986) rather than by direct measurement. Association of parameter values with physical factors such as vegetation, soil type, slope or geology may be the only way in which physically-based, distributed models can be applied. The situation then becomes very similar to less strongly physically-based conceptual models where the parameters have some demonstrated physical significance. If the realistic range of possible parameter values is known, as well as the simulation sensitivity to variations within that range, then quantifiable levels of uncertainty may be defined (Abbott, et al, 1986). This is an important characteristic and one that has been lacking in many of the existing models having very simple structures and parameters which ave little physical relevance.

The models tested include three essentially simple conceptualisations of the generation of flood hydrographs and use a rainfall-runoff ratio that is constant during a single event. One of these models (OSE1) has a component which attempts to relate the rainfall-runoff ratio to antecedent moisture conditions. Non-linear routing procedures are then used to delay and attenuate the resulting channel discharge. The fourth model (OSE2) incorporates more components in the runoff generation structure of the model in an attempt to make the model more conceptually realistic. The rainfall-runoff ratio at any time during a storm is variable and controlled partially by the moisture status of the catchment and partly by the rainfall intensity. All four models can be operated in semi-distributed mode through lumped modelling of user defined sub-catchments and channel routing procedures. Three of the models have separate lumped model formulations while the fourth (OSE4) can also be used in a lumped way by setting the number of sub-areas to unity.

The models have been calibrated using data from two different regions: the humid forested catchments of North Danville, Vermont, USA and the semi-arid Ecca catchment of South Africa. Appendix A lists the parameter values and fit statistics for all the model-catchment combinations while appendix B uses computer generated graphical plots to illustrate some of the fitting characteristics of the models. Some general conclusions can be made.

a) There is very little apparent difference between the lumped and semi-distributed versions of the model. However, the summary statistics in table 10.4, ignore the fact that there were fewer storms where totally unacceptable fits were possible with the semi-distributed versions than the lumped. There were also demonstrable improvements using the SD version when the spatially variable rainfall input was well defined.

b) There is a large variation in the amount of rainfall input data available for individual events. When the rainfall input is known to be variable, but is inadequately defined by the available data, model results must be interpreted with caution. Research studies designed to test the performance of models will always be faced with this problem. If model tests are confined to those few research areas where high density rainfall information is available then it is unlikely that models will ever be tested over a wide range of catchment types. Models are frequently applied where input data is deficient and it is important to investigate how successfully they perform in these situations as well. However, without at least some high level quality data, it would be difficult to conclude to what extent a model is truly able to reproduce the rainfall-runoff characteristics of a catchment.

c) The semi-distributed models were more difficult to calibrate due to the need to evaluate the sub-area parameter factors. Given more experience of the models and the physical relevance of parameter values these difficulties should be reduced. The importance and sensitivity of the sub-area parameter factors is unclear at present.

d) Table 10.4 suggests that the simple models can reproduce observed hydrograph shapes better than the more complex OSE2 model. However, the poorer overall OSE2 results are partly a consequence of the systematic errors in the fits on the North Danville catchments. This can be seen by comparing the coefficient of efficiency values of OSE2 with the others (±20% less and the coefficient of determination values of OSE2 with the others (±5% less). The poorer fits may be caused by inadequate storm input definition for some storms but a deficiency in the antecedent moisture status component is also considered to play a major role. This component, together with the S-curve function, in model OSE1 requires further investigation. The large differences in the S-curve parameters between storms are dif icult to explain and a new approach to calibration will be investigated in the future (section 10.2.2). Such problems are irrelevant to models OSE3 and 4 Systematic errors do not occur in these models as the volume of runoff is fixed by the single runoff proportion which has no constraints placed on it.

e) With respect to conclusion c) it should be noted that the results for OSE2 are achieved with a much higher degree of parameter stability. The antecedent precipitation parameter is the main exception to this conclusion although other parameters were also changed in order to simulate some of the very low response events on the Ecca catchments. Further work is necessary before any conclusions can be drawn about the variable parameter values on the simple models. There do not appear to be any simple relationships with the runoff coefficients and storm characteristics or antecedent precipitation for example. A more complete evaluation of possible relationships will only take place after more catchments have been calibrated.

Some of the results that have emerged from the calibrations of the model on the two different sets of catchments are encouraging. The parameter values of model OSE2 can be generally interpreted in terms of differences between catchments or sub-area physical characteristics. No firm quantitative relationships have been investigated and this will only be carried out after more experience of the model is obtained through application to a broader range of catchments.

The programme of future investigations (1986-1988) is designed to follow three main interlinked directions :

a) Further calibration and verification on more catchments from both humid and semi-arid parts of southern Africa and the United States. The available data cover a range of physiographic characteristics. Some of the data are of a better quality than those used in this report while some are of a poorer quality and less complete.

b) Sensitivity analyses of model parameters and sub-area parameter factors and investigations into an alternative calibration approach to OSE1.

c) Investigations into the association of parameter values with measurable storm or catchment characteristics or both and the feasibility of applying the models to ungauged situations.

This present report constitutes the first part of the overall study designed to investigate several aspects of the general applicability of isolated-event flood models. It has investigated the models' calibration performance in two areas with different rainfall-runoff response characteristics. This report has not addressed the problem of verifying the calibration results. Verification of the applicability of model parameters to events or catchments not used for calibration is an essential part of a thorough test of any models performance. The second report, which will be compiled during 1988, will concentrate on verification testing and try to reach some conclusions about the general applicability of the models discussed.

REFERENCES

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986) An introduction to the European Hydrological System - Systeme Hydrologique Europeen, "SHE", 1: History and Philosophy of a physically-based distributed modelling system, and 2: Structure of a physically-based, distributed modelling system. **J. Hydrol.** 87, 45-59 and 61-77.

Aitken, A.P. (1973) Assessing systematic errors in rainfall-runoff models. **J. Hydrol.**, 20, 121-136.

Anderson, M.G. and Burt, T.P. (editors) (1985) **Hydrological Forecasting**, John Wiley and Sons, England.

Bathurst, J.C. (1986) Physically-based distributed modelling of an upland catchment using the Systeme Hydrologique Europeen. **J. Hydrol.**, 87. 79-102.

Bauer, S.W. and Midgley, D.C. (1974) **A simple procedure for synthesizing direct runoff hydrographs.** Report no. 1/74, Hydrological Research Unit, University of the Witwatersrand and CSIR, Johannesburg, South Africa.

Beaudoin, P., Rouselle, J. and Marchi, G. (1983) Reliability of the design storm concept in evaluating runoff peak flow. **Water Res. Res.**, 19(3), 483-487.

Bernier, P.Y. (1985) Variable source areas and storm-flow generation : an update of the concept and a simulation effort. **J. Hydrol.**, 79, 195-213.

Beven, K.J. (1983) Surface water hydrology : Runoff generation and basin structure. **Reviews of Geophysics and Space Physics**, 21(3), 721-730.

Beven, K.J. and Hornberger, G.M. (1982) Assessing the effect of spatial pattern of precipitation in modelling stream flow hydrographs. **Water Res. Bull.** 18(5), 823-829.

Beven, K. J. and Kirkby, M.J. (1979) A physically based, variable contributing area model of basin hydrology. **Hydrol. Sci. Bull.** 24(1), 43-69.

Beven, K.J., Kirkby, M.J., Schofield, N. and Tagg, A.F. (1984) Testing a physically-based flood forecasting model (Top model) for three UK catchments. **J. Hydrol.**, 69, 119-143.

Beven, K.J. and O'Connell, P.E. (1982) **On the role of physically-based distributed modelling in hydrology.** Inst. of Hydrology, Wallingford, England, Report No. 81.

Bondelid, T.R., McCuen, R.H. and Jackson, T.J. (1982) Sensitivity of SCS models to curve number variation. **Water Res. Bull.** 18(1), 111-116.

Clark, R.D.S. (1980) Rainfall stormflow analysis to investigate spatial and temporal variability of excess rainfall generation. **J. Hydrol.**, 47, 91-101.

Cordery, I. (1970) Antecedent wetness for design flood estimation. **Civil Eng. Trans.**, Inst. of Engineers Australia, 12, 181-184.

Corradini, C. and Singh, V.P. (1985) Effect of spatial variability of effective rainfall on direct runoff by a geomorphogic approach. **J. Hydrol.**, 81, 27-43.

Danish Hydraulic Institute (1985) **Introduction to SHE, Systeme Hydrologique Europeen.** Danish Hydraulic Institute, Horsholm, Denmark.

Delleur, J.W., Tao, P.C. and Kawas, M.L. (1976) An evaluation of the practicality and complexity of some rainfall and runoff time series models. **Water Res. Res.**, 12(5), 953-970.

Devaurs, M. and Gifford, G.F. (1986) Applicability of the Green and Ampt infiltration equations to rangelands. **Water Res. Bull.**, 22(1), 19-28.

Dickenson, W.T. and Douglas, J.R. (1972) **A conceptual runoff model for the Cam catchment.** Inst. of Hydrology, Wallingford, England. Report No. 17.

Diskin, M.H., and Simon, E. (1977) A procedure for the selection of objective functions for hydrologic simulation models. **J. Hydrol.**, 34, 129-149.

Diskin, M.H., Wyseure, G. and Feyan, J. (1984) Application of a cell model to the Bellebeck watershed. **Nordic Hydrol.**, 15(1), 25-38.

Dooge, J.C.I. (1973) Linear theory of hydrologic systems. **Agric. Res. Service, U.S. Dept. of Agric. Bull.**, No. 1468.

Dunne, T. (1983) Relation of field studies and modelling in the prediction of storm runoff. **J. Hydrol.**, 65, 25-48.

Dunsmore, S.J., Schulze, R.E. and Schmidt, E.J. (1986) **Antecedent soil moisture in design stormflow estimation.** ACRU. Report no. 23. Dept. of Agricultural Engineering, Univ. of Natal, Pietermaritzburg, South Africa. pp 114.

Eyre, W.S. and Crees, M.A. (1984) Real-time application of the isolated event rainfall-runoff model. **J. Inst. Water Eng. and Sci.**, 38(1), 70-78.

Fleming, G. (1984) The successes and failures of contemporary approaches to integrated catchment modelling. In : H. Maaren (editor), **South African National Hydrological Symposium - Proceedings**, Dept. of Environment Affairs and Water Research Commission, Tech. Rep. TR 119, 1-17.

Flood Studies Report (1975) Natural Environment Research Council, London.

Foroud, N. and Broughton, R.S. (1981) Flood hydrograph simulation model. **J. Hydrol.** 49, 139-172.

Görgens, A.H.M. (1983) **Conceptual modelling of the rainfall-runoff process in semi-arid catchments.** Hydrological Research Unit, Report 1/83, Rhodes University, Grahamstown, South Africa.

Green, C.S. (1979) **An improved subcatchment model for the River Dee.** Inst. of Hydrology, Wallingford, Report No. 58, 45 pp.

Green, I.R.A. and Stephenson, D. (1986) Criteria for comparison of single event models. **Hydrol. Sci. Journ.**, 31, 395-411.

Gupta, S.K. and Solomon, S.I. (1977) Distributed numerical model for estimating runoff and sediment discharge of ungauged rivers. 1. The information system. **Water Res. Res.**, 13(3), 613-636.

Gupta, V.K. and Sorooshian, S. (1985) The relationship between data and the precision of parameter estimates of hydrologic models. **J. Hydrol.** 81, 57-77.

Hewlett, J.D. and Hibbert, A.R. (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In W.E. Sopper and H.W. Lull (editors). **Forest Hydrology**, Pergamon, London, 275-290.

Hiemstra, L.A.V. (1969) Joint probabilities in the rainfall-runoff relations. **Highway Research Record,** no. 261, 1-17, Highway Research Board, Pennsylvannia.

Hiemstra, L.A.V. and Francis, D.M. (1979) **The runhydrograph theory and application for flood predictions.** Univ. of Natal and Water Research Commission, Pretoria, South Africa.

Hope, A.S. (1983) An assessment of the R-index method for calculating stormflow volumes in Natal, South Africa. **J. Hydrol.**, 60, 243-255.

Hope, A.S. (1984) Estimation of stormflow volumes from small semi-arid catchments using the R-Index method. **J. Hydrol.**, 67, 129-139.

Huggins, L.F. and Monke, E.J. (1966) **Mathematical simulation of the hydrology of small watersheds**, Report no. 1, Water Res. Res. Cen., Purdue University, USA.

Hughes, D.A. (1980) Floodplain inundation : processes and relationships with channel discharge. **Earth Surface Processes**, 5, 297-304.

Hughes, D.A. (1983) **Preliminary investigations into isolated flood event modelling with specific reference to the southern Cape coastal lakes region.** Hydrological Research Unit, Report no. 3/83, Rhodes University, Grahamstown, South Africa.

Hughes, D.A. (1984) An isolated event model based upon direct runoff calculations using an implicit source area concept. **Hydrol. Sci. Journ.**, 29(3), 311-325

Hughes, D.A. (1985) Conceptual catchment model parameter transfer investigations in the southern Cape. **Water S.A.** 11(3), 149-156.

Hughes, D.A. (1986) Bivariate relationship between extreme rainfalls and antecedent catchment moisture status. In : R.E.Schulze (editor), **Proc. 2nd South African National Hydrology Symposium**, Sept. 1985, Pietermaritzburg, South Africa, 454-464.

Hughes, D.A. and Murrell, H.C. (1986) Non-linear runoff-routing - a comparison of solution methods. **J. Hydrol.**, 85, 339-347.

Ibbit, R.P. and O'Donnell, T. (1971) Fitting methods for conceptual catchment models. **J. Hydraul. Div. Amer. Soc. Civil Eng.**, 97 (HY9), 1331-1342.

James, L.D. and Hawkins, R.H. (1981) A taxonomy for evaluating surface water quantity model reliability. In, V.P. Singh (ed.) **Applied modelling in catchment hydrology,** Proc. Int. Sym. on Rainfall-Runoff modelling, May 1981, Mississippi, USA., 189-228.

Jayawardena, A.W. and White, J.K. (1977) A finite-element distributed catchment model, I. Analytical basis. **J. Hydrol.**, 34, 269-286.

Jayawardena, A.W. and White, J.K. (1979) A finite-element distributed catchment model, II. Application to real catchments. **J. Hydrol.**, 42, 231-249.

Kirkby, M.J. and Callen, J., Weyman, D.R. and Wood, J. (1976) **Measurement and modelling of dynamic contributing areas in very small catchments.** Working paper no. 167, School of Geography, University of Leeds.

Krzystofowicz, R. and Diskin, M.H. (1978) A moisture-accounting watershed model for single storm events based on time-area concept. **J. Hydrol.**, 37, 261-294.

Laurenson, E.M. and Mein, R.G. (1985) **RORB-version 3, Runoff Routing Program,** User Manual. Monash University, Dept. of Civil Engineering. Melbourne, Australia

Lee, M.T. and Delleur, J.W. (1976) A variable source area model of the rainfall-runoff process based upon the watershed stream network. **Water Res. Res.**, 12(5), 1029-1036.

Loage, K.M. and Freeze, R.A. (1985) A comparison of rainfall-runoff modelling techniques on small upland catchments. **Water Res. Res.**, 21(2), 229-248.

Lowing, M.J. and Mein, R.G. (1981) Flood event modelling - A study of two methods. **Water Res. Bull.** 17(4), 599-606.

Mandeville, A.N. (1983) **Augmented hydrograph hypothesis : Discussion of principles.** Inst. of Hydrology, Wallingford, England, Report No. 82.

Manley, R.E. (1977) The soil moisture component of mathematical catchment simulation models. **J. Hydrol.** 35, 341-356.

Marsalek, J. (1978) Research on design storm concept. **ASCE, UWRR Program,** Technical Memorandum no. 33, ASCE, New York.

Mein, R.G. and Brown, B.M. (1978) Sensitivity of optimized parameters in watershed models. **Water Res. Res.**, 14(2), 299-303.

Mein, R.G., Laurenson, E.M. and McMahon, T.A. (1974) Simple non-linear model for flood estimation. **J. Hydraulics Div. ASCE.**, 100, 1507-1518.

Moolman, J.H. (1985) **Data collection for the study of runoff, solute and sediment generating processes in a semi-arid catchment.** Hydrological Research Unit, Report 1/85, Rhodes University, Grahamstown, South Africa.

Moore, I.D., Mackay, S.M., Wallbrink, P.J., Burch, G.J. and O'Loughlin, E.M. (1986) Hydrologic characteristics and modelling of a small forested catchment in south eastern New South Wales. Pre-logging condition. **J. Hydrol.** 83, 307-335.

Murray, D.L. and Görgens, A.H.M. (1981) Storm runoff analyses on three semi-arid catchments. **Water S.A.**, 7(4), 223-233.

O'Donnell, T. (1966) Methods of computation in hydrograph analysis and synthesis. Recent trends in Hydrograph Synthesis Paper III. TNO Proc. no. 13, TNO, The Hague.

O'Loughlin, E.M. (1986) Saturation regions in catchments and their relations to soil and topographic properties. **J. Hydrol.**, 53, 229-246.

Packman, J.C. and Kidd, G.H.R. (1980) A logical approach to the design storm concept. **Water Res. Res.**, 16(6), 994-100.

Peck, A.J., Luxmoore, R.J. and Stolzy, J.L. (1977) Effect of spatial variability of soil hydraulic properties in water budget modelling. **Water Res. Res.**, 13, 348-354.

Pickup, G. (1977) Testing the efficiency of algorithms and strategies for automatic calibration of rainfall-runoff models. **Hydro. Sci. Bull.**, 22(2), 257-274.

Pirt, J. and Bramley, E.A. (1985) The application of simple moisture accounting models to ungauged catchments. **J. Inst. Water. Eng. Sci.** 39, 169-177.

Ponce, V.M. (1979) A simplified Muskingham routing equation. **J. Hydraul. Div. Am. Soc. Civ. Eng.**, 105(HY1), 85-91.

Rajendran, R. and Mein, R.G. (1986) Determination of rainfall excess on spatially variable catchments,. **J. Hydrol.**, 83, 67-89.

Roberts, P.J.T. (1978) **A comparison of the performance of selected conceptual models of the rainfall-runoff process in semi-arid catchments near Grahamstown.** Hydrological Research Unit, Report 1/78, Rhodes University, Grahamstown, South Africa.

Roberts, P.J.T. (1984) The need to adapt research effort in deterministic hydrology to meet changing requirements for water resource managememt in South Africa. In: H. Maaren (editor), **South African National Hydrological Symposium - Proceedings.** Dept. of Environment Affairs and Water Research Commission, Tech. Rep. TR119, 109-112.

Rogers, C.C.M., Beven, K.J., Morris, E.M. and Anderson, M.G. (1985) Sensitivity analysis, calibration and predictive uncertainty of the Institute of Hydrology distributed model. **J. Hydrol.**, 81, 179-191.

Rosenbrock, H.H. (1960) An automatic method for finding the greatest or least value of a function. **Computer J.**, 4, 175-184.

Schultz, C.B. (1985) **The sensitivity of output from a distributed hydrological model to rainfall input.** Unpublished MSc. Thesis, University of Natal, Pietermaritzburg, South Africa.

Schulze, R.E. (1984) **Hydrological models for application to small rural catchments in Southern Africa : Refinements and development.** ACRU Report No. 19, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.

