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Hydrological relationships between small and large catchments

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HYDROLOGICAL RELATIONSHIPS BETWEEN SMALL AND LARGE CATCHMENTS

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SYNOPSIS

Much hydrological research and investigation have been carried out on small catchments. Factors affecting the hydrological relationships between these small catchments and larger ones, and the transferability of results, have been reviewed. Three types of relationships have been investigated using large amounts of data, primarily from eastern New South Wales.

The review indicates that while general relationships can be expected, especially for flood parameters, considerable scatter is likely, and that hydrological characteristics of small catchments may be more variable than, and somewhat different to, those of larger catchments. The very concept of hydrological uniformity, even in small areas, is suspect. Some of the factors affecting the relations are poorly understood at present.

Annual rainfall-runoff curves are derived by McCutchan's method for 22 catchments in the Clarence and Hunter Valleys. These relations were found to vary consistently within individual regions, and losses increased with area, almost certainly as a result of channel transmission losses, which are shown to be important for Australian conditions. The relations varied from region to region, indicating that it would not be valid to transfer data from one region to another, and that no comprehensive generalisations seem possible.

The parameters C and K of the Clark unit hydrograph model were used to investigate flood characteristics. Data from 52 catchments in Queensland, New South Wales and Tasmania covering nearly six orders of magnitude of size gave consistent relationships. The degree of correlation is high and the derived relations provide greatly improved design data for flood estimation.

A total of 336 storm loss rates were derived or assembled for 27 catchments in N.S.W. ranging in size from 0.06 to 15000 km^2. Only minor trends of values with area were found, and for practical application, a median value of 2.5 mm/h could be adopted for design for all catchment sizes. However, variations would probably occur in initial losses.

The investigations indicate that individual studies based on observed data in a given region can generally produce consistent and usable relationships between specific hydrological characteristics and area. However, the form of the relationships may vary from region to region, so that they need to be evaluated for each region of application. The study also throws some doubt on the concept of uniform hydrological regions and on the use of a representative basin to indicate properties of a given region. The needs for collection of more high-quality data and for further investigations are discussed.

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1. INTRODUCTION

Much hydrological research in both Australia and other countries has been carried out on data from small catchments ranging upwards in size from a few hectares. An upper limit of "small" in this context is difficult to define, but could be taken as 100 km^2. There are several reasons for this concentration on small catchments:

- they are relatively homogeneous in physical characteristics and there is thus greater probability of being able to isolate the effects of individual factors;
- rainfall is more uniform than over large catchments;
- the relative spatial uniformity of the production of runoff is likely to be greater;
- many small catchments have been instrumented with dense networks of recording and manual raingauges which are needed for many types of research;
- small catchments are often instrumented and operated by research institutions to suit their objectives, and the data gathered are used in their research programmes.

Concern has often been expressed that the hydrological processes and relationships on these small catchments may not be representative of those on larger catchments, and that the relative importance of the various processes on the two types of catchments are different. Information on the transferability of the research results from these small catchments to larger catchments is of obvious practical importance.

Many hydrological studies have been published that are indirectly relevant to the relation of hydrological characteristics of small and large catchments. All regional studies are of some relevance. However, relatively little information is available that relates directly to the problem.

The objective of the study reported here was to compare hydrological characteristics such as annual runoff, flood response parameters and storm loss rates derived from sets of small and large catchments in one or more regions, and to investigate the relationships between these characteristics from the two sets of catchments. The scope of the investigation was necessarily limited by the time and resources available for the project. It could not be expected that a single project could answer the questions raised in a universal and definitive fashion. Most of the catchments analysed are in eastern New South Wales. The primary objectives adopted in the study were to review and investigate the processes and factors affecting the relationships between hydrological characteristics of small and large catchments, to develop methodologies that can be applied to investigate these relationships, and to use those procedures in two or more regions to determine the transferability of information on several selected types of hydrological characteristics. As well as achieving these objectives, the study has provided design relationships for flood estimation covering much greater ranges of catchment sizes and geographical regions than previously available.

The smallest catchment included in any aspect of the analysis has an area of 5 ha. Most of the small catchments analysed were considerably larger than this. No plot data have been analysed, and the relation of hydrological data for plots and small catchments is outside the scope of this project.

In addition to investigating the relationship between the hydrological characteristics of small and large catchments, the study is also relevant to the concepts of the Representative Basin Program, described by the Department of National Development (1969). Central to the Program is the concept that the representative basins are typical of catchments within the regions that they represent, and that data, parameters or relationships can be transferred from one catchment to another, or can be used as a basis for estimating values for ungauged catchments. As this would involve transfer of data between catchments of different sizes, the study reported herein gives direct information on the accuracy and validity of this approach.

In this report, a review is first made in Chapter 2 of the processes and factors that influence the variation of catchment runoff with area. Reasons for differing responses from small and large catchments are identified and discussed. Investigations of three types of hydrological relationships are then described in the following chapters:

- annual rainfall-runoff relations (Chapter 3);
- unit hydrograph parameters as measures of flood hydrograph response (Chapter 4);
- storm loss rates (Chapter 5).

While these three types of relationships by no means exhaust the hydrological characteristics that are of interest and practical importance, they cover a wide range of catchment data. Other characteristics could be investigated in a similar fashion to the three studies reported here, but the time available precluded further study. Conclusions from the project are reported in Chapter 6.

The study of annual rainfall-runoff relations reported in Chapter 2 and some other aspects of the project have also been described by Baron (1979).

2. REVIEW OF EFFECTS OF AREA ON CATCHMENT RUNOFF

2.1 GENERAL

Current knowledge of hydrological and geomorphological processes and the results of published studies indicate that catchment area can be expected to influence runoff in many direct and indirect ways. Various aspects of runoff, such as total yield, flood peaks, direct storm runoff and losses, will be affected differently. Not only will the average runoff characteristics be influenced by catchment area, but their relative variabilities may also be affected, with important practical implications.

Before the investigations and results of this study are described and discussed, the range of processes and factors influencing the relation of catchment runoff to area will be reviewed in this chapter. Physical processes and the effects of catchment characteristics will be discussed, the relevance of evidence for variations of runoff within relatively homogeneous areas will be examined, and published relationships between runoff characteristics and catchment area will be reviewed.

2.2 RUNOFF PROCESSES

2.2.1 Types of Runoff

To assess the possible variations of runoff with catchment area, it is necessary to consider the types of runoff that occur, the processes involved and their likely variations. Although runoff has been classified in many different ways, only the two types of direct storm runoff and baseflow will be considered here to simplify the discussion. The relative proportions of these two components can be expected to have an important influence on the variation of runoff with area. Although it is difficult to determine these proportions with any precision it is certain that they vary widely over Australia. They also vary with time. Lvovitch (1973) has mapped the average surface, underground and total runoffs for the world. For Australia, very generalized estimates of proportions of total runoff contributed by subsurface flow are about 50 per cent in eastern Victoria and south eastern N.S.W., 10-15 per cent in north eastern N.S.W., south eastern Queensland, southern Victoria and south eastern South Australia, 5 per cent in south western Western Australia, the Kimberleys and near Darwin, and 2 per cent in the Cape York Peninsula. The proportion probably approaches zero over the remaining major portion of the continent, although there is really insufficient information over most of the inland to provide firm data. In addition to these differing proportions of the flow components affecting the general relationship of hydrological characteristics with area, it is obvious that they will also produce differing effects on relationships for flood characteristics, low flows and total runoff.

In most locations, the smallest catchments are ephemeral and the contribution of baseflow increases downstream as catchment area increases, as discussed further in Section 2.2.3. The actual manner in which this occurs will depend on the location, and will be related to a complex set of catchment characteristics as well as to the average overall proportion of baseflow discussed above. In general, it would be expected that total runoff per unit area would increase as catchment area increases as a result of the increasing baseflow, but that the effect would be very variable.

Variations in the individual runoff processes from one location to another would also be expected to affect the relation of runoff to catchment area. These runoff processes are examined briefly below.

2.2.2 Storm Runoff Processes

In earlier years, storm runoff was generally considered to consist of surface runoff produced by rainfall excess which occurs at the ground surface when the rainfall intensity exceeds the infiltration capacity (Horton,1933). In practice, infiltration capacity was often considered to be fairly uniform with area, so that rainfall excess and volume of storm runoff would also be constant with area if rainfall was uniform. Over the last ten or fifteen years, this classical concept of storm runoff has been challenged as a result of observation of natural catchments during storm periods and many detailed studies of instrumented plots and small areas. Two alternative types of storm runoff mechanism have been proposed.

"Saturated overland flow" has been described by Kirkby and Chorley (1967) and Kirkby (1969). This occurs when the surface horizon of the soil becomes saturated, usually as a result of the build-up of a saturated zone above a lower horizon of low hydraulic conductivity. Further rain on the saturated soil then becomes surface runoff. These saturated areas have usually been found to occur in the bottoms of valleys and to expand outwards from the stream channels during major storms. Examples of studies where this type of runoff was found to be the main contributor to storm flow are those reported by Ragan (1968),Betson and Marius (1969) and Dunne and Black (1970a,b).

The other type of storm runoff is the "throughflow" of Kirkby and Chorley (1967) and Kirkby (1969). This refers to water that infiltrates into the soil but percolates rapidly, probably largely through macropores, such as cracks, root holes, and worm and animal holes, and quickly reaches the stream channels. It differs from other subsurface flow in the rapidity of its response and possibly in its relatively large magnitude. This phenomenon was suggested as the major source of storm runoff in the studies of Whipkey (1965,1969), Chamberlin (1972) and Arnett (1974). Weyman (1970, 1973, 1974) also found this form of subsurface flow to be a major source of runoff, but its delay and attenuation were such as to preclude its classification as direct storm runoff.

Associated with the recognition of these two types of storm runoff mechanism has been the development of the concept that storm runoff is generated on only a small part of many catchments. This was proposed by Betson (1964) and supported by the evidence of studies by Hewlett and Hibbert (1967), Betson and Marius (1969), Dunne and Black (1970a,b) and many subsequent workers. Moreover, these studies have shown that the source areas vary in extent from time to time, such as in different seasons. Source areas producing saturated overland flow generally expand during major storms. Anderson and Burt (1978) showed that source areas may vary under severe climatic conditions such as droughts.

It is clear that variations of storm runoff processes and variable source areas occupying only portions of catchment areas will influence the relation of runoff to area. They cut across simplistic concepts of fairly uniform spatial generation of runoff and simple relationships between hydrological variables and area. If the occurrence of the different storm runoff mechanisms were fully understood and the location of source areas were known, it might be possible to predict their effects on the relation of hydrological response to area. Unfortunately, these phenomena are not well understood and their very existence is still not universally recognised. Much of the developmental work has occurred in the east of the United States and in the United Kingdom where rainfall intensities are relatively low. Storm runoff has been found to occur as saturated overland flow and throughflow from relatively small source areas adjacent to stream channels in valley bottoms. It has become common for writers from the above regions to suggest that these conditions always occur in humid temperate regions and that Horton-type rainfall excess is never a significant process in such regions. They suggest that this latter process may only be of significance in areas of low precipitation. However, Pilgrim et al.(1978) found that all three processes occured on a large field plot near San Francisco in California. Also, Pilgrim (1966a) found that runoff was first produced in headwater areas of a small catchment near Sydney, rather than in source areas in the valley bottoms, and that as major storms progressed runoff was produced from the entire catchment. For two small catchments in Ohio, Amerman (1965) found that source areas were located in seemingly random fashion on ridgetops, valley slopes and valley bottoms, and were not necessarily connected to the valley streams by continuous surface flow paths.

Only a little work has been carried out on storm runoff processes in Australia, although there is considerable current interest. Saturated overland flow from valley bottoms, especially during winter, seems common in southern Australia. This is indicated in studies by Williamson and Turner (1979) in western Victoria and by Allison and West (1979) near Adelaide, although the latter found that heavy storms also produced Horton-type runoff from the remainder of the catchment. Langford and O'Shaughnessy (1979) found that for small catchments at North Maroondah to the north-east of Melbourne, 70-80% of total runoff was baseflow and the 20-30% stormflow was generated largely as saturated overland flow from swampy areas immediately around the streams. However, on a small forested catchment in north-east Victoria, Bren and Turner (1979) found that almost all of the storm runoff occurred as rapid subsurface flow or throughflow. Pilgrim (1966a) showed that surface runoff occurred from all of a small catchment near Sydney, although the runoff commenced first at higher elevations remote from the valley bottom. Much of this runoff was of the Horton type, although some temporary saturation of parts of the catchment could have occurred. Analytical studies by Bloomfield (1979) have indicated that partial area runoff may occur on the South Creek catchment west of Sydney. For a small catchment on the wet tropical coast of north Queensland, Gilmour and Bonell (1977) found that saturated overland flow occurred over virtually the whole catchment as a result of a temporary saturation of the top 200 mm of soil above a horizon with low hydraulic conductivity. Pilgrim et al.(1979) suggest that Horton-type surface runoff occurred with relatively small rainfalls on small catchments and plots at an arid zone location north of Broken Hill, with an average annual rainfall of 195 mm.

The available evidence from Australia and overseas indicates that it is not possible to draw generalized conclusions regarding storm runoff processes and the presence and location of source areas. Several processes may be operative on a given catchment and different processes may be dominant at various times. The processes operating in a particular region and the occurrence of source areas will affect the relation of runoff to catchment area, especially in comparing small headwater catchments with larger areas. Storm runoff dominates relationships for flood flows, but also has an important influence on total flows. It must be concluded that at the present time, it is not possible to deduce the effects that variations in storm runoff processes will have on these relations . Further information on the processes, their interrelationships and conditions of occurrence are required to increase our understanding of catchment runoff.

2.2.3 Baseflow

As noted in Section 2.2.1, baseflow may constitute a large portion of the total streamflow as well as providing virtually all of the dry weather flow.

In most locations, baseflow consists mainly of outflow of groundwater where the permanent water table intersects the catchment surface or a stream channel. It may also include some "interflow" of intermediate response time. This is generally considered to consist of lateral subsurface flow above a horizon of low hydraulic conductivity, similar to throughflow but with lower rates and slower response times. In addition, it may include return flow from streambank storage, delayed outflow of water stored in the stream channel or the flood plain, and true surface runoff from marshy areas or other areas with long storage delay times (Pilgrim, 1966a).

The volumes and rates of groundwater flow depend on the type and extent of the aquifers and the level and slope of the water table. High yields are often associated with unconsolidated sediments, alluvium, rocks containing large voids such as limestone and basalt, and granitic areas where widespread springs often occur. Medium yields occur from badly-jointed rock and some sedimentary rocks.

The contribution of baseflow to streamflow and its relation to the size of catchment area depend on several factors, and the occurrence and distribution of aquifer types discussed above will have a major effect. In general, baseflow contribution increases in a downstream direction, at least to catchment sizes of several thousand km^2. It is more likely that the water table will intersect the surface or stream channels in the downstream areas. Upstream channels are often ephemeral as their beds are above the water table. Unconsolidated sediments, alluvium and other high-yielding aquifers are more likely to occur in the lower sections of streams. It is of interest to note that in a study of coastal and inland N.S.W. streams, Klaassen and Pilgrim (1975) found that baseflow characteristics were more strongly related to the occurrence of alluvium along the stream channel than to the general rock types over the catchment. This alluvium is more likely to occur along the flatter downstream sections of streams.

Overall, it would be expected that where groundwater inflows are appreciable, runoff would increase with increasing catchment area. However, this would depend on the occurrence and distribution of aquifers and on the other factors discussed in this chapter.

2.2.4 Channel Transmission Losses

In sub-humid, semi arid and arid regions, substantial abstractions from runoff may occur as flow moves down the stream channel. Where the water table is below the water level in the stream, water infiltrates into the bed and the banks. This may cause appreciable reductions in flood peaks and volumes as the flood moves downstream, as illustrated by Renard and Keppel (1966) for the Walnut Gulch catchments in Arizona. Sharp and Saxton (1962) found transmission losses of up to 150 000 m^3 per km in a study of floods on 18 rivers in the Great Plains of U.S.A. In Australia, Laurenson (1962) found losses of between 9 000 and 70 000 m^3 per km in four floods on the Darling and Murrumbidgee Rivers in N.S.W. Some of the water infiltrated during floods may be returned later to the stream. However, much is lost to runoff as it is transpired by vegetation. Similarly, transmission losses often occur from low sustained flows and the water is eventually lost by evapotranspiration. The last two studies referred to above involve catchments with areas outside the range of interest in this study. However, the Walnut Gulch catchments are certainly of relevance. In addition, transmission losses have been reported in small catchments in humid eastern N.S.W. Mathematical model studies by Boughton (1965) indicated transmission losses of about 1500 m^3 per km on small catchments near Sydney. In a tracing study on a small catchment near Sydney with an average annual rainfall of 1300mm, Pilgrim (1966a) found considerable transmission losses from runoff at the start of floods, and some high rates of runoff were completely absorbed in the upper channels.

It therefore seems that even in humid areas of Australia, channel transmission losses can lead to considerable reductions in both flood peaks and volumes of runoff down a stream. This is the reverse of baseflow contributions discussed in Section 2.2.3. Whether runoff increases or decreases with increase of catchment area as a result of these factors will depend on the conditions applying to the particular catchment.

Depending on current and antecedent rainfalls, it is possible that baseflow contributions would occur over a section of a stream at some times, and transmission losses could occur at other times. It is also probable that transmission losses occur in the headwater sections of many Australian streams where the water table is below the bed, baseflow contributions occur a little further downstream where the water table is above the bed, and transmission losses again occur still further downstream where the river passes through drier country. As discussed in later chapters, these factors have a major influence on the relation between hydrological characteristics and catchment area.

2.2.5 Channel Storage

Temporary storage of flood water in transit in the stream channels and on the catchment surface causes attenuation and delay of the flood wave. This results in some relative reduction of flood peaks with increase of catchment area. However, volumes of floods and of long-term flows are basically unaffected. The only possible effect would be that the lengthened time base of the flood due to storage would lead to increased opportunity for transmission losses and for evapotranspiration with increasing catchment area.

2.3 VARIATIONS OF CATCHMENT CHARACTERISTICS WITH AREA

2.3.1 Effects of Land Use

A very large number of studies has been carried out on the effects of various types of land use on runoff. Most studies have utilized plots and small catchments, but large catchments have also been studied. Many of the results on small areas have not been reproduced on large catchments, where single land uses seldom apply, and the averaging resulting from the heterogeneous conditions often masks the effects of individual land uses.

A comprehensive review of studies to 1970 has been given by Boughton (1970) on the effects of different land uses on various aspects of hydrological response. A brief summary of Boughton's conclusions and the results of some recent studies is given below to indicate likely relationships between the response of small and large catchments

Urbanisation obviously increases storm runoff from catchments, but little change has been observed in baseflow. Total runoff from urbanised catchments is increased, although little quantitative information is available. The quality of the water is generally impaired (Cordery, 1976a,b). Flood flows are affected to a greater degree, with increase in volume of storm runoff, decrease of storage and concentration times, and encroachment and modification of channels. Increases in flood peaks of 200-300 per cent have frequently been reported. Roads in small rural and forested catchments have also been found to increase flood peaks and storm runoff. These large changes in response resulting from urbanisation and roads on small catchments become almost insignificant on large catchments where the areas affected are relatively small. The effects of urbanisation and roads can thus lead to considerable differences between the responses of small and large catchments in the one region.

The multitude of small dams and the fewer larger water supply storages obviously affect runoff by depleting and modifying downstream flows. Little definitive information is available, but it seems that a large effect is only apparent for a limited distance downstream of the dam, so that small catchments are again most affected. Construction of banks and terraces, normally as soil conservation measures, has been found to have little effect on total runoff, but reduced flood flows from small areas have been observed. No evidence has been found of appreciable reductions in major floods from large catchments.

One of the most important changes in land use is the clearing of forests and replacement by shallow-rooted pasture and crops. These changes include thinning of forests, replacement of natural forests with exotic trees (usually softwoods in Australia), and removal of phreatophytes from stream channels. Many studies of the hydrological effects of these changes have been reported, and several reviews of these studies are available, including those of Hibbert (1967) in the U.S.A. and Langford and O'Shaughnessy (1977) in Australia. The general conclusion, supported by almost every individual study, is that runoff is increased by clearing of forests and replacement by shallow-rooted vegetation. Similarly, re-establishment of forest cover reduces runoff. However, it has also been generally concluded that the increases in runoff volumes and flood peaks with clearing are so highly variable that no general relationships can be established, and that the magnitudes of the changes are for the most part unpredictable. The increases in runoff seem to be small compared with the large variability of most Australian streams.

It is generally considered that the increase in runoff with clearing results from a rise in the groundwater table rather than from increases in storm runoff. The opportunity for evapotranspiration decreases when deep-rooted trees are replaced by shallow-rooted pasture and crops. Differences in interception, infiltration and depression storage for trees and grasses do not show any systematic effects of the same magnitude as those caused by differences in root depths. Comparisions of water use of hardwood and softwood trees have shown no differences that could not be attributed to differences in root depths. Studies where forests were defoliated and ground litter removed have shown small and inconsistent increases in flood peaks, but resulting increases in erosion are of much greater practical significance.

Homogeneous vegetation generally covers only relatively small areas. The effects of forests or clearing on runoff will thus be more apparent on small than on large catchments. For the latter, the averaging effects of areas of different land use will tend to mask out any effects. In addition, forested areas tend to be concentrated in steeper headwater regions with small catchment areas, whereas the large flatter areas of large catchments are mainly cleared. Both of these factors will tend to lead to differences between the hydrological characteristics of small and large catchments, and to a greater variability of the characteristics of small catchments.

Forest fires also affect runoff, but there is no simple relationship governing the effects of fire, which depend on the site and on rainfall and climatic conditions after the burn. Studies of the effects of fire on Australian catchments have been given by Brown (1972), Langford (1976), and Mackay and Perrens (1979). The concensus of opinion is that low intensity burns have little effect, but that high intensity wildfires often increase flood peaks and to a lesser extent total runoff for some time after the fire. These hydrologic changes are caused by reduced interception, transpiration, catchment roughness and possibly infiltration, and by modifications to the chemistry of the catchment surface. As fire is likely to affect relatively larger postions of small than large catchments, its effects on the former will be greater. As for other factors, this will increase the variability of the reponse of small catchments and tend to cause differences between the hydrological characteristics of small and large catchments.

Variations in agronomic practices form a further change in land use. These cover such activities as pasture improvement, crop rotation, mulching, changes of cover type, changes in type and stocking density of grazing animals, and land treatment to control erosion. The greatest influence of these measures is on evapotranspiration, rather than on interception, infiltration or depression storage. Evapotranspiration is reduced by replacement of deep-rooted by shallow-rooted vegetation, and by measures such as fallowing and overgrazing where the density of vegetation is reduced. As a consequence, the groundwater table will rise and runoff is increased. Once again, such effects apply more specifically to small catchments. This is particularly the case for flood flows, where the evidence indicates only localised effects.

In summary, the results of a great number of studies indicate that changes in the various types of land use affect the hydrological characteristics of small catchments more than those of large catchments. Land use types are rarely uniform over large catchments, and their effects are averaged out and are rarely discernible. The hydrological response of small catchments thus tends to be more variable than that of large catchments, and the factors discussed can be expected to lead to differences between the characteristics of the two types of catchments.

2.3.2 Effects of Variations of Soil Type and Geology

It would be expected that variations of soil types and geology would lead to variations in hydrological response. Most of the evidence for variations resulting from these causes relate to small catchments, plots, infiltrometer tests and laboratory tests of small samples. Very few cases of relations between observed values of hydrological variables and soil types or geology have been reported for medium and large catchments. At least part of the reason is probably that soil type and geology normally remain constant over only relatively small areas. This can be illustrated with baseflow recession characteristics. Several investigators (such as Farvolden (1963), Knisel (1963), Ineson and Downing (1964), Schneider (1965) and Grant (1971)) have reported relationships between baseflow recessions and geological and geomorphological characteristics. However, these have mainly applied to very small catchments, and Farvolden (1963) found that lack of geological homogeneity masked differences between catchments for areas greater than 5 km^2. It would therefore be expected that from this viewpoint, hydrological responses of small catchments would be more variable than and different to those of large catchments.

Several other factors would influence relationships. Many small catchments that are of interest are at generally higher elevations than the larger catchments of which they form part or which are in the same region. The fact that their average elevation is higher probably indicates that rock types are harder and more resistant to erosion than those for the remainder of the large catchments. Secondly, soil types tend to occur in sequences across a valley cross-section. The wider. flatter valleys occupying much of large catchments tend to have different soil sequences to those of the steeper and narrower valleys of small catchments. Thirdly, average rainfall, vegetation and soil type are interrelated. Comparing a location with low rainfall to one with high rainfall, vegetation will generally be less dense in the former case, so that addition of organic matter to the soil and root activity will be less. This will further inhibit infiltration of the low rainfall, providing less water for leaching of the soil and for soil profile development. The effects of these differences are most pronounced in comparing the extremes of humid and arid zone hydrological characteristics, and at least partially account for observed differences in runoff response under these conditions, as illustrated for far-western and eastern N.S.W. by Pilgrim et al. (1979). The same trends probably apply on a much smaller scale in comparing headwater catchments at higher elevations and often having higher rainfall with the lower elevations and rainfalls covering much of the large catchments. All of the above three factors could lead to differences in hydrological characteristics of small and large catchments

Overall steepness of catchments affects their hydrological responses, especially flood characteristics. Steepness is related to soil types.

In all of the above discussion, it should be remembered that the soils or geology of relatively small areas of a catchment may dominate its response. For example, Klaassen and Pilgrim (1975) found that baseflow characteristics were more related to the occurrence of alluvium along the stream channel than to the general rock types over the catchment, as mentioned in Section 2.2.3.

2.3.3 Effects of Climatological Factors

Variation of average rainfall over a catchment, often with higher totals in the higher headwater areas, obviously affects the magnitude of hydrological response. However, the actual relations governing runoff and also the response functions may remain unchanged over the whole area, and apply to both small headwater catchments and to large catchments embracing the lower elevations. Investigation of the constancy of the basic relations despite varying rainfall inputs is discussed in the later chapters of this report.

The only real influence of rainfall on the basic response relationships and functions is where the rainfall regime over a long period of time has affected the development of the soil profile and its infiltration and water holding characteristics, as discussed above in Section 2.3.2.

Evapotranspiration accounts for most of the water input to catchments. However, its major influence on the relationship between the hydrological characteristics of small and large catchments is of a secondary nature through variations in land use and the effects of short and long rooted vegetation. The only direct influence is through differing radiation input and hence evapotranspiration and runoff on small areas with northerly and southerly aspects. Several studies have reported differences in runoff due to this cause from small areas that are otherwise similar. This could thus lead to variations in the hydrological characteristics of small catchments with different aspects, and cause differences from those of large catchments where this effect would be averaged out.

2.4 GEOMORPHOLOGICAL RELATIONS WITH AREA

Many geomorphological variables describing the physical form of catchments have been found to be strongly correlated with area. As runoff in general, and flood peaks and hydrographs in particular, are related to physical characteristics of catchments, these correlations should indicate firm relationships between hydrological response and catchment area. As they thus provide support for consistency of hydrological characteristics for small and large catchments, the range of geomorphological relationships of variables with area will be briefly reviewed.

The best-known relation with area is for stream length. Hack (1957), Gray (1961) and Leopold et al. (1964) all derived relations in which mainstream length is a function of area to a power of approximately 0.6. Using a stratified sample of 250 catchments with areas of 0.3 km^2 to 8 x 10^6 km^2 selected from several thousand sets of data, Mueller (1973) derived a similar relation with an exponent of 0.55. Meynink (1975) obtained an exponent 0.58 for 76 small Australian catchments. Shreve (1974) claimed that the relation tended to vary a little with area, and that the exponent tended to decrease from 0.6 to 0.5 as catchment area increased. Shreve and also Werner and Smart (1973) were able to verify the form of the relation between mainstream length and area from channel network theory.

Length from the outlet to the centre of area of a catchment has often been related to flood characteristics, and has been shown by Gray (1961) to be highly correlated with mainstream length. Length to centre of area is thus also correlated with area.

Gray (1961) also found that over a given region, stream slope is inversely related to mainstream length. It is thus also related to area. Different relations applied to three different regions in the U.S. Flint (1974) found that slopes of individual stream segments within a catchment were related to variables which themselves are related to area, although Onesti and Miller (1974) found that this type of relation did not apply to very small areas with stream orders below four. In this case, geology and other factors controlled slope. However, it seems that within a fairly homogeneous region, slope of individual stream segments is related to drainage area. As overland slope has been found to be correlated with stream slope (Strahler, 1974), this is also related to area.

A great deal of work has been carried out in recent years on describing and quantifying channel networks. Many measures have been developed. Onesti and Miller (1978) found that several of the network measures were related to area and to other characteristics closely determined by area, and that other physical and hydraulic characteristics could not be related to the measures.

Overall, the strong dependence of many physical characteristics on area provides support for the expectation that hydrological relationships derived for small catchments should be able to be extrapolated to large catchments, especially for flood flows. However, the scatter and lack of perfect correlation in the geomorphological relations indicates that similar scatter will be reflected in the hydrological relations.

2.5 VARIATIONS OF HYDROLOGICAL CHARACTERISTICS WITHIN SMALL HOMOGENEOUS AREAS

The search for hydrological relationships between small and large catchments implies that hydrological characteristics remain sensibly uniform within fairly homogeneous regions. This is also really implied in the representative basins concept, as noted in Section 1.1.

Considerable experimental evidence has accrued to indicate that large variations often occur in hydrological characteristics over small, apparently homogeneous areas. Much of the discussion of partial area runoff and variable source areas for storm runoff in Section 2.2.2 indicates these variations. The studies of Hewlett and Hibbert (1967), Betson and Marius (1969), Dunne and Black (1970a,b) and Pilgrim (1966a) indicated some consistent but differing variations of runoff over small areas. The randomly-located source areas of runoff reported by Amerman (1965) on a small catchment in Ohio are of more importance in this context. Also, the study reported by Pilgrim and Huff (1978) and Pilgrim et al. (1978) on a large plot selected for its apparent uniformity graphically illustrates the variations of runoff within a small area. Small-scale variations in runoff can also occur in very arid areas, as reported by Yair and Lavee (1976).

Large variations of infiltration characteristics and hydraulic conductivity over small, apparently homogeneous areas have also been reported (e.g. Rogowski, 1972; Nielson et al., 1973; Sharma and Seely, 1976).