Sefe, F.T. and Broughton, W.C. (1982) Variation of model parameter values and sensitivity with type of objective function. **J. Hydrol. (New Zealand)**, 21(2), 117-132.

Serban, P. (1976) A mathematical model of the 'reservoir' type designed for flood-wave modelling and forecasting. **Hydrol. Sci. Bull.**, 21(1), 139-147.

Singh, V.P. and Buapeng, S. (1977) Effect of rainfall-excess determination on runoff computation. **Water Res. Bull.** 13(3), 499-514.

Sorooshian, S. (1983) Surface water hydrology : On-line estimation. **Reviews of Geophysics and Space Physics**, 21(3), 706-721.

Sorooshian, S. and Arfi, F. (1982) Response surface parameter sensitivity analysis methods for post calibration studies. **Water Res. Res.** 18(5), 1531-1538.

Stedinger, J.R. and Taylor, M.R. (1982) Synthetic streamflow generation. 1. Model verification and validation. **Water Res. Res.** 18(4), 900-918.

Stephenson, D. (1980) Peak runoff from small areas - A kinematic approach. **Water S.A.** 6(2), 59-65.

Surkan, A.J. (1974) Simulation of storm velocity effects on flow from distributed channel networks. **Water Res. Res.** 10(6), 1149-1160.

Tennesse Valley Authority (1965) Area-stream factor Correlation, **Hydrol. Sci. Bull.**, 10(2), 22-37.

Urbonas, B. (1979) Design storm use in a semi-arid climate. In: **The Design Storm Concept.** Proc. Seminar, Ecole Polythechnique, Montreal, May 29, 1979, Report GREMU 79/02, Montreal Canada.

U.S.D.A. (1960-1973). **United States Department of Agriculture, Agricultural Research Service, Hydrologic data for experimental agricultural watersheds in the United States.** Misc. Publ. Series compiled by H.W. Hobbs, J.B. Burford and J.M. Clark.

Ward, R.C. (1984) Hypothesis testing by modelling catchment response. **J. Hydrol.**, 67, 281-205.

Watson, M.D. (1981) **Time area method of flood estimation for small catchments.** Report no. 7/81, Hydrological Research Unit, University of the Witwatersrand, Johannesburg.

Wenzel, H.G. and Voorhees, M.L. (1978) **Evaluation of the design storm concept.** Proc. Fall Meeting, AGU, San Francisco, California.

APPENDIX A

MODEL CALIBRATION RESULTS : TABLES

The tables are arranged in the following way.

Model name and type	Q9M20	Q9M21	Q9M24	ND1	ND3	ND4	ND5
OSE2 Lumped	A1	A2	A3	A4	A5	A6	A7
S.dist.	A8		A10	A12		A14	A16
sub-area factors	A9		A11	A13		A15	A17
OSE1 Lumped	A18	A19		A20			A21
S.dist.	A22			A24			A26
sub-area factors	A23			A25			A27
OSE3 Lumped	A28	A29		A30			A31
S.dist.	A32			A34			A36
sub-area factors	A33			A35			A37
OSE4 S.dist.	A38			A39			A40

(Columns Q9M20–ND5: Catchment)

Notes: a) Parameter values that change between storms on the same catchment are listed in the tables, other are given below the tables.

b) Coefficients Eff. = Efficiency = $1 - \frac{\Sigma(\text{Obs-Sim})^2}{\Sigma(\text{Obs-Obs.mean})^2}$

Det. = Determination = $(\text{corr.coefficient})^2$

c) AAOE (OSE4) Average absolute ordinate error %

$$\frac{1}{N}\sum \frac{\text{Obs-Sim}}{\text{Obs}} * 100$$

where N = number of data points.

Table **A1** Calibration results

Catchment Ecca, **Q9M20** Area 73,9km²

Model S-curve model - **OSE2** Type **Lumped**

Storm No.	Date	Parameters A (6)	APF (14)	CLP (15)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	2,00	0,913	2,32	8,8	-1,9	0,772	0,824
2	6.03.77		Not modelled (rainfall very spatially variable)					
3	7.05.77	5,38	0,880	2,32	-21,3	9,8	0,725	0,761
4	19.04.78	3,00	0,975	2,32	-12,8	-13,6	0,827	0,845
5	21.04.78	2,00	0,920	2,32	6,7	11,9	0,303	0,637
6	20.07.79	5,38	0,963	2,32	3,2	-2,0	0,972	0,974
7	23.07.79	5,38	0,963	2,32	-1,6	-3,8	0,902	0,911
8	19.08.79	5,38	0,970	2,32	3,2	4,9	0,856	0,869
9	26.03.81	1,75	0,810	2,32	5,9	-2,7	0,941	0,956
10	22.10.81	5,38	0,913	1,80	1,1	44,3	-0,142	0,519
11	23.12.81		No acceptable fit possible					
12	2.11.85	5,38	0,963	2,32	-8,4	-18,3	0,923	0,946
13	25.11.85	5,38	0,963	2,32	-15,4	3,1	0,534	0,597
14	1.12.85	5,38	0,945	2,32	7,7	-19,3	0,583	0,612
15	3.12.85		Not modelled (data errors)					
Mean					8,0	11,3	0,683	0,788
St. dev.					6,0	12,1	0,327	0,159

Other parameters:

K(1) =	10,00	N(2) =	0,6
DEL(5) =	0,25	B(7) =	0,098
SMAX(8) =	175,05	DA(9) =	0,282
C(10) =	0,672	PCSLP(11) =	340,0
PCVSA(12) =	0,43	IAF(13) =	0,67

Table A2 Calibration results

Catchment Ecca, Q9M21 Area 9,1km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,870	23,0	-40,2	0,313	0,438
2	6.03.77	0,897	16,6	-24,2	0,778	0,794
3	7.05.77	0,956	5,8	-1,3	0,557	0,673
4	19.04.78	not modelled	(suspect data)			
5	21.04.78	0,800	-1,6	3,9	0,300	0,506
6	20.07.79	0,943	-0,6	-9,6	0,981	0,981
7	23.07.79	0,943	-1,1	13,7	0,955	0,980
8	19.08.79	0,960	5,2	13,9	0,858	0,864
9	26.03.81	0,850	2,3	-19,1	0,157	0,395
10	22.10.81	not modelled	(zero flow)			
11	23.12.81	0,870	-26,9	18,5	-0,656	0,039
12	2.11.85	0,943	-1,7	-4,7	0,948	0,949
13	25.11.85	not modelled	(missing data)			
14	1.12.85	0,918	-13,9	9,7	0,354	0,790
15	3.12.85	not modelled	(data errors)			
Mean			9,0	14,4	0,504	0,673
St. dev.			9,5	11,1	0,490	0,299

Other parameters:

K(1) =	6,69	N(2) =	0,6
DEL(5) =	0,0	A(6) =	1,45
B(7) =	0,1	SMAX(8) =	159,0
DA(9) =	0,248	C(10) =	0,693
PCSLP(10) =	370,1	RCVSA(12) =	0,656
IAF(13) =	0,839	CLP(15) =	2,43

Table A3 Calibration results

Catchment Ecca, Q9M24 Area 23,1km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	20.07.79	0,960	25,9	3,9	0,847	0,934
2	23.07.79	0,960	-2,8	-11,4	0,945	0,947
3	19.08.79	0,956	-7,2	10,5	0,859	0,919
4	2.11.85	0,910	4,2	4,4	0,793	0,833
Mean			10,0	7,5	0,861	0,908
St. dev.			10,7	3,9	0,063	0,051

Other parameters:

K(1) = 6,83	N(2) = 0,6
DEL(5) = 0,25	A(6) = 2,00
B(7) = 0,098	SMAX(8) = 200,8
DA(9) = 0,21	C(10) = 0,62
PCSLP(11) = 327,9	PCVSA(12) = 0,53
IAF(13) = 0,60	CLP(15) = 2,70

Table **A4** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model S-curve model - OSE2 Type **Lumped**

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	0,90	-1,0	9,5	0,990	0,991
2	30.07.60	0,85	35,9	17,3	0,790	0,970
3	2.06.61	No acceptable fit possible				
4	31.07.62	0,85	-11,8	-17,4	0,903	0,953
5	30.07.63	Not modelled (rainfall very spatially variable)				
6	22.07.64	Not modelled (rainfall very spatially variable)				
7	7.06.65	0,85	-25,3	-33,2	0,773	0,978
8	19.10.66	0,90	-26,4	-26,3	0,667	0,980
9	16.07.67	0,85	8,7	8,6	0,661	0,772
10	11.09.68	0,85	10,2	-4,4	0,959	0,972
11	7.09.69	0,85	20,9	21,4	-0,277	0,527
12	23.08.71	0,85	62,2	59,5	-0,786	0,981
13	3.07.72	0,85	10,0	16,4	0,510	0,637
14	10.07.72	0,85	4,0	-3,0	0,941	0,945
15	17.09.73	0,85	4,4	-10,9	0,961	0,967
Mean			18,4	19,0	0,591	0,889
St. dev.			17,4	15,5	0,555	0,157

Other parameters:

K(1) =	5,0	N(2) =	0,7
DEL(5) =	0,25	A(6) =	2,9
B(7) =	0,15	SMAX(8) =	214,5
DA(9) =	0,377	C(10) =	0,251
PCSLP(11) =	127,7	PCVSA(12) =	3,8
IAF(13) =	0,39	CLP(15) =	0,0

Note: Some of the poorer fits (e,g, 2,8 and 12) can be improved by modification to APF only.

Table A5 Calibration results

Catchment North Danville, ND3 Area 8,37km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,868	23,9	11,2	0,495	0,619
2	2.06.61	No acceptable fit				
3	31.07.62	0,868	9,0	-4,9	0,934	0,953
4	30.07.63	No acceptable fit				
5	22.07.64	No acceptable fit				
6	7.06.65	No acceptable fit				
7	19.10.66	0,918	6,3	2,6	0,678	0,723
8	16.07.67	No acceptable fit				
9	11.09.68	0,868	3,7	-28,1	0,903	0,933
10	7.09.69	No acceptable fit				
11	23.08.71	0,868	28,7	16,6	0,726	0,973
12	10.07.72	0,868	-5,4	-42,9	0,696	0,729
13	17.09.73	0,868	6,0	-31,7	0,864	0,886
Mean			11,8	19,7	0,756	0,831
St. dev.			10,1	14,9	0,154	0,139

Other parameters:

K(1) =	4,6	N(2) =	0,7
DEL(5) =	0,001	A(6) =	1,5
B(7) =	0,15	SMAX(8) =	227,0
DA(9) =	0,394	C(10) =	0,279
RCSLP(11) =	126,0	PCVSA(12) =	3,70
IAF(13) =	0,43	CLP(15) =	0,0

Table A6 Calibration results

Catchment North Danville, ND4 Area 43,51km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	errors: Volume	errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	7.06.65	0,872	7,0	16,7	0,749	0,820
2	19.10.66	0,922	-13,7	-9,3	0,894	0,987
3	16.07.67	0,872	14,1	-19,9	0,384	0,486
4	11.09.68	0,872	-8,3	-16,1	0,937	0,968
5	7.09.69	no acceptable fit possible				
6	23.08.71	0,872	45,3	36,6	0,007	0,959
7	10.07.72	0,872	6,5	2,8	0,843	0,854
8	14.07.73	0,872	-2,1	-5,2	0,961	0,968
9	17.09.73	0,872	-12,6	-29,2	0,841	0,936
Mean			13,7	17,0	0,702	0,872
St. dev.			13,4	11,6	0,335	0,167

Other parameters:

K(1) =	5,5	N(2) =	0,7
DEL(5) =	0,25	A(6) =	2,82
B(7) =	0,15	SMAX(8) =	200,0
DA(9) =	0,359	C(10) =	0,290
PCSLP(11) =	130,0	PCVSA(12) =	3,80
IAF(13) =	0,29	CLP(15) =	1,0

Table A7 Calibration results

Catchment North Danville, ND5 Area 111,60km²

Model S-curve model - OSE2 Type Lumped

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,848	34,0	22,3	0,757	0,919
2	2.06.61	No acceptable fit possible				
3	31.07.62	0,848	1,0	19,1	0,957	0,957
4	30.07.63	Not modelled (rainfall very spatially variable)				
5	22.07.64	Not modelled (rainfall very spatially variable)				
6	7.06.65	0,848	-1,5	-2,9	0,918	0,920
7	19.10.66	0,898	-21,5	-19,9	0,789	0,989
8	16.07.67	0,848	2,8	-4,9	0,874	0,877
9	11.09.68	0,848	12,6	10,3	0,934	0,974
10	7.09.69	No acceptable fit possible				
11	23.08.71	0,848	34,9	41,8	0,280	0,954
12	10.07.72	0,848	-21,2	-19,0	0,795	0,909
13	20.07.72	0,848	-32,6	-33,7	0,700	0,974
14	14.07.73	0,848	-24,8	-28,2	0,732	0,985
15	17.09.73	0,848	-8,3	-21,3	0,921	0,961
Mean			17,7	20,3	0,787	0,947
St. dev.			13,2	11,6	0,190	0,036

Other parameters:

K(1) =	5,75	N(2) =	0,7
DEL(5) =	0,5	A(6) =	2,68
B(7) =	0,15	SMAX(8) =	218,0
DA(9) =	0,451	C(10) =	0,245
PCSLP(11) =	131,0	RCVSA(12) =	3,87
IAF(13) =	0,30	CLP(15) =	0,0

Table A8 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model S-curve model - OSE2 Type Semi-distributed

Storm No.	Date	Parameters APF (14)	CLP (15)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,910	2,70	11,0	4,6	0,704	0,776
2	6.03.77	0,925	2,70	-1,9	2,5	0,615	0,745
3	7.03.77	0,948	2,70	-17,4	10,2	0,428	0,502
4	19.04.78	0,968	2,70	4,1	-6,7	0,971	0,974
5	21.04.78	0,930	2,70	-10,1	3,6	0,277	0,667
6	20.07.79	0,960	2,70	-8,3	-6,2	0,966	0,971
7	23.07.79	0,960	2,70	-11,8	6,9	0,725	0,855
8	19.08.79	0,965	2,70	-10,4	-10,1	0,814	0,830
9	26.03.81	0,880	2,70	12,7	-6,3	0,878	0,918
10	22.10.81	0,915	2,40	-17,9	16,1	-0,069	0,526
11	23.12.81	0,910	2,33	-39,3	60,1	-0,901	0,001
12	2.11.85	0,960	2,70	2,9	11,1	0,673	0,871
13	25.11.85	0,960	2,70	-0,3	127,8*	0,113	0,804
14	1.12.85	0,910	2,20	-46,8	2,2	-0,030	0,532
15	3.12.85	Not modelled (data errors)					
Mean				13,9	11,3**	0,440	0,712
St. dev.				13,5	15,2**	0,522	0,259

Other parameters:

K(1) =	6,0	N(2) =	0,6
CDEL(3) =	1,0	KC(4) =	0,5
SMAX(8) =	200,0	DA(9) =	0,25
C(10) =	0,695	PCSLP(11) =	400,0
PCVSA(12) =	0,6	IAF(13) =	0,6

Sub-catchment weighting factors are given in Table A9

* Large error possibly caused by data errors.

** Does not include result for storm 13.

Table **A9** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M20** Area 73,9km²
Model S-curve model - OSE2 Type **semi-distributed**

		Parameters										
Sub-cat.	Area	1	3	4	8	9	10	11	12	13	14	15
No.	(%)	K	CDEL	KC	SMAX	DA	C	PCSLP	PCVSA	IAF	APF	CLP
1	13,0	1,00	5,25	0,80	1,10	0,72	0,83	0,75	1,00	0,92	1,00	1,00
2	5,9	0,92	4,50	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
3	5,6	0,92	4,50	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
4	7,0	0,92	4,00	1,00	0,90	0,92	0,95	0,90	0,83	1,05	0,99	0,94
5	6,4	0,90	4,00	0,75	0,82	1,05	0,95	0,90	0,83	1,10	1,00	0,85
6	7,0	0,90	4,00	0,75	0,82	1,05	0,95	0,90	0,83	1,10	1,00	0,85
7	11,4	0,85	3,00	0,50	0,78	1,15	0,95	0,92	0,83	1,30	1,00	0,75
8	7,9	0,80	2,75	0,60	0,78	1,15	0,95	0,92	0,90	1,30	1,00	0,75
9	6,0	0,65	2,25	0,96	0,78	1,15	0,95	0,92	0,90	1,30	1,00	0,75
10	9,7	0,95	1,25	1,40	0,90	1,07	0,92	0,90	1,00	1,20	1,01	0,88
11	12,9	1,05	0,75	1,00	0,80	0,99	0,99	0,92	0,83	1,40	0,99	0,85
12	7,4	0,80	0,25	0,60	0,90	1,07	1,07	0,90	1,00	1,20	1,01	0,80

Parameter N(2) all weights = 1,00

Table **A10** Calibration results

Catchment Ecca, **Q9M24** Area 23,1km²

Model S-curve model - **OSE2** Type **Semi-distributed**

Storm No.	Date	Parameters APF (14)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	20.07.79	0,960	14,8	-3,8	0,936	0,965
2	23.07.79	0,960	-6,8	-6,5	0,953	0,971
3	19.08.79	0,960	-9,7	10,1	0,857	0,887
4	2.11.85	0,910	-9,8	-4,1	0,713	0,775
Mean			10,3	6,1	0,865	0,899
St. dev.			3,3	2,9	0,109	0,091

Other parameters:

K(1) =	6,0	N(2) =	0,60
CDEL(3) =	1,0	KC(4) =	0,50
SMAX(8) =	200,0	DA(9) =	0,25
C(10) =	0,965	PCSLP(11) =	400,0
PCVSA(12) =	0,6	IAF(13) =	0,6

Table **A11** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M24** Area 23,1km²

Model S-curve model - **OSE2** Type **Semi-distributed**

Sub-cat. No.	Area (%)	1 K	3 CDEL	4 KC	8 SMAX	9 DA	10 C	11 PCSLP	12 PCVSA	13 IAF	14 APF	15 CLP
1	41,2	1,00	1,50	0,80	1,10	0,72	0,83	0,75	1,00	0,92	1,00	1,00
2	18,8	0,92	0,75	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
3	17,8	0,92	0,75	0,90	0,95	0,84	0,93	0,82	0,83	1,03	1,00	0,89
4	22,0	0,92	0,00	0,90	0,90	0,92	0,95	0,90	0,83	1,05	0,99	0,94

Parameter N(2) all weights = 1,00

Table **A12** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model S-curve model - OSE2 Type **Semi-distributed**

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	0,90	-2,2	3,7	0,983	0,985
2	30.07.60	0,85	46,9	20,8	0,651	0,975
3	2.06.61	No acceptable fit possible				
4	31.07.62	0,85	-10,2	-20,9	0,913	0,963
*5	30.07.63	0,85	334,6	297,6	-51,8	0,559
*6	22.07.64	0,85	52,2	43,6	-1,218	0,787
7	7.06.65	0,85	-25,6	-38,4	0,731	0,943
8	19.10.66	0,90	-25,2	-25,7	0,682	0,987
9	16.07.67	0,85	2,5	0,7	0,933	0,942
10	11.09.68	0,85	13,6	-4,0	0,955	0,978
*11	7.09.69	0,85	152,4	201,7	-30,3	0,258
12	23.08.71	0,85	83,8	72,9	-2,002	0,992
13	3.07.72	0,85	12,3	9,9	0,444	0,579
14	10.07.72	0,85	-1,2	-10,0	0,959	0,961
15	17.09.73	0,85	2,9	-12,0	0,906	0,973
Mean			20,6	19,9	0,565	0,934
St. dev.			25,1	20,8	0,869	0,119

Other parameters:

K(1) =	5,0	N(2) =	0,7
CDEL(3) =	1,0	KC(4) =	0,85
SMAX(8) =	214,5	DA(9) =	0,251
C(10) =	0,251	PCSLP(11) =	127,7
PCVSA(12) =	3,8	IAF(13) =	0,39
CLP(15) =	0,0		

* Values not used to calculate mean and St. dev.

Note: Some of the poorer fits (eg, 2,3,6,8,12) can be improved by modification to APF only.

Table **A13** Sub-catchment parameter weighting factors

Catchment North Danville, **ND1** Area 42,94km²

Model S-curve model - OSE2 Type **Semi-distributed**

Sub-catch. No.	Area %	1 K	3 CDEL	4 KC	8 SMAX	11 PCSLP	12 PCVSA	13 IAF	14 APF
1	19,5	1,00	1,00	0,80	1,00	1,00	1,00	1,11	0,99
2	13,4	1,50	0,50	0,87	1,15	0,85	0,85	0,89	1,00
3	18,0	1,00	0,75	1,35	1,00	1,00	1,00	1,00	1,00
4	19,6	0,80	0,80	0,85	0,90	1,10	1,10	1,11	0,99
5	16,9	0,90	0,90	0,77	1,00	1,00	1,00	0,94	1,00
6	12,6	0,80	0,80	0,73	0,95	1,05	1,05	0,95	1,01

Parameters N(2), DA(9), C(10), CLP(15) all weights = 1,00

Table A14 Calibration results

Catchment North Danville, ND4 Area 43,51km²

Model S-curve model - OSE2 Type Semi-distributed

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	7.06.65	0,872	11,4	24,9	0,582	0,713
2	19.10.66	0,922	-6,8	-4,4	0,952	0,965
3	16.07.67	0,872	29,1	-5,5	0,686	0,740
4	11.09.68	0,872	1,9	-5,9	0,981	0,983
5	7.09.69	No acceptable fit possible				
6	23.08.71	0,872	57,7	44,6	-0,429	0,335
7	10.07.72	0,872	-25,9	-31,6	0,735	0,850
8	14.07.73	0,872	-5,9	-12,3	0,934	0,958
9	17.09.73	0,872	-19,8	-32,9	0,786	0,909
Mean			19,8	20,3	0,653	0,807
St. dev.			18,2	15,3	0,459	0,216

Other parameters:

K(1) =	5,55	N(2) =	0,7
CDEL(3) =	1,00	KC(4) =	0,85
SMAX(8) =	200,0	DA(9) =	0,359
C(10) =	0,245	PCSLP(11) =	130,0
PCVSA(12) =	3,80	IAF(13) =	0,30
CLP(15) =	0,0		

Table **A15** Sub-catchment parameter weighting factors

Catchment North Danville, ND4 Area 43,51km²

Model S-curve model - OSE2 Type **Semi-distributed**

Sub-catch.	Area	Parameters							
		1	3	4	8	11	12	13	14
No.	%	K	CDEL	KC	SMAX	PCSLP	PCVSA	IAF	APF
1	18,5	0,75	1,50	0,60	1,00	1,00	1,00	1,12	0,99
2	12 6	0,85	1,25	0,65	1,05	0,90	0,90	0,94	0,99
3	12 6	1,45	0,75	1,00	1,15	0,85	0,85	0,91	1,00
4	11 4	1,20	1,50	0,87	1,05	1,00	1,00	1,11	0,99
5	19,2	0,90	1,00	1,05	0,95	1,05	1,05	1,15	1,00
6	11,8	0,75	0,50	0,75	0,90	1,10	1,10	1,15	0,99
7	13,9	1,00	0,00	0,42	0,90	1,10	1,10	1,15	1,01

Parameters N(2), DA(9), C(10), CLP(15) all weights = 1,00

Table **A16** Calibration results

Catchment North Danville, ND5 Area 111,60km²

Model S-curve model - OSE2 Type Semi-distributed

Storm No.	Date	Parameters APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,848	34,2	13,7	0,816	0,971
2	2.06.61	No acceptable fit possible				
3	31.07.62	0,848	-4,9	-1,2	0,937	0,946
4	30.07.63	No acceptable fit possible				
5	22.07.64	No acceptable fit possible				
6	7.06.65	0,848	-1,9	-7,8	0,957	0,959
7	19.10.66	0,898	-20,0	-18,9	0,810	0,986
8	16.07.67	0,848	0,4	-11,0	0,944	0,947
9	11.09.68	0,848	1,6	1,6	0,964	0,979
10	7.09.69	No acceptable fit possible				
11	23.08.71	0,848	44,6	51,1	0,040	0,990
12	10.07.72	0,848	-23,0	-28,6	0,813	0,976
13	20.07.72	0,848	-21,0	-23,6	0,838	0,937
14	14.07.73	0,848	-22,9	-30,1	0,691	0,920
15	17.09.73	0,848	-13,2	-26,9	0,885	0,958
Mean			17,7	19,5	0,790	0,960
St. dev.			13,7	14,7	0,262	0,022

Other parameters:

K(1) =	5,75	N(2) =	0,7
CDEL(3) =	1,0	KC(4) =	0,85
SMAX(8) =	218,0	DA(9) =	0,451
C(10) =	0,245	PCSLP(11) =	131,0
PCVSA(12) =	3,87	IAF(13) =	0,30
CLP(15) =	0,0		

Table **A17** Sub-catchment parameter weighting factors

Catchment North Danville, ND5 Area 111,60km²

Model S-curve model - OSE2 Type **Semi-distributed**

		Parameters							
Sub-catch.	Area	1	3	4	8	11	12	13	14
No.	%	K	CDEL	KC	SMAX	PCSLP	PCVSA	IAF	APF
1	7,5	0,85	1,50	0,80	1,00	1,00	1,00	1,11	0,99
2	5,2	1,40	1,00	0,87	1,10	0,80	0,80	0,89	1,00
3	6,9	0,80	1,25	1,35	1,05	0,90	0,90	1,00	1,00
4	7,5	0,75	1,50	0,85	0,95	1,05	1,05	1,11	0,99
5	6,5	0,80	1,00	0,77	1,05	0,90	0,90	0,94	1,00
6	4,8	0,75	0,50	0,73	1,00	1,00	1,00	1,11	1,01
7	5,2	1,20	1,00	0,97	1,05	0,95	0,95	1,00	0,99
8	5,6	1,35	0,75	0,45	1,10	0,80	0,80	0,91	0,99
9	4,3	1,30	0,50	0,67	1,05	1,00	1,00	1,00	1,00
10	7,7	0,75	2,25	0,65	0,95	1,05	1,05	1,12	0,99
11	4,9	0,85	2,00	0,70	1,10	0,90	0,90	0,94	0,99
12	4,9	1,45	1,50	1,00	1,10	0,85	0,85	0,91	1,00
13	4,4	1,20	2,25	0,95	1,00	1,00	1,00	1,11	0,99
14	7,5	0,90	1,75	1,05	0,90	1,05	1,05	1,15	1,00
15	4,6	0,75	1,25	0,75	0,90	1,10	1,10	1,15	0,99
16	5,4	1,00	0,75	0,80	0,90	1,10	1,10	1,15	1,01
17	2,0	0,80	0,00	0,37	0,95	1,05	1,05	1,13	0,99
18	5,1	1,70	0,00	0,50	1,05	1,00	1,00	1,00	1,02

Parameters N(2), DA(9), C(10), CLP(15) all weights = 1,00

Table **A18** Calibration results

Catchment Ecca, **Q9M20** Area 73,9km²

Model Simple antecedent moisture model - **OSE1** Type **Lumped**

Storm No.	Date	DEL (5)	K (1)	A (6)	DA (9)	C (10)	APF (14)	IL (15)	% errors: Volume	Peak	Coeff: Eff.	Det.
1	28.02.77	0,00	3,0	2,0	0,147	0,600	0,90	1,0	-4,6	1,2	0,915	0,923
2	6.03.77	0,00	6,0	1,0	0,300	0,290	0,90	1,0	30,2	-31,0	0,622	0,748
3	7.05.77	0,00	2,5	3,0	0,260	0,420	0,90	25,0	-4,0	1,4	0,735	0,742
4	19.04.78	0,00	2,5	2,5	0,250	0,380	0,90	22,0	-7,5	-4,3	0,845	0,847
5	21.04.78	0,00	6,0	1,0	0,170	0,495	0,95	1,0	-3,6	0,8	0,790	0,878
* 6	20.07.79	1,50	9,0	4,5	0,940	0,030	0,95	50,0	-15,6	15,1	0,744	0,770
* 7	23.07.79	1,50	10,0	6,5	0,265	0,500	0,95	1,0	-3,9	-5,8	0,949	0,962
* 8	19.08.79	1,50	10,0	7,0	0,660	0,095	0,90	30,0	-10,8	-1,6	0,861	0,887
9	26.03.81	0,00	5,0	1,5	0,095	0,600	0,90	1,0	15,8	-11,6	0,923	0,955
10	22.10.81	0,00	5,5	2,0	0,450	0,130	0,85	1,0	-1,6	-4,4	0,871	0,884
11	23.12.81	0,00	1,5	2,0	0,350	0,180	0,85	16,0	5,3	-12,2	0,957	0,959
*12	2.11.85	1,50	11,5	5,5	0,610	0,580	0,90	1,0	-1,7	-6,6	0,934	0,943
*13	25.11.85	0,00	10,0	4,0	0,360	0,280	0,90	1,0	-4,2	2,6	0,551	0,617
14	1.12.85	1,00	4,5	4,0	0,350	0,380	0,90	1,0	2,2	-18,7	0,819	0,832
15	3.12.85	Not modelled (data errors)										
Mean									7,9	8,4	0,822	0,853
St. dev.									7,9	8,6	0,123	0,102

Other parameters: N(4) = 0,7 B(7) = 0,15

SMAX(8) = 200,0

* 'Large' storm events.

Table A19 Calibration results

Catchment Ecca, Q9M21 Area 9,1km²

Model Simple antecedent moisture model - OSE1 Type Lumped

Storm No.	Date	K (1)	A (6)	DA (9)	C (10)	APF (14)	IL (15)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	28.02.77	0,5	0,5	0,170	0,880	0,90	1,0	9,0	-19,9	0,806	0,815
2	6.03.77	1,0	0,5	0,150	0,370	0,90	10,0	26,3	-17,2	0,794	0,794
3	7.05.77	2,5	1,5	0,700	0,100	0,85	40,0	-18,4	-21,5	0,836	0,836
4	19.04.78			not modelled		(suspect data)					
5	21.04.78	3,0	0,5	0,160	0,560	0,95	10,0	-0,9	-0,4	0,660	0,779
* 6	20.07.79	7,5	0,5	0,950	0,028	0,95	58,0	-15,4	-4,9	0,773	0,794
* 7	23.07.79	10,0	1,5	0,190	0,510	0,95	0,1	-4,3	-3,8	0,952	0,975
* 8	19.08.79	17,0	5,0	0,600	0,095	0,90	25,0	1,7	-0,7	0,897	0,912
9	26.03.81	2,0	1,0	0,120	0,690	0,90	1,0	13,6	-14,4	0,409	0,524
10	22.10.81			not modelled		(zero flow)					
11	23.12.81	1,0	1,5	0,400	0,120	0,85	15,0	2,1	-21,5	0,710	0,729
*12	2.11.85	11,5	1,5	0,490	0,560	0,90	1,0	-6,9	-9,3	0,927	0,957
*13	25.11.85			not modelled		(missing data)					
14	1.12.85	3,5	1,5	0,250	0,500	0,90	1,0	-0,1	1,3	0,977	0,984
15	3.12.85			Not modelled		(data errors)					
Mean								9,0	10,4	0,794	0,827
St. dev.								8,5	8,7	0,162	0,133

Other parameters: N(2) = 0,7 DEL(5) = 0,0

SMAX(8) = 200,0

* 'Large' storm events.

Table A20 Calibration results

Catchment North Danville, ND1 — Area 42,94km²

Model Simple antecedent moisture model - OSE1 — Type Lumped

Storm No.	Date	Parameters DEL (5)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	0,25	0,420	0,280	0,90	-2,5	3,2	0,914	0,928
2	30.07.60	0,50	0,710	0,115	0,80	6,3	-25,7	0,831	0,850
3	2.06.61	No acceptable fit possible							
4	31.07.62	0,25	0,830	0,110	0,80	4,7	-13,9	0,863	0,891
5	30.07.63	Not modelled (rainfall very spatially variable)							
6	22.07.64	Not modelled (rainfall very spatially variable)							
7	7.06.65	1,50	0,885	0,103	0,80	3,4	-3,8	0,910	0,942
8	19.10.66	1,25	0,620	0,260	0,90	-7,8	6,9	0,875	0,942
9	16.07.67	0,00	0,697	0,204	0,80	-6,0	6,2	0,803	0,875
10	11.09.68	0,00	0,705	0,163	0,80	3,3	-10,2	0,977	0,980
11	7.09.69	1,00	0,650	0,750	0,80	-5,5	-4,7	0,810	0,881
12	23.08.71	0,00	0,420	0,256	0,80	-2,3	-5,2	0,974	0,977
13	3.07.72	1,00	0,590	0,245	0,80	-8,3	3,2	0,921	0,946
14	10.07.72	0,00	0,506	0,155	0,80	-3,4	-2,2	0,945	0,952
15	17.09.73	0,25	0,528	0,263	0,80	3,5	-5,8	0,936	0,936
Mean						4,7	7,6	0,896	0,925
St. dev.						2,0	6,6	0,060	0,041

Other parameters:

K(1) = 5,5	N(2) = 0,7
A(6) = 4,0	B(7) = 0,15
SMAX(8) = 150,0	IL(15) = 0,0

Table **A21** Calibration results

Catchment North Danville, **ND5** Area 111,60km²

Model Simple antecedent moisture model - **OSE1** Type **Lumped**

Storm No.	Date	DEL (5)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	1,00	0,585	0,088	0,80	5,0	-21,5	0,882	0,892
2	2.06.61	0,00	0,585	0,060	0,80	-12,8	6,1	0,913	0,970
3	31.07.62	0,25	0,585	0,098	0,80	2,0	-3,9	0,965	0,972
4	30.07.63	Not modelled (rainfall very spatially variable)							
5	22.07.64	0,00	0,600	0,230	0,80	3,0	-1,1	0,772	0,797
6	7.06.65	3,00	0,575	0,063	0,80	-9,1	10,9	0,924	0,970
7	19.10.66	0,25	0,620	0,240	0,90	-5,0	5,4	0,956	0,978
8	16.07.67	0,00	0,550	0,160	0,80	2,5	-0,2	0,859	0,884
9	11.09.68	0,00	0,575	0,126	0,80	1,9	-0,6	0,963	0,966
10	7.09.69	0,75	0,575	0,423	0,80	0,6	-0,8	0,936	0,963
11	23.08.71	0,00	0,605	0,281	0,80	-3,9	1,8	0,974	0,984
12	10.07.72	0,00	0,640	0,150	0,80	-4,9	-1,4	0,933	0,943
13	20.07.72	0,00	0,500	0,135	0,80	2,3	-2,0	0,893	0,909
14	14.07.73	No acceptable fit possible							
15	17.09.73	0,25	0,585	0,218	0,80	0,9	-8,9	0,938	0,938
Mean						4,1	5,1	0,916	0,936
St. dev.						3,4	5,9	0,055	0,053

Other parameters: K(1) = 6,0 N(2) = 0,7

A(6) = 5,5 B(7) = 0,15

SMAX(8) = 150,0 IL(15) = 0,0

Table A22 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Simple antecedent moisture model - OSE1 Type Semi-distributed

Storm No.	Date	K (1)	DA (9)	C (10)	APF (14)	IL (15)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,5	0,150	0,610	0,90	1,0	6,6	-4,8	0,944	0,960
2	6.03.77	0,5	0,200	0,330	0,90	1,0	5,7	-15,3	0,819	0,846
3	7.05.77		No acceptable fit possible							
4	19.04.78	0,5	0,250	0,360	0,90	30,0	1,1	-6,4	0,950	0,961
**5	21.04.78	1,0	0,130	0,510	0,95	1,0	-15,1	10,7	-0,367	-0,321
* 6	20.07.79	6,0	0,930	0,034	0,95	45,0	-23,4	-23,5	0,654	0,779
* 7	23.07.79	11,0	0,200	0,510	0,95	1,0	-1,9	-5,8	0,960	0,970
* 8	19.08.79	10,0	0,700	0,090	0,90	34,0	-8,1	-4,0	0,869	0,970
9	26.03.81	0,5	0,080	0,800	0,90	1,0	7,9	-7,4	0,795	0,825
10	22.10.81	2,0	0,370	0,160	0,85	1,0	-3,2	1,1	0,648	0,774
11	23.12.81	0,5	0,300	0,200	0,85	15,0	-14,8	-32,1	0,751	0,795
*12	2.11.85	11,0	0,610	0,580	0,90	1,0	-2,2	-4,0	0,962	0,972
*13	25.11.85		No acceptable fit possible							
14	1.12.85	2,0	0,350	0,380	0,90	5,0	-16,6	4,1	0,670	0,881
15	3.12.85		No acceptable fit possible							
Mean							8,8	9,9	0,820	0,885
St. dev.							7,0	9,3	0,126	0,084

Other parameters: N(2) = 0,7 CDEL(3) = 1,0

KC(4) = 0,8 SMAX(8) = 200,0

** Does not include the result for storm 5.

* 'Large' storm events.