The concept of uniformity of hydrological characteristics over even small homogeneous areas thus seems suspect. Any uniformity that does occur at the macro-scale may largely result from averaging of these small-scale variations.

Once again, it is likely that greater variability will occur in the characteristics of small catchments than in those of large catchments as a result of small-scale variations.

2.6 PUBLISHED RELATIONSHIPS FOR SMALL AND LARGE CATCHMENTS

There is an abundance of literature that is of indirect relevance to the relationship between hydrological characteristics of small and large catchments. All regional studies are of some relevance, whether they are investigations of hydrological variables or processes, or the development of design relationships. However, computer literature searches over two data bases indicated that there are relatively few publications directly addressing the problem.

It is not possible to review all of the relevant literature, and only a few publications will be referred to here. Vorst and Bell (1977) have reviewed a wide range of regional relationships. They found that only three catchment variables were consistently significant in predicting hydrological characteristics. These were area for the prediction of runoff volumes, and mainstream length and slope for hydrograph response times. The relationships discussed in Section 2.4 indicate that length can be considered as a surrogate for area, and slope is also correlated with area in a given region. Thus hydrological characteristics have consistently been found to be related to area in empirical studies. However, the derived relations often involve other variables and also generally incorporate considerable scatter of data. None have been successful over a wide range of conditions, reflecting the effects of the various factors discussed in this chapter.

Derived relationships are often not consistent with one another and show considerable variability. This is graphically illustrated by relationships of mean annual runoff with area for three regions in the United States reported by Renard (1977). In one relation for a humid area, runoff increases with area as a result of baseflow contributions. In a subhumid area runoff remains constant, and in a semiarid region the runoff decreases with increasing area as a result of channel transmission losses. Amerman and McGuinness (1967) discussed the relation of hydrological characteristics of small and large catchments, and the conditions necessary for the use of the former to estimate the latter.

There are many examples in the published literature of poor or non-existent relations between hydrological variables and catchment area. However, there are also many studies that have been successful, such as those of Allis (1962), Sopper and Lull (1965) and Kincaid et al. (1966). Design flood relationships also represent a common type of successful correlation of hydrological characteristics and area. The index flood (Dalrymple, 1960) and multiple regression (U.S. Geological Survey, 1967) methods of regional flood frequency analysis involve such relations, as do most of the design hydrograph methods reviewed by Cordery and Pilgrim (1970). Synthetic unit hydrograph methods, such as those in "Australian Rainfall and Runoff" (Institution of Engineers, Australia, 1977) and the procedure of Cordery and Webb (1974) also relate flood characteristics to stream length and hence to area.

In summary, the literature abounds with empirical studies that are directly or indirectly relevant to the relation of hydrological characteristics and catchment area. Although many successful relations have been derived, unsuccessful studies are also common. Large scatter of data is generally evident, as a result of the factors discussed in other sections of this chapter, and no relations have been successful over a wide range of conditions. It therefore seems that care is needed in applying derived relations outside the immediate range and location of their derivation and that further study is desirable on the effects of area and other causative factors on hydrological characteristics.

2.7 EFFECT OF DATA ERRORS

Discussion of the relation between hydrological characteristics and area would not be complete without a mention of the effects of data errors. These are likely to introduce scatter, inconsistencies and bias, and even to mask the presence of relationships.

Data errors take many forms. Estimates of catchment rainfall always involve some degree of error. Spatial variability of rainfall causes problems with large catchments, especially with relationships involving mean or lumped rainfall values. Much of the analysis in Chapter 3 involved the reduction of errors from this cause. Rainfall estimates in headwater locations often cause problems as a result of lack of gauges and high variability of rainfall. This may affect data for small headwater catchments or bias data for large catchments. In a previous project, a large body of data collected for a medium-sized catchment in mountainous country in northern N.S.W. had to be abandoned because the runoff in many years exceeded the estimated rainfall, due to bias of the latter data as there were no gauges in the upper catchment where high rainfall occurs.

Some error is also inherent in all runoff data. Likely errors are particularly large for high discharges on small catchments. Much of the total runoff may occur in relatively short durations of high flow. An examination of gauging information for about 250 catchments in N.S.W. with areas less than 250 km^2 and records generally of 10 years or more indicates that the highest gauging on half the catchments is less than half the once in one year flood, and on 20 per cent of the catchments is less than one fifth of the once in one year flood (McDermott and Pilgrim, 1980). The relative magnitude of the highest gauging tends to decrease as catchment size decreases. At least under Australian conditions of high variability of stream flow, gross extrapolation of gauging station rating curves is thus involved in computation of runoff, especially for small catchments.

Measures of area and related catchment characteristics are also subject to considerable error. Area itself is not greatly affected, but its common surrogate of streamlength is. Variations of 10 per cent are common in individual measurements of lengths from the one map. Different map scales can cause differences of measured lengths of greater than 50 per cent (McDermott and Pilgrim, 1980). Measured lengths on small and large catchments in the one region may be affected to quite different degrees. Stream slope, which is also related to area, is also difficult to measure, and differences in methods of estimating effective slope can lead to heterogeneity of data, as discussed in Chapter 4. Other catchment characteristics related to area, such as stream orders and channel network measures, are also subject to considerable measurement errors.

A further cause of error is differences in defining and evaluating a given parameter used to quantify a hydrological characteristic. This can again cause heterogeneity in a body of data, as dicusssed in Chapter 4 for values of the parameters C and K for the Clark runoff routing model for flood estimation.

Even if perfect relationships existed between hydrological characteristics for small and large catchments, the various types of data errors discussed above would cause considerable scatter and possible bias in derived relationships, and must always cause some doubt in drawing conclusions. It is important that considerable care be taken in the preparation of data and development of analytical procedures to reduce or eliminate as much data error as possible. The effects of the unavoidable residual errors must then be carefully assessed in evaluating derived relationships.

2.8 SUMMARY

The review of this Chapter has demonstrated that a very large number of factors affects the relation of hydrological characteristics of small and large catchments. In fact, these factors cover much of the scope of the science of hydrology. Without consideration of the factors reviewed, study of relationships between small and large catchments cannot rise above mere empiricism, and cannot be more than site specific. It is for these reasons that the broad review of factors has been given in this Chapter. The review indicates that while general relationships will exist between small and large catchments, no closely-defined and simple relationships are likely. These indications are borne out by published relationships.

Inconsistencies in relationships will result from variations of runoff processes operating on the catchments. These variations are still not fully understood, and it is not possible to generalize regarding their effects. Baseflow contributions tend to increase runoff in a downstream direction while transmission losses have the opposite effect, and their nett effect on the relation between runoff from small and large catchments depends on the conditions applying in the particular region.

Many factors affect the hydrological characteristics of small, relatively homogeneous areas, but their effects over large areas tend to be masked as a result of averaging. These factors include land use, soil type and geology, and climatological characteristics. The result is that the characteristics of small catchments exhibit greater variability than those of large catchments, and differences between the characteristics of the two types of catchments are likely. However, there is considerable evidence for appreciable variability of hydrological characteristics within small, surficially uniform areas, so that the very concept of even small-scale uniformity of hydrological characteristics is suspect.

Geomorphological studies have demonstrated the dependence of many physical characteristics of catchments on area. This provides support for the expectation that hydrological characteristics of small and large catchments should be related, especially for flood flows.

Overall, it must be expected that it will generally be possible to derive relationships between the hydrological characteristics of small and large catchments, as area is probably the most important catchment characteristic affecting all aspects of runoff. However, the wide range of factors discussed will lead to many differences in these relationships, and even to differences in the direction of trends. Considerable scatter is inevitable in derived relationships as a result of the factors that cannot be explicity included and the effects of data errors. Empirical studies may seek generalized and simple relations, but the range of factors reviewed indicates that these simple and consistent relations are unlikely to be achieved.

In view of this, the approach adopted in this study has been to examine the relationship of three types of hydrological characteristics of small and large catchments over one or several regions. The results provide examples of regional relationships from which some general conclusions regarding Australian conditions can be drawn. They also demonstrate methodologies than can be applied elsewhere. The derived relations are of use for practical design in their regions of derivation, although considerable scatter is inevitably involved, as discussed above. However, the factors reviewed demonstrate clearly that any derived relations cannot safely be extrapolated beyond their region of derivation.

3. ANNUAL RAINFALL-RUNOFF RELATIONS

3.1 APPROACH ADOPTED

The first of the three hydrological characteristics investigated was the form of the relationship between annual rainfall and runoff. As discussed in more detail in Section 3.2, an annual time period was selected for analysis of runoff volumes, as random variations in antecedent conditions and water storages in the catchment have less effect on annual runoffs than on runoff volumes for shorter time intervals.

A simple preliminary analysis was carried out on average annual runoffs for all gauging stations with records of more than about 10 years in several river basins on the coast and on the western slopes of New South Wales. Runoff volumes were obtained from data published by the Department of National Resources (1974) and the New South Wales Water Conservation and Irrigation Commission (various dates). Average annual runoff coefficients were calculated and examined for the effects of catchment area, average rainfall, location, and catchment characteristics. As expected, considerable variations were evident in the derived coefficients, and different trends were present in different river basins. Two examples will be discussed briefly. Table 3.1 lists average annual runoff coefficients and other data derived for 32 gauging stations and estimated at six major confluences in the Clarence River valley on the north coast of New South Wales. Coefficients range from 0.15 to 0.83, and are strongly related to average annual rainfall. Not only does runoff increase with increasing rainfall, but the runoff coefficient also increases rapidly which follows from the shape of the annual rainfall-runoff relation discussed in Section 3.2. The coefficient values are plotted on a map of the basin in Figure 3.1, in which isohyets of median annual rainfall are also shown. The coefficient values are obviously strongly related to rainfall, and they also tend to decrease with increasing catchment area where average rainfall is approximately constant, probably reflecting the effects of transmission losses, even though the rainfalls are high. There is also considerable scatter of values which may result from data errors or the effects of other factors discussed in Chapter 2.

Table 3.2 lists data for stations in the Gwydir River basin in north-western New South Wales. Unfortunately, very few small catchments with long records are available on the west-flowing inland streams. There is some scatter of data in Table 3.2, but there is a definite trend of decreasing runoff with increasing catchment area. Although average rainfall decreases with increasing area, the main reason for this trend is almost certainly transmission losses.

Consideration of the various trends and scatter of data illustrated by the two examples discussed above, and also the range of factors discussed in Chapter 2, indicates that derivation of meaningful relationships between small and large catchments would be very unlikely using simple rainfall and runoff data. The data in Table 3.1 are nonlinear, posing problems for regression techniques. The approach chosen for this study has thus been to investigate the consistency of the form of the relation between annual rainfall and runoff. This not only promises greater likelihood of success, but also provides more real information on the variation of annual runoff with area and with other factors. Use of the relation between rainfall and runoff on a given catchment also takes care of the effects of the rainfall values that have such a marked influence in Table 3.1. Different rainfalls simply apply to different ranges of the one rainfall-runoff relation, which in itself may not change. A single rainfall-runoff relationship could thus apply over the whole of the Clarence River basin, despite the wide variations in runoffs and

Table 3.1

Annual Runoff Coefficients for Selected Stations in the Clarence River Basin

River	Gauging Station	National Gauging Station Number	Area km^2	Approx. average annual rainfall mm	Annual runoff coefficient
Maryland	D/S Wylie Ck	204039	373	910	0.18
Bookookoorara	Undercliffe	204006	127	910	0.22
Koreelah	Hewetsons Mill	204040	231	1030	0.34
Boonoo Boonoo	Wilnor	204035	135	940	0.29
Tooloom	Tooloom Falls	204042	308	1140	0.25
Cataract	Sandy Hill	204036	236	940	0.31
Peacock	Bonalbo	204043	47	1140	0.16
Gorge	Bonalbo	204044	41	1140	0.21
Rocky	Glen Elgin	204032	47	1040	0.28
Rocky	Billyrimbah	204033	985	1020	0.22
Rocky	Total estd.	-	690	1020	0.20
Clarence	Tabulum	204002	4430	960	0.21
Nymboida	Bostobrick	204019	220	1520	0.53
Little Murray	North Dorrigo	204016	104	1730	0.73
Rocky	Dorrigo	204010	16	1950	0.77
Bielsdown	Dorrigo No. 1	204009	31	1950	0.55
Bielsdown	Dorrigo Nos. 2&3	204017	78	1950	0.61
Wild Cattle	Megan	204024	31	1950	0.83
Majors	Grafton Road	204012	12	1450	0.59
Jocks Water	Maida Vale	204013	9	1450	0.82
Blicks	Hernani	204021	70	1400	0.48
Blicks	Dundurrabin	204020	251	1400	0.38
Sheep Station	U/S Clouds Ck Junction	204038	18	1140	0.24
Mole	Moleton	204028	21	1270	0.66
Bobo	Bobo Nursery	204026	80	1570	0.83
Camp	Lowanna	205029	10	1400	0.51
Little Nymboida	Timmsvale	204027	31	1570	0.58
Clouds	Clouds Ck	204037	62	1020	0.33
Nymboida	Nymboida	204001	1660	1400	0.36
Little	Broadmeadows	204015	2670	940	0.20
Little	Above Nymboida Junction	-	3180	940	0.16
Nymboida	Buccarumbi	204005	5260	1070	0.23
Mann	Above Nymboida Junction	-	1870	940	0.15
Mann	Jackadgery	204004	7800	1020	0.23
Mann.	Total estd.	-	8400	1040	0.22
Clarence	Above Mann Junction	-	7600	990	0.22
Clarence	Lilydale	204007	16700	1020	0.22
Orara	Total estd.	-	2020	1220	0.25

Table 3.2

Annual Runoff Coefficients for Selected Stations in the Gwydir River Basin

River	Gauging Station	National gauging station number	Area km²	Approx. average annual rainfall mm	Annual runoff coefficient
Gwydir	Yarrowyck	418014	855	840	0.15
Gwydir	Bundarra	418008	3990	810	0.12
Gwydir	Pinegrove	418012	6480	790	0.16
Gwydir	Bingara	418010	6650	760	0.15
Horton	Rider	418015	1970	740	0.12
Gwydir	Gravesend Road Bridge	418013	10750	740	0.10
Gwydir	Pallamallawa	418001	12310	710	0.09
Gwydir	U/S Meehi offtake	418006	12430	710	0.04

runoff coefficients evident in Table 3.1 and Figure 3.1.

3.2 FORM OF ANNUAL RAINFALL-RUNOFF RELATION

The general form of the relation between rainfall and runoff, and the factors affecting it, can be examined by means of the catchment water balance equation:-

$$P = Q + Q_{sub} + ET + \Delta S$$

where P = rainfall
Q = runoff measured at the catchment outlet,
Q_{sub} = subsurface flow of water across the catchment boundary
ET = evapotranspiration loss from the catchment
and ΔS = change in amount of water stored within the catchment.

This equation applies to any selected time period. On most catchments, Q_{sub} is small compared with Q and, depending on the circumstances, with one or both of the other terms. Its effects will be neglected here, but in some cases it can be of sufficient magnitude to appreciably affect the relation between P and Q. For relatively short periods ΔS can be large, and it is very difficult or impossible to measure in practice, especially the changes in groundwater and soil water storage. Even for monthly values, the variation in ΔS from month to month causes large scatter in relations between runoff Q and rainfall P. For this reason, annual values were selected in this study, as the values of ΔS are small relative to the other terms in equation (3.1) over periods of a year. Even longer periods would further reduce the influence of variations in ΔS, but would also reduce the sample size of available data. As rainfall and evapotranspiration vary seasonally, it is advantageous to select a period of measurement of one year that will not reflect these variations, and that will thus tend to minimize the value of ΔS.

For annual data, the relation between rainfall and runoff will then be largely governed by the evapotranspiration ET. Denmead and Shaw (1962) and Slatyer and Denmead (1963) have shown that while potential evapotranspiration depends on meteorological conditions, the actual evapotranspiration also depends on the availability of soil water. This is shown in Figure 3.2 which is generalized from their data. Depending on the potential evapotranspiration and the vegetation type, the actual evapotranspiration is restricted as the available soil water is reduced. This can be considered conveniently in terms of the evaporation opportunity, the ratio of actual to potential evapotranspiration.

Figure 3.3 shows the general form of the relation between annual runoff and rainfall. Over the range 0-a of very low rainfalls, virtually all of the rain is infiltrated and disposed of by evapotranspiration, even though the evaporation opportunity is low. The runoff is effectively nil. Within the range of rainfalls a-b, runoff occurs and its volume increases with increasing rainfall but at a lower rate than that of increase of rainfall. The evapotranspiration loss, shown in Figure 3.3 as the difference between P and Q (from equation 3.1), increases with increasing average wetness of the catchment and evaporation opportunity, in accordance with Figure 3.2. Runoff occurs because over at least some parts of the year, rainfall is greater than evapotranspiration and the consequent recharge of groundwater raises the water table resulting in baseflow and periods of storm runoff. At high rainfalls in the range b-c and beyond, the catchment is sufficiently wet all of the time for evapotranspiration to occur at its potential rate in accordance with Figure 3.2 and evaporation opportunity is unity. The evapotranspiration losses are effectively constant over this range, and hence the rainfall-runoff relation is a straight line at 45^{o} and parallel to the Q=P line.

It has been suggested that as a result of increased cloud cover, relative humidity and albedo at high rainfalls, the loss to stream runoff should in fact decrease with further increases in rainfall and not remain constant. However, only a small decrease would be likely, and the data used in this study did not support this suggestion. A constant loss at high rainfalls has thus been assumed.

While the general form of the relation between annual rainfall and runoff is as developed in the idealised discussion above, considerable scatter occurs about the general relation when real data are plotted. The scatter results from several causes:-

(a) Temporal variations of rainfall. The same total rainfall can occur with many different time patterns over the period of a year. Concentration of most of the rain over a fairly short period could cause surface runoff and raising of the water table with consequent baseflow, whereas relatively uniform rain might be disposed of by evapotranspiration and give little runoff. Rain in summer when potential evapotranspiration is high would be less likely to produce runoff than the same rain in winter. Figure 3.2 shows a further effect in that the decrease in the rate of actual evapotranspiration as soil water availability decreases depends on the potential evapotranspiration, and hence on the season in which the water deficits occur.

(b) Spatial variations of rainfall. In a similar fashion to temporal variations, concentration of rainfall over limited areas would be likely to produce more runoff than more uniformly distributed rainfall. Where orographic effects are important, spatial patterns may maintain some consistency, but considerable variations generally occur from year to year and within a given year.

(c) Changes in water stored at the end of each year. Reference to equation (3.1) shows that runoff depends directly on the change of storage between the start and end of each period . Variations in storage within the period do not affect the annual runoffs, but only the distribution of runoff during the year. However, concentration of rainfall and runoff near the end of a year can lead to high storage at the end of the period, and a high value of the ΔS term in that year and a negative value over the next year. These variations are

directly reflected in the runoff values.
(d) The effects of all factors discussed in Chapter 2. All of the many factors discussed affect the runoff from a given rainfall, so that variations in these factors from time to time will also affect the runoff and lead to scatter in the rainfall-runoff relation. Aspects of particular relevance are variations in the runoff processes and their relative contributions, variations in land use and in the type and condition of vegetation, and variations in the type and magnitude of data errors.

3.3 METHOD OF ANALYSIS

3.3.1 General Considerations

The objective of the analysis described in this chapter is to derive annual rainfall-runoff relations of the form shown in Figure 3.3 for a range of small and large catchments in one or more regions, and to compare the derived relations for the different catchment sizes. As small variations in the derived relations may be of importance, it is essential that these relations should be of the highest possible accuracy and that all available data should be used as efficiently as possible. Bias or random errors and scatter of data could hide or distort any differences or trends in the relations.

A considerable proportion of the duration of the project was spent on the preparation and checking of the large volume of data utilized. Without this, any results would have been meaningless or misleading. Many months were lost in the preparation of data that later proved to be of insufficient quality.

Little could be done to reduce several of the four causes of scatter of data discussed in the previous section. The effects of changes in storage were minimized by using annual data, as discussed. Calendar years were used, as there is no marked seasonal occurrence of rainfall and runoff in New South Wales. Use of yearly periods means that it is not possible to explicitly consider temporal variations of rainfall. However, the long periods may lead to some averaging of the effects of these variations.

Catchments were selected with the longest records that could be obtained. The large data samples reduce probable errors resulting from scatter of the data points, but increase the possibility of changes in land use and vegetation type. This cause of scatter can only be accepted and borne in mind during analysis and interpretation. As discussed in Chapter 2, the effect is likely to be greater for the small catchments. However, no major changes in land use are apparent on the catchments used in the study during the periods of record analysed.

The only factor causing scatter of data whose effect can be greatly reduced by analytical techniques is the spatial variation of rainfall. Two complementary techniques were used to account for the effects of these spatial variations. The first was to explicitly consider the spatial pattern of rainfall in each year by means of the equivalent of isohyetal maps and analysis. The second was the derivation of the rainfall-runoff relations by McCutchan's (1963) method to allow for different rainfall on a large number of sub-areas within each catchment. These two techniques will be described in the two following sub-sections.

3.3.2 Analysis of Rainfall

Rainfall data and station locations were manually collected and carefully screened for errors. These data were then punched on cards and a computer program was written and used to check the data on a station by station basis for errors and inconsistencies. Baron (1979) gives the program listing. The checked data were then stored on a yearly rather than station basis for derivation of yearly catchment rainfalls.

Of the various manual procedures for evaluating the distribution of catchment rainfall, isohyetal maps make the best use of available data. However, the very large volume of data to be analysed made the use of manual procedures not only tedious but virtually impossible. The maximum number of rainfall stations used on any catchment was about 200, with up to 76 years of records over 22 catchments. With periods of missing records for some stations and different periods of record, the number and distribution of stations generally varied with each year of record. This would have destroyed the computational efficiency of the Thiessen method and similar procedures, as new polygons would have been necessary for each year.

To overcome these problems, computer generated maps and numerical methods were developed to analyse the annual rainfall data and to evaluate their spatial distribution. There are a number of rainfall surface generation techniques and they can be grouped according to the type of rainfall data used, either in gridded or non-gridded format. In a detailed comparison of two such techniques Shaw and Lynn (1972) found that the use of Bicubic Spline functions on gridded data gave the best overall reproduction of two mathematically defined test surfaces. However, if the data were not in a gridded format satisfactory results were achieved using Multiquadric analysis. Since the rainfall data used in this study were not available in a gridded format and because such a conversion using essentially arbitrary interpolation techniques would introduce further errors, the Multiquadric techniques using the raw rainfall data was used to evaluate the rainfall distribution across the catchments studied.

A computer program MQUAD was written in Fortran IV to fit a multiquadric surface to rainfall values at stations with any distribution over a catchment, and to evaluate the rainfall depth at any point and the average depth over the catchment. A listing of MQUAD is given in Appendix A. As many rainfall stations as desired can be analysed by the program by changing the relevant dimension statement. In the program, catchment boundaries are defined by cartesian coordinates using latitudes and longitudes from topographic maps. A grid is then imposed over the area to create rectangular subareas. Typically 105-115 subareas are created within the catchment boundary. For each year, station coordinates and rainfall depths are read in and a multiquadric surface is fitted. As with most generated surfaces, rainfall stations outside of and around the catchment boundaries are required to "tie down" the fitted surface near the boundaries and to maintain the stability of the surface over the catchment. The results from two catchments have been excluded from the study as the stability of the generated rainfall surfaces was not considered to be satisfactory. Computer generated maps were produced and checked for each year for each catchment so as to ensure that the resultant rainfall surface was stable and sufficiently defined within and around the catchment boundaries.

The program also checks the possibility of two rainfall stations having the same coordinates but different annual totals. The slope of the fitted surface between two such stations would be theoretically infinite and an unstable rainfall surface would result. Checks are therefore carried out in MQUAD for any number of stations sharing the same coordinates. If found, only one station is included in the analysis, its rainfall total being the mean value of those stations sharing these same coordinates.

From the fitted multiquadric surface, the program calculates average rainfall depths for the whole catchment, at grid intersections, or for any specified subareas.

The performance of the multiquadric surface fitting technique was tested against annual rainfall values derived from manually drawn isohyetal maps over the catchment of the Nymboida River at Nymboida for the years 1920 - 1970. Over this period of record the number and distribution of relevant rainfall data varied considerably both in time and space and yet the relative difference between the two procedures was of the order of 1% with one extreme case of 3%. Since errors in measurement of rainfall of the order of 15% are not uncommon, the performance of MQUAD was thus deemed to be very satisfactory.

3.3.3 <u>Derivation of Rainfall-Runoff Relations by McCutchan's Method</u>

The form of the annual rainfall-runoff relation developed in Section 3.2 and illustrated in Figure 3.3 really only applies to a point.

The application of the relation to a catchment involves lumping or averaging of the point relation over the catchment. Where the rainfall-runoff relation is nonlinear and the rainfall varies over the catchment as generally occurs in practice, the average runoff plotted against the average rainfall will not fall on the true curve. This will be illustrated by the simplified example in Figure 3.4(a) where the catchment has five equal subareas, each having a rainfall that can be considered to be uniform. Nonlinear and linear rainfall-runoff relations that apply at every point on the catchment are denoted as (i) and (ii) on Figure 3.4(b). In Table 3.3, weighted average runoffs calculated from the subarea runoffs are compared with the runoffs estimated directly from the catchment average rainfall of 700 mm for the two relations. Where the rainfall-runoff relation is linear, there is no difference and thus no error is caused by using the average catchment rainfall. However, there is a considerable error in the nonlinear case (12 percent in this example).

Table 3.3

Comparison of Weighted Average Runoff and Runoff estimated from Average Rainfall

Sub-Area Av. R'fall Depth (mm) Fig. 3.4(a)	Weighting Factor $A_i/\Sigma A_i$	Sub-Area Runoff Depth (mm) Qi	
		Nonlinear Fig. 3.4(b) (i)	Linear Fig. 3.4(b) (ii)
500	0.2	90	170
600	0.2	140	210
700	0.2	200	250
800	0.2	305	290
900	0.2	405	330
Catchment Runoff, calculated as weighted average of sub-area depths		228	250
Runoff corresponding to average rainfall of 700 mm		200	250

Varying errors of this type with different spatial rainfall patterns in each year will cause increased scatter of data when average catchment rainfalls are used, and bias of the relation will also result as errors similar to that in Table 3.3 will all be of the same sign. To fit observed catchment runoffs, the apparent relation based on average catchment rainfalls will be too high. That is, the apparent relation will overestimate the runoff produced at a point by a given rainfall, although it will give the best lumped estimate of catchment runoff based on average catchment rainfall. It should be noted that in the above discussion and in all of the analysis in this study, it has been assumed that the true relation between annual rainfall and runoff is the same at all points in a given catchment. While there is no doubt that this is an approximation, it is the best assumption with the available data.

The objective in this study was to derive the true point rainfall-runoff relation for each catchment, thus eliminating scatter and bias due to spatial variations of rainfall. McCutchan (1963) has described a method for estimating this relation. This involves an initial estimate of the rainfall-runoff relation for a particular catchment, usually based on a plot of catchment average rainfall and runoff. Using this relation, subarea runoffs are determined from subarea rainfalls and the weighted average catchment runoff is computed in similar fashion to the example in Table 3.3. The computed annual runoffs are then compared with the observed runoffs and the rainfall-runoff relation is adjusted on this basis. The procedure is repeated until the best possible agreement is obtained between the calculated and observed runoffs.

A computer program QR was written for carrying out McCutchan's procedure with some additional refinements. The program listing is given in Appendix B. McCutchan delineated subareas between isohyets of 250 mm increments, but a much finer subdivision was used in this study. Rectangular subareas were defined by the grid imposed over the area with generally 105-115 intersections within the catchment. For each year of record, rainfalls for each grid subarea generated by MQUAD were used to estimate subarea runoff from a trial rainfall-runoff curve, the total catchment runoff being the sum of these subarea runoffs. The program then computed a regression of calculated runoffs on recorded runoffs and plotted this regression. On the basis of these results, an adjusted rainfall-runoff curve was adopted and the process repeated until a close correlation of calculated and recorded runoffs was obtained. It was decided that adjustment of the rainfall-runoff curve should be carried out manually using the operator's judgement rather than attempting to incorporate an automatic adjustment in the program QR. Although the final selection of the best relation for a given catchment was carried out subjectively, little variation in the final relation would be possible.

McCutchan's method involves much more work than derivation of simple relationships between catchment average rainfall and runoff but its use is justified in the context of this study for the reasons discussed earlier. Rainfalls varied widely over the catchments studied (Section 3.4). Also application of the rainfall-runoff relation to each of many subareas tests the relation much more thoroughly than using the lumped data. This is of practical importance where the size of data samples is necessarily limited

3.4 DESCRIPTION OF CATCHMENTS

As this study is concerned with the variation in catchment response with area, the ideal situation would be to keep all hydrological and geomorphological characteristics constant except for those which are in themselves a function of area. For example, maximum average rainfall intensity over a catchment must of necessity decrease with increase in area. Physical characteristics dependent on area were discussed in Section 2.4. As these characteristics are numerous and their interaction very complex, "nests" of catchments were deemed to be the closest realisation in nature. That is, the small catchments should be subareas of larger ones. Nests of catchments should share common characteristics across as many different sized areas as possible, although small headwater catchments may differ in many ways from the larger catchments of which they are part, as discussed in Chapter 2.

Considerable time was spent on examining data from several regions in New South Wales. After a thorough investigation of data in the central coast and tablelands regions - that originally selected for study - it was concluded that data of sufficient quality and length of record were not available over a range of catchment sizes. Small gauged catchments west of the Great Dividing Range were not available. Finally, nests of catchments in two northern coastal river basins of New South Wales were selected for study.

The first comprises seven catchments in the southern region of the Clarence River valley. The largest is the Mann River at Jackadgery with an area of 7800 km^2, and the others are nested within it with areas ranging down to 70 km^2. The catchments are shown on Figure 3.5 and median annual rainfalls over the region are shown in Figure 3.1. Streams in the region typically drain plateau areas around the catchment boundaries and pass through steep rugged valleys with little development of alluvial flats. Geologically, the Mann River catchment is dominated by Silurian series. Figure 3.6 shows a division of the region into approximate hydrological regions based on information in the regional report of the New South Wales Water Conservation and Irrigation Commission (various dates). These subdivisions are of a qualitative nature only.