Table A23 Sub-catchment parameter weighting factors

Catchment Ecca, Q9M20 Area 73,9km²

Model Simple antecedent moisture model - OSE1 Type Semi-distributed

		Parameters			
Sub-cat.	Area	1	3	4	15
No.	(%)	K	CDEL	KC	IL
1	13,0	1,00	5,25	0,80	1,50
2	5,9	0,92	4,50	0,90	1,50
3	5,6	0,92	4,50	0,90	1,50
4	7,0	0,92	4,00	1,00	1,50
5	6,4	0,90	4,00	0,75	1,50
6	7,0	0,90	4,00	0,75	1,50
7	11,4	0,85	3,00	0,50	1,30
8	7,9	0,80	2,75	0,60	1,20
9	6,0	0,65	2,25	0,96	1,10
10	9,7	0,95	1,25	1,40	0,95
11	12,9	1,05	0,75	1,00	0,90
12	7,4	0,80	0,75	0,60	0,85

Parameters N(2), SMAX(8), DA(9), C(10), APF(14), all weights = 1,00

Table **A24** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model Simple antecedent moisture model - **OSE1** Type **Semi-distributed**

Storm No.	Date	Parameters CDEL (3)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	1,50	0,560	0,310	0,90	-1,1	0,4	0,929	0,936
2	30.07.60	1,75	0,613	0,090	0,80	26,2	-14,2	0,732	0,816
3	2.06.61	1,75	0,545	0,056	0,80	-11,9	9,6	0,867	0,943
4	31.07.62	1,75	0,650	0,095	0,80	2,6	-21,7	0,884	0,891
5	30.07.63	No acceptable fit							
6	22.07.64	No acceptable fit							
7	7.06.65	2,50	0,490	0,068	0,80	3,9	-5,2	0,862	0,894
8	19.10.66	4,00	0,570	0,237	0,90	-4,7	4,5	0,935	0,967
9	16.07.67	1,25	0,580	0,173	0,80	-7,2	7,3	0,857	0,916
10	11.09.68	1,50	0,680	0,150	0,80	5,4	-12,8	0,972	0,978
11	7.09.69	No acceptable fit							
12	23.08.71	1,25	0,630	0,328	0,80	-1,7	-7,4	0,992	0,993
13	3.07.72	2,50	0,435	0,200	0,80	-1,8	0,8	0,825	0,853
14	10.07.72	1,25	0,620	0,153	0,80	-2,0	-0,9	0,952	0,962
15	17.09.73	1,50	0,613	0,280	0,80	2,0	7,2	0,921	0,921
Mean						5,9	7,7	0,894	0,922
St. dev.						7,1	6,3	0,072	0,052

Other parameters: K(1) = 6,0 N(2) = 0,7

KC(4) = 0,80 SMAX(8) = 150,0

IL(15) = 0,0

Table **A25** Sub-catchment parameter weighting factors

Catchment North Danville, **ND1** Area 42,94km²

Model Simple antecedent moisture model - OSE1 Type **Semi-distributed**

Sub-catch. No.	Area %	Parameters 3 CDEL	4 KC
1	19,5	1,00	0,50
2	13,4	0,50	0,75
3	18,0	0,75	0,90
4	19,6	1,25	0,65
5	16,9	0,50	0,70
6	12,6	0,00	1,00

Parameters N(2), SMAX(8), DA(9), C(10), APF(14), IL(15) all weights = 1,00

Table A26 Calibration results

Catchment North Danville, ND5 | Area 111,60km²

Model Simple antecedent moisture model - OSE1 | Type Semi-distributed

Storm No.	Date	Parameters CDEL (3)	DA (9)	C (10)	APF (14)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	1,75	0,620	0,090	0,80	9,0	-20,0	0,844	0,857
2	2.06.61	1,50	0,550	0,056	0,80	-10,7	10,7	0,889	0,970
3	31.07.62	1,25	0,585	0,100	0,80	-5,3	-11,7	0,960	0,968
4	30.07.63	No acceptable fit possible							
5	22.07.64	1,00	0,630	0,263	0,80	-0,7	-1,9	0,926	0,931
6	7.06.65	2,00	0,585	0,095	0,80	2,2	-6,6	0,902	0,909
7	19.10.66	1,25	0,585	0,225	0,90	-4,6	1,0	0,960	0,976
8	16.07.67	1,25	0,585	0,160	0,80	-2,4	-4,2	0,930	0,937
9	11.09.68	1,25	0,585	0,125	0,80	1,7	0,5	0,954	0,960
10	7.09.69	No acceptable fit possible							
11	23.08.71	1,25	0,560	0,267	0,80	-4,7	3,9	0,957	0,985
12	10.07.72	1,25	0,585	0,140	0,80	-8,7	4,5	0,924	0,954
13	20.07.72	1,50	0,585	0,148	0,80	1,9	-1,7	0,869	0,869
14	14.07.73	1,00	0,565	0,135	0,80	-5,6	2,9	0,971	0,994
15	17.09.73	1,50	0,585	0,215	0,80	-0,1	-8,6	0,917	0,918
Mean						4,4	6,0	0,923	0,941
St. dev.						3,4	5,5	0,042	0,043

Other parameters: K(1) = 6,0 N(2) = 0,7

KC(4) = 0;85 SMAX(8) = 150,0

IL(15) = 0,0

Table **A27** Sub-catchment parameter weighting factors

Catchment North Danville, **ND5** Area 111,60km²

Model Simple antecedent moisture model - OSE1 Type **Semi-distributed**

Sub-catch. No.	Area (%)	Parameters 3 CDEL	4 KC
1	7,5	1,50	0,80
2	5,2	1,00	0,87
3	6,9	1,25	1,35
4	7,5	1,55	0,85
5	6,5	1,00	0,77
6	4,8	0,50	0,73
7	5,2	1,00	0,97
8	5,6	0,75	0,45
9	4,3	0,50	0,67
10	7,7	2,25	0,65
11	4,9	2,00	0,70
12	4,9	1,50	1,00
13	4,4	2,25	0,95
14	7,5	1,75	1,05
15	4,6	1,25	0,75
16	5,4	0,75	0,80
17	2,0	0,00	0,37
18	5,1	0,00	0,50

Parameters K(1), N(2), SMAX(8), DA(9), C(10), APF(14), I,L(15) all weights 1,0

Table A28 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Augmented Hydrograph - OSE3 Type Lumped

Storm No.	Date	ROP (3)	DEL (5)	A (6)	K (8)	IL (9)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,029	0,00	2,5	13,5	0,0	-1,9	2,6	0,938	0,942
2	6.03.77	0,110	0,00	2,0	4,0	0,0	-0,2	3,0	0,737	0,830
3	7.05.77	0,022	0,00	6,0	9,0	30,0	-21,3	5,4	0,735	0,775
4	19.04.78	0,006	0,25	5,5	8,0	22,0	-0,3	-2,9	0,960	0,961
5	21.04.78	0,064	0,00	1,0	21,0	0,0	-4,2	-0,4	0,828	0,888
* 6	20.07.79	0,320	1,50	4,5	24,0	65,0	-1,0	2,1	0,876	0,879
* 7	23.07.79	0,470	1,25	7,0	15,0	0,0	-0,6	-0,7	0,950	0,900
* 8	19.08.79	0,540	1,50	8,0	16,0	32,0	-6,5	1,8	0,917	0,936
9	26.03.81	0,008	0,00	4,0	8,5	0,0	2,2	-1,2	0,938	0,939
10	22.10.81	0,030	0,00	5,0	10,0	0,0	-16,7	14,4	0,356	0,694
11	23.12.81	0,007	0,50	5,5	6,0	11,0	0,3	-3,5	0,979	0,980
*12	2.11.85	0,300	1,25	7,5	16,5	0,0	-6,8	2,5	0,928	0,962
*13	25.11.85	0,191	0,00	5,0	18,0	0,0	-19,1	4,6	0,524	0,628
14	1.12.85	0,130	1,00	5,5	9,0	0,0	-3,9	-23,8	0,821	0,825
15	3.12.85	No acceptable fit possible								
Mean		0,159					6,1	4,9	0,821	0,867
St. dev.		0,180					7,4	6,4	0,189	0,106

Other parameters: N(4) = 0,5 B(7) = 0,15

* 'Large' storm events.

Table A29 Calibration results

Catchment Ecca, Q9M21 Area 9,1km²

Model Augmented Hydrograph - OSE3 Type Lumped

Storm No.	Date	Parameters ROP (3)	A (6)	K (8)	IL (9)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,018	1,0	3,0	1,0	9,5	-10,6	0,848	0,872
2	6.03.77	0,045	1,0	2,5	10,0	5,3	-6,8	0,866	0,868
3	7.05.77	0,190	2,0	6,0	40,0	-12,9	-18,9	0,870	0,892
4	19.04.78		Not modelled		(suspect data)				
5	21.04.78	0,041	0,5	13,0	1,0	-1,6	3,9	0,664	0,771
* 6	20.07.79	0,310	1,5	23,0	50,0	1,2	2,9	0,832	0,841
* 7	23.07.79	0,435	1,5	16,0	1,0	-1,8	2,6	0,960	0,978
* 8	19.08.79	0,480	2,0	25,0	32,0	-5,6	9,4	0,938	0,967
9	26.03.81	0,014	1,0	6,5	1,0	-5,1	4,6	0,598	0,656
10	22.10.81		Not modelled		(zero flow)				
*11	23.12.81	0,026	5,0	1,0	15,0	-2,7	-16,4	0,760	0,783
*12	2.11.85	0,305	1,5	20,0	1,0	-4,1	1,9	0,896	0,956
13	25.11.85		Not modelled		(missing data)				
14	1.12.85	0,049	2,5	6,4	3,0	-0,0	-0,2	0,967	0,968
15	3.12.85		Not modelled		(data errors)				
Mean		0,174				4,5	7,1	0,836	0,868
St. dev.		0,179				3,8	6,1	0,119	0,101

Other parameters: N(4) = 0,5 DEL(5) = 0,001

B(7) = 0,15

* 'Large' storm events.

Table A30 Calibration results

Catchment North Danville, ND1 Area 42,94km²

Model Augmented Hydrograph - OSE3 Type Lumped

Storm No.	Date	Parameters ROP (3)	DEL (5)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	24.10.59	0,435	0,25	-0,9	7,1	0,991	0,991
2	30.07.60	0,090	1,00	7,3	-8,8	0,900	0,908
3	2.06.61	0,385	0,25	-1,8	0,1	0,974	0,975
4	31.07.62	0,238	0,50	6,6	-3,8	0,958	0,967
5	30.07.63	Not modelled (rainfall very spatially variable)					
6	22.07.64	0,068	0,25	-2,0	5,9	0,284	0,511
7	7.06.65	0,165	1,75	5,3	0,3	0,945	0,958
8	19.10.66	0,135	0,75	-4,1	2,5	0,930	0,961
9	16.07.67	0,160	0,00	-2,4	-2,2	0,856	0,888
10	11.09.68	0,090	1,00	-3,2	-1,9	0,981	0,982
11	7.09.69	No acceptable fit possible					
12	23.08.71	0,110	0,50	2,3	-1,5	0,963	0,970
13	3.07.72	0,240	1,25	3,0	0,1	0,967	0,969
14	10.07.72	0,140	0,50	-1,8	0,7	0,969	0,971
15	17.09.73	0,170	0,75	4,4	-6,8	0,977	0,980
Mean		0,187		3,5	3,2	0,899	0,925
St. dev.		0,112		2,0	3,0	0,189	0,128

Other parameters: N(3) = 0,5 A(6) = 4,0

B(7) = 0,15 K(8) = 15,0

IL(9) = 2,5

Table **A31** Calibration results

Catchment North Danville, **ND5** Area 111,60km²

Model Augmented hydrograph - **OSE3** Type **Lumped**

Storm No.	Date	Parameters ROP (3)	DEL (5)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,100	1,75	4,8	-2,4	0,925	0,929
2	2.06.61	0,370	0,25	-4,2	0,3	0,961	0,965
3	31.07.62	0,195	0,50	-0,9	8,2	0,986	0,988
4	30.07.61	No acceptable fit possible					
5	22.07.64	0,135	0,00	1,6	0,6	0,923	0,925
6	7.06.65	0,110	2,00	-0,6	-0,2	0,945	0,950
7	19.10.66	0,125	0,00	-1,2	4,9	0,945	0,957
8	16.07.67	0,190	0,00	5,7	-3,7	0,900	0,916
9	11.09.68	0,093	1,25	-9,0	8,4	0,968	0,983
10	7.09.69	0,215	1,00	1,8	-8,5	0,887	0,894
11	23.08.71	0,125	0,75	-2,5	4,6	0,985	0,993
12	10.07.72	0,160	0,75	-3,9	5,1	0,963	0,969
13	20.07.72	0,235	0,50	-0,7	0,8	0,966	0,967
14	14.07.73	0,300	0,00	4,4	-2,1	0,931	0,937
15	17.09.73	0,185	0,50	6,3	-2,6	0,950	0,958
Mean		0,181		3,4	2,9	0,945	0,952
St. dev.		0,080		2,5	2,6	0,029	0,029

Other parameters: N(4) = 0,5 A(6) = 5,0

B(7) = 0,15 K(8) = 15,0

IL(9) = 2,5

Table A32 Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Augmented Hydrograph - OSE3 Type Semi-distributed

Storm No.	Date	Parameters CDEL (1)	ROP (3)	K (8)	IL (9)	% errors: Volume	Peak	Coefficients: Eff.	Det.
1	28.02.77	0,5	0,022	5,0	20,0	-3,8	3,5	0,889	0,909
2	6.03.77	1,0	0,095	3,5	6,0	-6,5	-3,4	0,744	0,846
3	7.05.77	0,5	0,062	7,5	30,0	-3,4	0,3	0,807	0,819
4	19.04.78	0,5	0,010	4,5	22,0	12,1	-7,5	0,944	0,949
**5	21.04.78	0,5	0,030	5,0	1,0	-25,1	9,4	-0,438	0,587
* 6	20.07.79	1,0	0,350	16,0	65,0	-0,7	-13,8	0,910	0,915
* 7	23.07.79	1,0	0,410	16,0	0,0	0,23	1,9	0,966	0,933
* 8	19.08.79	1,0	0,580	17,0	32,0	-6,75	-1,2	0,953	0,966
9	26.03.81	0,5	0,008	3,0	0,0	9,8	-12,3	0,950	0,962
10	22.10.81	0,5	0,028	9,0	10,0	-2,8	11,1	0,493	0,736
11	23.12.81	0,5	0,007	1,0	13,0	4,0	-11,2	0,747	0,783
*12	2.11.85	1,0	0,310	18,0	0,0	-3,4	0,8	0,949	0,972
*13	25.11.85		No acceptable fit possible						
14	1.12.85	0,5	0,130	9,5	4,0	-0,5	-3,7	0,898	0,925
15	3.12.85		No acceptable fit possible						
Mean			0,157			6,1	6,2	0,854	0,868
St. dev.			0,190			6,7	4,9	0,138	0,113

Other parameters: KC(2) = 0,8 N(4) = 0,5

** Does not include the result for storm 5.

* 'Large' storm events.

Table **A33** Sub-catchment parameter weighting factors

Catchment Ecca, **Q9M20** Area 73,9km²

Model Augmented Hydrograph - **OSE3** Type **Semi-distributed**

Sub-cat. No.	Area (%)	Parameters 1 CDEL	2 KC	8 K	9 IL
1	13,0	5,25	0,80	1,00	1,50
2	5,9	4,50	0,90	0,92	1,50
3	5,6	4,50	0,90	0,92	1,50
4	7,0	4,00	1,00	0,92	1,50
5	6,4	4,00	0,75	0,90	1,50
6	7,0	4,00	0,75	0,90	1,50
7	11,4	3,00	0,50	0,85	1,30
8	7,9	2,75	0,60	0,80	1,20
9	6,0	2,25	0,96	0,65	1,10
10	9,7	1,25	1,40	0,95	0,95
11	12,9	0,75	1,00	1,05	0,90
12	7,4	0,75	0,60	0,80	0,85

Parameters ROP(3), N(4) all weights = 1,00

Table **A34** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model Augmented Hydrograph - OSE3 Type Semi-distributed

Storm No.	Date	Parameters ROP (3)	% errors: Volume	% errors: Peak	Coefficients: Eff.	Coefficients: Det.
1	24.10.59	0,438	-3,8	2,5	0,987	0,991
2	30.07.60	0,090	11,6	-10,8	0,869	0,886
3	2.06.61	0,405	0,9	3,7	0,983	0,989
4	31.07.62	0,230	2,4	-10,5	0,972	0,973
5	30.07.63	Not modelled (rainfall very spatially variable)				
*6	22.07.64	0,100	-1,4	-0,9	0,043	0,378
7	7.06.65	0,190	7,5	-6,6	0,906	0,915
8	19.10.66	0,148	-2,1	-0,3	0,967	0,986
9	16.07.67	0,198	-5,3	-12,3	0,871	0,883
10	11.09.68	0,095	1,7	-2,7	0,996	0,997
11	7.09.69	No acceptable fit possible				
12	23.08.71	0,091	-1,3	-1,3	0,972	0,984
13	3.07.72	0,242	-1,3	-12,6	0,797	0,779
14	10.07.72	0,168	2,7	-0,6	0,957	0,966
15	17.09.73	0,165	1,9	-7,0	0,972	0,972
Mean		0,197	3,4	5,5	0,934	0,943
St. dev.		0,112	3,1	4,7	0,062	0,066

Other parameters: CDEL(1) = 1,0 KC(2) = 0,80

N(4) = 0,5 K(8) = 15,0

IL(9) = 2,5

*Does not include the result for storm 6.

Table **A35** Sub-catchment parameter weighting factors

Catchment North Danville, **ND1** Area 42,94km^2

Model Augmented Hydrograph - **OSE3** Type **Semi-distributed**

		Parameters	
Sub-catch.	Area	1	2
No.	%	CDEL	KC
1	19,5	1,00	0,50
2	13,4	0,50	0,75
3	18,0	0,75	0,90
4	19,6	1,25	0,65
5	16,9	0,50	0,70
6	12,6	0,00	1,00

Parameters ROP(3), N(4), K(8), IL(9) all weights = 1,00

Table **A36** Calibration results

Catchment North Danville, **ND5** Area 111,60km²

Model Augmented hydrograph - OSE3 Type **Semi-distributed**

Storm No.	Date	Parameters ROP (3)	errors: Volume	Peak	Coefficients: Eff.	Det.
1	30.07.60	0,100	6,8	-6,8	0,838	0,859
2	2.06.61	0,385	1,2	10,1	0,938	0,960
3	31.07.62	0,205	-0,1	0,9	0,994	0,995
4	30.07.61	No acceptable fit possible				
5	22.07.64	0,101	-1,5	2,7	0,901	0,914
6	7.06.65	0,120	-0,9	-9,6	0,911	0,912
7	19.10.66	0,125	-1,6	3,9	0,965	0,968
8	16.07.67	0,170	0,3	3,2	0,947	0,958
9	11.09.68	0,100	-6,8	0,0	0,981	0,988
10	7.09.69	0,080	0,2	-0,1	0,718	0,773
11	23.08.71	0,125	-1,2	1,0	0,976	0,983
12	10.07.72	0,205	2,6	2,8	0,978	0,985
13	20.07.72	0,238	1,4	3,6	0,937	0,949
14	14.07.73	0,270	2,8	1,7	0,871	0,881
15	17.09.73	0,195	1,7	-2,9	0,978	0,980
Mean		0,173	2,1	3,5	0,924	0,936
St. dev.		0,084	2,1	3,2	0,075	0,063

Other parameters: CDEL(1) = 1,0 KC(2) = 0,85

N(4) = 0,5 K(8) = 15,0

IL(9) = 2,5

Table **A37** Sub-catchment parameter weighting factors

Catchment North Danville, **ND5** Area 73,9km²

Model Augmented Hydrograph - **OSE3** Type **Semi-distributed**

Sub-catch No.	Area (%)	Parameters 1 CDEL	2 KC
1	7,5	1,50	0,50
2	5,2	1,00	0,70
3	6,9	1,25	0,85
4	7,5	1,55	0,60
5	6,5	1,00	0,65
6	4,8	0,50	0,95
7	5,2	1,00	0,55
8	5,6	0,75	0,25
9	4,3	0,50	0,55
10	7,7	2,25	0,45
11	4,9	2,00	0,55
12	4,9	1,50	0,90
13	4,4	2,25	0,50
14	7,5	1,75	0,65
15	4,6	1,25	0,40
16	5,4	0,75	1,05
17	2,0	0,00	0,15
18	5,1	0,00	1,00

Parameters ROP(3), N(4), K(8), IL(9) all weights = 1,0

Table **A38** Calibration results

Catchment Ecca, Q9M20 Area 73,9km²

Model Runoff-routing - OSE4 Type **Semi-distributed**

Storm No.	Date	KC	Parameters I.Loss.	R.Coeff	% errors: Volume	Peak	AAOE %
1	28.02.77	1,0	15,0	0,03	-8,8	-7,3	34,7
2	6.03.77	4,0	8,0	0,15	-3.6	-2,8	35,2
3	7.05.77	3,0	42,0	0,05	-12,0	-4,8	63,8
4	19.04.78	0,8	45,0	0,02	-25,7	-1,9	50,5
5	21.04.78	3,0	5,0	0,03	-2,6	-26,8	32,7
*6	20.07.79	9,0	65,0(0)	0,05(0,38)	0,1	-4,6	18,8
7	23.07.79	8,0	10,0	0,25	-3,3	-12,1	15,1
8	19.08.79	15,0	50,0	0,60	-0,7	-2,1	20,8
9	26.03.81	1,0	12,0	0,01	-33,7	-61,4	64,0
10	22.10.81	2,5	5,0	0,02	-4,1	-0,2	28,3
11	23.12.81	No acceptable fit possible					
12	2.11.85	10,0	10,0	0,17	-2,6	4,5	19,3
13	25.11.85	8,0	10,0	0,19	-0,6	27,8	31,1
14	1.12.85	13,0	13,0	0,12	-2,6	-3,3	56,0
15	3.12.85	Not modelled (data errors)					
Mean				0,148	8,4	12,3	36,2
St. dev.				0,169	10,4	17,3	17,1

Other parameters: Parameter N = 0,7

* 2 rainfall bursts in storm - figures in parenthesis refer to 2nd burst.

Table **A39** Calibration results

Catchment North Danville, **ND1** Area 42,94km²

Model Runoff - routing - OSE4 Type **Semi-distributed**

Storm No.	Date	KC	Parameters I.Loss	R.Coeff	errors: Volume	Peak	AAOE %
1	24.10.59	9,0	8,0	0,38	-3,9	-5,4	13,7
2	30.07.60	5,0	25,0	0,10	-7,0	-4,5	18,0
3	2.06.61	8,0	10,0	0,34	-4,4	2,5	13,4
4	31.07.62	7,0	20,0	0,26	-1,9	-3,3	14,2
5	30.07.63	no acceptable fit possible					
6	22.07.64	3,5	0,0	0,04	-7,6	3,6	34,3
7	7.06.65	10,0	12,0	0,20	-5,1	-4,2	26,6
8	19.10.66	3,8	10,0	0,09	-5,9	-6,1	20,2
9	16.07.67	8,0	25,0	0,35	-5,3	6,0	20,6
10	11.09.68	4,0	22,0	0,10	-10,0	-3,6	29,8
11	7.09.69	no acceptable fit possible					
12	23.08.71	3,5	15,0	0,10	-4,6	-2,6	21,2
13	3.07.72	6,0	22,0	0,71	-3,7	2,7	38,2
14	10.07.72	5,8	10,0	0,12	-4,5	-5,9	13,8
15	17.09.73	6,0	15,0	0,16	-4,1	1,9	10,6
Mean				0,227	5,2	4,0	21,1
St. dev.				0,183	2,1	1,4	8,7

Other parameters: N = 0,7

Table A40 Calibration results

Catchment North Danville, ND5 Area 111,60km²

Model Runoff-routing - OSE4 Type **Semi-distributed**

Storm No.	Date	Parameters KC	I.Loss	R.Coeff	% errors: Volume	Peak	AAOE %
1	30.07.60	5,5	22,0	0,10	-3,4	-1,5	17,5
2	2.06.61	9,0	10,0	0,32	-3,6	1,3	17,1
3	31.07.62	8,0	20,0	0,24	-1,7	6,8	14,8
4	30.07.61		No acceptable fit possible				
5	22.07.64	5,0	10,0	0,08	-6,5	10,5	26,2
6	7.06.65	6,5	18,0	0,12	-4,1	-2,7	8,2
7	19.10.66	4,5	10,0	0,08	-5,8	-9,5	11,5
8	16.07.67	6,0	15,0	0,11	-2,1	-12,1	16,7
9	11.09.68	5,0	20,0	0,10	-3,3	-2,1	26,0
10	7.09.69	4,0	22,0	0,12	-11,5	-8,9	31,4
11	23.08.71	5,5	15,0	0,11	-6,5	-0,5	24,1
12	10.07.72	7,0	5,0	0,12	-4,3	-3,7	15,9
13	20.07.72	7,0	10,0	0,18	-2,0	-0,1	20,6
14	14.07.73	5,5	5,0	0,15	-3,1	1,7	9,8
15	17.09.73	7,0	15,0	0,17	-2,8	-3,1	10,0
Mean				0,143	4,3	4,6	17,8
St. dev.				0,067	2,6	4,1	7,0

Other parameters: N = 0,7

APPENDIX B

MODEL CALIBRATION RESULTS : GRAPHICAL PLOTS

Figure	Catchment	Storm date	Different models A	B	C	D
B1	Q9M20	6.03.77	OSE2-SD	OSE1-LM	OSE3-SD	OSE4-SD
B2	Q9M20	21.04.78	OSE2-LM	OSE2-SD	OSE3-LM	OSE4-SD
B3	Q9M21	21.04.78	OSE2-LM	OSE3-LM		
B4	Q9M20	20.07.79	OSE2-LM	OSE3-LM	OSE4-SD	
B5	Q9M20	23.07.79	OSE2-LM	OSE3-LM	OSE4-SD	
B6	ND1	21.10.59	OSE2-SD	OSE1-SD		
B7	ND1	21.10.59	OSE3-SD	OSE4-SD		
B8	ND1	22.07.64	OSE2-SD	OSE3-SD	OSE4-SD	
B9	ND1	19.10.66	OSE2-LM	OSE3-LM		
B10	ND1	16.07.67	OSE2-LM	OSE2-SD		
B11	ND4	16.07.67	OSE2-LM	OSE2-SD		
B12	ND5	16.07.67	OSE2-LM	OSE2-SD		
B13	ND5	16.07.67	OSE3-LM	OSE3-SD		
B14	ND1-ND5	19.10.67	OSE2-SD			
B15	ND1-ND5	11.09.68	OSE2-SD			

Note: The same scale is used for streamflow discharges (always in cumecs) and rainfall (in mmh^{-1} multiplied by a variable factor). Thus using mmh^{-1}*0.1-2.0 on the axis represents $20mmh^{-1}$.

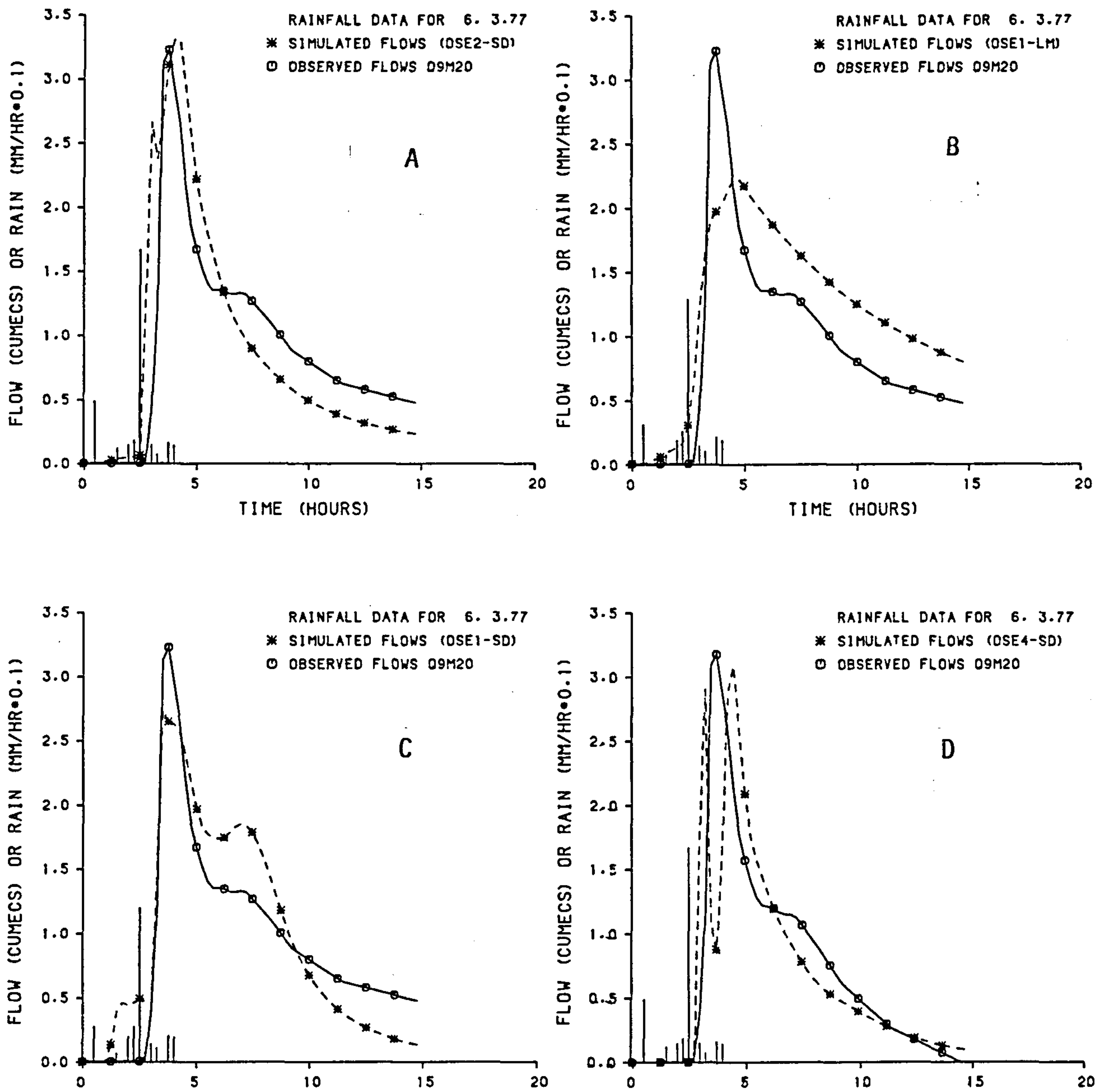


FIGURE B1 A-D Ecca Q9M20

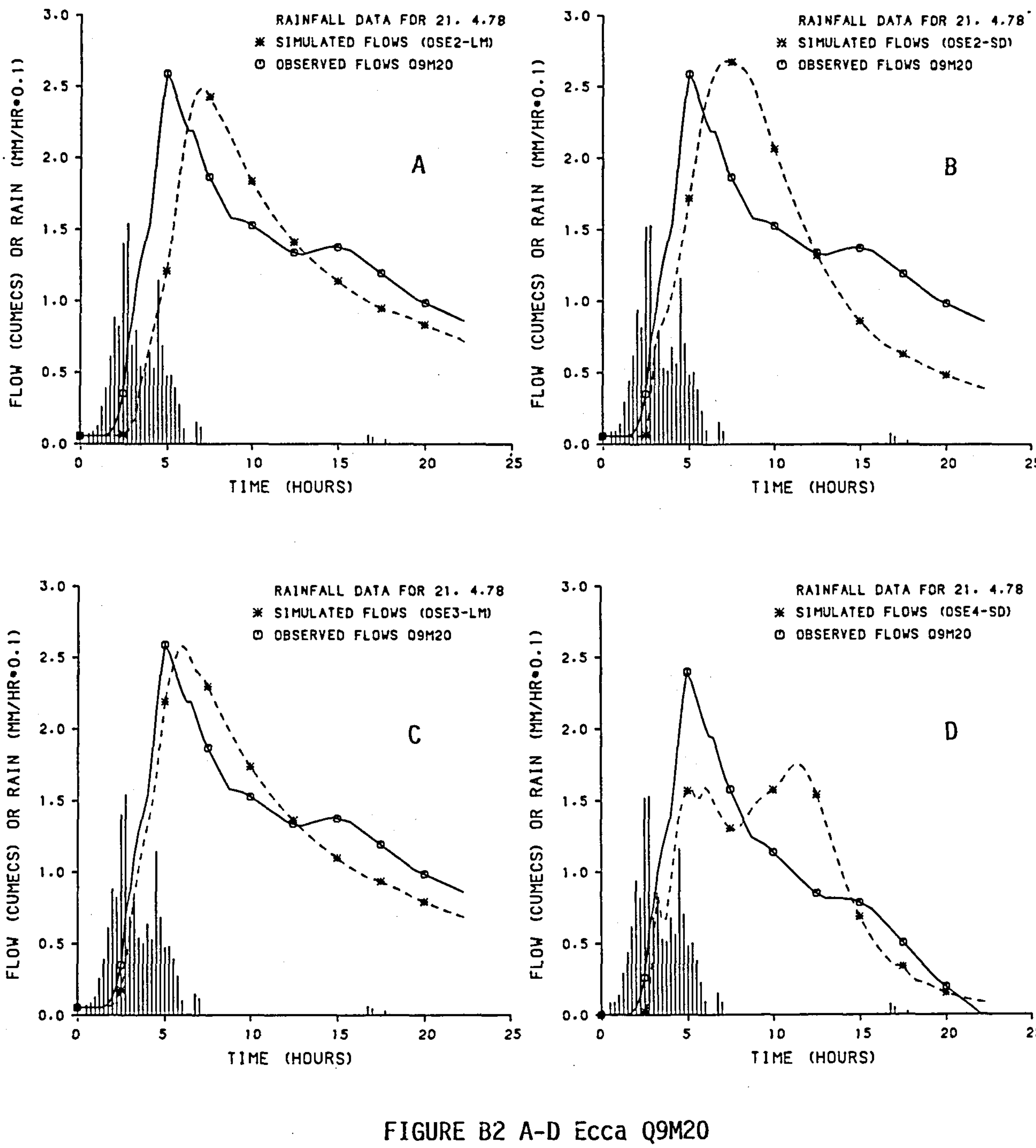
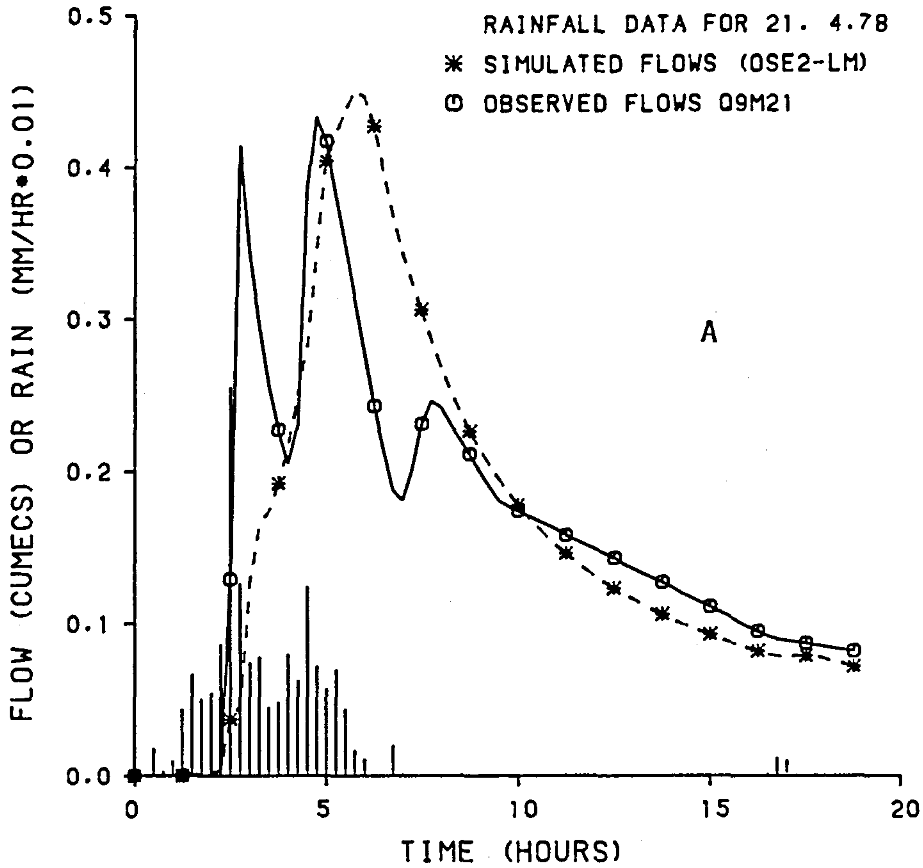