Table 3.4

Comparison of landslopes of the largest catchments in each of the two regions studied

Classification	Percent area of largest catchment			
	Clarence Valley:- Mann River at Jackadgery (7,800 km^2)		Upper Hunter Valley:- Hunter River at Singleton (16,400 km^2)	
Mostly flat slopes < 3^0	7	27	16	36
Undulating to hilly slopes 3 - 8^0	20		20	
Hilly to steep 8 - 15^0	34	73	20	64
Rugged or mountainous slopes >15^0	39		44	

Derived from N.S.W. Conservation and Irrigation Commission (various dates).

As a contrast to the Clarence valley, the second group of fifteen catchments was selected in the Upper Hunter River valley. The largest is the Hunter River at Singleton with an area of 16400 km^2 and the others are nested within it with areas ranging down to 4.9 km^2. The catchments are shown on Figure 3.7 and median annual rainfalls over the region are shown in Figure 3.8. The average annual median rainfall over the Upper Hunter River is only 650 mm compared with 1025 mm over the Mann River catchment. Rainfall variability in both time and space is lower in the Hunter than the Mann River but is still quite large. Other aspects of climate are similar over the two regions, although potential evaporation is a little higher over the Hunter.

Streams in the Hunter valley generally drain rugged terrain around the catchment boundaries onto rich alluvial flats. Slopes on the Hunter catchment are generally similar to those on the Clarence, as shown on Table 3.4.

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Table 3.5 DETAILS OF STREAMGAUGING STATIONS OF CATCHMENTS STUDIED

Index No.	River	Gauging Station	Area km^2	Period of Record	Control	Max. Gauging m^3s^{-1}	Est.max. Discharge m^3s^{-1}	Mean annual Discharge $m^3 \times 10^6$
	Clarence Catchments							
204 004	Mann	Jackadgery	7800	1919 to date	Rock & boulders	3720	13600	1780
204 015	Little	Broadmeadows	2670	1945 " "	Rock & gravel	85	2300	460
204 005	Nymboida	Buccarumbi	5260	1921 " "	Rock bar	3450	5610	1290
204 001	Nymboida	Nymboida	1660	1908 " "	Gravel bar	3450	5610	820
204 020	Blicks	Dundurrabin	251	1948 " "	Rock	297	790	102
204 021	Blicks	Hernani	70	1950 " "	Rock	61	375	47
204 026	Bobo	Bobo Nursery	80	1951 " "	Rock & Concrete	182	935	98
	Upper Hunter Catchments							
210 001	Hunter	Singleton	16400	1891 " "	Sand	3115	12500	863
210 028	Wollombi Bk	Bulga	1590	1949 " "	Sand	750	1500	164
210 063	First Ck	Polkolbin site 1	14.8	1961 " "	V-notch weir	31	49	0.6
210 068	Deep Ck	Polkolbin site 3	24.9	1963 " "	V-notch weir	32	54	0.7
210 069	Deep Ck	Polkolbin site 4	4.9	1963 " "	V-notch weir	1.06	8.1	0.1
210 051	Wollombi Bk	Hanging Rock	388	1958 " "	Sand	240	540	36.0
210 044	Glennies Ck	Middle Falbrook	466	1956 " "	Sand	78	910	81.0
210 045	Saltwater Ck	Plashett	41.0	1956 " "	Rock & gravel	0.15	64	1.6
210 059	Gardiners Ck	Liddell	70.5	1959 " "	Concrete	4.53	5.53	6.0
210 042	Bowmans Ck	Ravensworth	205	1956 " "	Sand & Gravel	2.3	99	11.0
210 014	Rouchel Bk	Rouchel Bk	386	1934 " "	Rock & concrete	36	650	64.0
210 040	Wybong Ck	Wybong	658	1955 " "	Rock bar	11.3	540	48.0
210 016	Goulburn	Kerrabee	4790	1940 " "	Sand	53.8	4330	164
210 031	Goulburn	Sandy Hollow	6840	1953 " "	Sand	270	5100	257
210 006	Goulburn	Coggan	3340	1912 " "	Gravel	37.4	3960	82.0

Data compiled from:
Department of National Resources (1974)
New South Wales Water Conservation and Irrigation Commission (Various dates and verbal communication).

The Hunter valley has been extensively cleared for pastoral and grazing purposes. Geologically, the valley can be divided into three regions, the northeast with basalt and limestone, the north with basalt, and the south with Triassic sandstone. Figure 3.9 shows approximate hydrological regions based again on information in the regional report of the New South Wales Water Conservation and Irrigation Commission (various dates).

A more detailed description of the characteristics of the two regions is given in Appendix C. Details of the streamgauging stations of the catchments studied are listed in Table 3.5. The period of record varies from catchment to catchment. Although this introduces some heterogeneity into the data, the maximum available period of record has been used for each catchment to give the best possible estimates of the rainfall-runoff relations. The last year of data used for each catchment depended on the latest records computed by the Water Resources Commission at the time of collection of the data. For Australian conditions, the highest gaugings on most catchments are quite reasonable fractions of the estimated maximum recorded discharges. Large extrapolations of station rating curves would be involved on some of the catchments, and appreciable errors are inevitable in most of the runoff data. However, the quality of the runoff data utilized is generally good.

3.5 RESULTS

3.5.1. Clarence River Valley Catchments

The annual rainfall-runoff relations derived by McCutchan's method for each of these catchments are shown in Figures 3.10 to 3.16 and are combined together in Figure 3.17. This last figure shows that six of the seven relations were of a consistently similar shape. The exception is the relation derived for Nymboida River at Nymboida (1920-70) where the loss to runoff is markedly less than the others in the non-linear portion of the relation.

However, a general trend is apparent. The maximum constant loss increases with an increase in catchment area. This loss is defined as the difference between rainfall and runoff in that portion of rainfall-runoff relation that is parallel to the line of equality of rainfall and runoff (in the region b-c of high rainfalls in Figure 3.3). A plot of this loss against the logarithm of area is shown in Figure 3.18. The data closely fit a straight line on this plot, except for the anomalous result from the Nymboida River at Nymboida. It must be pointed out that this trend only considers the maximum constant losses and that the relationship between loss and catchment area, while it also exists in the variable loss portion of the rainfall-runoff relationship, deteriorates with decreasing rainfall. This is discussed further in Section 3.6.3.

Only the linear portion of the relation could be derived for the Bobo River at Bobo Nursery (1951-65). This received such high annual rainfalls (average 2 020mm) during its period of record that its lowest subarea rainfall is in excess of 1 000mm. Consequently, no nonlinear portion of the rainfall-runoff relationship was warranted, as shown in Figure 3.16. Also, rainfall in the vicinity of this catchment displays such a high orographic effect that some difficulty was encountered in fitting consistent surfaces to the rainfall data.

A feature of the relations in Figures 3.10 to 3.16 is the fact that the derived curves fall below the mean trend of the plotted points for observed annual rainfalls and runoffs for each catchment. This is particularly obvious in Figures 3.12 and 3.14, but also occurs to some extent with the other catchments. This reflects the bias in the apparent relation derived from catchment average values which results from nonlinearity of the point relationship and from spatial variation of rainfall, as discussed in Section 3.3.3.

3.5.2 Upper Hunter River Valley Catchments

Graphs of the annual rainfall-runoff relationships derived by McCutchan's Method for these catchments are shown in Figures 3.19 to 3.33. Several of the catchments have short records, sometimes with some years of missing data, and the relationships for these catchments are somewhat uncertain.

Initially, all 15 catchments were used to investigate the relation between maximum constant loss and catchment area. However, no trends were evident for either these losses or for the variable loss portion of the relations. With one exception the catchments were then divided into three sub-regions, based on the rainfall, land slope and geological characteristics represented in Figures 3.8 and 3.9. The Hunter River at Singleton was not included in the sub-division since it drains all three sub-regions. The results were then generally consistent within each of the subdivided regions.

The Western region includes the four catchments on the Goulburn River and Wybong Creek. Maximum constant loss appears to increase with the logarithm of catchment area (Figure 3.34) in a similar fashion to the relation for the Clarence catchments. Figure 3.35 shows that the shapes of the relations are generally consistent but that the Goulburn River at Sandy Hollow does not follow the above trend.

In the Southeast region are included the six catchments on the Wollombi Brook and Polkolbin areas. With the exception of Deep Creek, Polkolbin Site 4, maximum constant loss again appears to increase with the logarithm of catchment area (Figure 3.36). The rainfall-runoff relations in Figure 3.37 all have consistent shapes. The data for the Hunter River at Singleton at the outlet of the whole catchment have also been plotted in Figures 3.36 and 3.37. Although this very large catchment deviates to some extent from the trends of the catchments in the Southeast region its maximum constant loss and rainfall-runoff relation are reasonably consistent with the other data.

The remaining four catchments to the north of Singleton and northeast and east of Muswellbrook were grouped into the Northeast region. Only a relatively small range of areas is represented in this group, and the plot of maximum constant loss against logarithm of area in Figure 3.38 for these catchments shows a large range of loss but no apparent relation with area. More catchments would be required to confirm the absence or presence of a relationship. The shapes of the rainfall-runoff curves on Figure 3.39 are quite consistent.

The grouping of the Upper Hunter catchments into three regions allowed some order to be deduced from the results although sample sizes were greatly reduced. Consistent trends between maximum constant loss and catchment area were indicated for two of the regions. For both of these, the trends deteriorate with a decrease in rainfall across the variable loss portion of the rainfall-runoff relations.

3.6 DISCUSSION OF RESULTS

3.6.1. Relations for Individual Catchments

For all of the catchments analysed, the McCutchan method converged fairly quickly and the rainfall-runoff relations could be determined with confidence. The only possible exceptions were a few catchments with only a small number of usable years of record. In all cases the scatter in the plot of calculated runoff against observed runoff was lower for the final relation than for the initial estimated relation based on catchment average values. As noted earlier, the final relation generally lay below a mean curve through the average data, correcting the bias resulting from the nonlinear nature of the relation as discussed in Section 3.3.3. Use of sub-area rainfalls also extended the range of the relation that was tested, as some sub-area rainfalls must always exceed the catchment average values. Overall, the results in this study confirm the McCutchan method as a very satisfactory procedure for deriving physically realistic rainfall-runoff relations and eliminating the effects of variations in the spatial distribution of rainfall.

Although the fit of the calculated to the observed annual runoffs was improved by the relations derived using McCutchan's method, considerable scatter still remained for all catchments. This is because the factors causing scatter as discussed in Section 3.2, other than spatial distribution of rainfall, cannot be considered explicitly. Some scatter of the data is thus unavoidable.

The consistency of the derived relation over the period of record was checked for many of the stations with long records. The record was divided into two periods and three relations were derived, one for each of these periods and one for the entire period of record. Examples of the results are shown in Figures 3.40 to 3.42 In most cases the relations for the different periods were very similar, as illustrated in Figures 3.40 and 3.41 for the two half-periods at the Mann River at Jackadgery, and in Figure 3.10 for the whole period. In a few cases, such as for the Hunter River at Singleton shown in Figure 3.42, appreciable differences occurred in the relations for the different periods. These could reflect differences in land use or in accuracy of the records, but the actual reasons for these differences are uncertain. In general, is seems that the annual rainfall-runoff relation derived from the entire period of record at each gauging station should be a close estimate of the long-term relation for the catchment, and that sampling errors resulting from the period over which data were obtained should be small.

3.6.2. Comparison of Rainfall-Runoff Relations

While the derived annual rainfall-runoff relations for the Clarence catchments exhibited general consistency, the relations for the entire Hunter Valley varied appreciably and were inconsistent. Examination of the characteristics of the Hunter Valley indicated that consideration of the whole valley as a single homogeneous region was inadequate. Division of the valley into three regions on the basis of rainfall, land use and slope, and geology as shown in Figure 3.9 produced reasonable consistency within the relations for each region (Figures 3.35, 3.37, 3.39). While the basis of delineation of these regions is very qualitative and approximate, it has proved useful in defining the runoff characteristics of the catchments studied. The characteristics of the Clarence catchments were more uniform and all drain through mainly Silurian strata. The relations over the entire southern portion of the Clarence were generally consistent, as shown in Figure 3.17. In view of the above results, it seems that general trends and consistencies in annual rainfall-runoff relations for small and large catchments may occur within regions of similar hydrological characteristics of rainfall, land use and slope and geology. However, it is not possible to use these trends in other regions or to transpose derived relations.

In general, there was a trend in the relations derived in each region of decreasing runoff with increasing area. The reasons for and implications of these trends are discussed in Section 3.6.3. While the relations in each region reveal consistency, considerable variations also occur. This scatter from the general trends would result from the effects of all of the factors reviewed in Chapter 2. A few anomolous relations also occur, in terms of both shape and general location of the curves. These anomolous catchments are the Nymboida River at Nymboida in the Clarence region, the Goulburn River at Sandy Hollow in the western region of the Upper Hunter Valley, and Deep Creek at Pokolbin Site 4 in the southeast region of the Upper Hunter Valley. The reasons for these anomolous results are not clear, and again probably relate to the factors reviewed in Chapter 2. Data errors may have a large effect. On the small Pokolbin Site 4 catchment, land use patterns may be important. The relations for the four catchments in the northeast region of the Upper Hunter Valley show no discernible trend, which might reflect the small range of areas sampled. It may also result from wide variations in physical characteristics in the region, especially of geology, and from data errors. Whatever the reasons for all of these anomolous results, they sound a warning for the development of relationships between small and large catchments, and for transferring results from any catchment to any other catchment.

The different periods of records analysed for the various stations are not considered to have any appreciable influence on the consistency or otherwise of the derived relations within each region. As discussed in the previous section, the derived relation for each catchment should be a close estimate of the long-term relation for that catchment.

3.6.3 Relation of Loss to Area

The loss of annual rainfall to runoff adopted for analysis in this study is the maximum constant loss in the high rainfall region b-c in Figure 3.3. Some aspect of the variable loss in the region of lower rainfall a-b could also have been used, but this portion of the rainfall-runoff relation is not as well defined by the data, is more liable to error in derivation, and any measure would be less obvious and have less physical meaning than the constant loss. Also, losses in the region b-c in Figure 3.3 are not affected by the time pattern of rainfall within a year as the catchment is sufficiently wet all of the time for the evaporation opportunity to be effectively unity, and the term ΔS in equation 3.1 is relatively small compared with the large rainfall and runoff terms in this range.

Two trends are apparent in the annual loss data derived in this study. The first and less important of these is that the rainfall at which the constant loss is reached (point b on Figure 3.3) increases with increasing value of the constant loss. This is apparent for each of the four regions from Figures 3.17, 3.35, 3.37 and 3.39. This is logical, as it indicates that the higher the potential evapotranspiration loss on a catchment, the higher the annual rainfall has to be to maintain soil water over the whole catchment at such a level throughout the year to not restrict evapotranspiration at any time. Also the data of Denmead and Shaw (1962) in Figure 3.2 indicate that as potential evapotranspiration (and thus maximum constant loss) increases, the soil water content at which restriction of actual evapotranspiration commences increases appreciably. The annual rainfall required to prevent this restriction would also be increased appreciably. The data derived in this study confirm these logical deductions.

Of more direct practical importance is the observation that for three of the four regions, loss increases consistently as catchment area increases. This is shown in Figures 3.18, 3.34 and 3.36, while no relation of this type was evident in Figure 3.38 for the northeast region of the Upper Hunter Valley. Although no direct evidence is available, the increase of loss with increasing catchment area almost certainly results from channel transmission losses, as discussed in Section 2.2.4. These losses are apparently of greater magnitude than any contribution of baseflow that may occur from groundwater along the stream. Transmission losses not only occur on the subhumid Hunter catchment with a median annual rainfall of 650 mm, but also on the humid Clarence catchment with median annual rainfalls averaging 1025 mm over the entire catchment and up to 1900 mm on some parts of it (Figure 3.1). The results thus confirm the evidence of Boughton (1965) and Pilgrim (1966a) discussed in Section 2.2.4 that channel transmission losses are important in humid eastern New South Wales, and probably lead to considerable reductions in both floods and long-term flow volumes in many areas of Australia. These losses will have a major influence on the relation between hydrological characteristics of small and large catchments.

As the maximum constant loss should reflect potential evapotranspiration, and this should be fairly constant over a region, it could be argued on the basis of equation 3.1 that even transmission losses should not increase the loss to runoff. There are two possible reasons why the water infiltrated along the channels may increase the losses, even though the potential evapotranspiration cannot be increased. Some of the infiltrated water may recharge major aquifers or deep groundwater, which eventually moves out of the catchment below the surface. This would certainly occur on west-flowing streams in New South Wales in recharge areas for the Great Artesian Basin.

The second reason could be that for most catchments, even in very wet years where the rainfall is in the zone of apparently constant loss on Figure 3.3, all of the catchment does not have a sufficiently high soil water content all of the time for evapotranspiration to be at the potential rate. The constant loss is thus somewhat less than the potential rate, especially for small catchments where water moves out of the catchment relatively quickly. Transmission losses would have the effect of maintaining high water contents over longer periods and increasing the overall losses. Unfortunately, it is difficult to estimate potential evapotranspiration with any confidence. The annual losses of over 1000 mm for the large catchments in the regions studied are approaching values that are reasonable for potential evapotranspiration. However, maximum constant losses of less than 800 mm per year for the smaller catchments are too low for potential evapotranspiration, indicating some restriction of actual rates. This gives some support to the above reasoning.

Maximum constant loss increases approximately linearly with the increase of the logarithm of area. Approximate straight lines of best fit have been drawn on the semi-log plots in Figures 3.18, 3.34 and 3.36, although anomolous points have been disregarded in each case. This semi-logarithmic relation indicates that considerable losses occur in the small headwater catchments, and that while the total loss increases downstream, it only increases slowly and at a decreasing rate as catchment area increases. This implies that the actual rate of transmission loss is greatest in the upstream channels, and decreases in a downstream direction. High transmission losses in headwater channels in a humid region near Sydney were also reported by Pilgrim (1966a) as discussed in Section 3.2.4. The reduction in the rate of transmission loss in a downstream direction may result from the increasing contribution of baseflow in some reaches and at some periods of the year as catchment area increases.

As the rainfall at which the constant loss is reached increases with increasing value of the constant loss, as discussed for the first trend, it follows from the second trend that this threshold rainfall is also related to the logarithm of catchment area.

3.6.4 Comparison of Regions

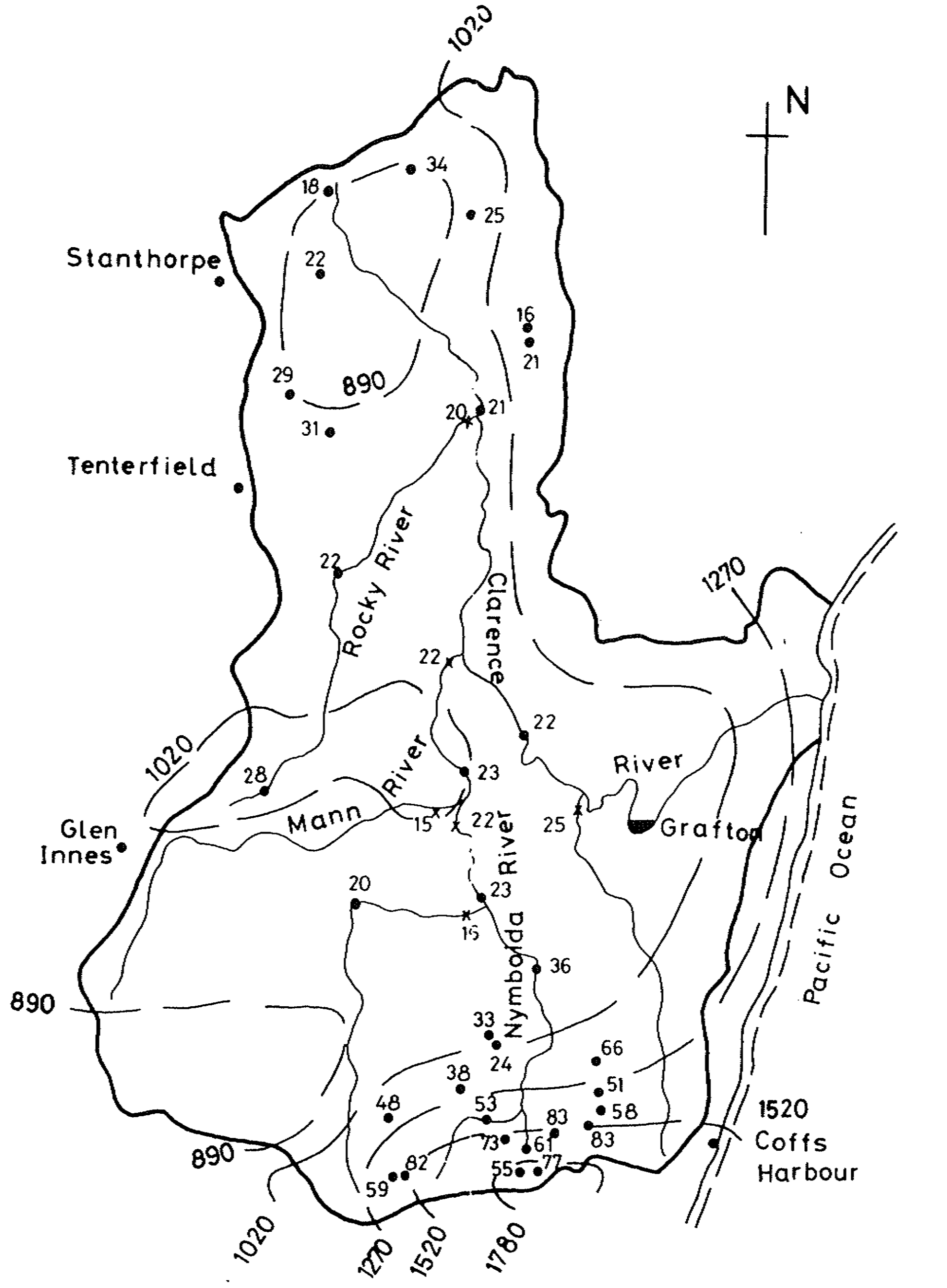
The linear relations of maximum constant loss and logarithm of area for the Clarence and southeast and western Upper Hunter regions are compared in Figure 3.43. It would be expected that the relative positions of the lines and hence losses would be related to the annual potential evapotranspiration in each of the regions. However, no trend of this type is apparent. This might result from the small number of catchments used to derive the relationships, especially for the Hunter region, and the very approximate nature of the linear relations. It might also reflect the influences of land use patterns, vegetation types and geology. The scatter of the lines on Figure 3.43 emphasises the impracticability of transferring results from one hydrological region to another.

3.6.5 Summary of Results

McCutchan's method has been shown to provide a good technique for deriving rainfall-runoff relations. The derived relations are corrected for the effects of spatial variations of rainfall and the bias that is introduced when catchment average values of rainfall and runoff are used to derive the relations in the conventional fashion. Within the limits of the available data, most of the derived annual rainfall-runoff relations varied in a consistent fashion within each of the qualitatively defined hydrological regions. The maximum constant loss defined by the relations was found to increase with area, almost certainly as a result of channel transmission losses.

All available data of sufficient quality were used in each region, and the regions were selected because of the availability of data. However, the amount of data available was insufficient to define relationships of hydrological variables with area with confidence. Annual rainfall data were generally adequate with up to 200 stations being analysed in one region. More long-term streamgauging data of high quality are needed over a range of catchment sizes, particularly for small areas. After expending considerable time and effort on the collection and screening of data in several regions at the start of the project, these regions had to be abandoned as insufficient data from long records and of good quality were found to be available.

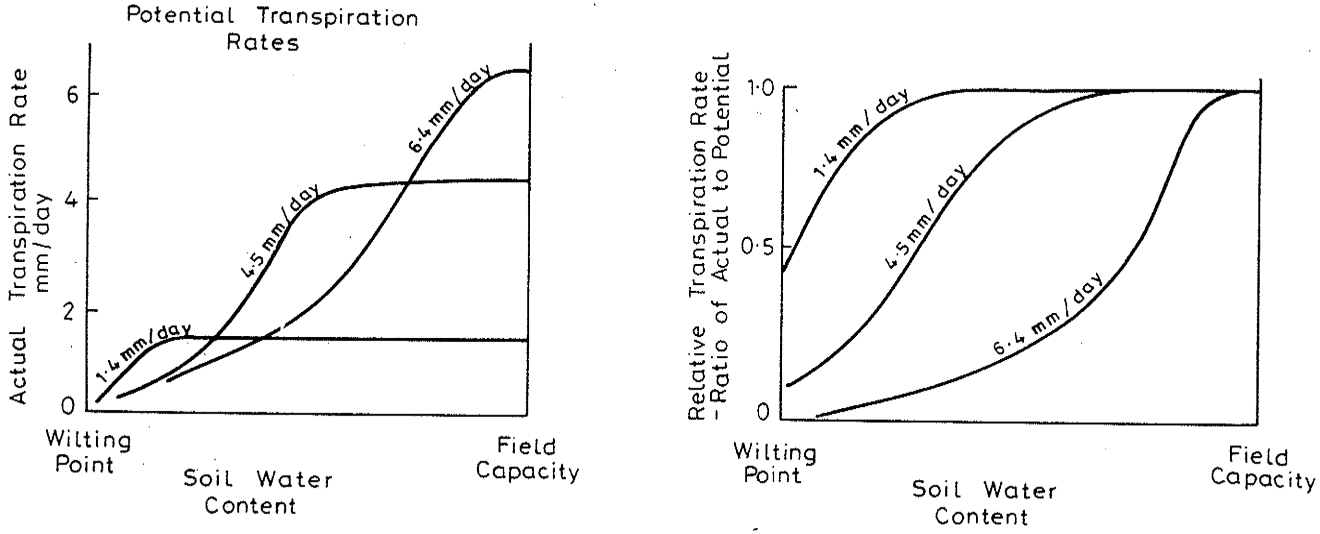
The results obtained indicate that annual rainfall-runoff relations may vary consistently with area in a given region, but the form of variation may be different from region to region. Thus before annual runoff data from a small catchment could be transferred to a large catchment, the form of variation and the effect of transmission losses in that particular region would need to be determined. It would not be valid to transfer data from one region to another, and the results indicate that no comprehensive generalizations are possible.



— —	Isohyet of median annual rainfall - mm
•	Gauging stations
x	Points of estimated runoff

Figures represent annual runoff coefficients expressed as percentages.

Fig. 3.1 Annual Runoff Coefficients for Clarence River Basin.



(a) Actual Transpiration (b) Relative Transpiration

Fig. 3.2 Transpiration Rate as a Function of Soil Water Content (after Denmead & Shaw, 1962)

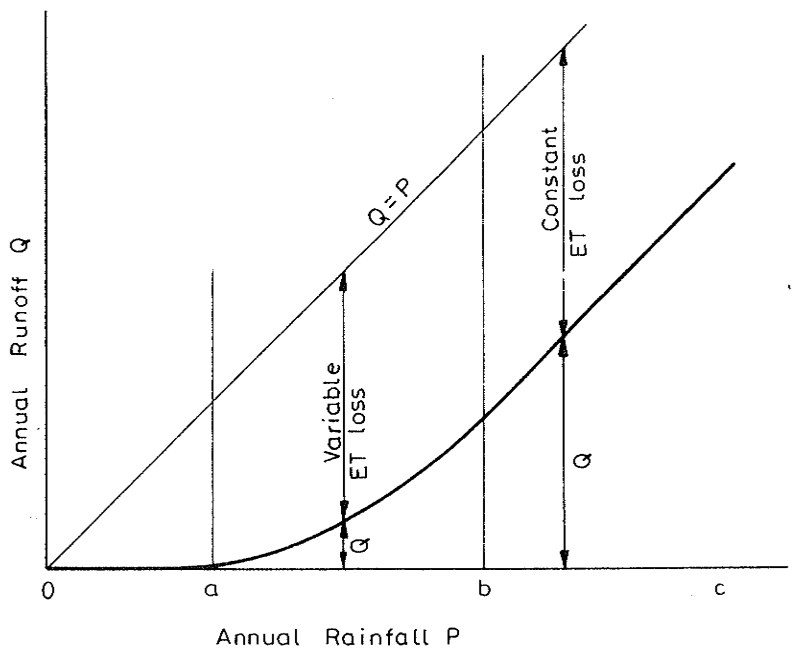
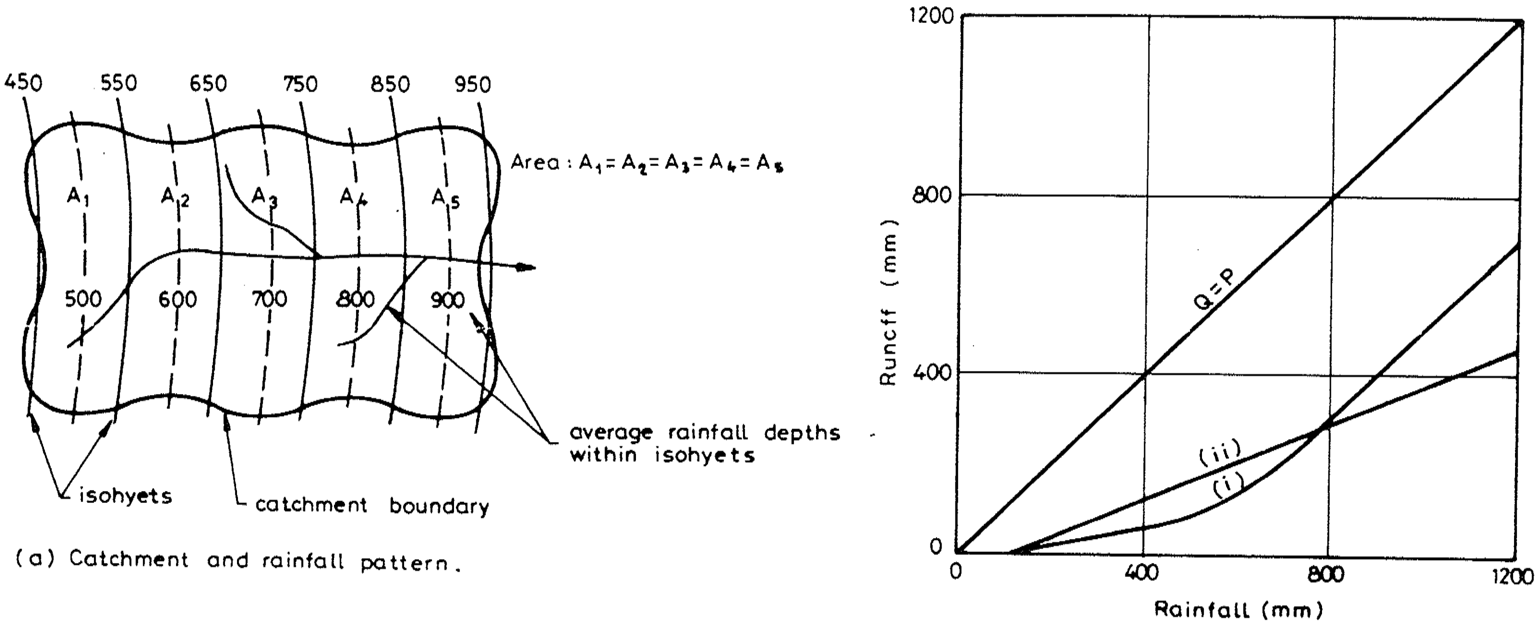


Fig. 3.3 General Form of Relation Between Annual Runoff and Rainfall.