FIGURE B2 A-D Ecca Q9M20



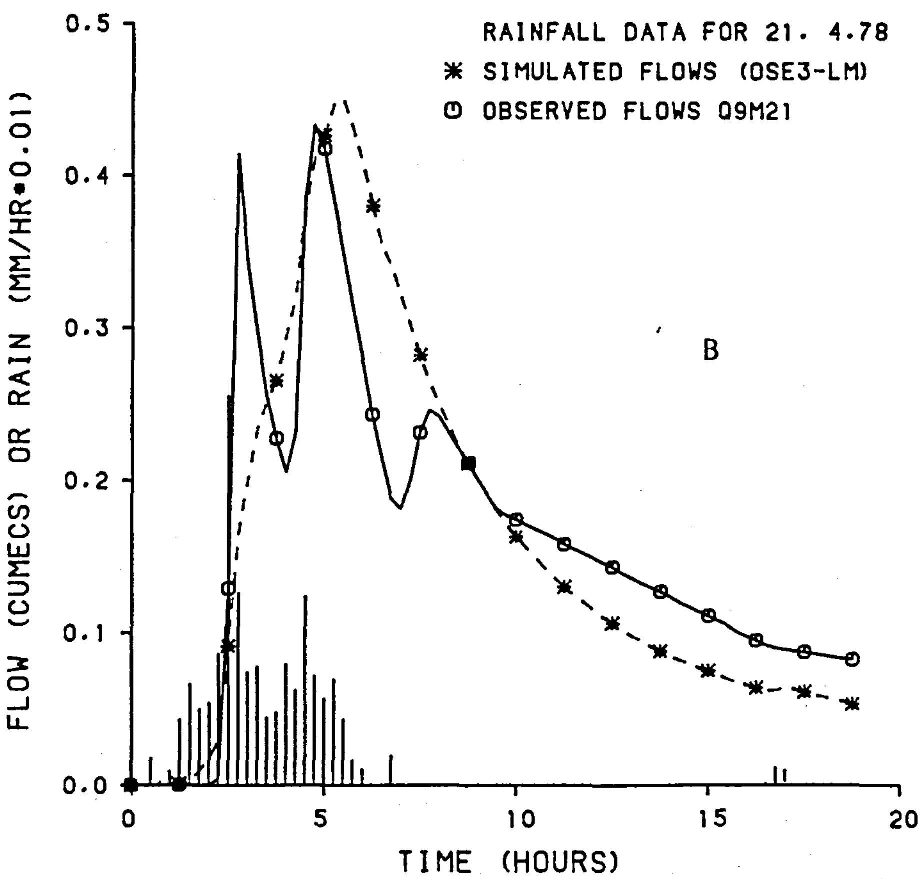


FIGURE B3 A-B Ecca Q9M21

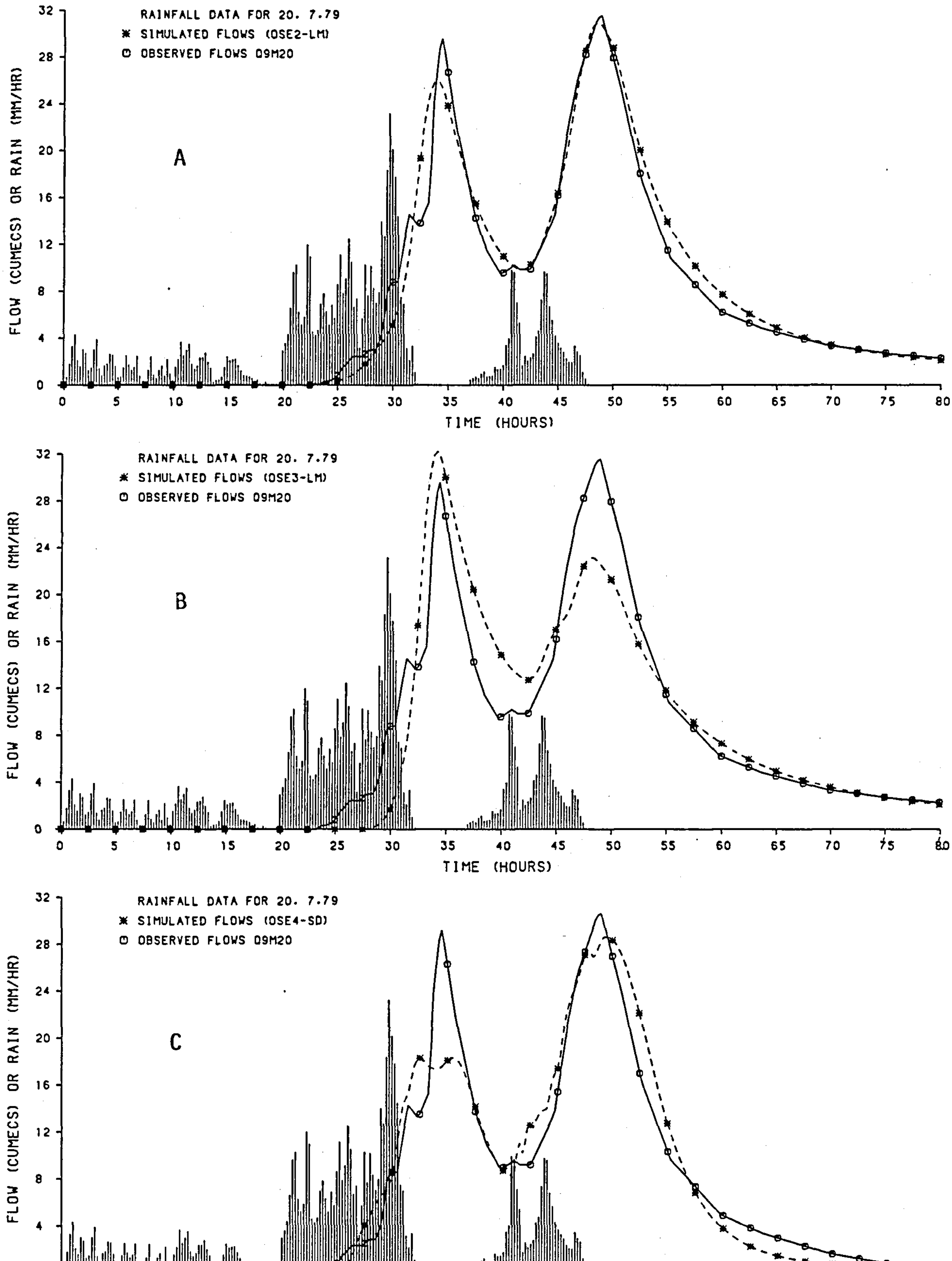


FIGURE B4 A-C Ecca Q9M20

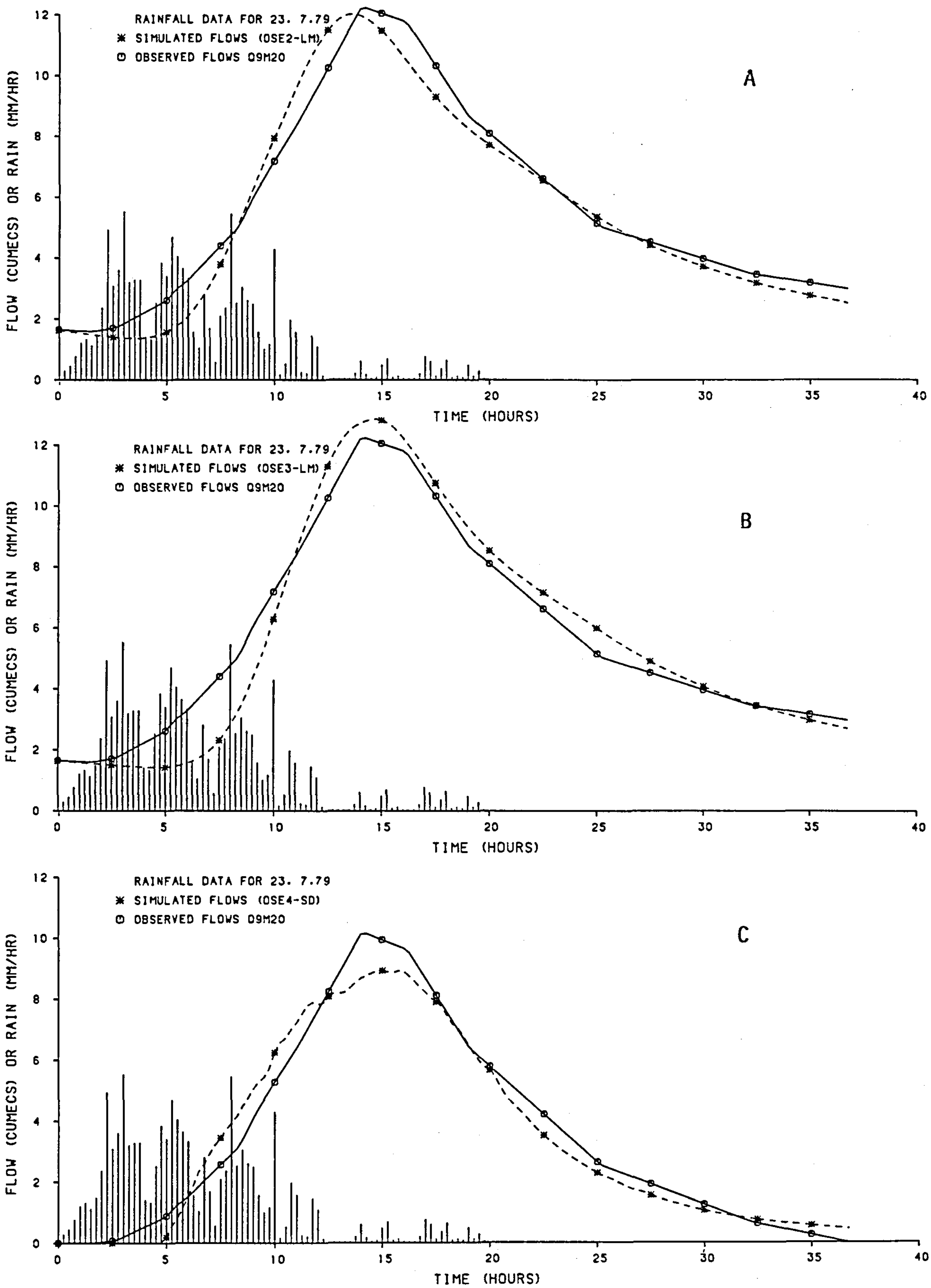


FIGURE B5 A-C Ecca Q9M20

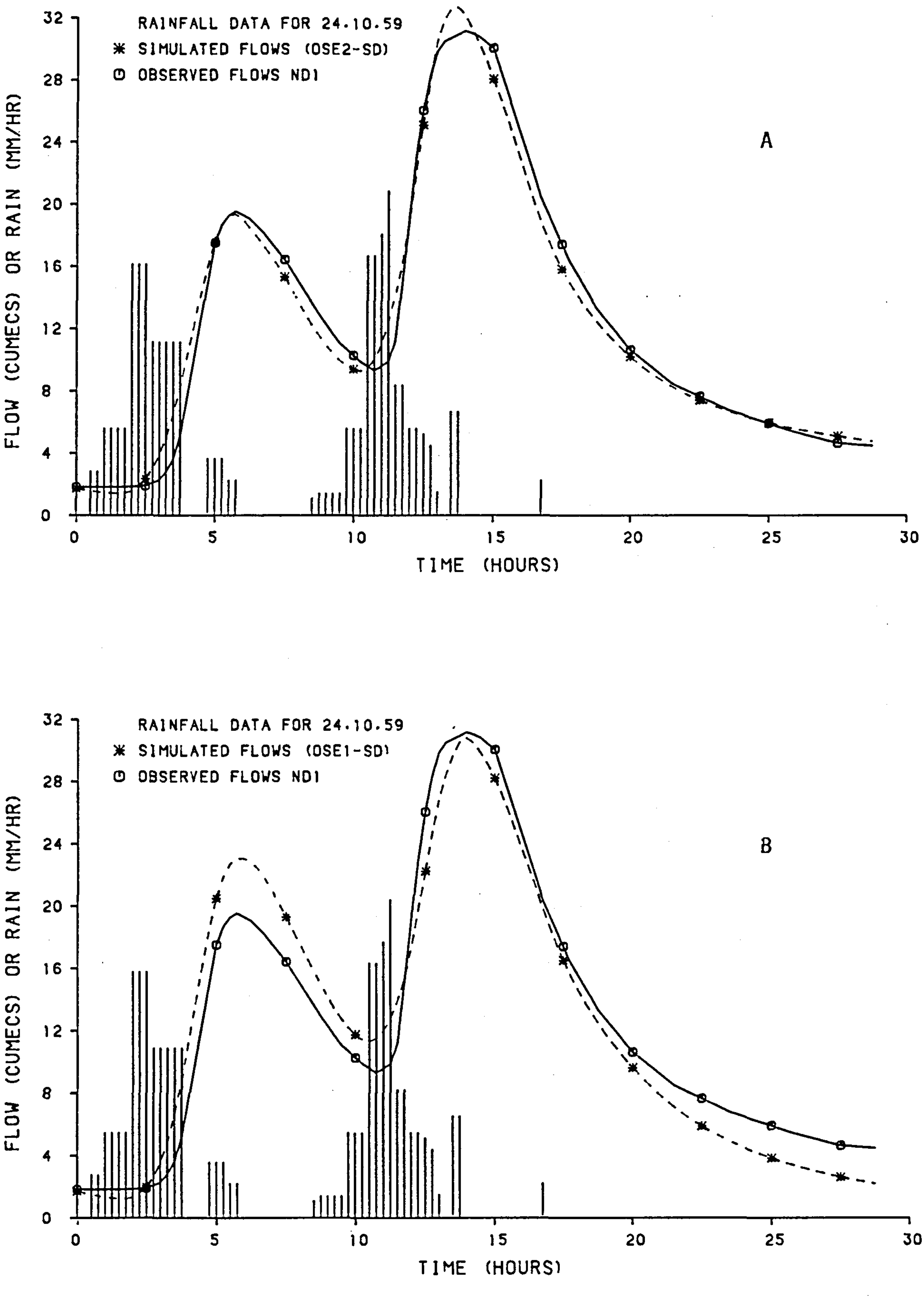
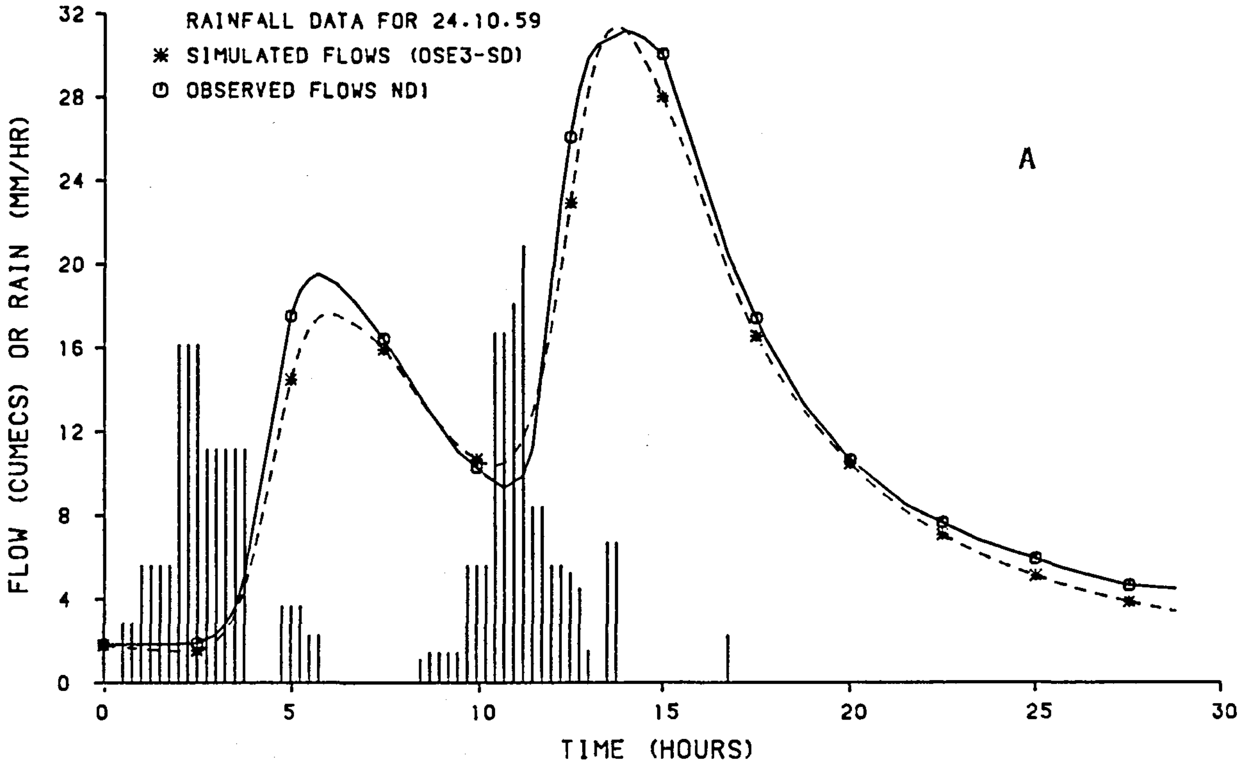