(a) Catchment and rainfall pattern.

(b) Annual rainfall-runoff relations

Fig. 3.4 Examples for Demonstrating Effect of Spatial Distribution of Rainfall on Calculated Runoff.

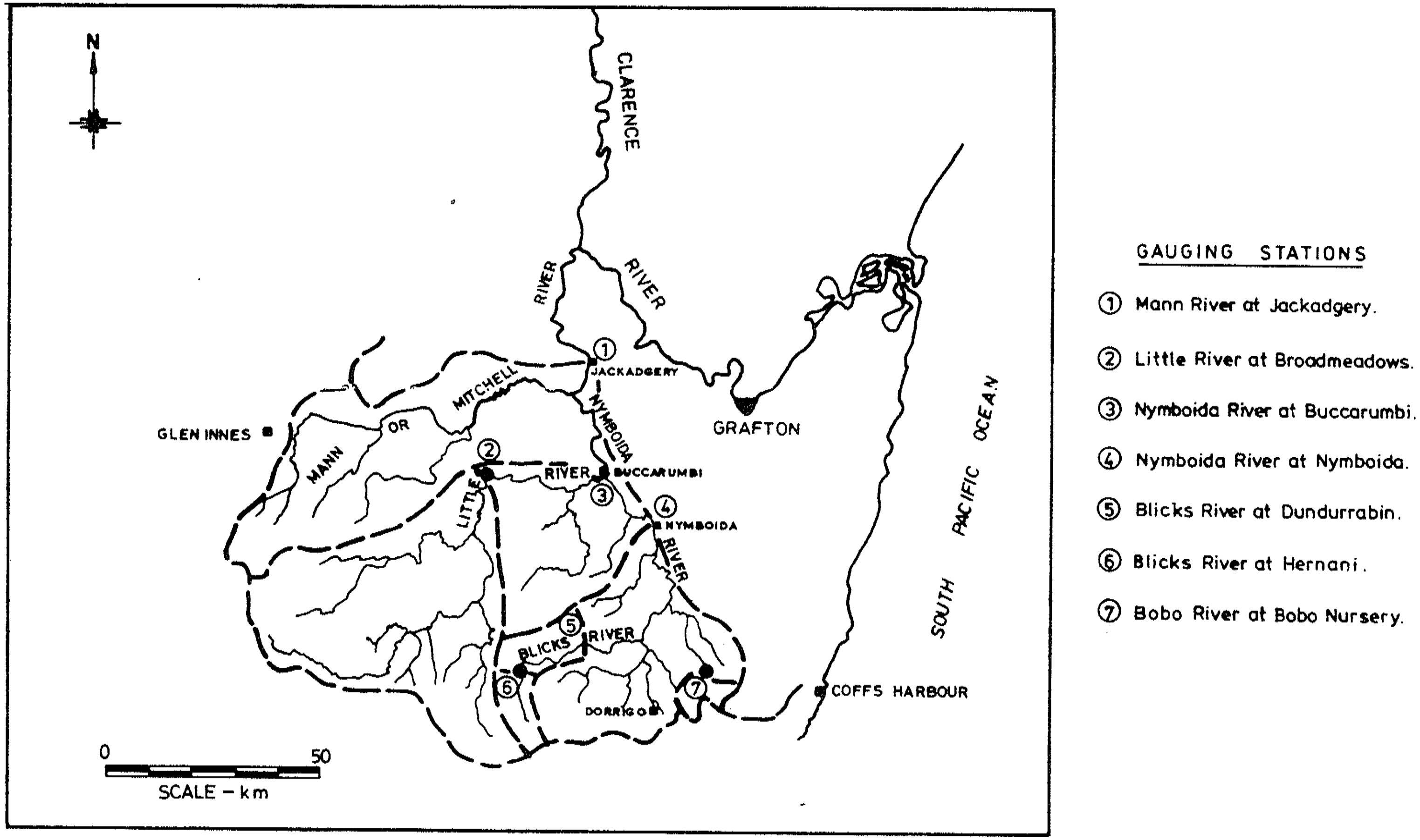


Fig. 3.5 Catchments studied in Clarence River valley

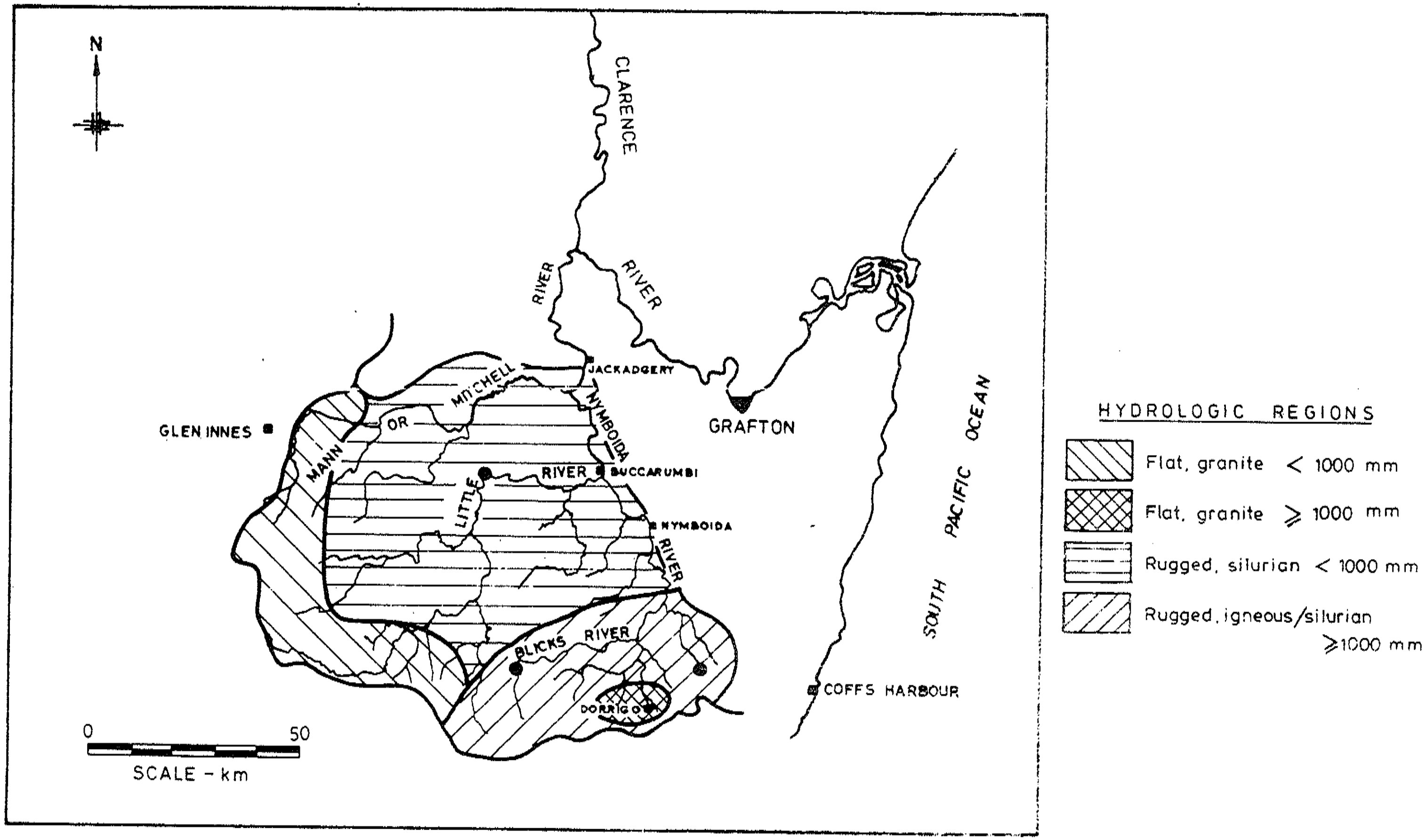


Fig. 3.6 Hydrological regions in the southern portion of the Clarence River valley.

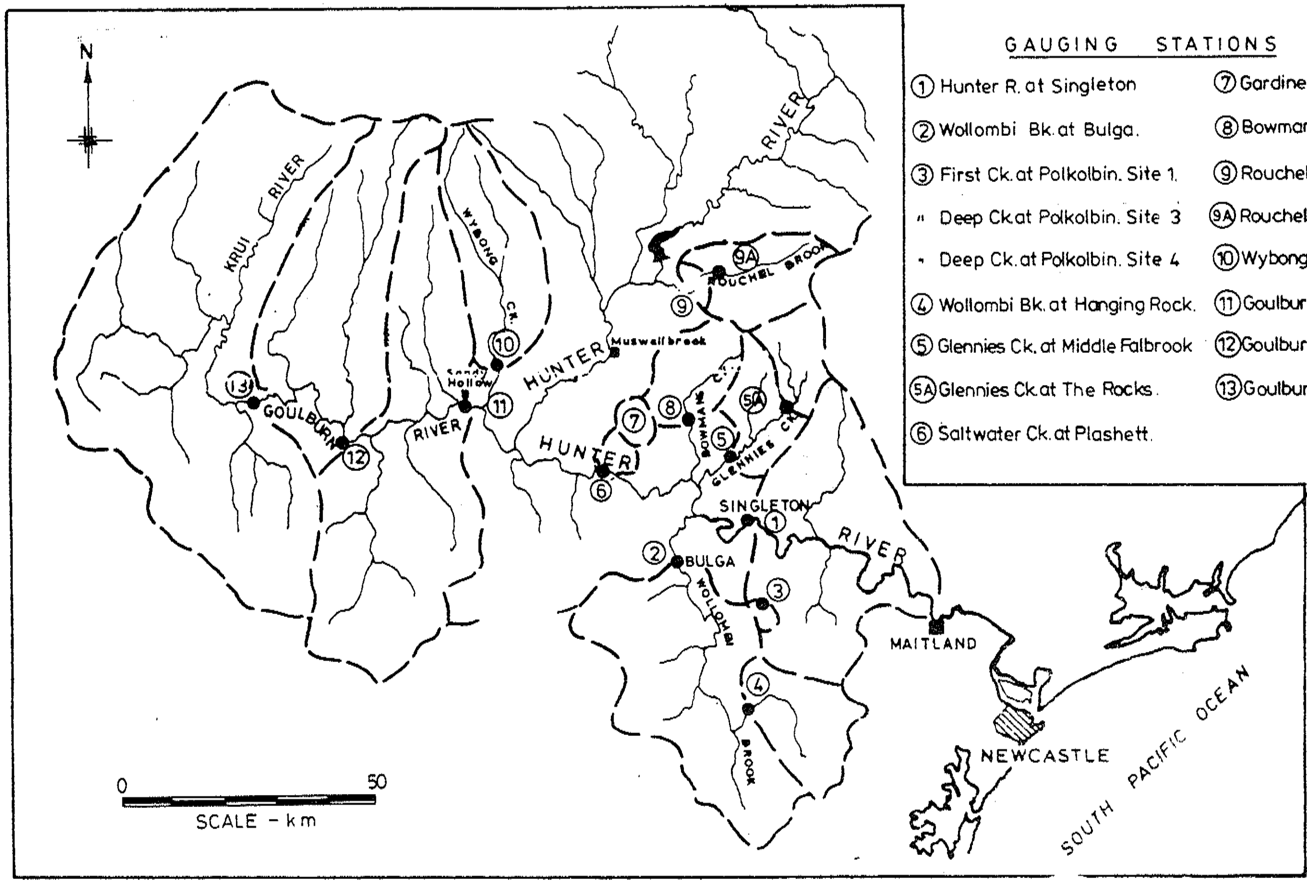


Fig. 3.7 Catchments studied in the Upper Hunter River valley.

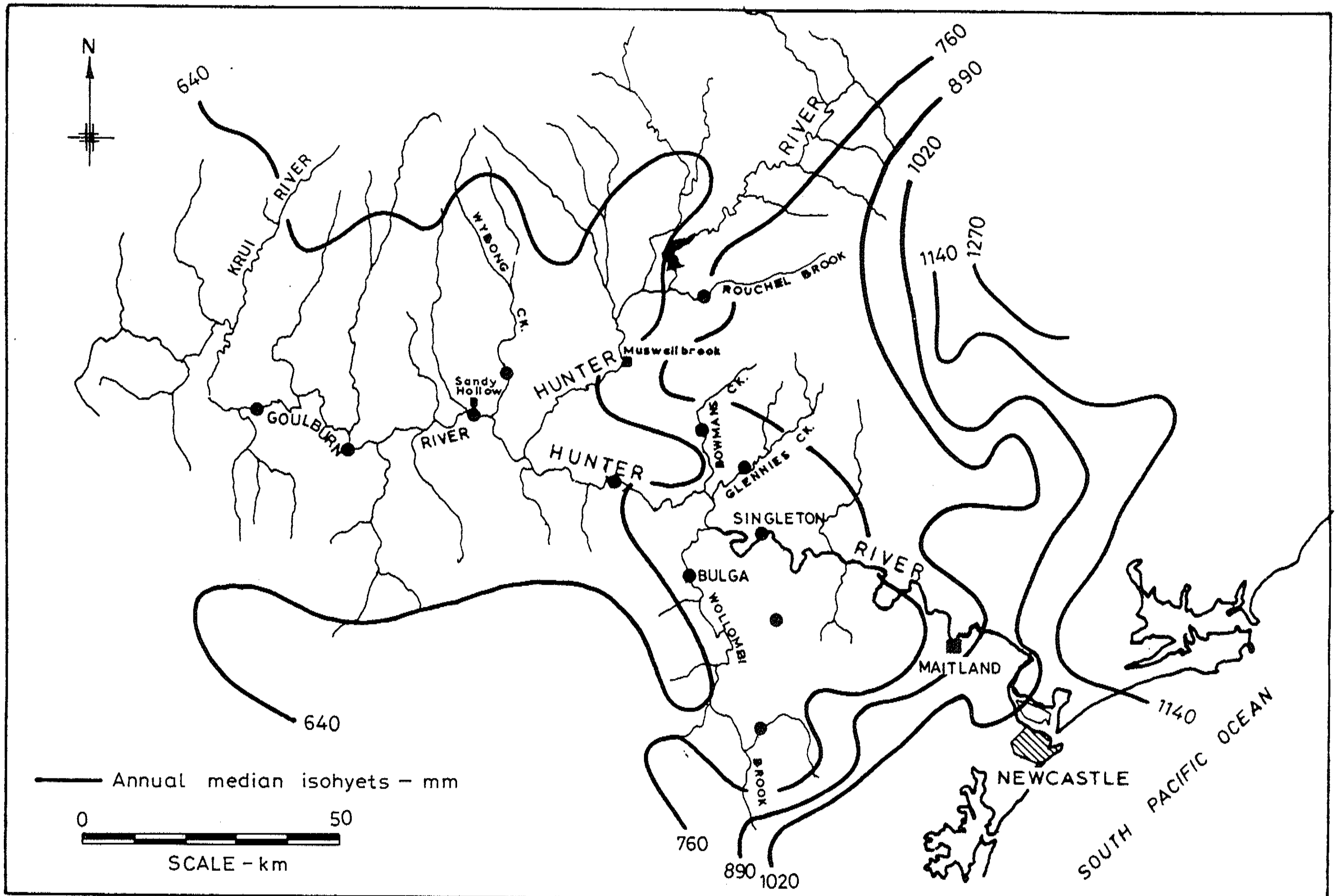


Fig. 3.8 Annual median rainfalls in the Hunter River valley.

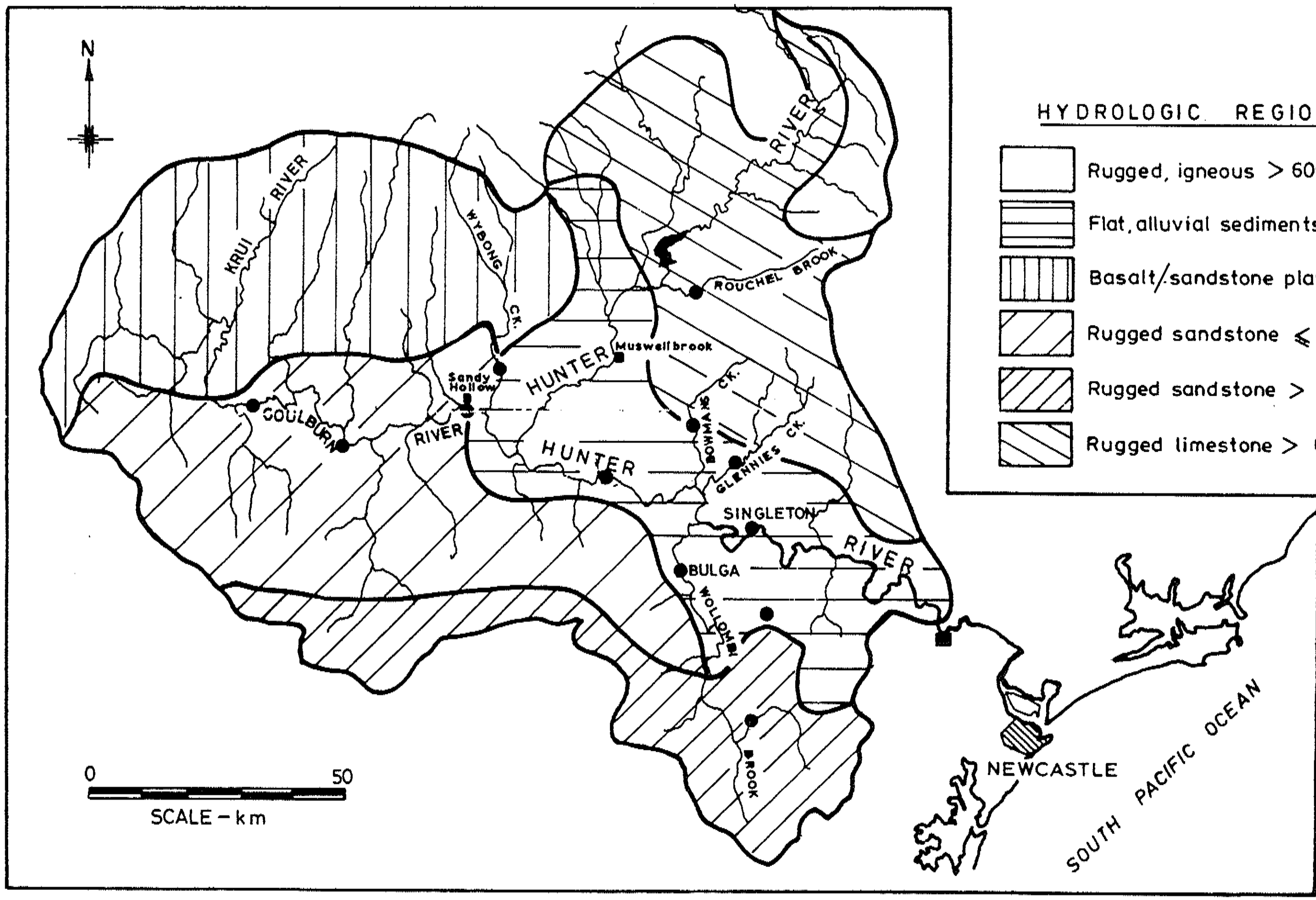


Fig. 3.9 Hydrological regions in the Upper Hunter River valley

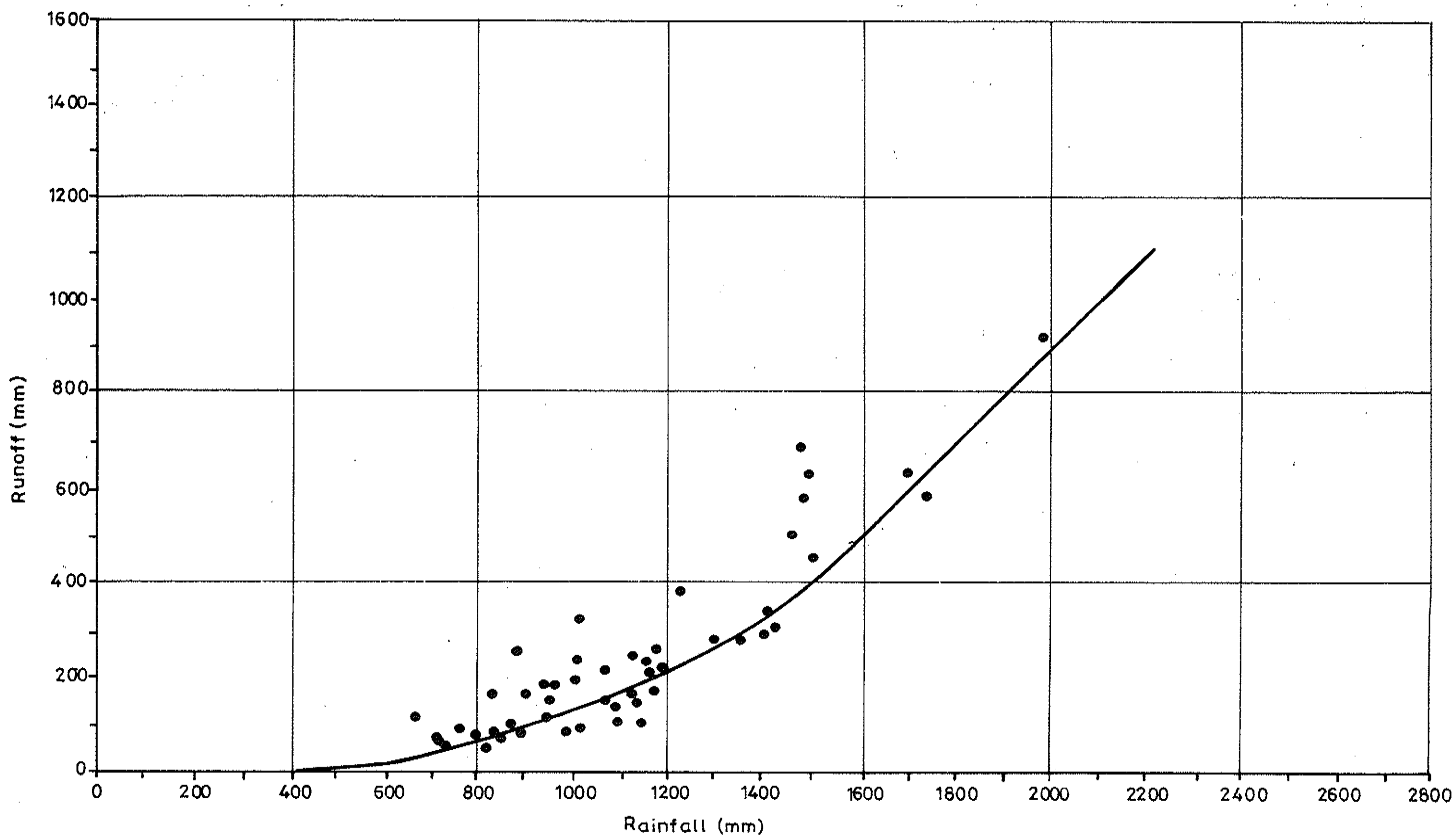


Fig. 3.10 Mann River at Jackadgery. Annual Rainfall-Runoff Relation, 1920 - 1970.

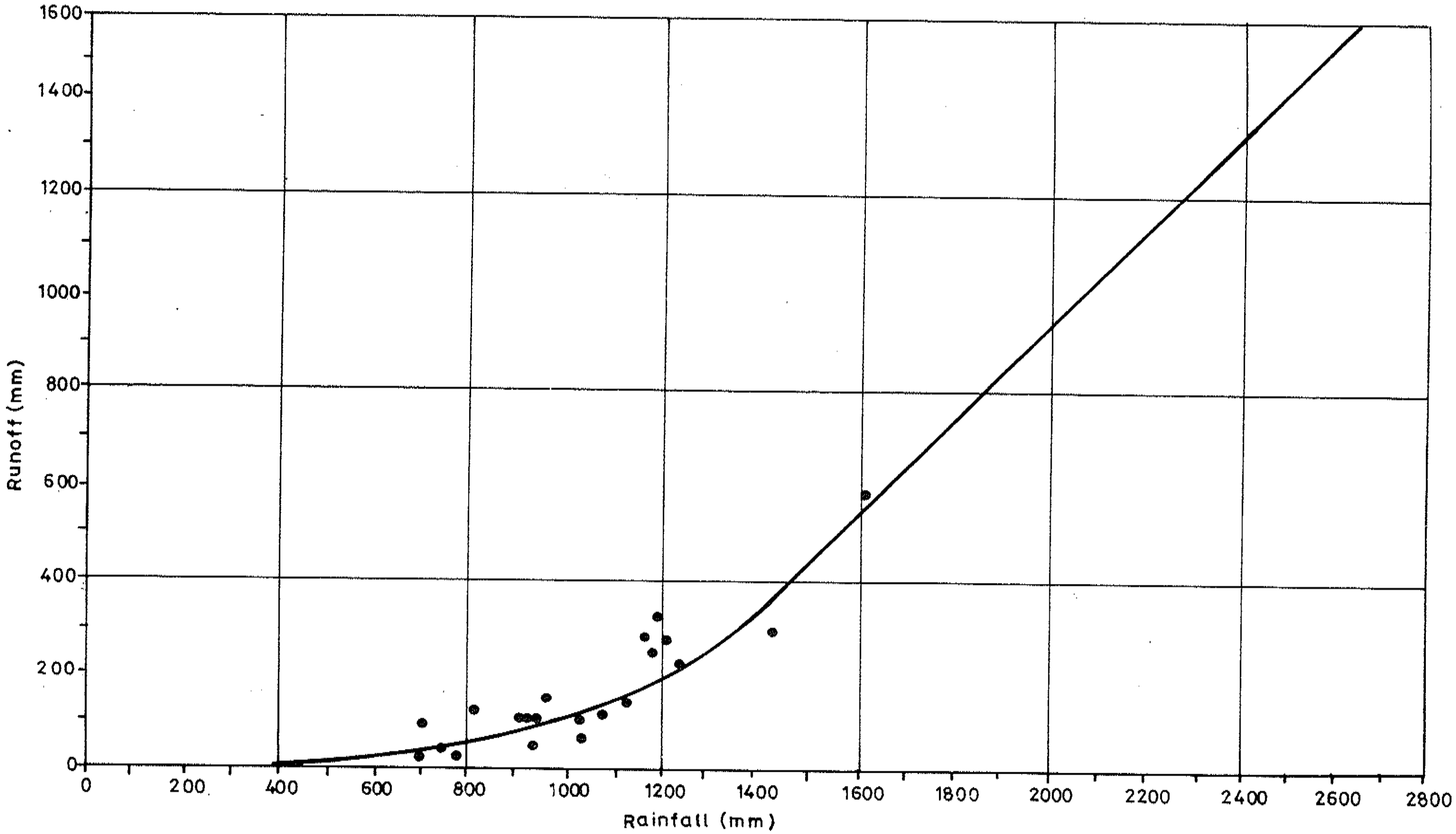


Fig. 3.11 Little River at Broadmeadows. Annual Rainfall-Runoff Relation, 1947 - 1969.

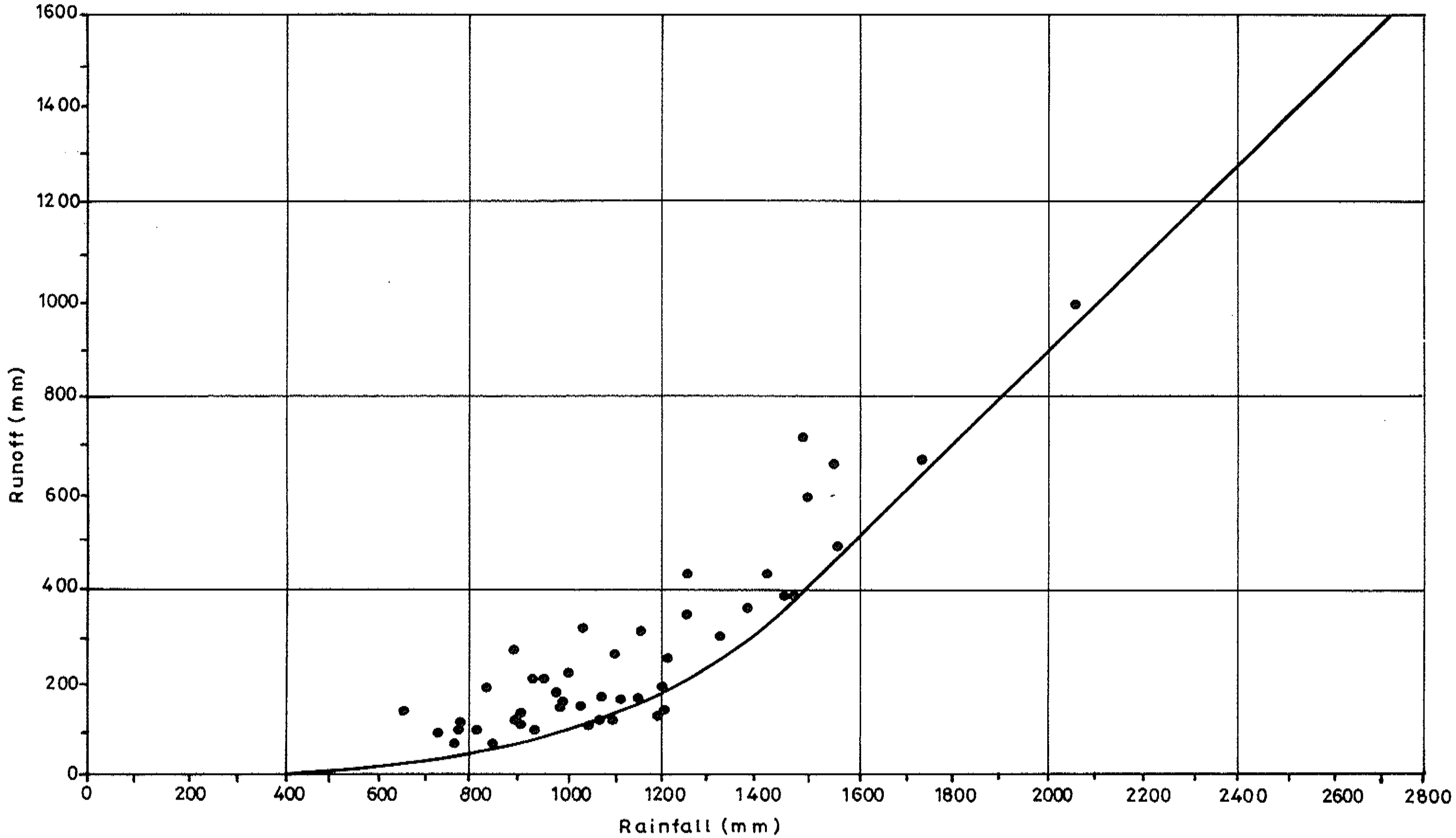


Fig. 3.12 Nymboida River at Buccarumbi. Annual Rainfall-Runoff Relation, 1923 - 1970.