FIGURE B6 A-B N.Danville ND1



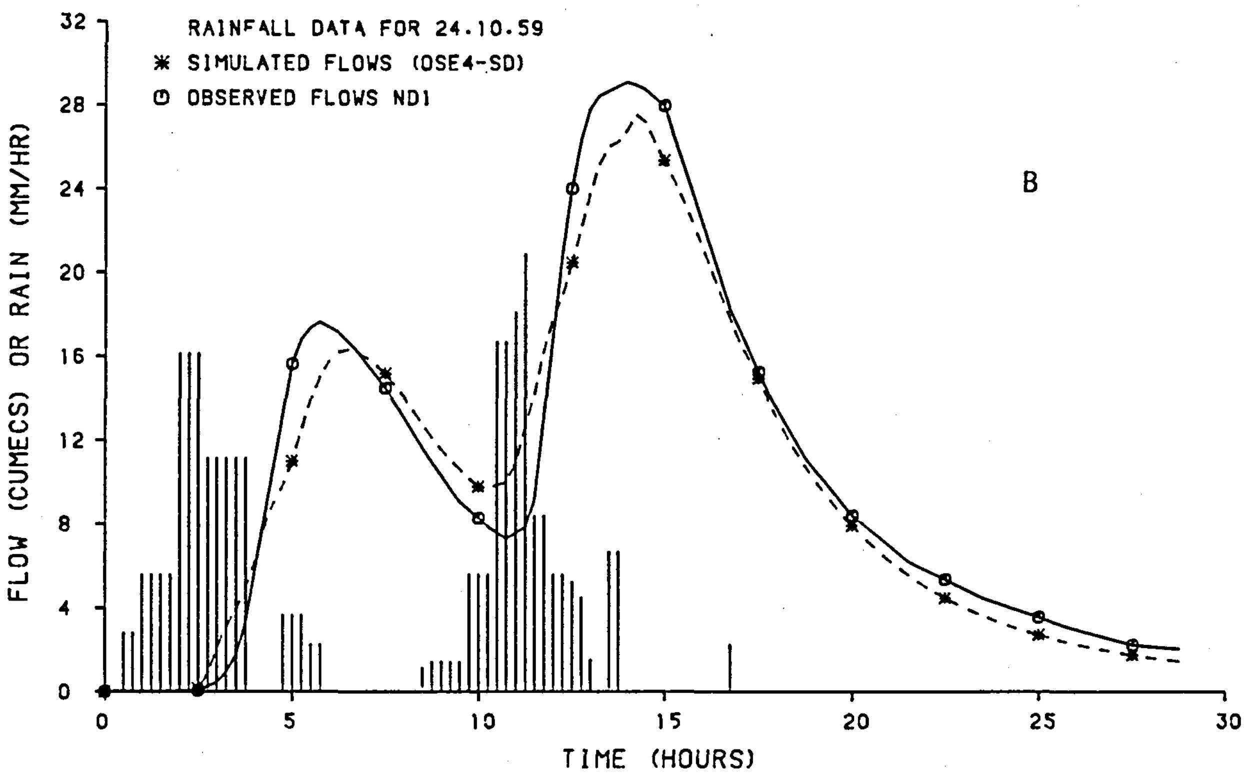


FIGURE B7 A-B N.Danville ND1

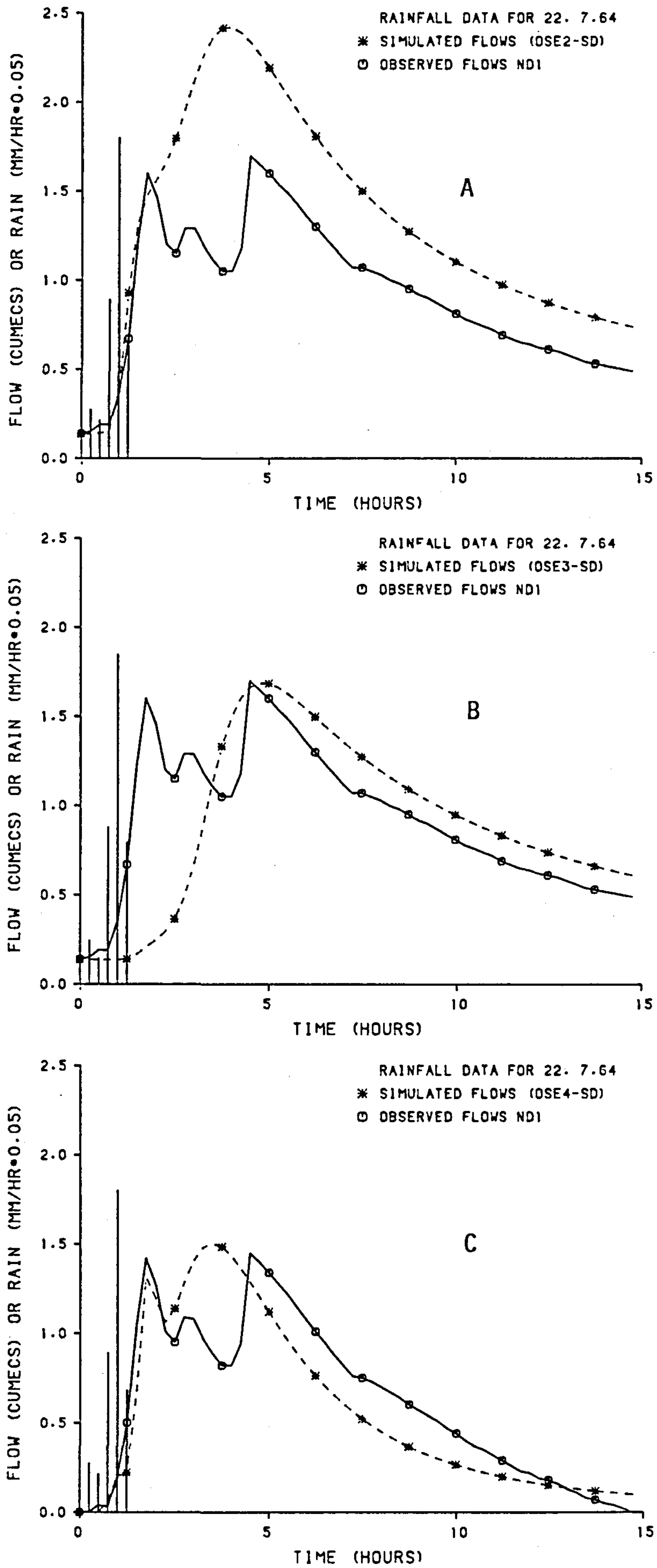
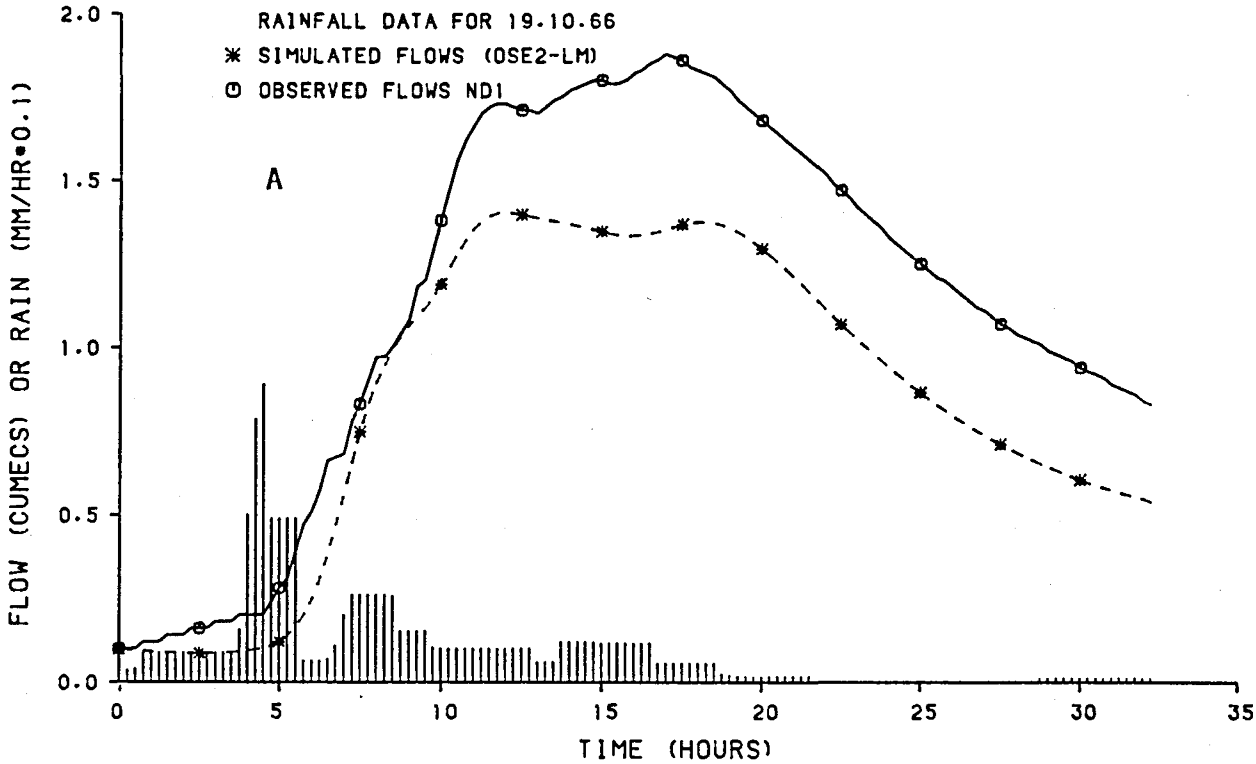


FIGURE B8 A-C N.Danville ND1



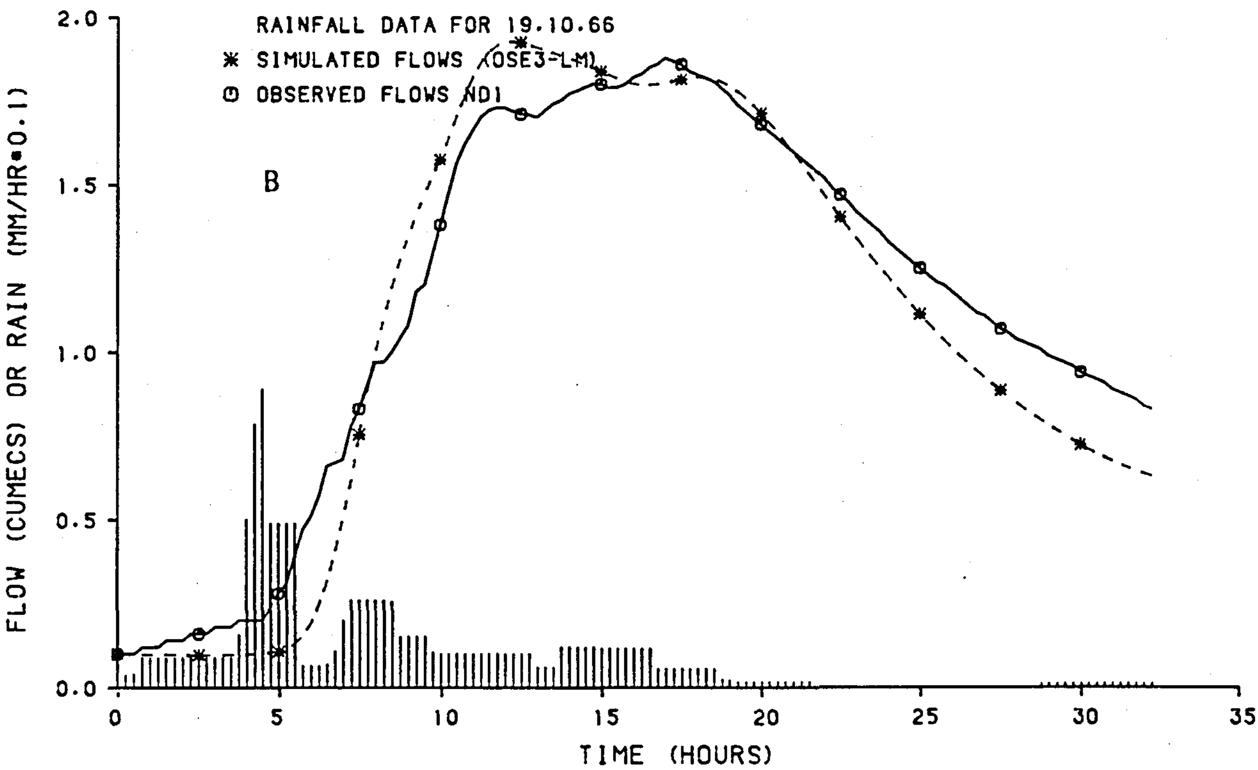
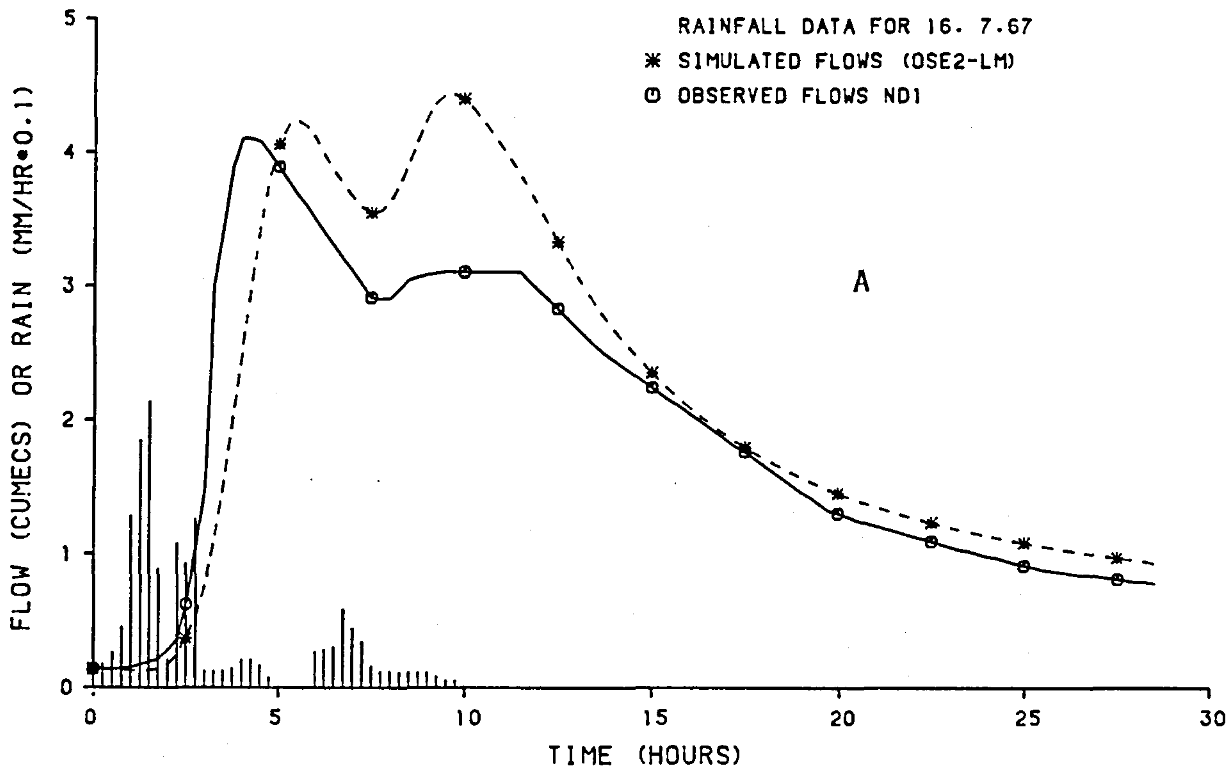


FIGURE B9 A-B N.Danville ND1



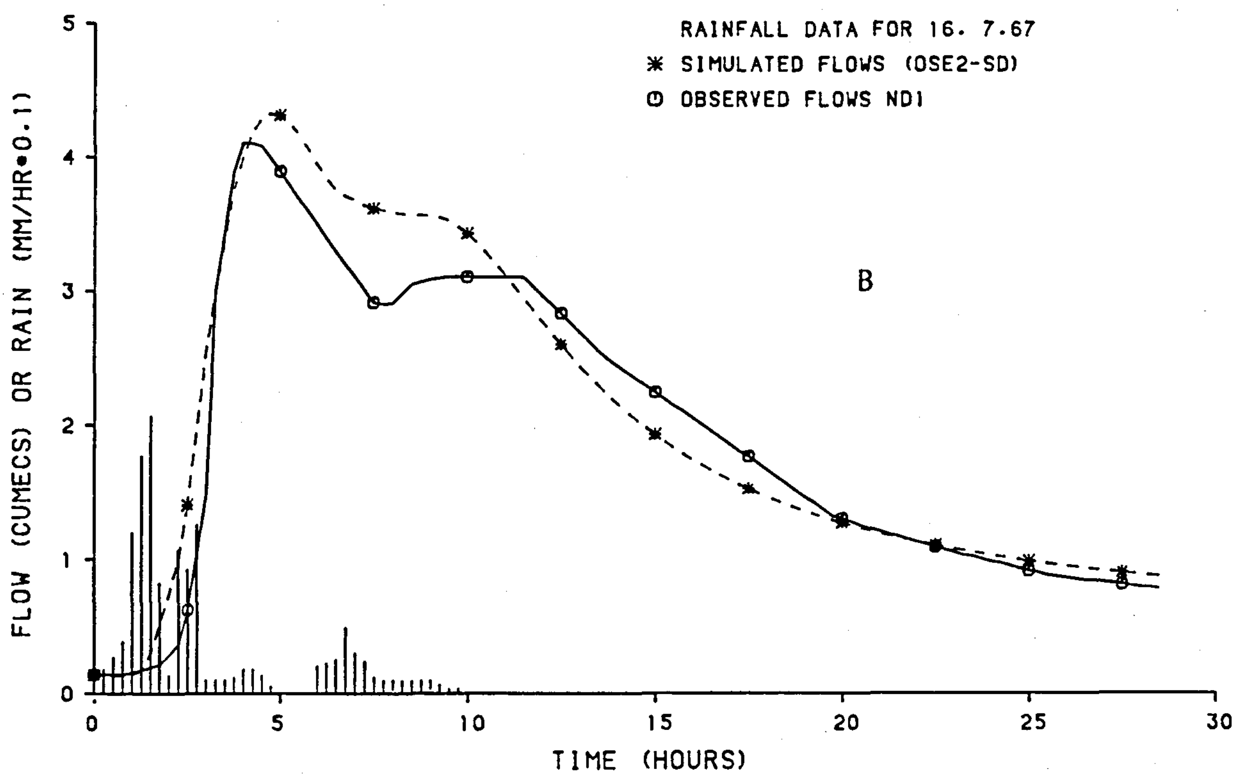
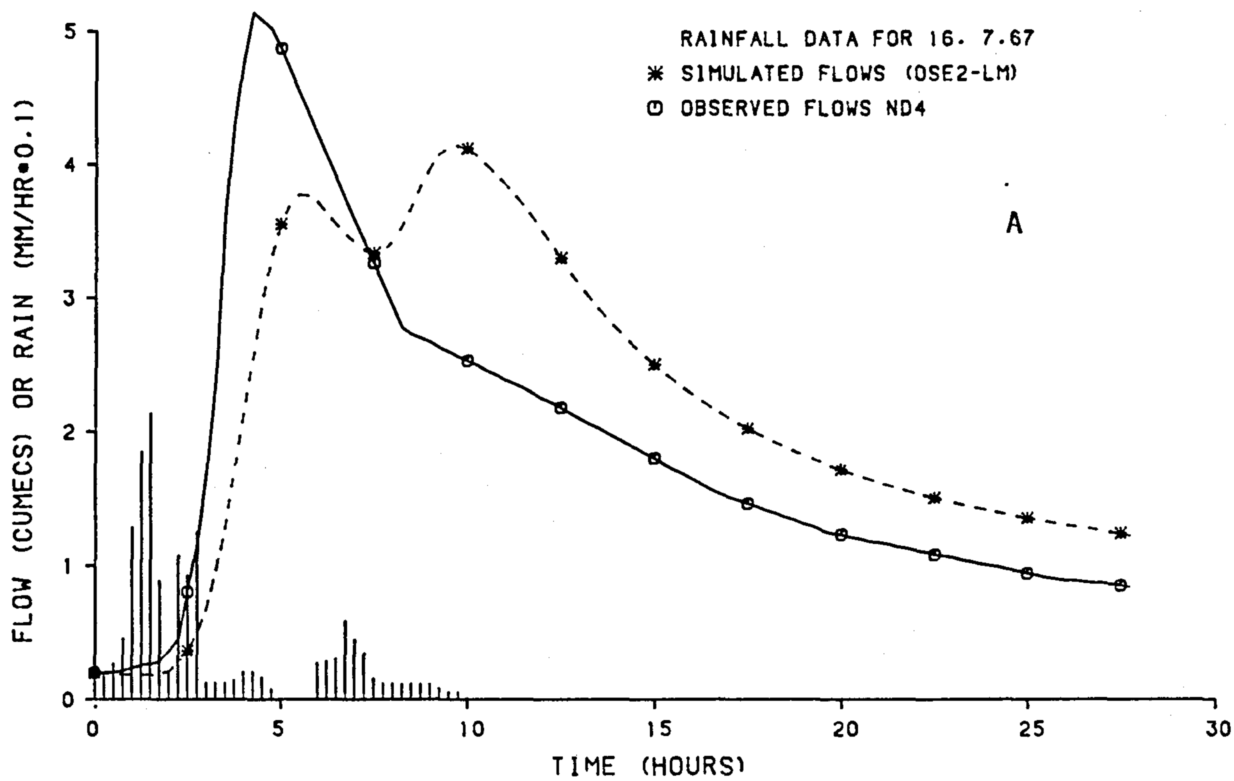