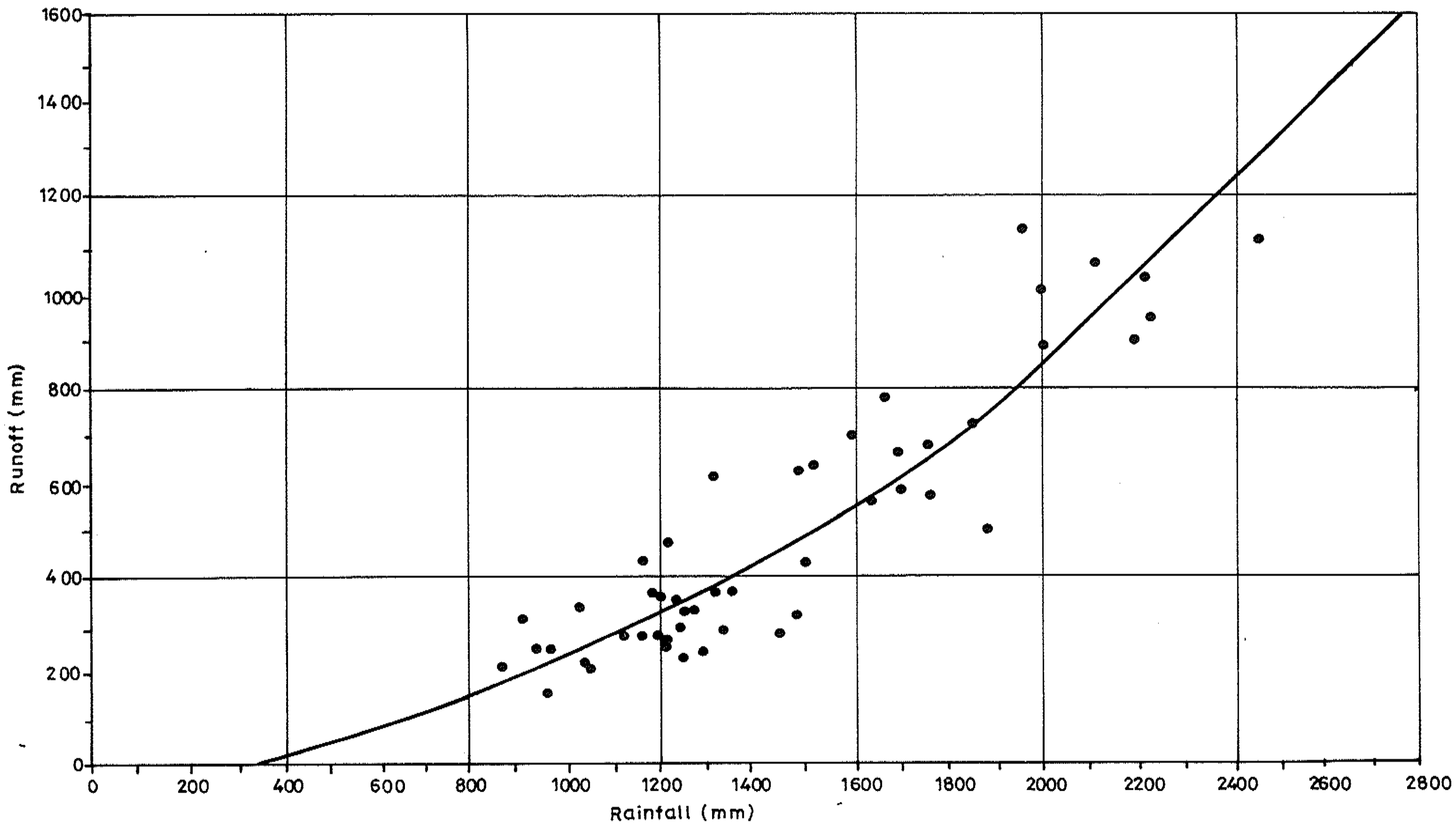


Fig. 3.13 Nymboida River at Nymboida. Annual Rainfall-Runoff Relation, 1920 - 1970.

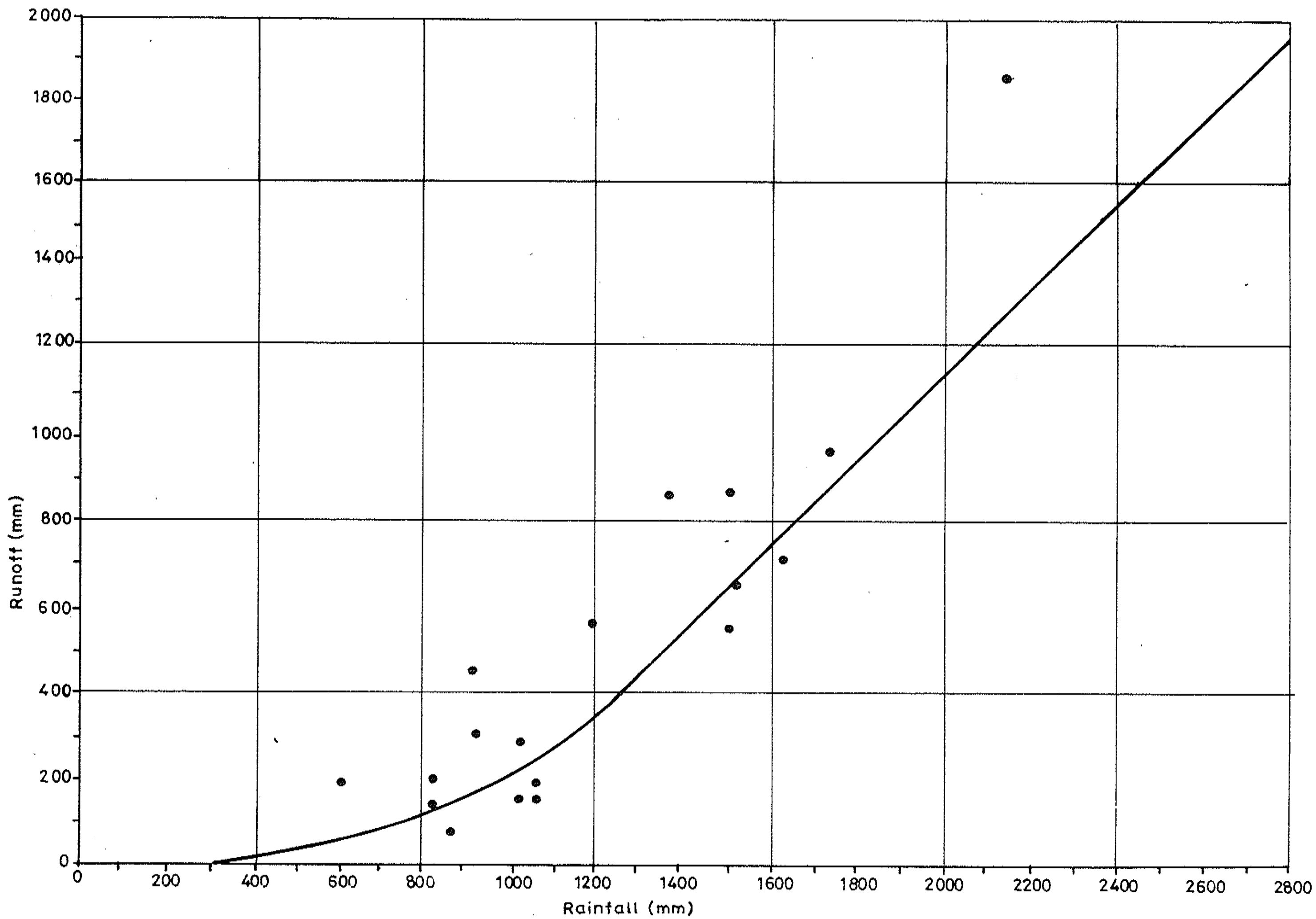


Fig. 3.14 Blicks River at Dundurrabin. Annual Rainfall-Runoff Relation, 1949-1966.

Fig. 3.14 Blicks River at Dundurrabin. Annual Rainfall-Runoff Relation,

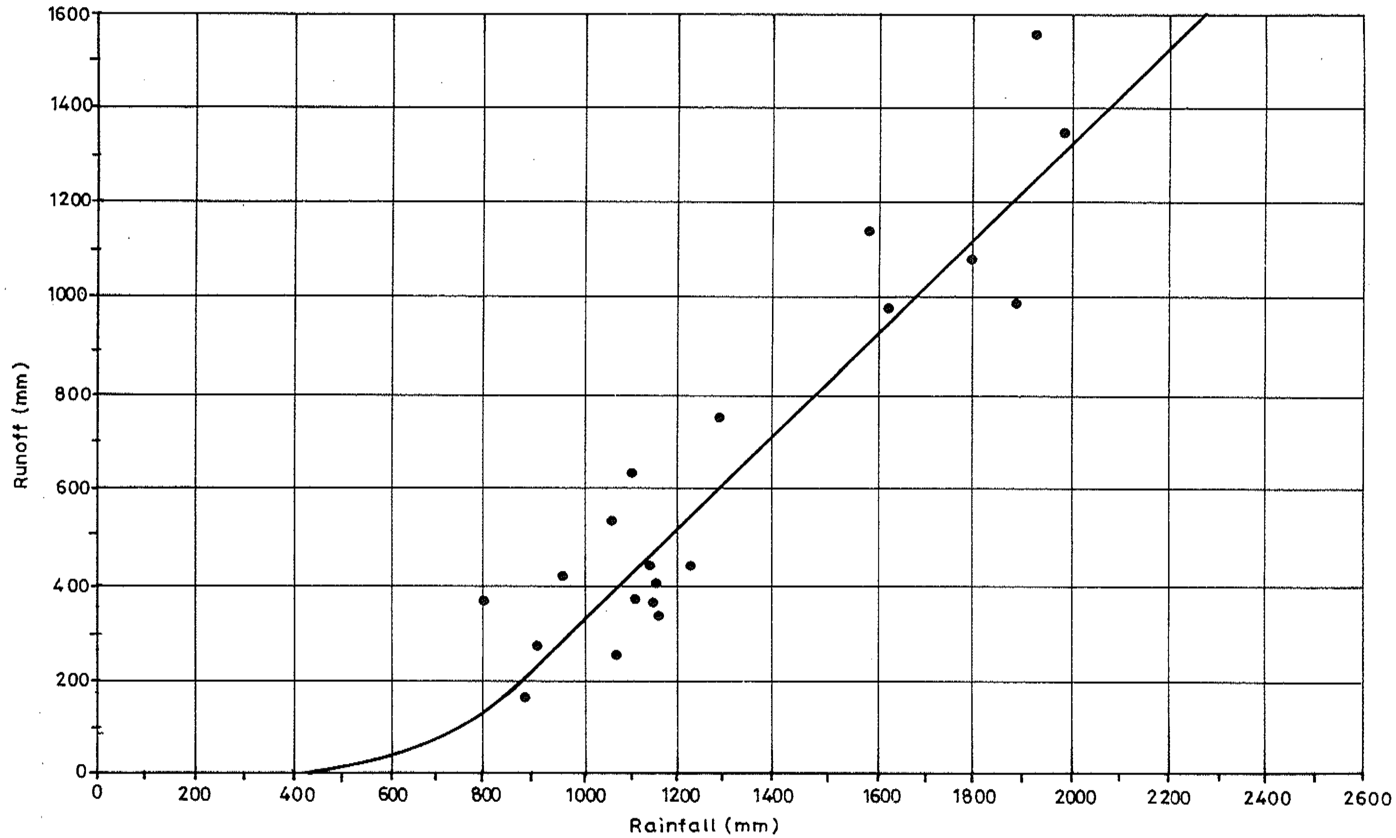


Fig. 3.15 Blicks River at Hernani. Annual Rainfall-Runoff Relation, 1951-1970.

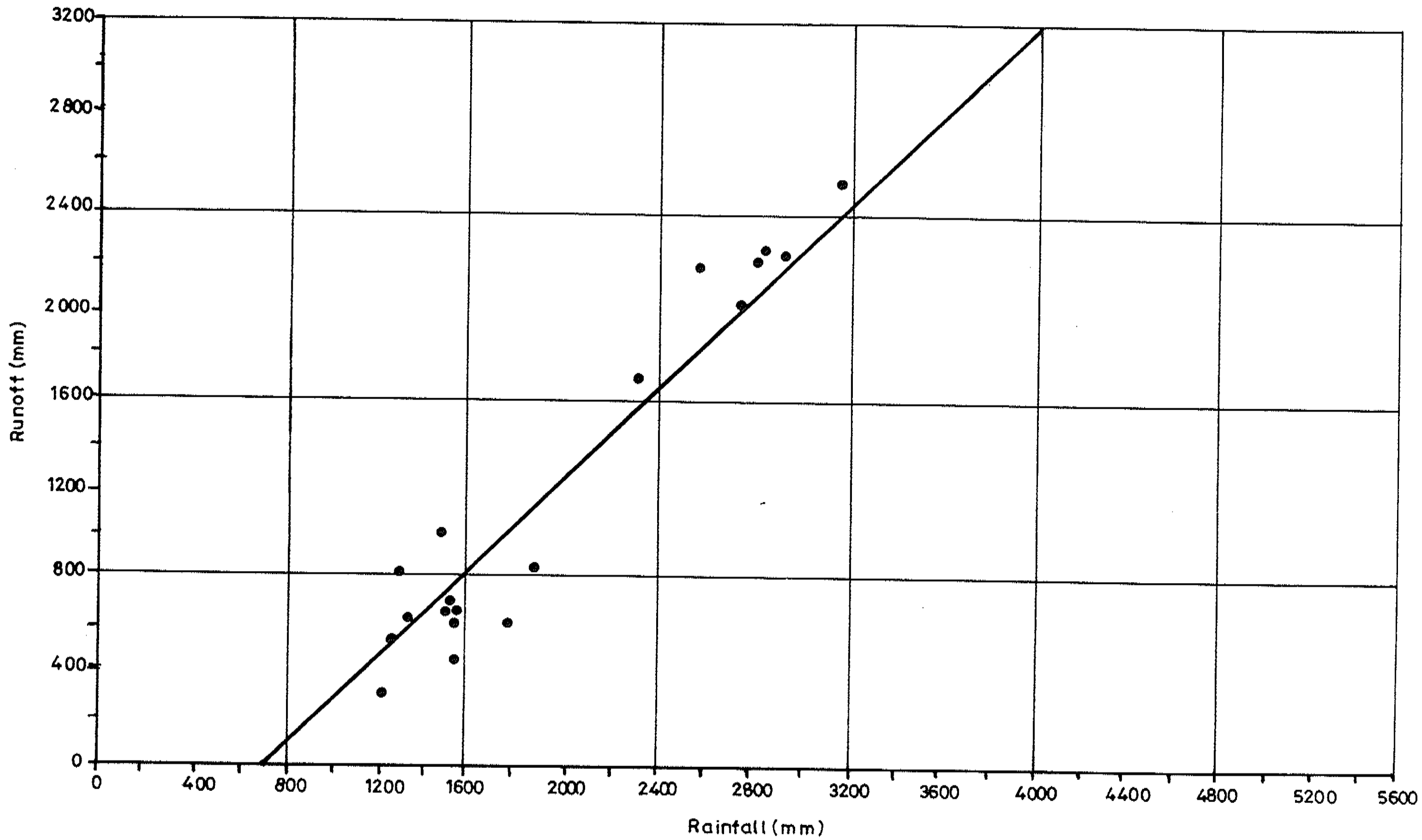


Fig. 3.16 Bobo River at Bobo Nursery. Annual Rainfall-Runoff Relation, 1951-1965.

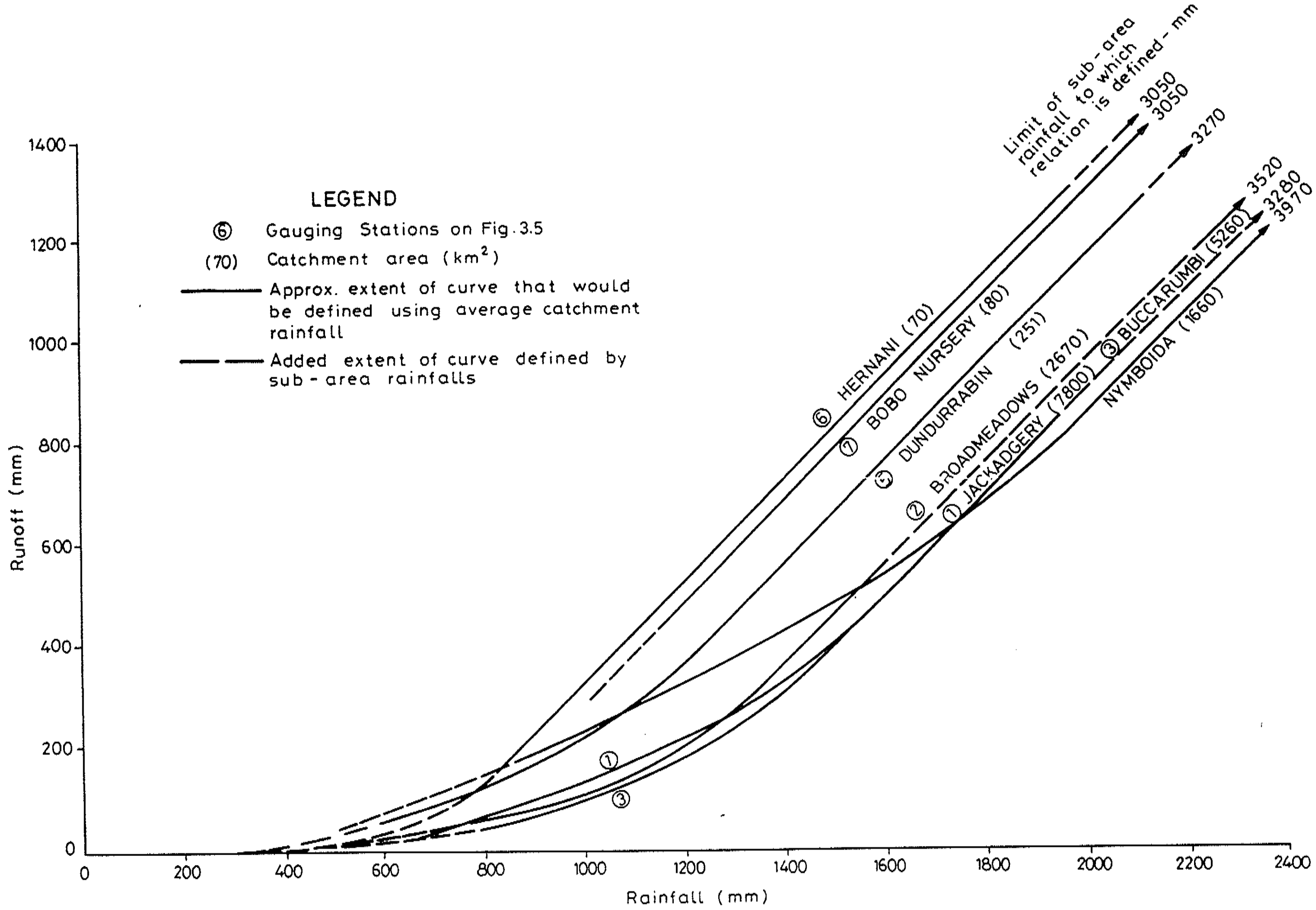


Fig. 3.17 Clarence River Valley. Annual Rainfall - Runoff Relations.

Note : For location of catchments see Fig. 3.5

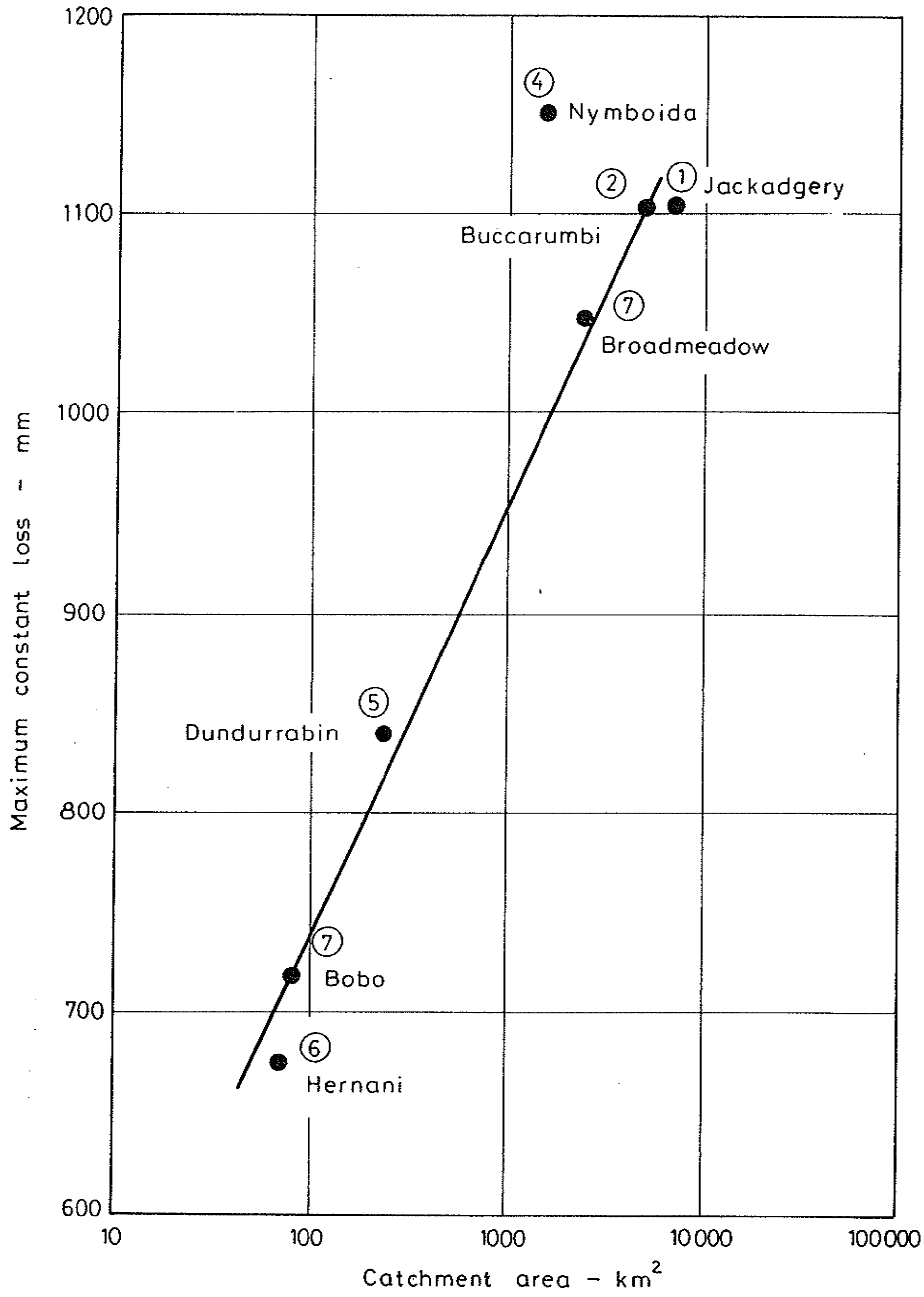


Fig. 3.18 Relation of Maximum Constant Loss to Area for Clarence Valley Catchments.

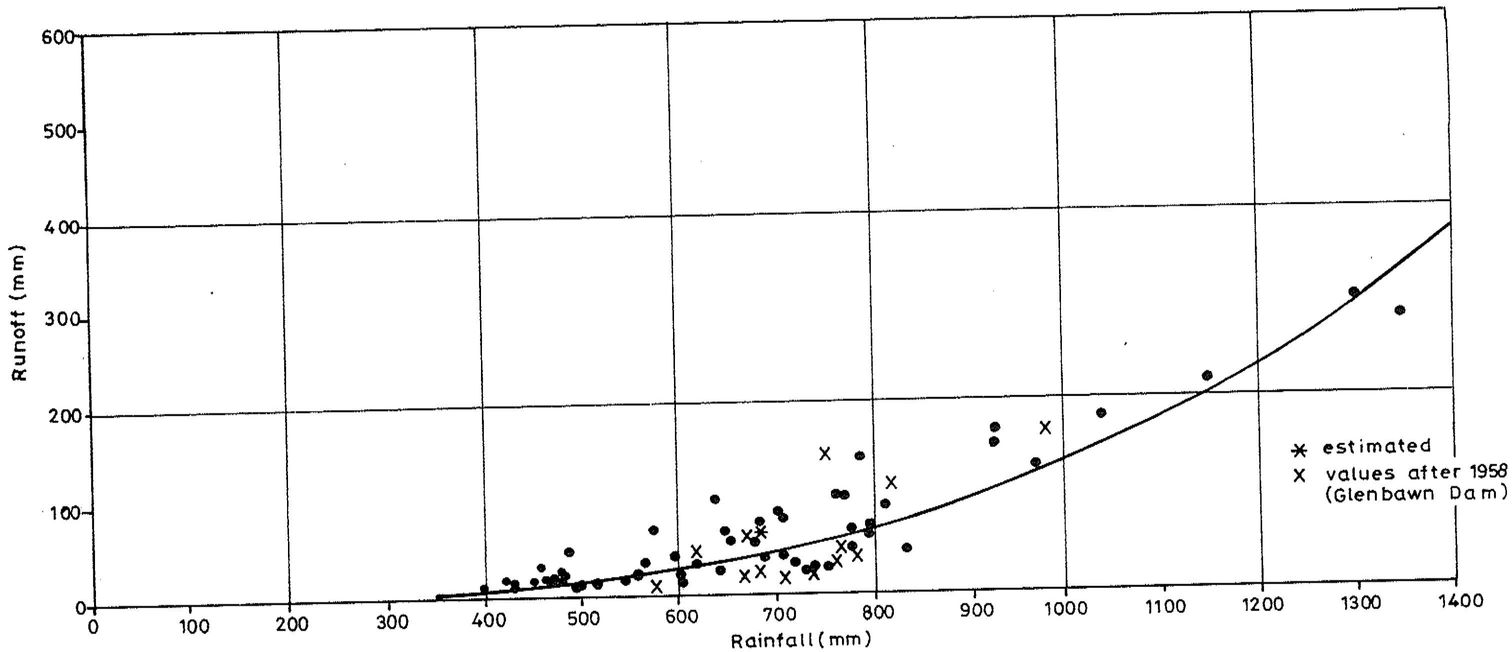


Fig. 3.19 Hunter River at Singleton. Annual Rainfall-Runoff Relation, 1900-1975.

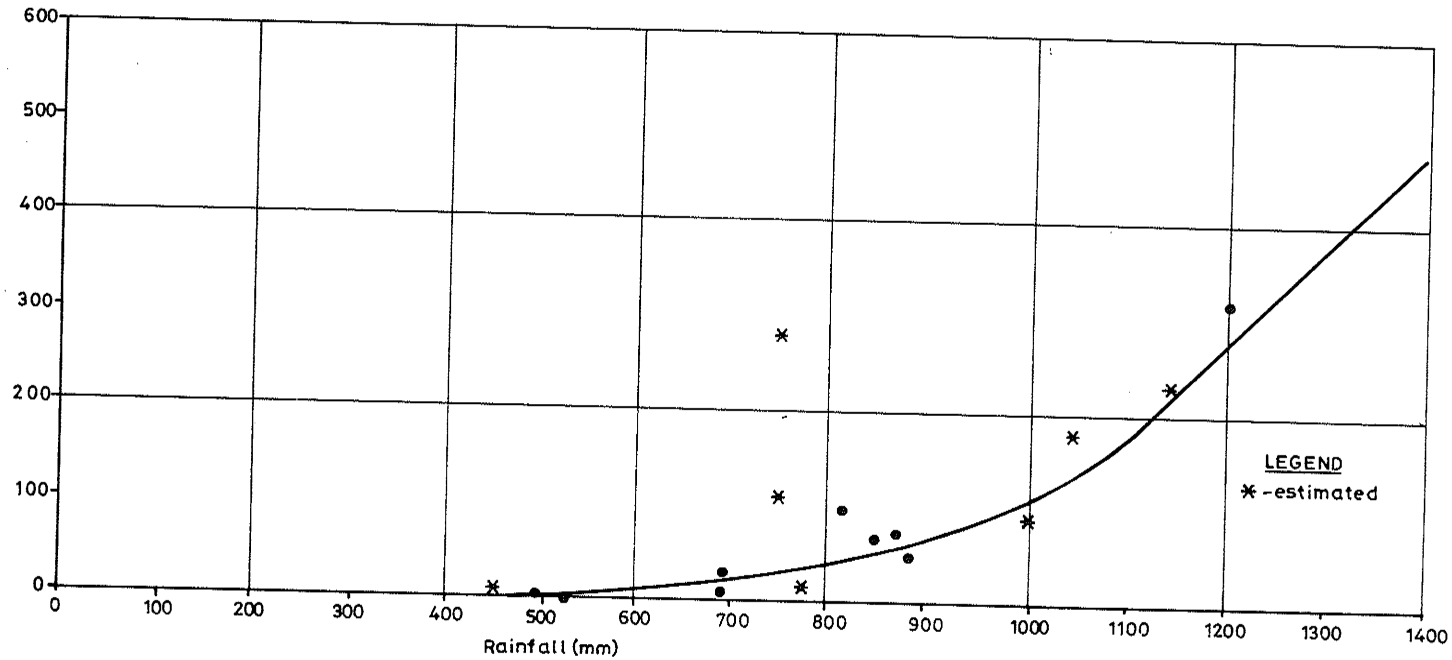


Fig. 3.20 Wollombi Brook at Bulga. Annual Rainfall-Runoff Relation, 1953-1972.

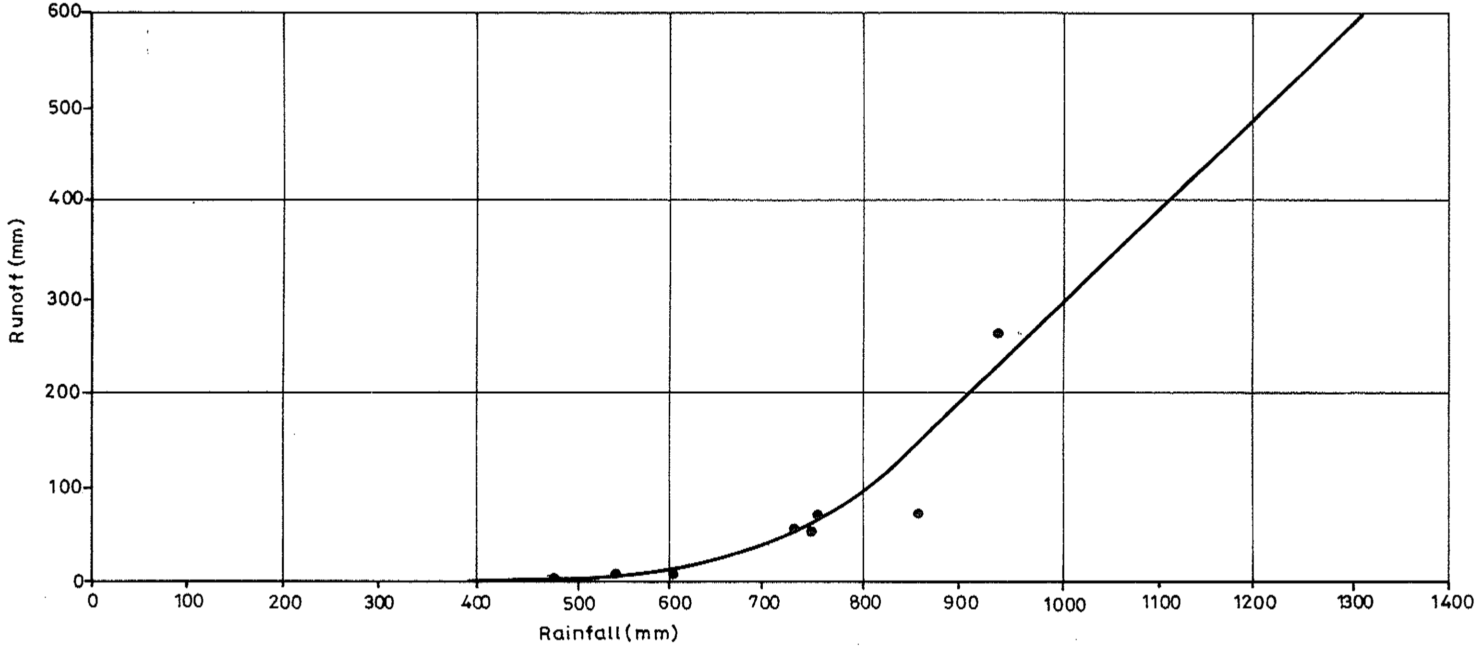


Fig. 3.21 First Creek at Pokolbin Site 1. Annual Rainfall-Runoff Relation, 1964-1974.

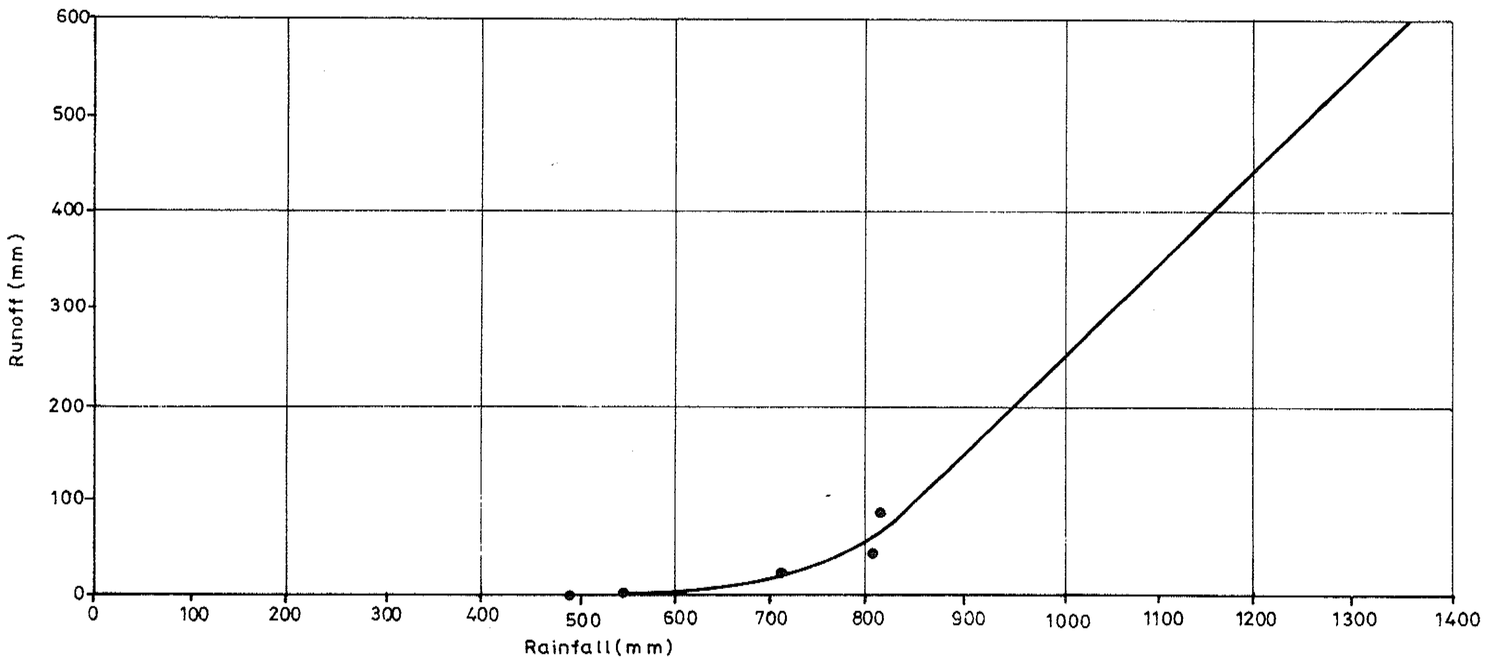


Fig. 3.22 Deep Creek at Pokolbin Site 3. Annual Rainfall-Runoff Relation, 1965-1973.

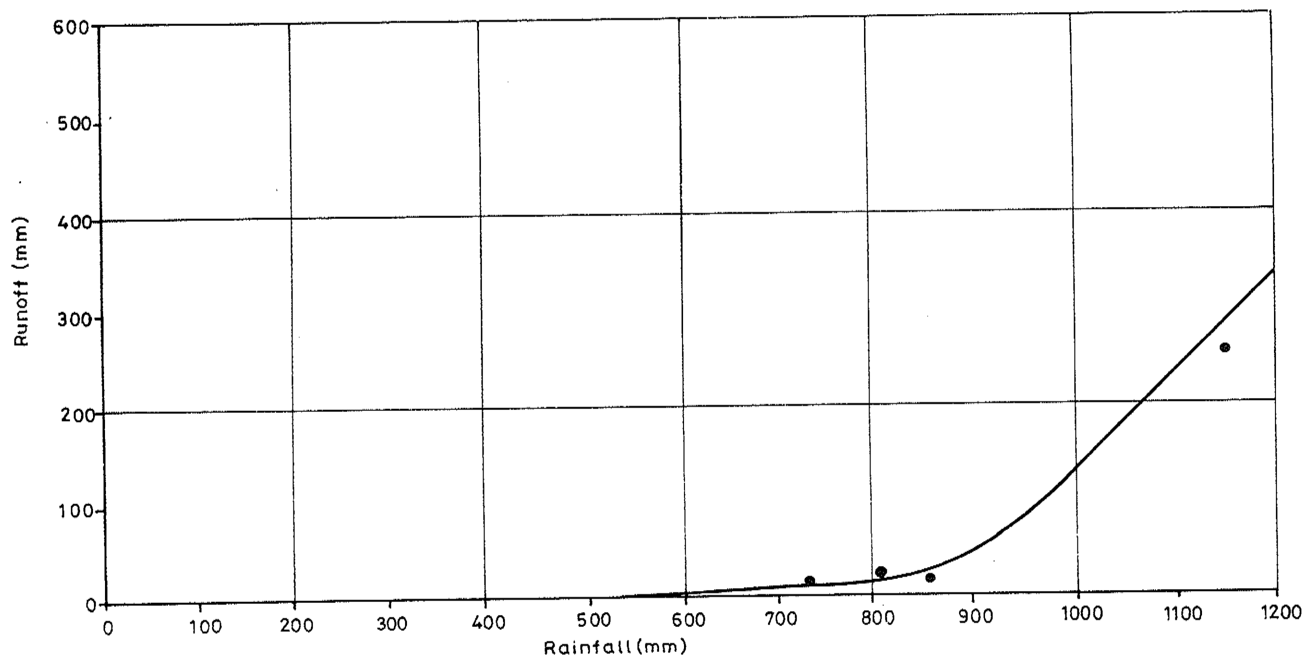


Fig. 3.23 Deep Creek at Pokolbin Site 4. Annual Rainfall-Runoff Relation, 1965-1975.

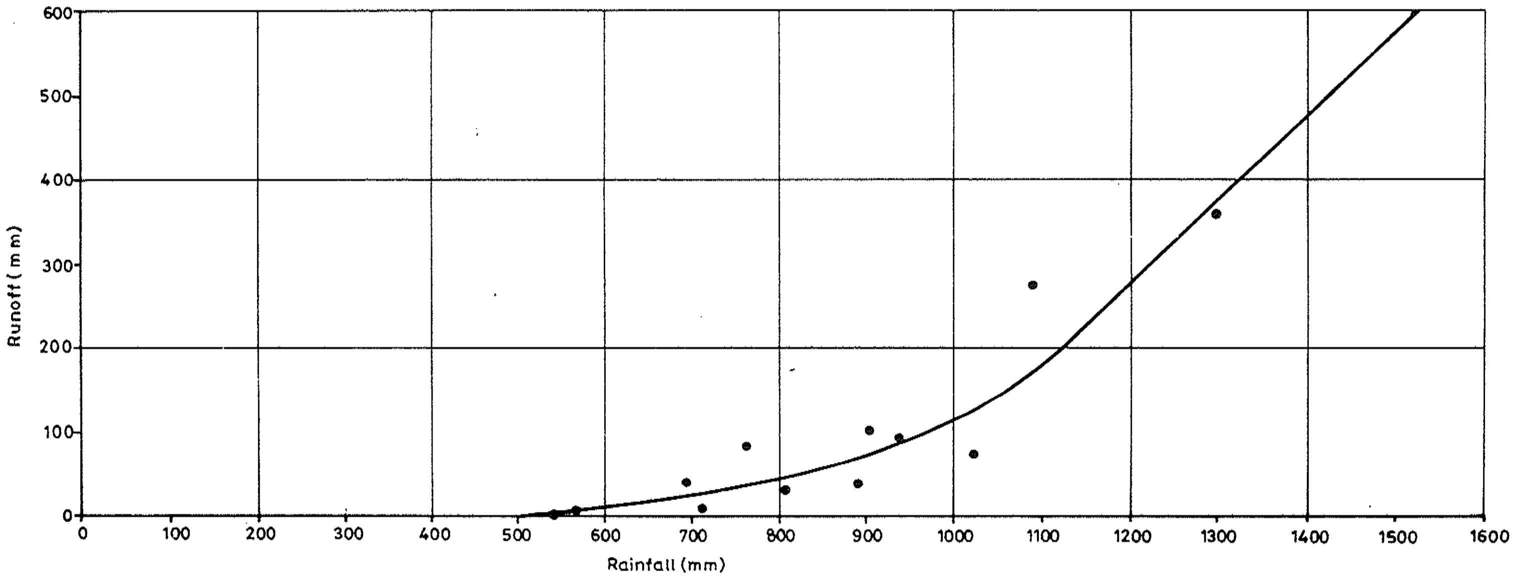


Fig. 3.24 Wollombi Brook at Hanging Rock. Annual Rainfall-Runoff Relation, 1960-1972.

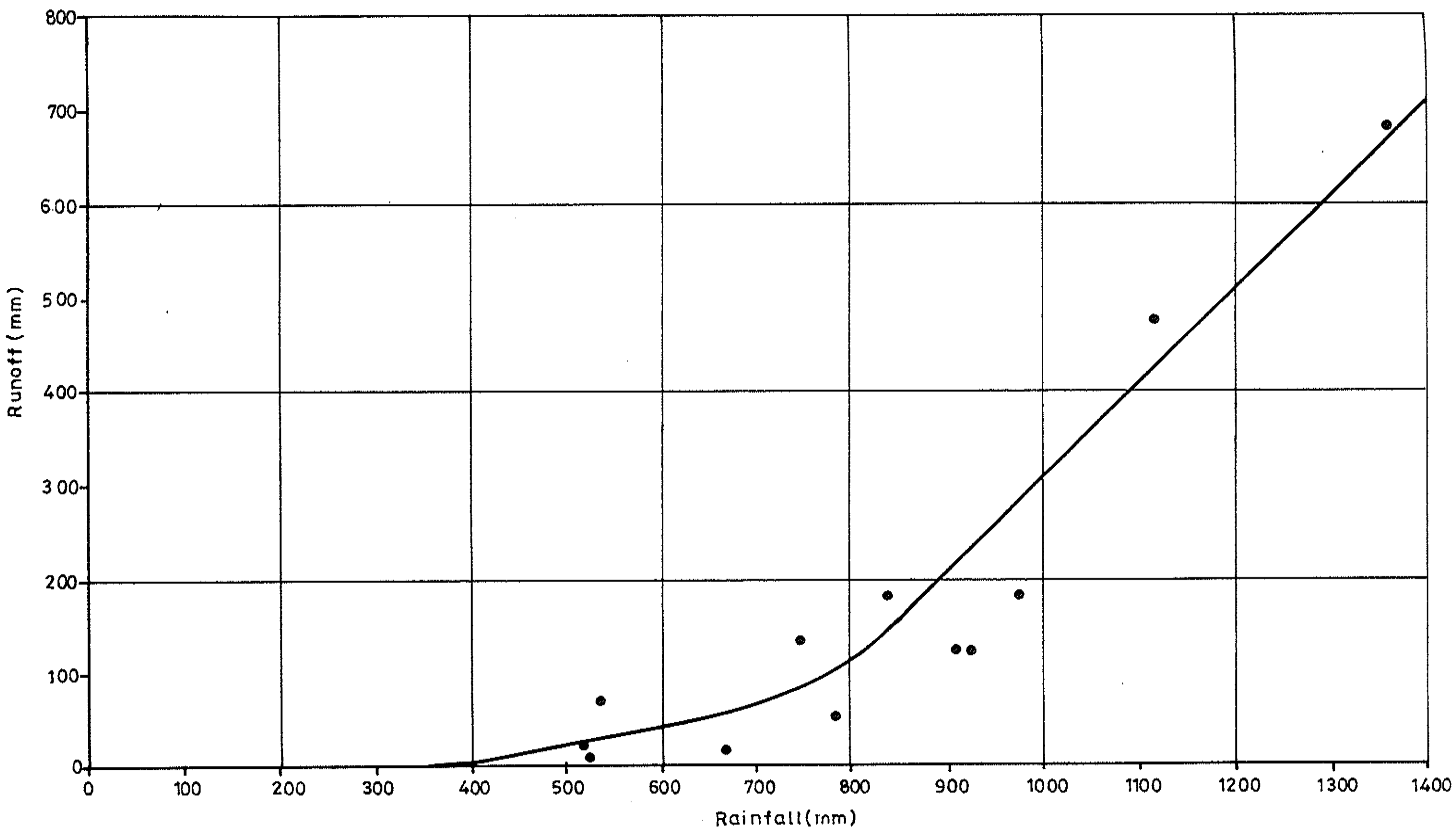


Fig. 3.25 Glennies Creek at Middle Falbrook. Annual Rainfall-Runoff Relation, 1957-1969.

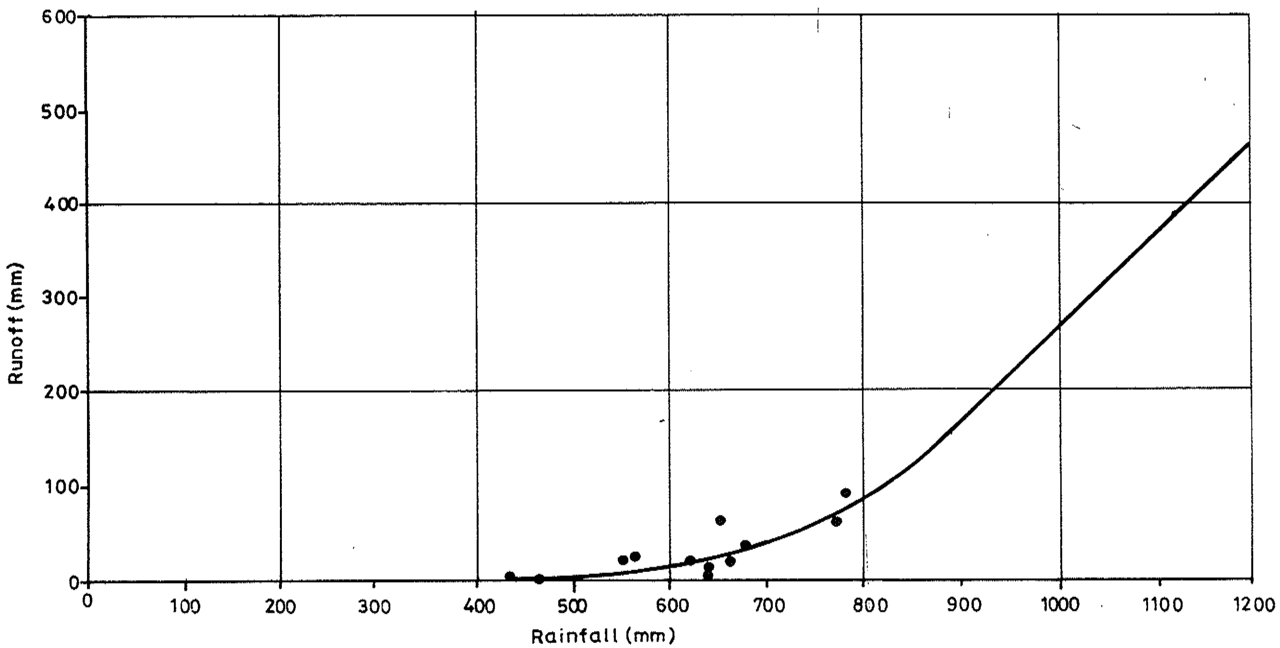


Fig. 3.26 Saltwater Creek at Plashett. Annual Rainfall-Runoff Relation, 1962-1975.

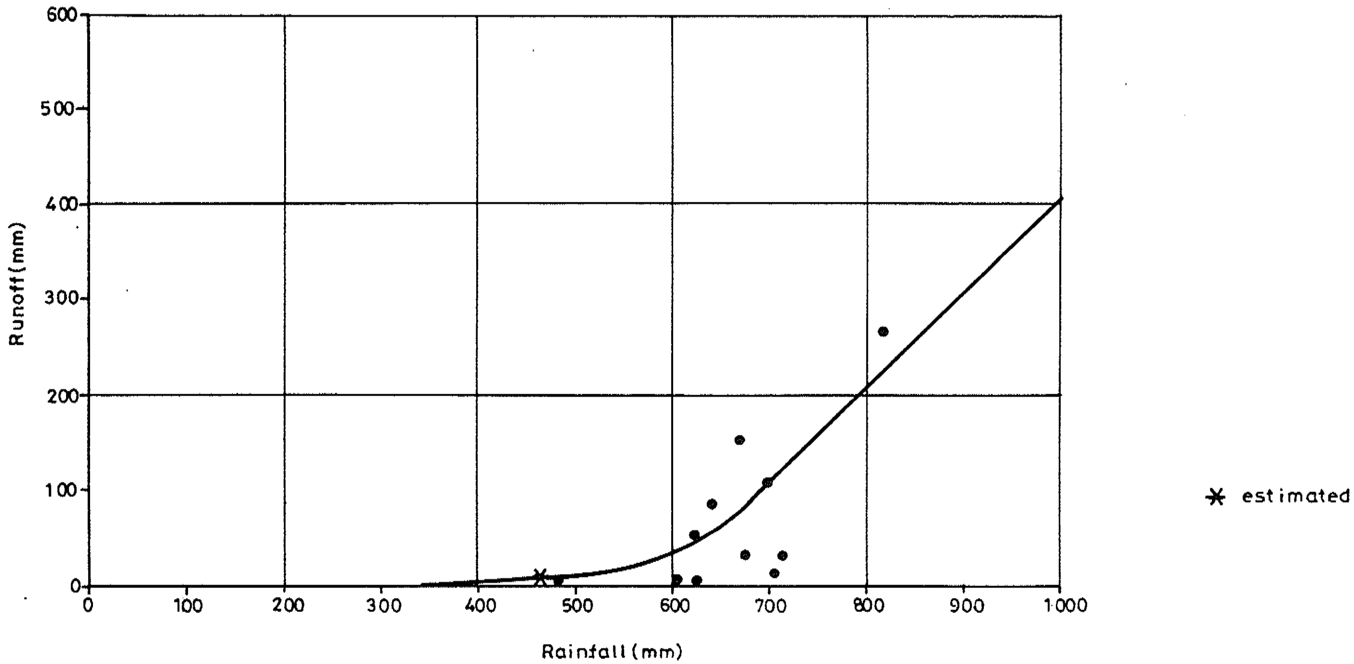


Fig. 3.27 Gardiners Creek at Liddell. Annual Rainfall-Runoff Relation, 1960-1975.

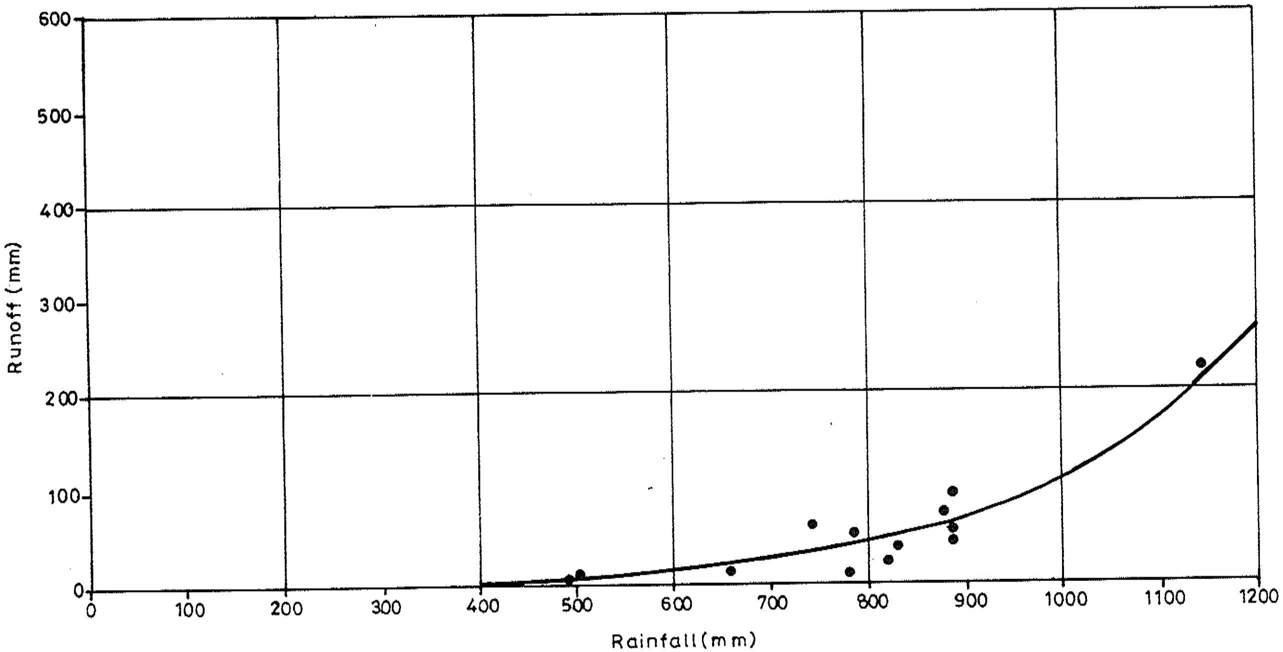


Fig. 3.28 Bowmans Creek at Ravensworth. Annual Rainfall-Runoff Relation, 1957-1972.

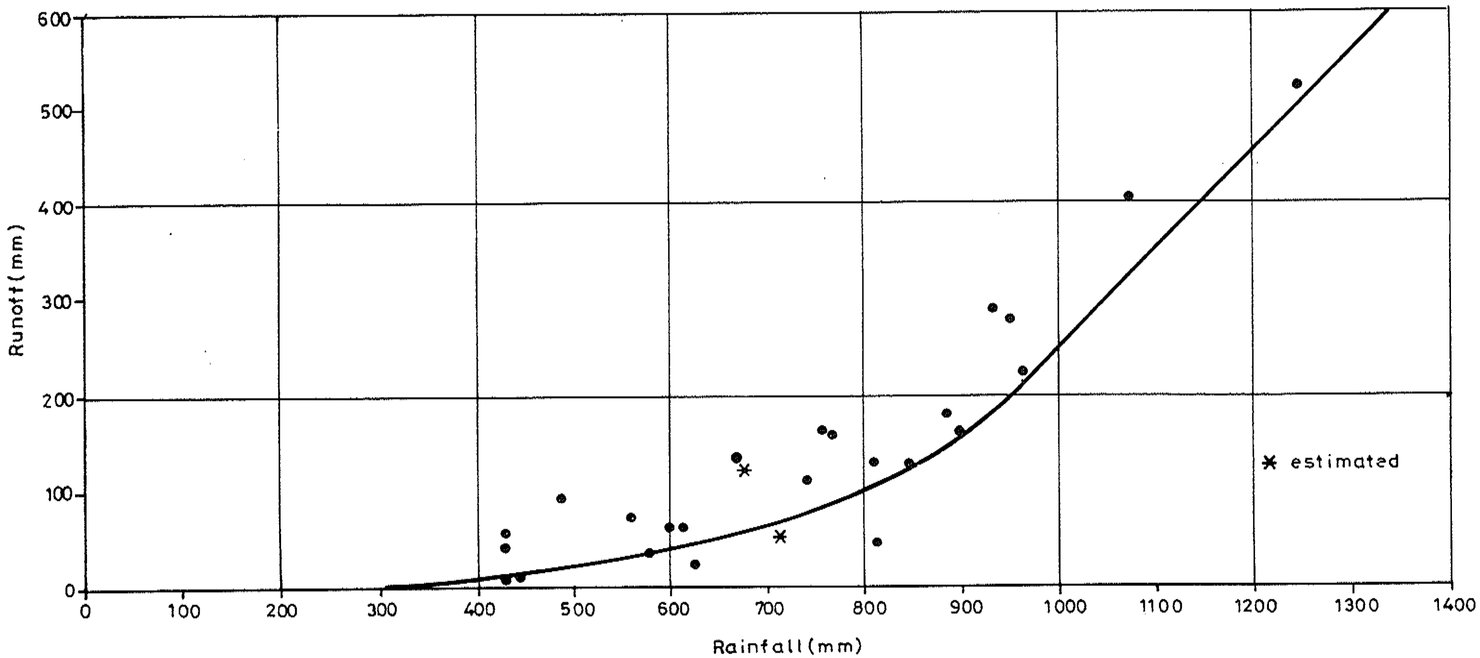


Fig. 3.29 Rouchel Brook at Rouchel Brook. Annual Rainfall-Runoff Relation, 1935-1975.

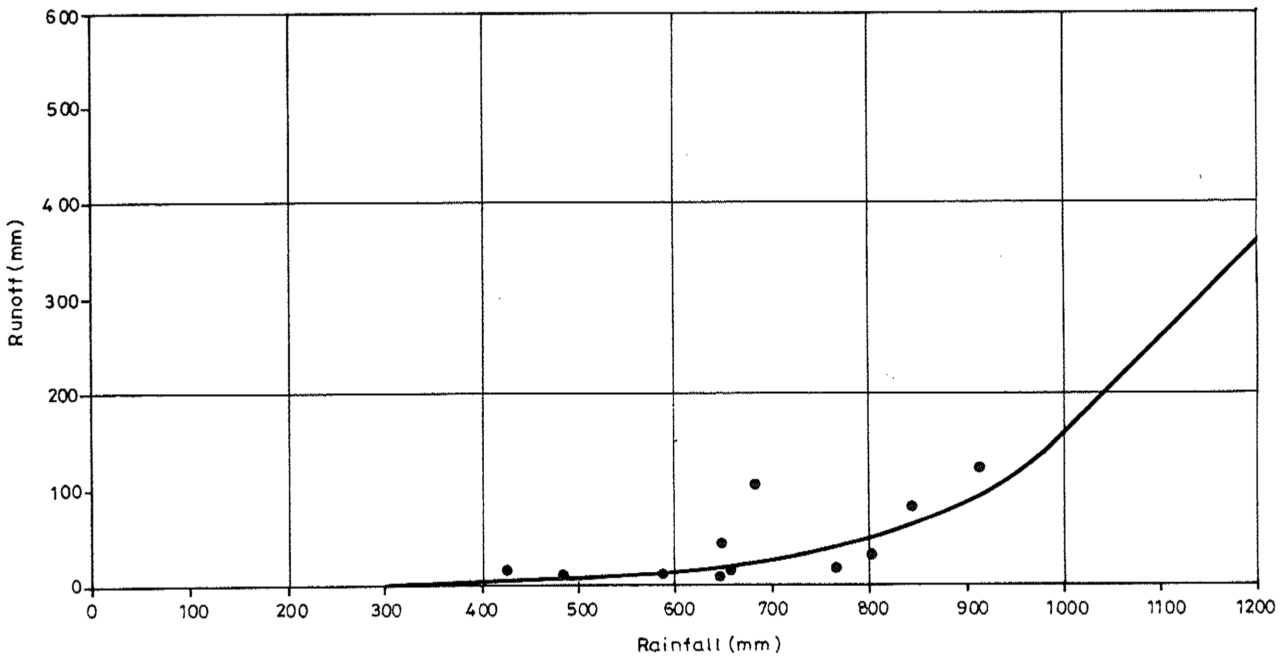


Fig. 3.30 Wybong Creek at Wybong. Annual Rainfall-Runoff Relation, 1956-1970.