FIGURE B10 A-B N.Danville ND1



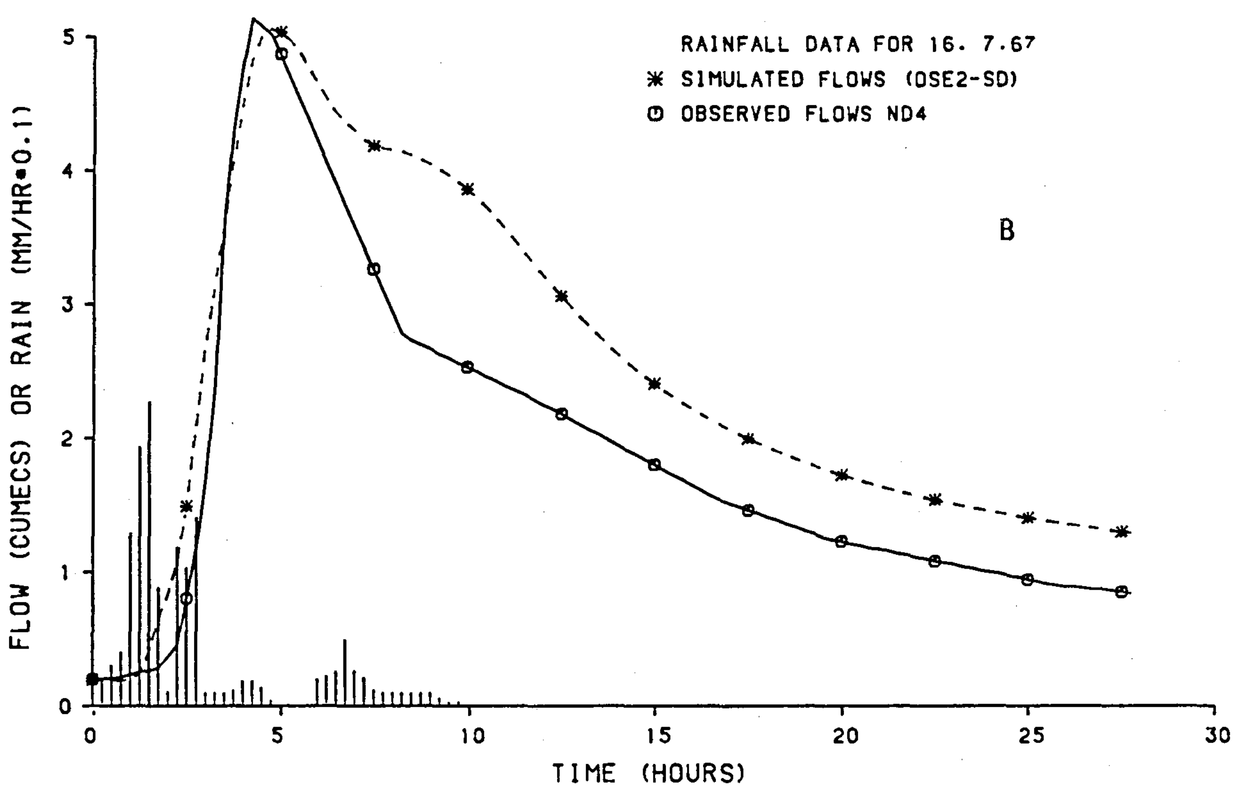


FIGURE B11 A-B N.Danville ND4

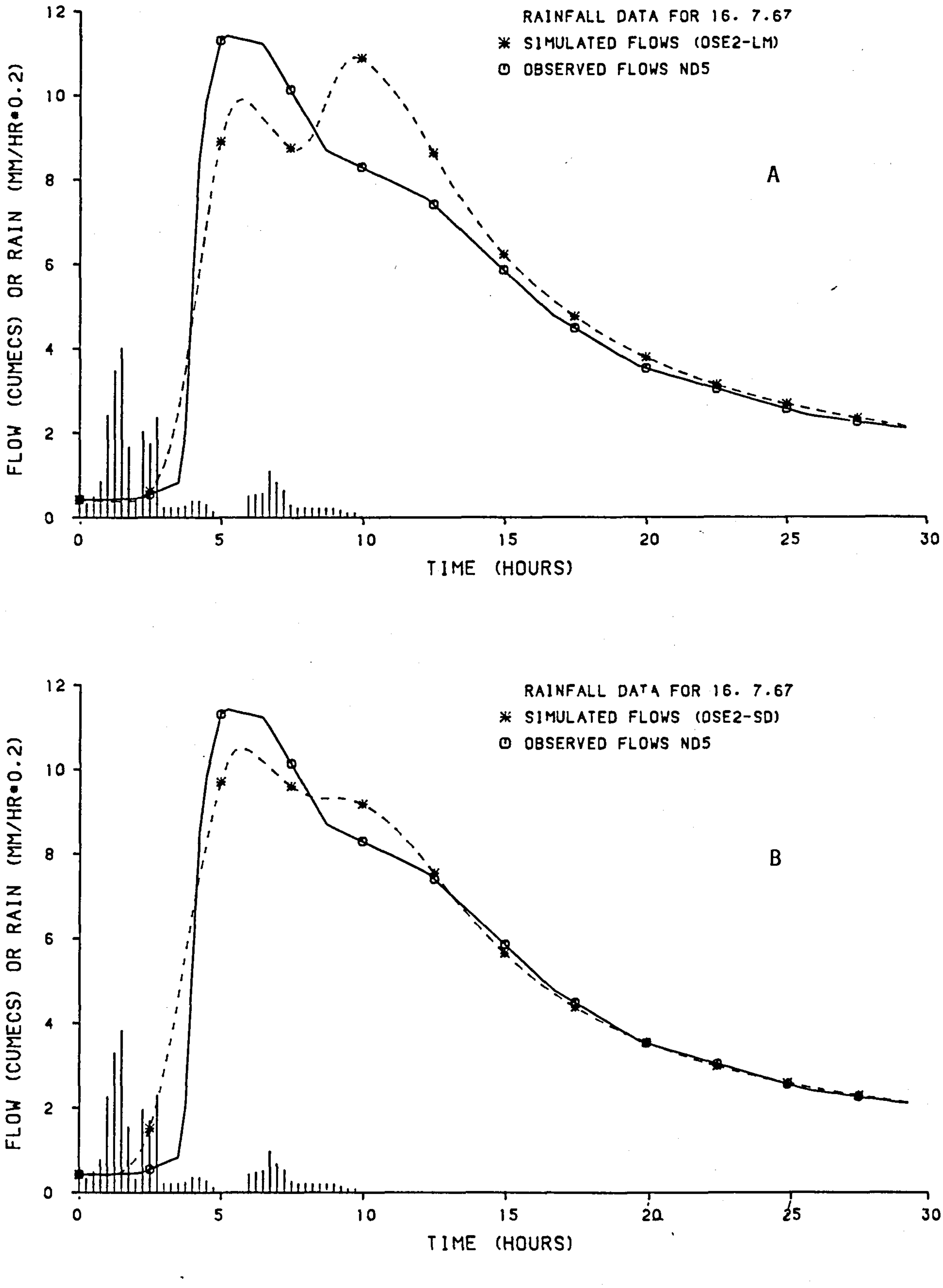
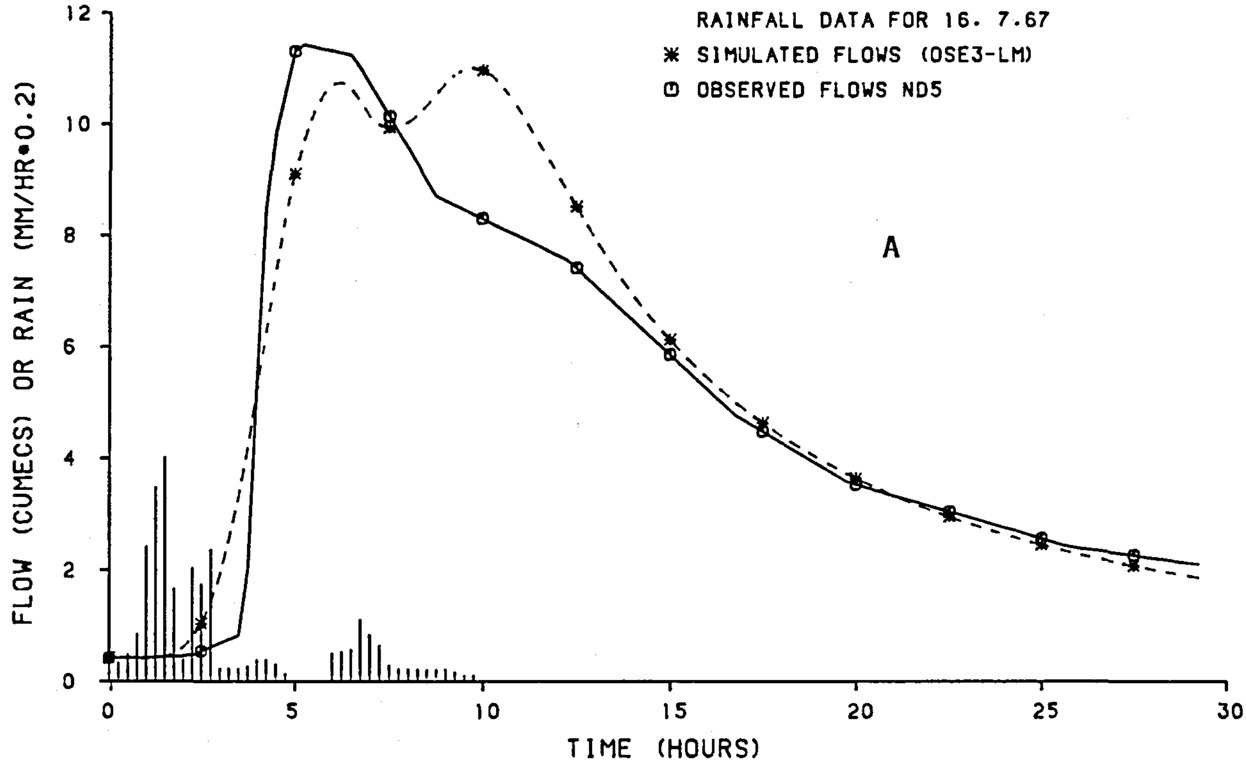


FIGURE B12 A-B N.Danville ND5



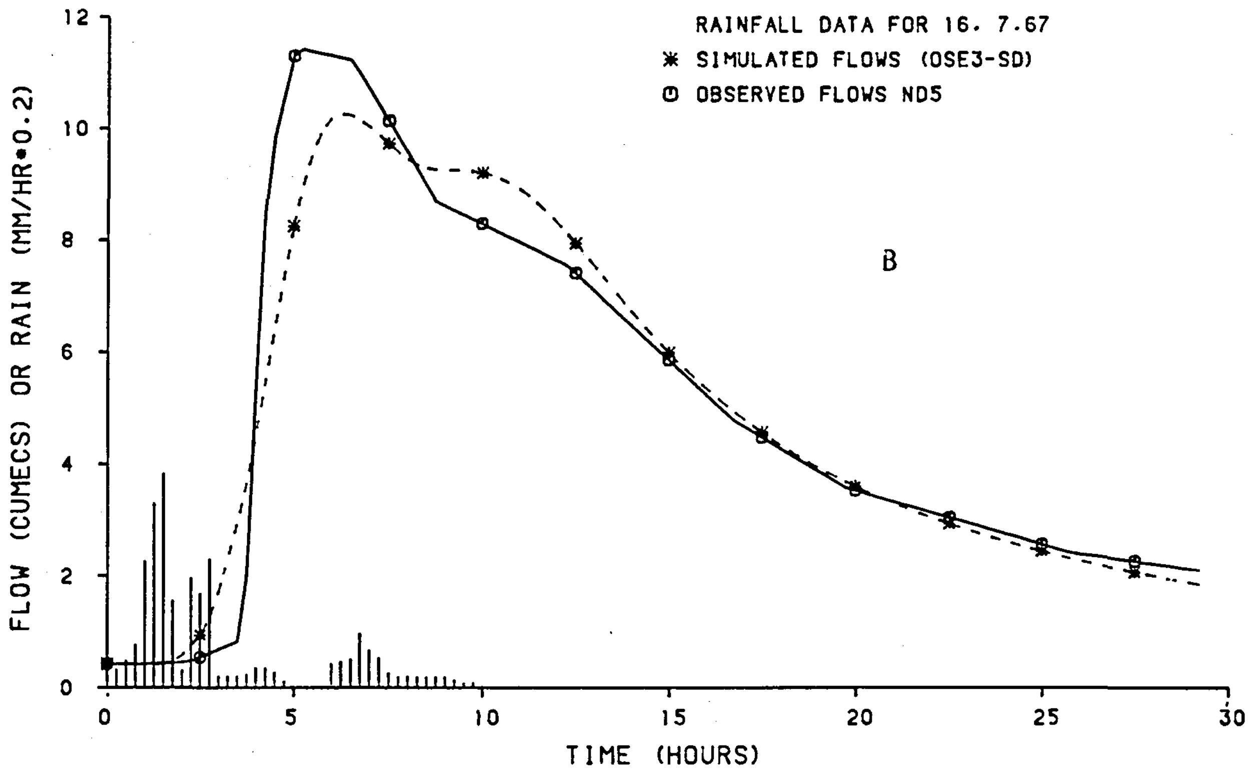


FIGURE B13 A-B N.Danville ND5

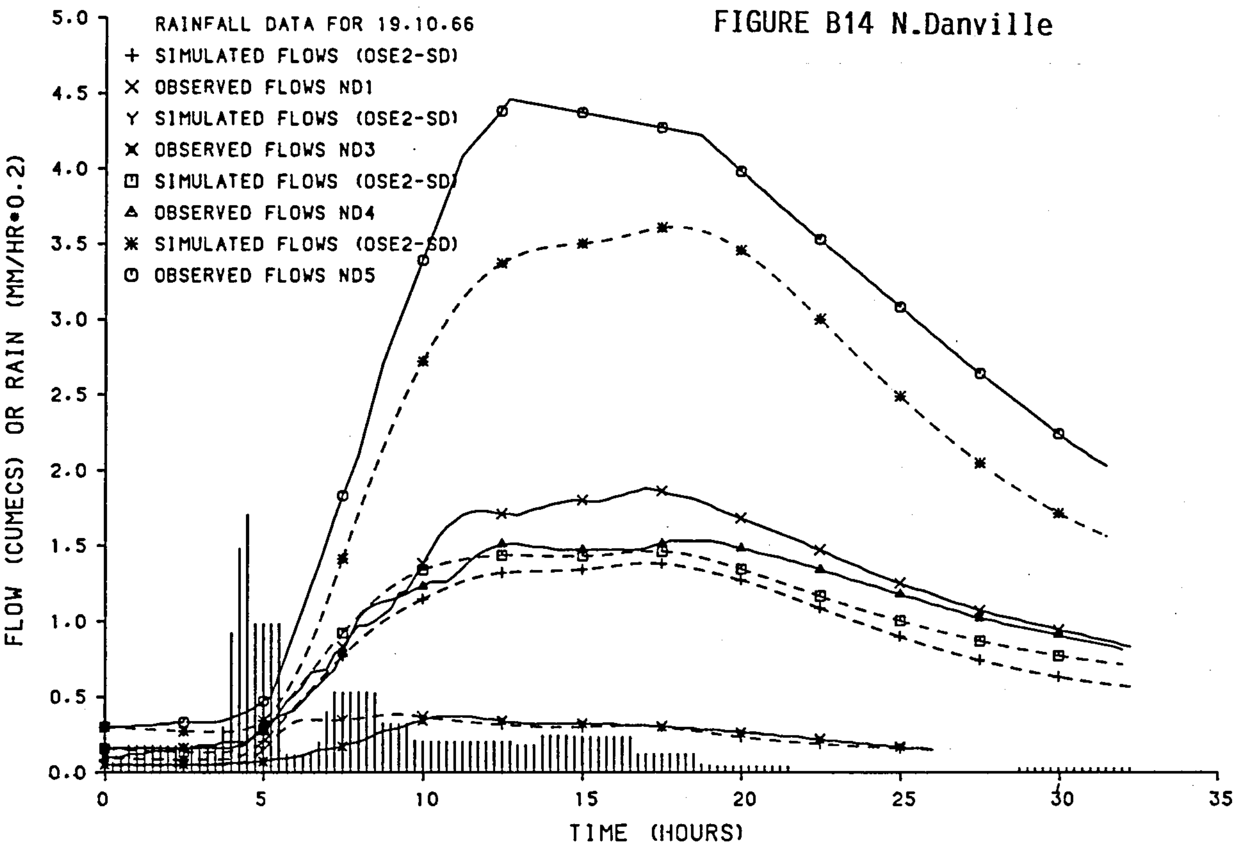


FIGURE B14 N.Danville
RAINFALL DATA FOR 19.10.66
+ SIMULATED FLOWS (OSE2-SD)
X OBSERVED FLOWS ND1
Y SIMULATED FLOWS (OSE2-SD)
X OBSERVED FLOWS ND3
SIMULATED FLOWS (OSE2-SD)
OBSERVED FLOWS ND4
SIMULATED FLOWS (OSE2-SD)
OBSERVED FLOWS ND5
FLOW (CUMECS) OR RAIN (MM/HR•0.2)
TIME (HOURS)

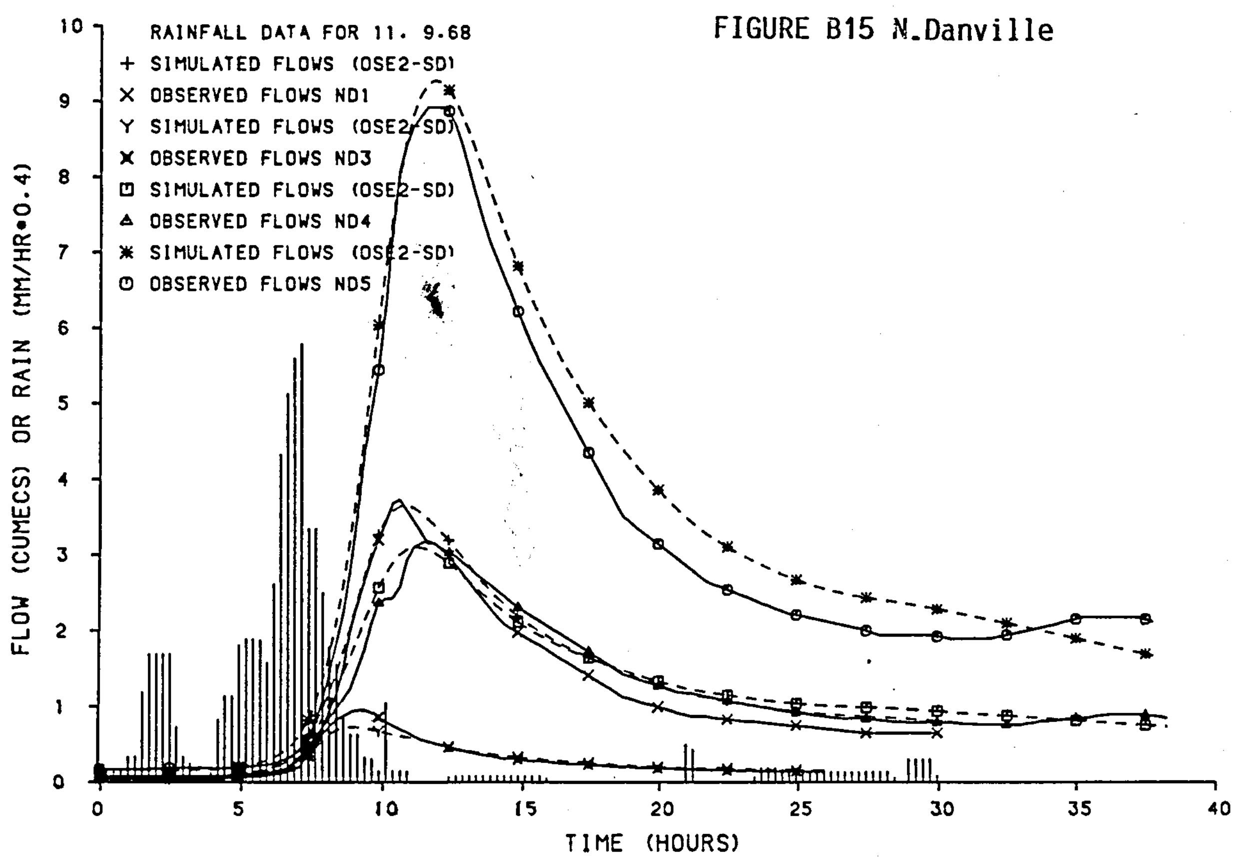


FIGURE B15 N.Danville
RAINFALL DATA FOR 11. 9.68
+ SIMULATED FLOWS (OSE2-SD)
X OBSERVED FLOWS ND1
Y SIMULATED FLOWS (OSE2-SD)
X OBSERVED FLOWS ND3
SIMULATED FLOWS (OSE2-SD)
OBSERVED FLOWS ND4
SIMULATED FLOWS (OSE2-SD)
OBSERVED FLOWS ND5
FLOW (CUMECS) OR RAIN (MM/HR•0.4)
TIME (HOURS)