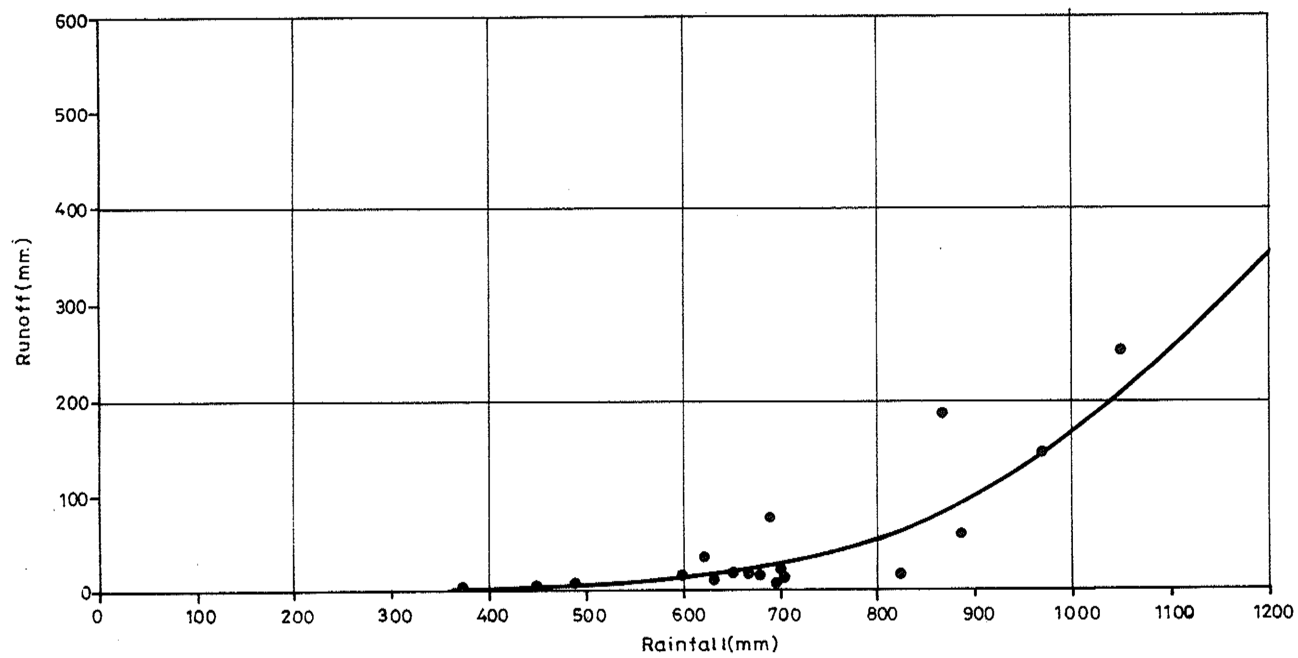


Fig. 3.31 Goulburn River at Sandy Hollow. Annual Rainfall-Runoff Relation, 1955-1972.

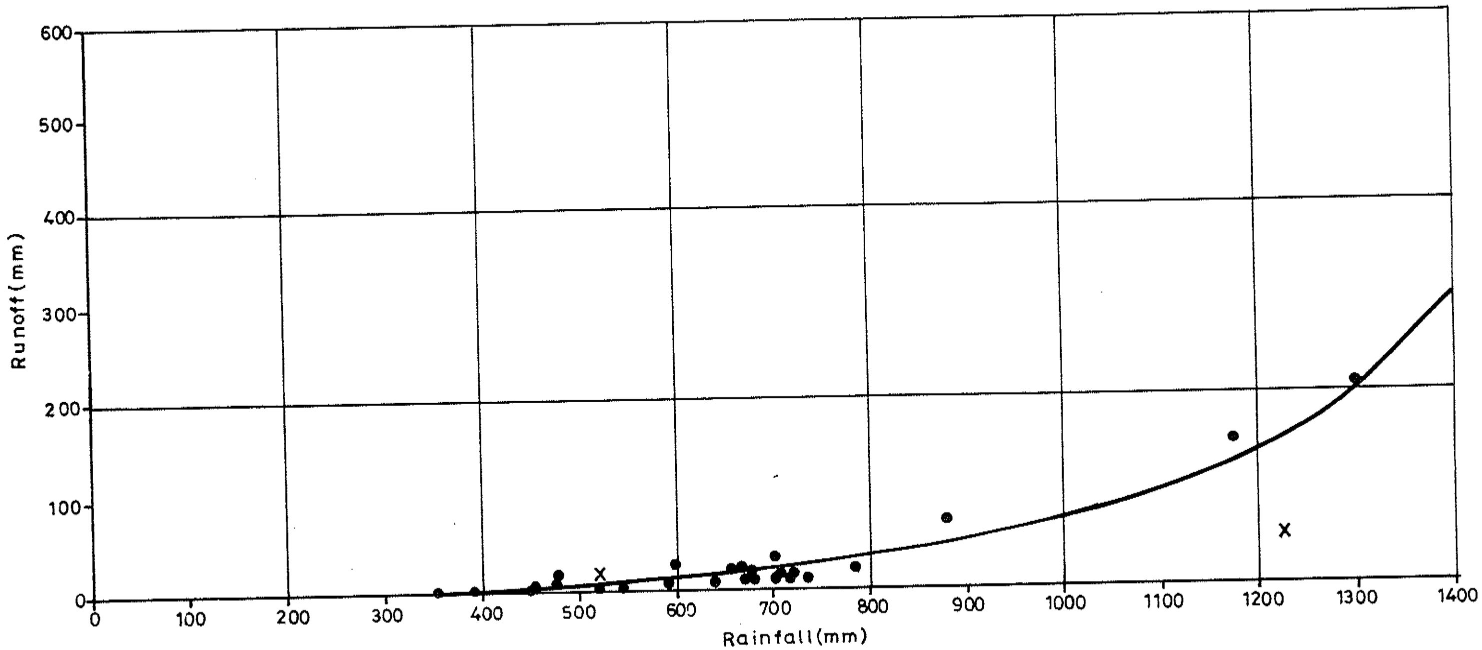


Fig. 3.32 Goulburn River at Kerrabee. Annual Rainfall-Runoff Relation, 1941-1970.

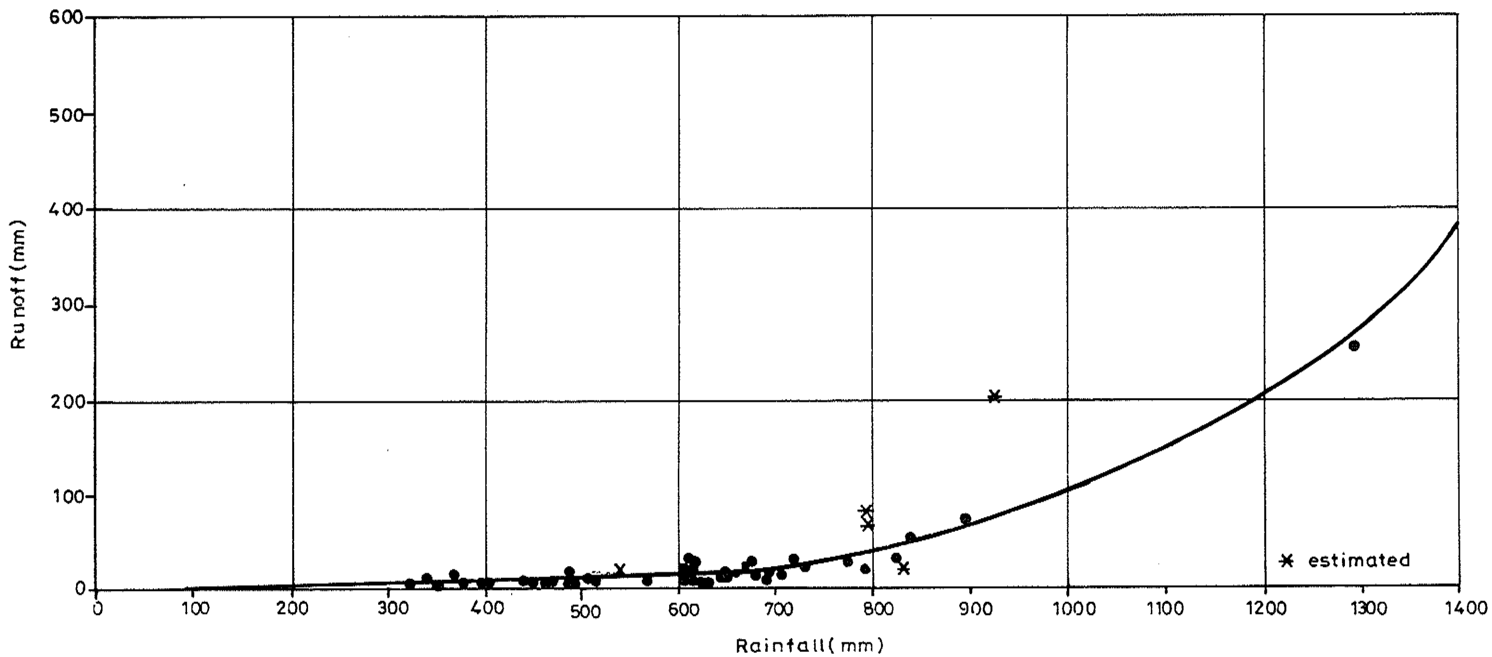


Fig. 3.33 Goulburn River at Coggan. Annual Rainfall-Runoff Relation, 1913-1975.

Note: For location of catchments see Fig. 3.7

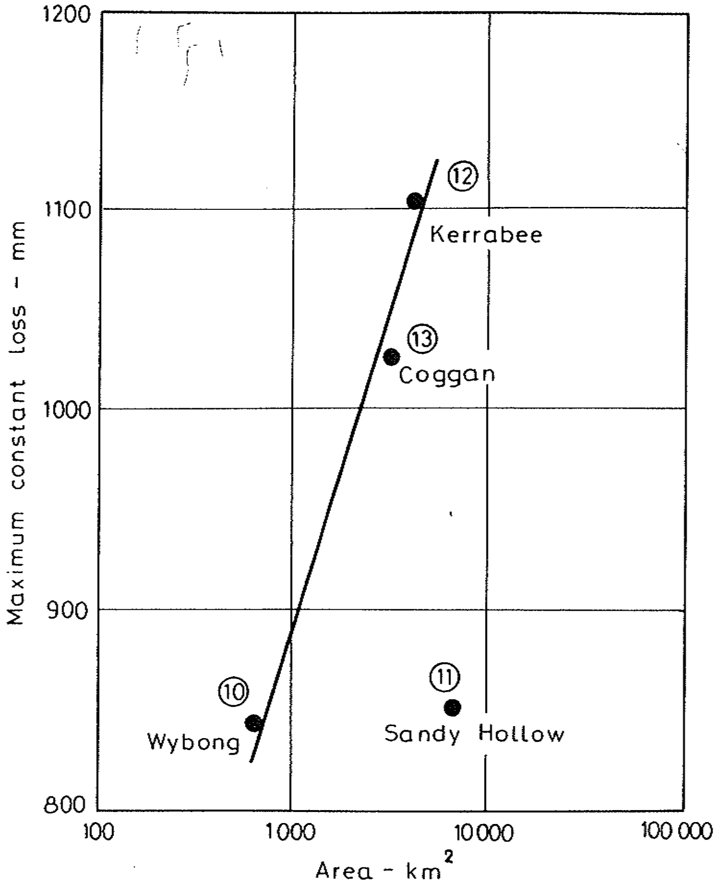


Fig. 3.34 Relation of Maximum Constant Loss to Area for Western Region of Upper Hunter Valley.

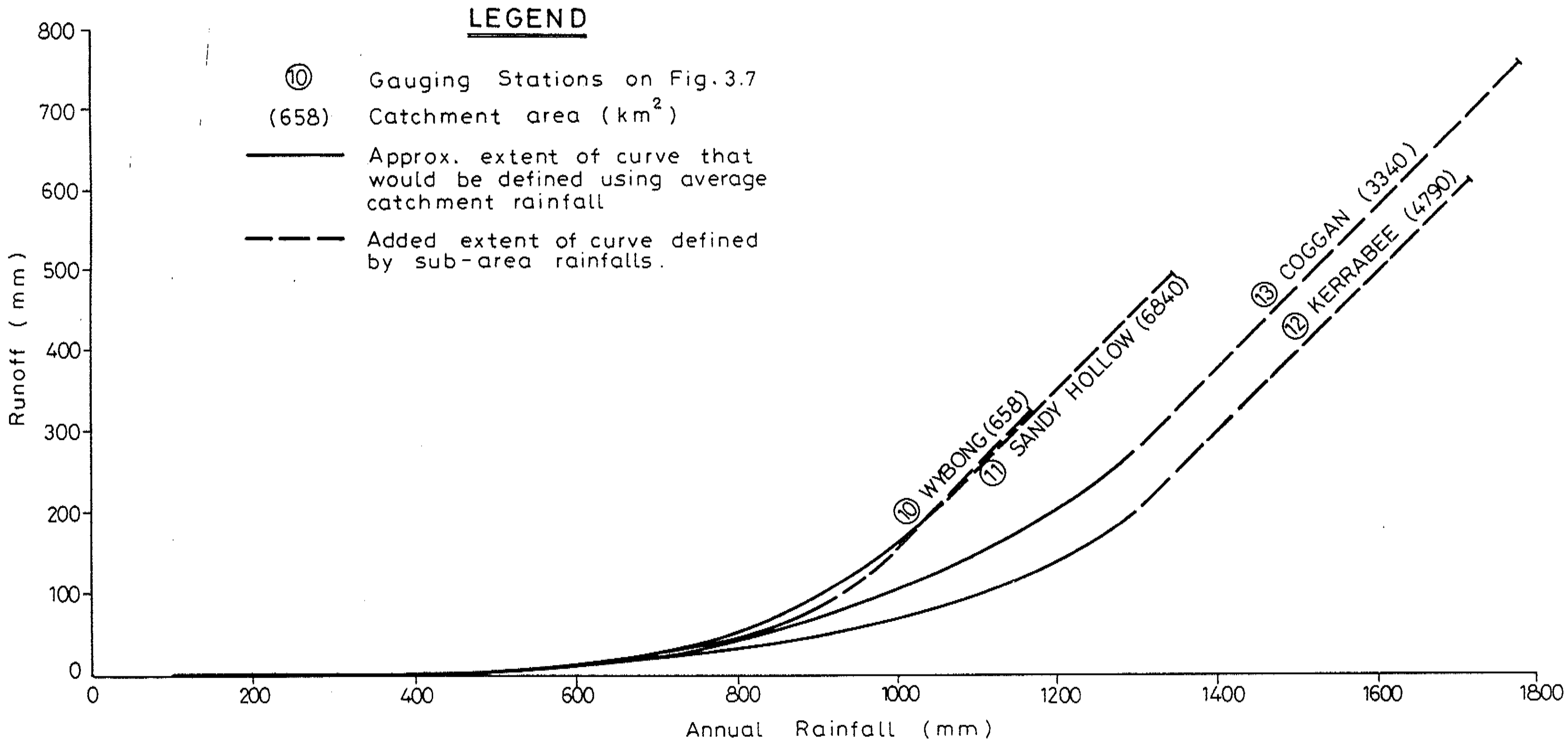


Fig. 3.35 Western Region of Upper Hunter Valley. Annual Rainfall - Runoff Relations.

Note: For location of catchments see Fig. 3.7

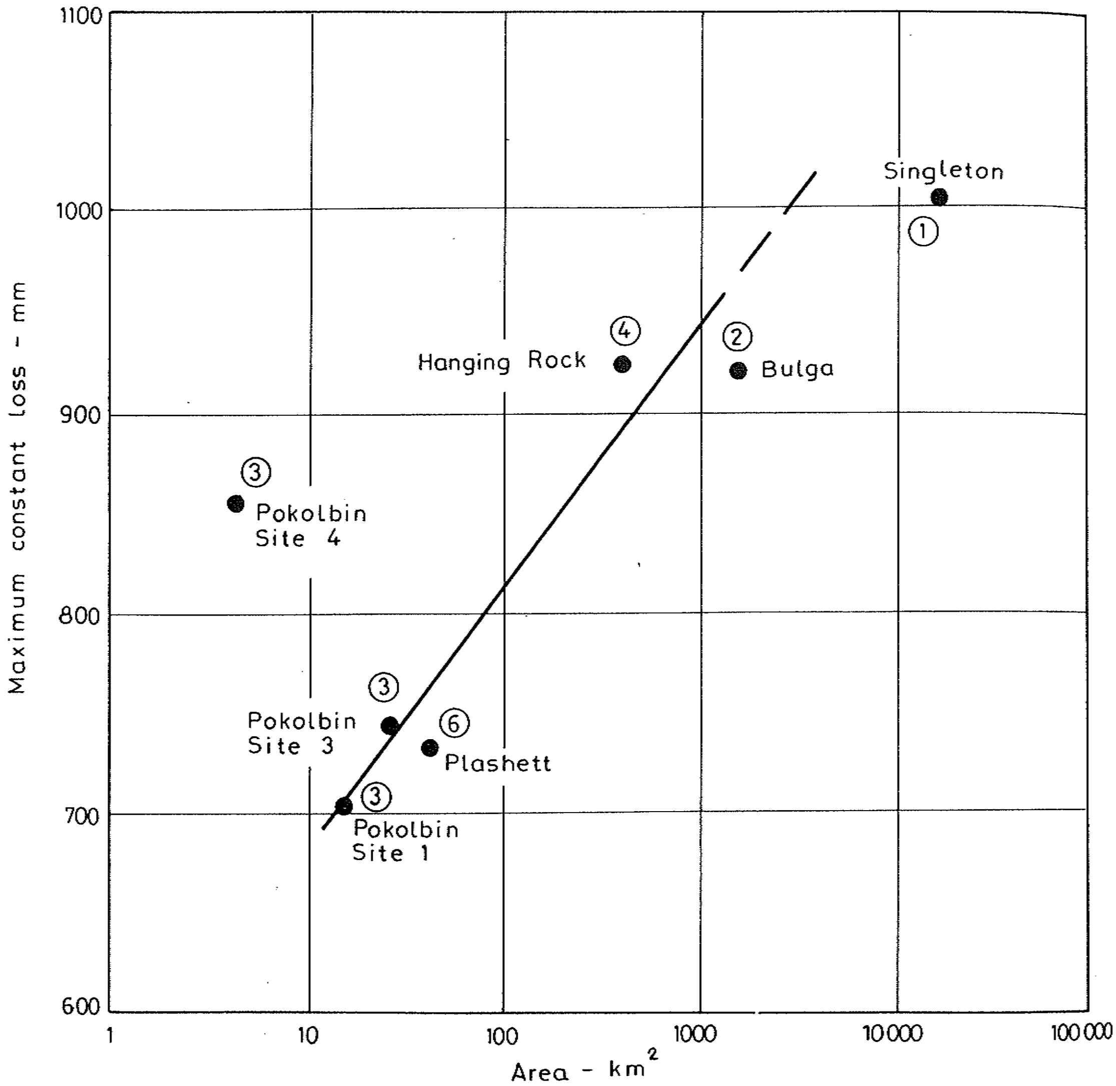


Fig. 3.36 Relation of Maximum Constant Loss to Area for Southeast Region of Upper Hunter Valley and Singleton.

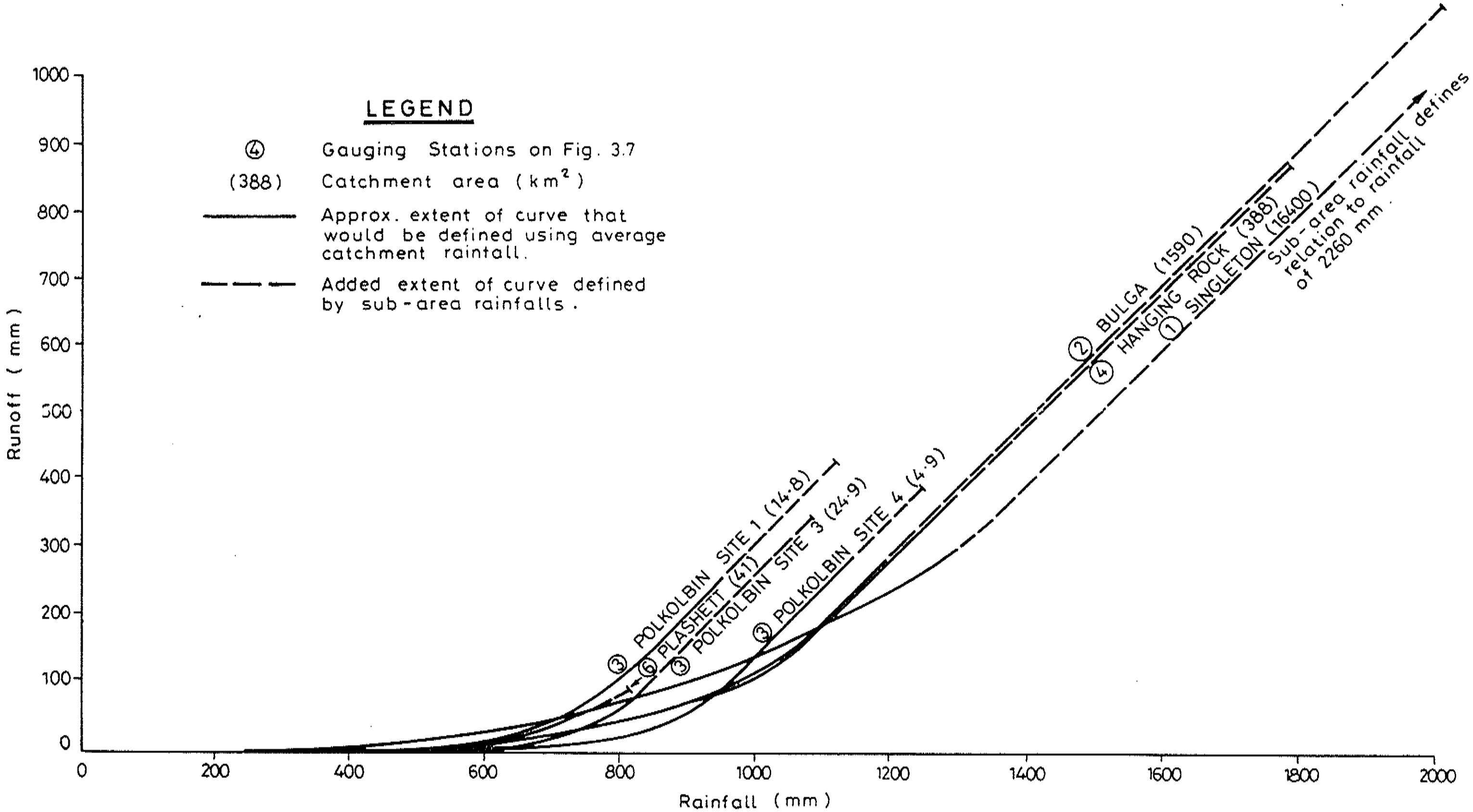


Fig. 3.37 Southeast Region of Upper Hunter Valley. Annual Rainfall - Runoff Relations

Note : For location of catchments see Fig. 3.7

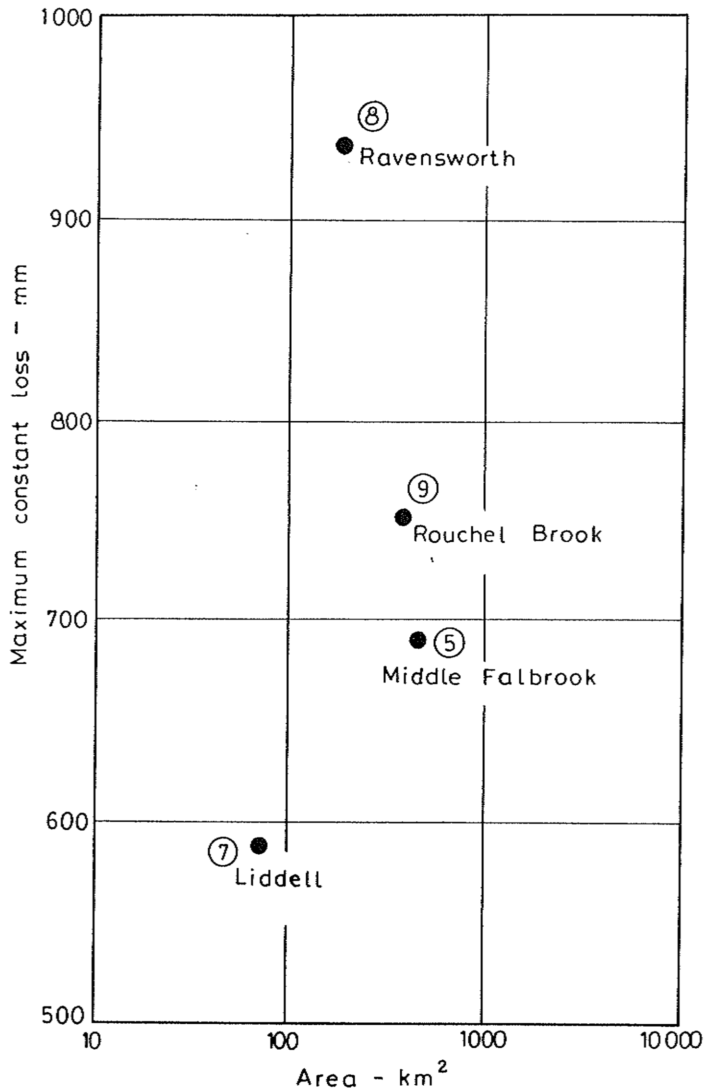


Fig. 3.38 Relation of Maximum Constant Loss and Area for Northeast Region of Upper Hunter Valley.

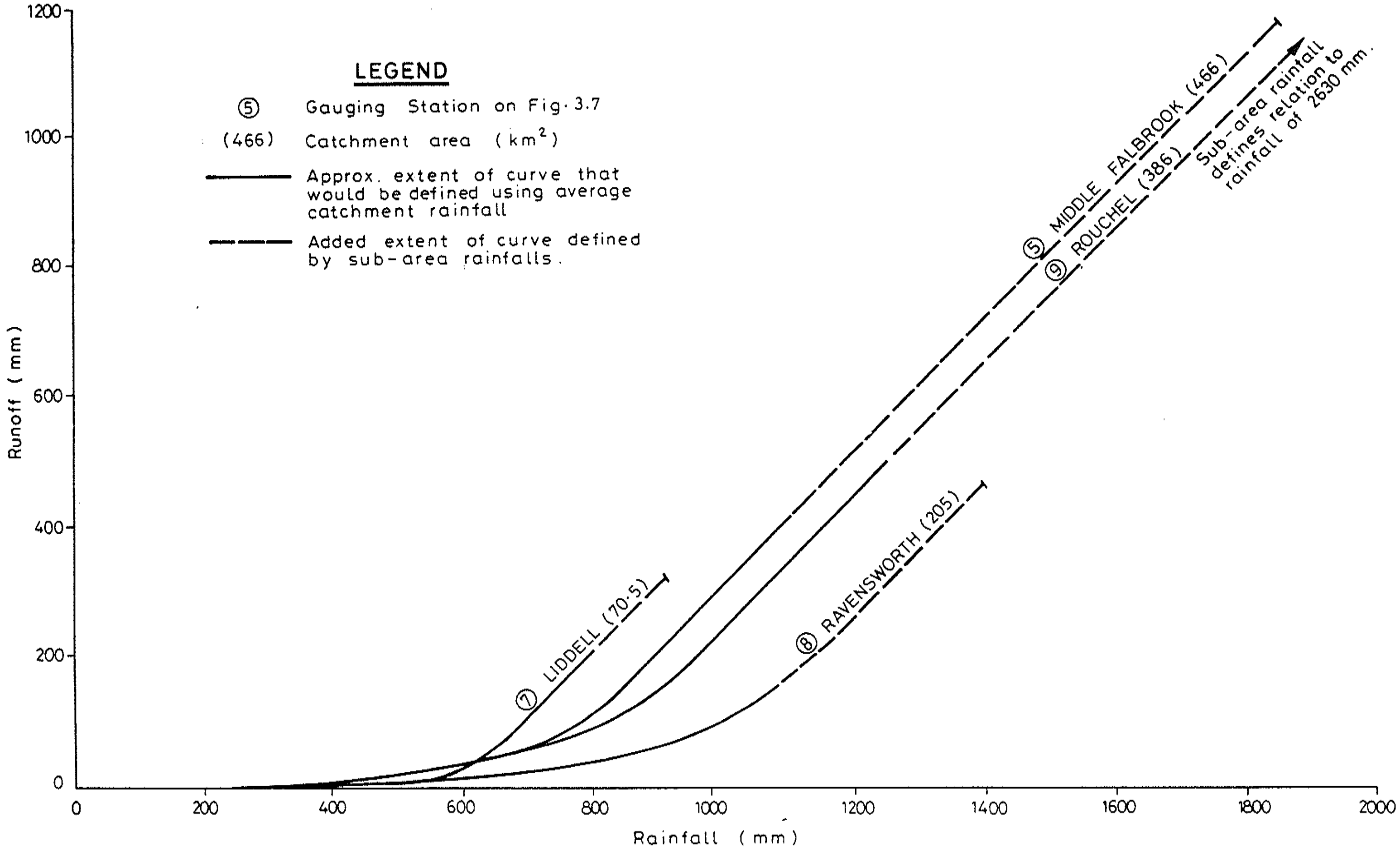


Fig. 3.39 Northeast Region of Upper Hunter Valley. Annual Rainfall - Runoff Relations.

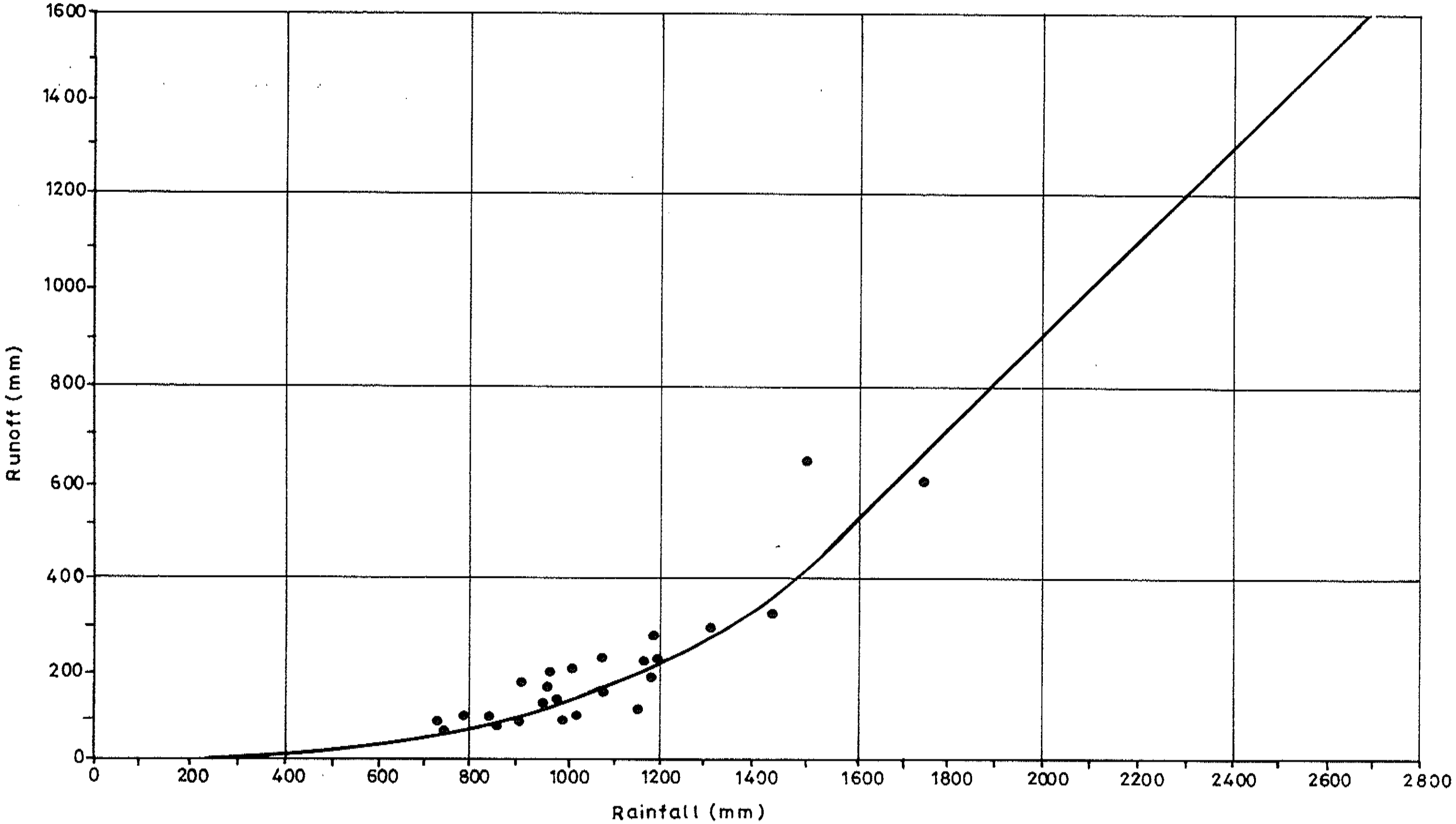


Fig. 3.40 Mann River at Jackadgery. Annual Rainfall-Runoff Relation for Half-Period 1920-1945.

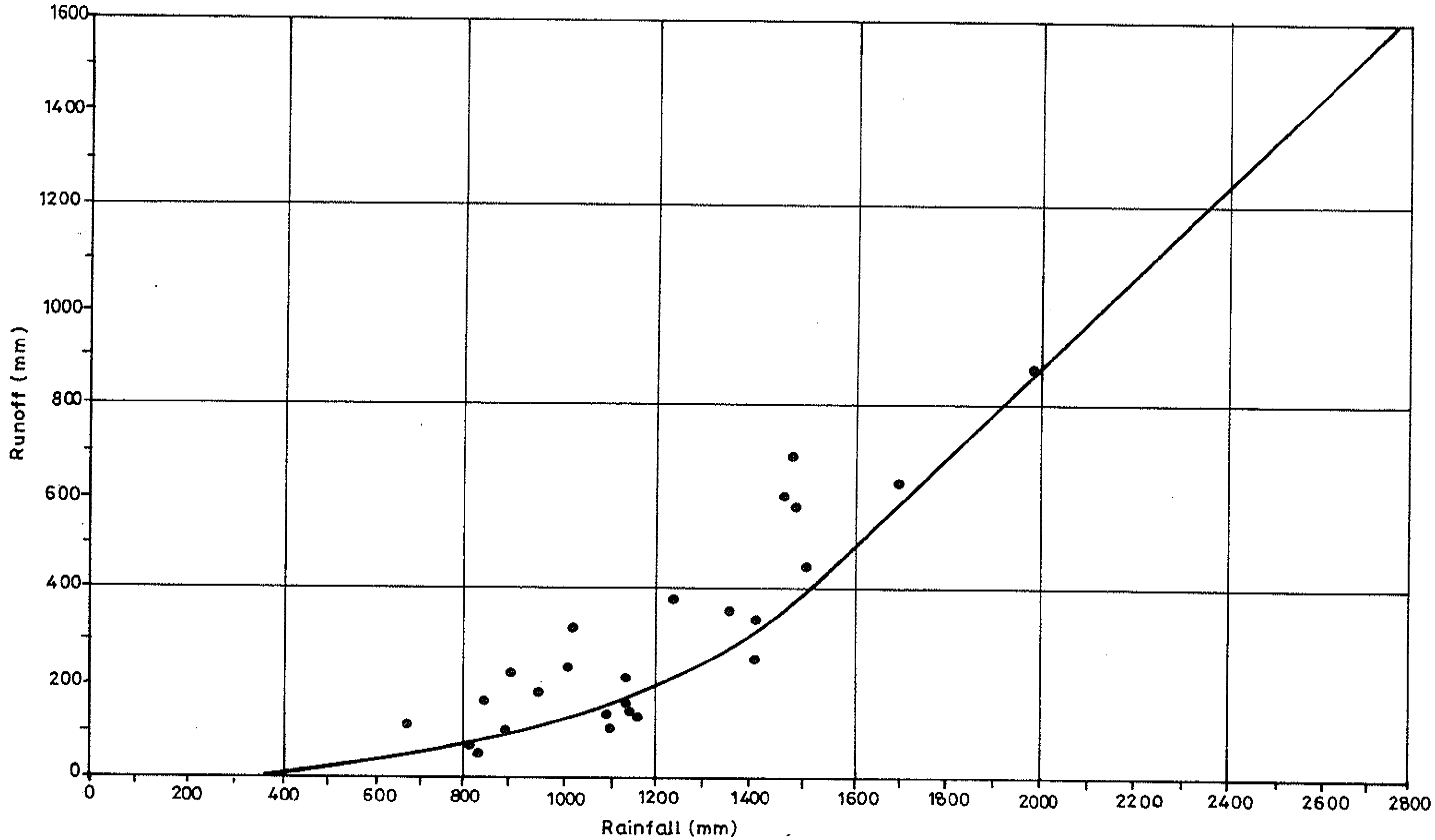


Fig. 3.41 Mann River at Jackadgery. Annual Rainfall-Runoff Relation for Half-Period 1946 - 1970.

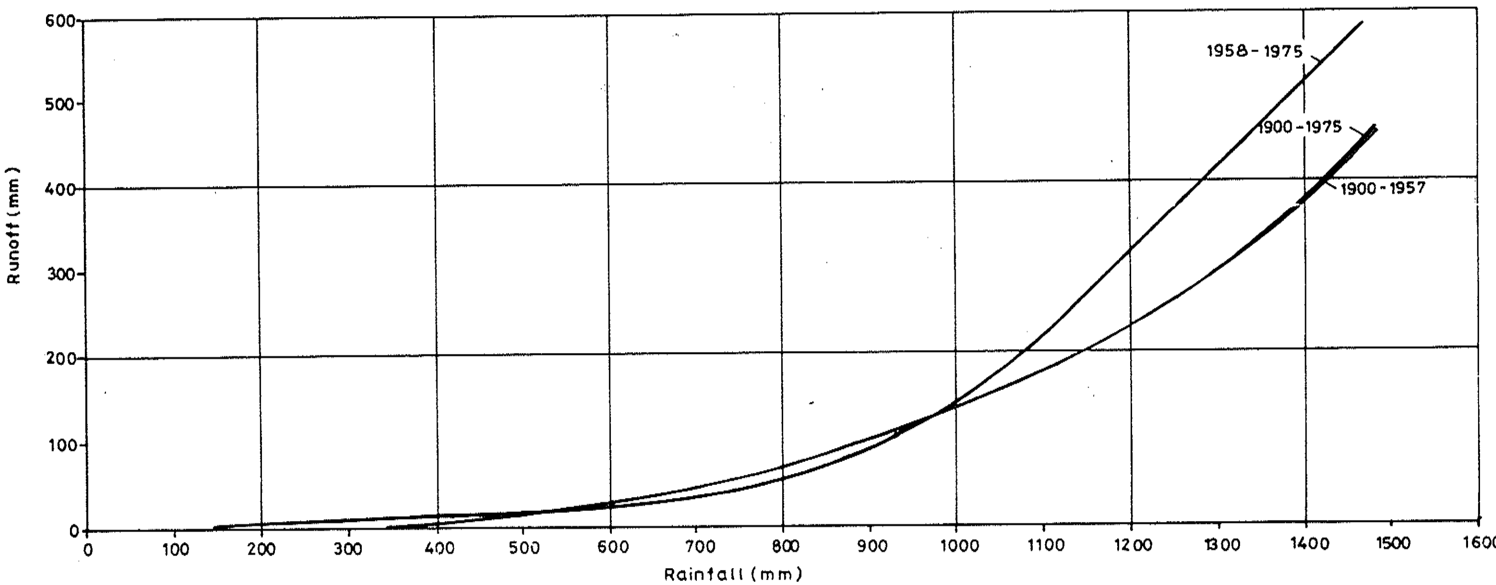


Fig. 3.42 Hunter River at Singleton. Annual Rainfall-Runoff Relations for Various Periods.

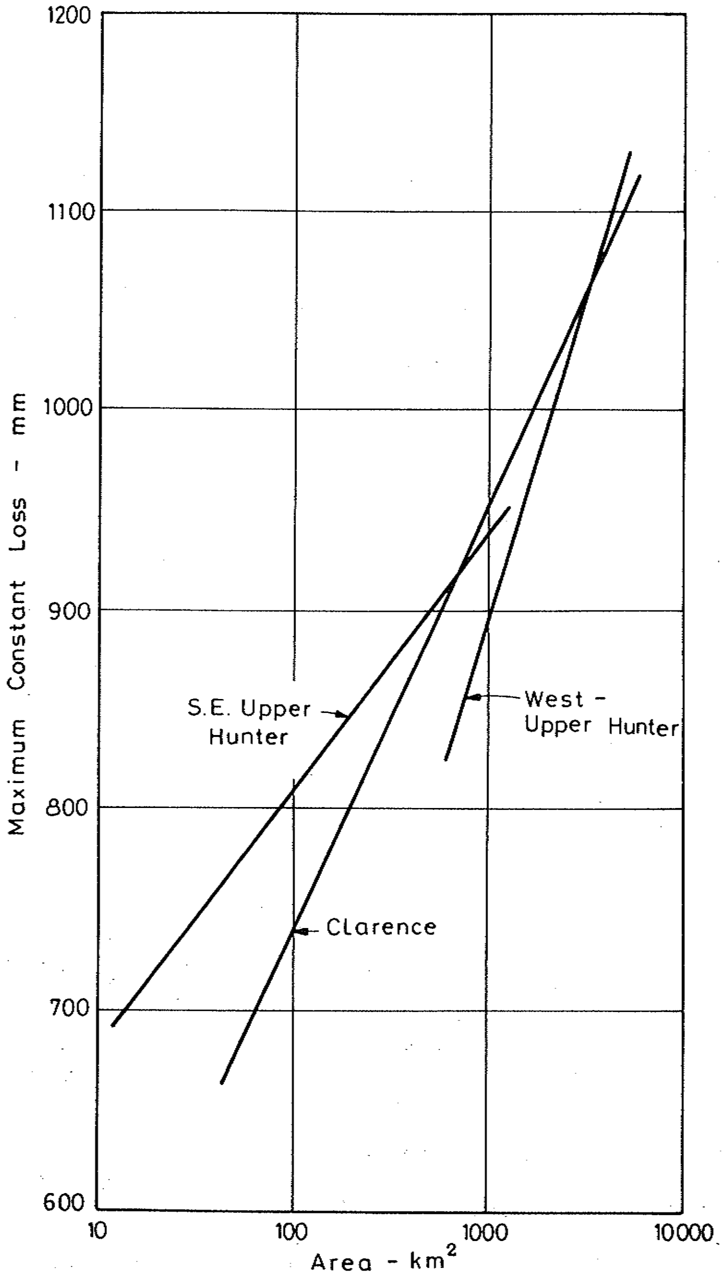


Fig. 3.43 Relations of Maximum Constant Loss and Area for Three Regions.

4. EFFECTS OF AREA ON FLOOD HYDROGRAPHS

To investigate the effects of catchment area on flood hydrographs, it was decided to accept the unit hydrograph as being a measure of the flood response of a catchment. Unit hydrographs are widely used for flood estimation in Australia.

In order to examine any relationships between catchment area and unit hydrographs, some parameters must be chosen as suitably representative measures of the unit hydrograph. Since the unit hydrograph represents unit depth of runoff from the surface of the catchment, its volume is perfectly correlated with catchment area. However, the shape of the unit hydrograph varies with many other catchment characteristics such as slope, surface roughness (macroscale roughness) and catchment shape. Hence it was proposed to investigate the relationship of flood response to area by relating unit hydrograph parameters to catchment characteristics, as has been common practice in synthetic unit hydrograph studies. Several synthetic unit hydrograph studies have been undertaken in Australia but none of these has involved a large range of catchment sizes.

4.1 THE CLARK MODEL

The Clark model (Clark, 1945) as presented by Johnstone and Cross (1949) has been used fairly widely in Australia for estimating synthetic unit hydrographs for small catchments. The model comprises a time-area diagram (TAD) which represents the translation of rainfall excess across the catchment surface to the outlet, and a concentrated linear storage located at the catchment outlet which represents the effects of catchment storage. Cordery and Webb (1974) simplified the model slightly by showing that the TAD could be represented adequately by a right angled triangle with area increasing linearly from zero at time zero to a maximum at the maximum translation time, and this modified Clark Model has been widely accepted for estimation of design floods in eastern N.S.W. Since this model has been widely accepted it was decided to adopt the Clark model parameters C and K as representative measures of catchment response.

4.2 UNIT HYDROGRAPH STUDY

A considerable amount of data has been published in Australia in recent years on catchment characteristics and Clark-model synthetic unit hydrograph parameters. Some of these data have been collected in Table 8.3 of "Australian Rainfall and Runoff" (Institution of Engineers, Australia, 1977, subsequently referred to as ARR). However, no attempt has been made previously to examine the possibility of deriving relationships between unit hydrograph parameters and catchment characteristics that could be applicable to catchments of various sizes located throughout Australia. Two groups of relationships between Clark model parameters C and K and catchment characteristics are reported in section 8.2.6 of ARR but no attempt is made in that publication to find a widely applicable relationship.

As part of this project to examine the possible application to large catchments of data and relationships obtained from small catchments, all of the readily available unit hydrograph data were gathered together and examined. Data for 42 catchments in Tasmania, Western Australia, Queensland and New South Wales are given in ARR, Table 8.3. However, as discussed later, the five Western Australian catchments were not included. The catchments listed generally range in size from 0.05 km^2 to 2300 km^2, with one catchment of 8900 km^2. Thirty two of the thirty seven catchments listed are of less than 800 km^2. Data for five additional Tasmanian catchments ranging in size from 110 km^2 to 2500 km^2 are given by Watson (1978), who also provides updated information on three of the Tasmanian catchments listed in Table 8.3 of ARR. Unit hydrograph data were also supplied by the N.S.W. Water Resources Commission for seven catchments ranging in size from 540 km^2 to 15 000 km^2, five of which were larger than 3000km^2. These data were for unit hydrographs derived from observed rainfall and streamflow data. The measurement of catchment characteristics and derivation of synthetic unit hydrograph parameters for those seven catchments was carried out in the University as part of this project.

In all, unit hydrograph data were available for 52 catchments. The distribution of catchments by State and size are shown in Table 4.1

Table 4.1

Distribution of Size and Location of Catchments Used in Unit Hydrograph Study

Size km^2	Number of catchments		
	NSW	QLD	TAS
0- 1	5		
1.01- 10	2		1
10.1-100	7		2
101-500	1	3	7
501-1000	2	5	5
1001-5000	3	2	3
5001-10000	3		
10001-20000	1		
TOTALS	24	10	18

4.3 RELATIONSHIPS BETWEEN CATCHMENT CHARACTERISTICS AND UNIT HYDROGRAPH PARAMETERS

The relationships suggested by Cordery and Webb (1974) are

$$C = 0.17 \left(\frac{L}{S}\right)^{0.41} \text{ hours} \qquad (4.1)$$

and

$$K = 0.66L^{0.57} \text{ hours} \qquad (4.2)$$

and the relationships given in ARR (equations 8.7 and 8.8) are

$$C = 0.20 \left(\frac{L}{\sqrt{S}}\right)^{0.58} \text{ hours} \qquad (4.3)$$

and

$$K = 0.08L^{1.05} \text{ hours} \qquad (4.4)$$

where L is main stream length in km and S is main stream slope in dimensionless form. It should be noted that equations (4.2) and (4.4) are of the same form.

The data given in Table 8.3 of ARR are somewhat inconsistent in that the values of a given parameter have been estimated differently for different catchments. For instance the slope, S, has been estimated as the "equivalent uniform slope" for some catchments and as the "main channel slope" (see ARR, p. 82 for definition) for others. Similarly the values of C and K have been derived by different methods. For some catchments the values were optimised to obtain the best fit between synthetic unit hydrographs and unit hydrographs derived from observed rainfall and streamflow data. For others they were derived as suggested by Clark (1945).

The above relationships were examined as possible "universal" relationships. It was immediately apparent that the Western Australian data given in ARR were from one population and that all the other data which are listed in Table 4.2 were from a different population. As a result the five Western Australian catchments listed in Table 8.3 of ARR were not included in this study. Any general conclusions from this current study would not be applicable in Western Australia.

As discussed in Section 2.4, catchment area and length are highly correlated. Since length has been shown in equations 4.1 to 4.4 to be related to unit hydrograph parameters, it was decided to use similar relationships here to further examine the relationship between the parameters and catchment area.

The data and their sources are shown in Table 4.2. Figures 4.1 and 4.2 show TAD base-length C plotted against $\frac{L}{S}$ and $\frac{L}{\sqrt{S}}$ respectively and Figures 4.3 and 4.4 show K plotted against L and A respectively. It can be seen that C is highly correlated with both $\frac{L}{S}$ and $\frac{L}{\sqrt{S}}$ in the form of power relationships as given in ARR. The relationships given by the regression of C on $\frac{L}{S}$ and $\frac{L}{\sqrt{S}}$ are

$$C = 0.19 \left(\frac{L}{S}\right)^{0.40} \quad \text{hours} \qquad (4.5)$$

and

$$C = 0.30 \left(\frac{L}{\sqrt{S}}\right)^{0.50} \quad \text{hours} \qquad (4.6)$$

These two relationships are almost equally good estimators of C for the 51 catchments, as can be seen from the correlation coefficient and standard error of estimate values given in Table 4.3. C is slightly better related to $\frac{L}{S}$ than $\frac{L}{\sqrt{S}}$ and so it is suggested equation (4.5) should be adopted. It is also suggested that for application of equation (4.5) S should be derived by plotting the stream profile and finding the slope of a line drawn through the outlet such that the areas above and below the line enclosed by the profile are equal. Equation (4.5) is only a few per cent different from the Cordery-Webb relationship,equation (4.1) which was derived from data for 16 catchments.

The relationships obtained between K and catchment characteristics were

$$K = 0.70\ L^{0.57} \quad \text{hours} \qquad (4.7)$$

and

$$K = 1.00\ A^{0.31} \quad \text{hours} \qquad (4.8)$$

As was discussed in Section 2.4, L has been shown to be related to area raised to a power of 0.5-0.6, and this correspondence is confirmed by these relationships.

Equation (4.7) gives slightly better estimates of K than equation (4.8) as indicated by the correlation coefficient and standard error of estimate values given in Table 4.3 and thus it is recommended that equation (4.7) should be adopted. Again it can be seen that equation (4.7) gives K values which are only 6 per cent different from values given by the Cordery-Webb equation, quoted above as equation (4.2)

The two equations given in ARR for Queensland data (quoted here as equations (4.3) and (4.4))are different from the corresponding best-fit equations derived from all the data given in Table 4.2. Equation (4.3),

Table 4.2 Catchment Characteristics and Unit Hydrograph Parameters

Catchment	No. shown against plotted data point	National gauging station number	Area, A km^2	Mainstream length L, km	Slope of mainstream m/m	C	K	Source of data
South Ck	1	212320	88	22.8	0.0023	9.9	4.4	Cordery & Webb
Eastern Ck	2	212340	25	10.0	0.0058	5.6	2.2	"
Mt Vernon Ck	3	212333	0.70	1.56	0.033	0.68	0.42	"
Hacking R	4	214340	40	16.7	0.093	2.08	2.46	"
Cawleys Ck	5	214334	5.4	5.4	0.041	1.54	0.89	"
Research Ck	6	214330	0.39	0.80	0.059	0.31	0.37	"
Grose R	7	212291	642	48	0.098	2.60	5.78	"
Lidsdale No.1	8	212301	0.054	0.37	0.170	0.36	0.62	"
Lidsdale No.5	9	212305	0.062	0.37	0.066	0.31	0.54	"
Lidsdale No.9	10	212309	0.23	0.71	0.038	0.44	0.56	"
Pokolbin No.1	11	210063	14	15.6	0.0052	5.3	4.0	"
Pokolbin No.2	12	210067	7.8	9.2	0.011	4.7	4.3	"
Pokolbin No.3	13	210068	25	14.6	0.0067	4.2	2.1	"
Blicks R at Hernani	14	204021	70	22.8	0.011	4.6	5.2	"
Blicks R at Dundurrabin	15	204020	252	43	0.019	3.5	6.5	"
Bobo R	16	204026	80	17.7	0.0098	4.3	4.5	"
Severn R	17	416006	3010	194	0.0045	7.0	13.8	"
Gwydir R	18	418010	6650	282	0.0025	15.7	18.1	"
Namoi R	19	419022	15043	245	0.0038	22.1	9.6	NSW Water
Mann R	20	204004	7800	252	0.0036	14.0	10.0	Resources
Cudgegong R	21	421019	3935	186	0.0017	12.6	14.6	Commission
Cudgegong R	22	421038	544	63	0.0020	8.3	8.7	"
Cudgegong R	23	421079	1070	106	0.0024	16.4	13.7	"
Macleay R	24	206019	8940	275	0.0034	21.0	21.0	"
Albert R (Q)	25	145102	545	59.4	0.0102	8.0	5.0	ARR
Proserpine R (Q)	26	122003	260	30.6	0.0078	5.0	3.0	"
Three Moon Ck (Q)	27	136107	375	62.1	0.0017	11.0	6.2	"
Reynolds Ck (Q)	28	143103	225	23.5	0.0197	4.0	2.1	"
Warrill Ck (Q)	29	143108	920	83.7	0.0035	15.0	10.6	"
Bremer R (Q)	30	143107	620	65.8	0.0052	15.0	6.6	"
Barambah Ck (Q)	31	136202	640	90.2	0.0019	15.0	9.5	"
Wild R (Q)	32	116014	585	57.5	0.0053	9.0	5.6	"
Houghton R (Q)	33	119005	1092	63.7	0.0060	12.0	6.0	"

Table 4.2 Catchment Characteristics and Unit Hydrograph Parameters(continued)

Catchment	No. shown against plotted data point	National gauging station number	Area, A km²	Mainstream length L, km	Slope of mainstream m/m	C	K	Source of data
Gunpowder Ck (Q)	34	913006	2331	95	0.0023	17.0	7.8	ARR
Forth R (T)	35	315006	316	37	0.012	10.0	9.0	"
Forth R (T)	36	315002	713	68	0.006	10.0	8.0	"
Mackintosh R (T)	37	310006	523	48	0.0080	9.0	5.0	Watson (1978)
Murchison R (T)	38	310007	756	67	0.0062	6.0	6.0	"
Westons Rivulet (T)	39	318039	9.3	5.0	0.013	2.0	2.0	ARR
Pine Ck (T)	40	304108	19.4	6.4	0.052	2.0	3.0	-"
Wilmot R (T)	41	315003	158	26	0.019	3.0	4.0	"
Mersey R (T)	42	316004	350	52		16.0	20.0	"
Fisher R (T)	43	316003	78	13	0.0095	8.0	8.0	"
Huon R (T)	44	306002	2075	111	0.0030	10.0	11.0	"
Gordon R (T)	45	308002	455	67.5	0.0029	27	14.0	"
Franklin R (T)	46	308003	757	55	0.0091	6.0	10.0	Watson (1978)
Ouse R (T)	47	304058	216	20.8	0.0059	4.0	4.0	ARR
Pieman R (T)	48	310008	2529	114	0.0033	12.0	9.0	Watson (1978)
Henty R (T)	49	309200	112	23	0.022	1.4	4.2	"
King R (T)	50	309001	449	46	0.0048	10.0	8.0	"
King R (T)	51	309002	541	53	0.0048	8.0	5.0	"
Franklin R (T)	52	308004	1590	102	0.0057	8.0	12.0	"

which is plotted on Figure 4.2 is the best fit to the Queensland data plotted on that figure. The regression coefficient in the logarithmic form of the plotted lines (equations 4.3 and 4.6) are not significantly different. Also equation (4.4), which is plotted on Figure 4.3 again fits the Queensland data plotted on that figure, but is very different from equation (4.7) which is the line of best fit to all the data points plotted on Figure 4.3. The regression coefficients of equations(4.4) and (4.7) are significantly different at the 5% level, indicating that the Queensland data , and the whole data sample plotted on Figure 4.3 cannot be assumed to be drawn from the same population of data. Conclusions which may be drawn from this finding are either that the Queensland data are from a different population from the remainder of the data, or that they are simply a part of the total sample shown. The ten Queensland data points (numbered 25 to 34) shown in Figures 4.3 and 4.4 are scattered about the line of best fit to about the same degree as all the other data. However the range of values of the Queensland data is very small, K ranging from 2.1 to 10.6 hours among total data values ranging from 0.37 to 21 hours, and L ranging from 23 to 95 km, among total data values ranging from 0.37 to 282 km. These smaller ranges of values of the variables, on a logarthmic plot, could lead to the conclusion that the differences are due to sampling error.

Table 4. 3

Degree of association between unit hydrograph parameters and catchment characteristics

Relationship	Number of data points	Correlation coefficient (of logs)	Standard error of estimate (of log of U/H parameter)
$C = 0.19(\frac{L}{S})^{0.40}$	51	0.940	0.166
$C = 0.30\ (\frac{L}{\sqrt{S}})^{0.50}$	51	0.935	0.173
$K = 0.70\ L^{0.57}$	52	0.920	0.170
$K = 1.00\ A^{0.31}$	52	0.902	0.259

4.4 CONCLUSION

The general conclusion to be drawn from this study is that relationships derived from small catchment data for estimating parameters of Clark model synthetic unit hydrographs can be used to estimate these parameters for large catchments. More specifically the relationships between Clark model C and K and catchment characteristics given by Cordery and Webb (1974) are applicable to large catchments, not only in N.S.W., but in Tasmania and Queensland as well. The larger range of data that has been available for this study than was available to Cordery and Webb has resulted in slight modifications to the Cordery and Webb relationships which lead to estimates of C and K which are up to 10 per cent different from the Cordery and Webb values.

The relationships for C and K have quite high correlation coefficients (>0.92) and not a great scatter of data. These strong relationships over a large range of catchment areas probably reflect the fact that the conversion of flood runoff on the catchment surface to the flood hydrograph at the outlet depends largely on the geomorphological characteristics of the drainage network. As discussed in Section 2.4, the various geomorphological variables are strongly correlated with area over many orders of magnitude of area. Strength of the relationships is also improved by use of L and S rather than area, as flood response depends more directly on those variables. Use of area in the relations would reduce the degree of correlation, as evidenced by the lower correlation coefficient for equation (4.8). The scatter in the relations for C and K would be partly accounted for by the scatter in the relations between geomorphological variables. Part would also result from data errors and differences in the methods used to derive parameter and variable values. Some scatter must also result from factors discussed in Chapter 2 that are not accounted for in the relations for C and K. Differences of land use with their effect on hydraulic roughness would be expected to influence flood response. Partial and variable source area production of flood runoff, if they occur, should also have an effect. Further reduction of the scatter of the relations might require some means of accounting for such factors. This is a problem that has not been solved in practice, and it would require a major research effort before appreciable progress would be likely. It would also require data of a different type and better quality than those presently available.

In view of the above discussion, the derived relationships for C and K over a large range of catchment sizes and for three States are remarkably good. The degree of correlation is more than adequate for a wide range of practical applications of the relationships in flood estimation. Strength of the relationships may also be aided by the fact that only a relatively small range of mean annual rainfalls occur on the 52 catchments included in the study. All are in humid regions. The relationships may not apply as accurately in semi-arid and arid regions.

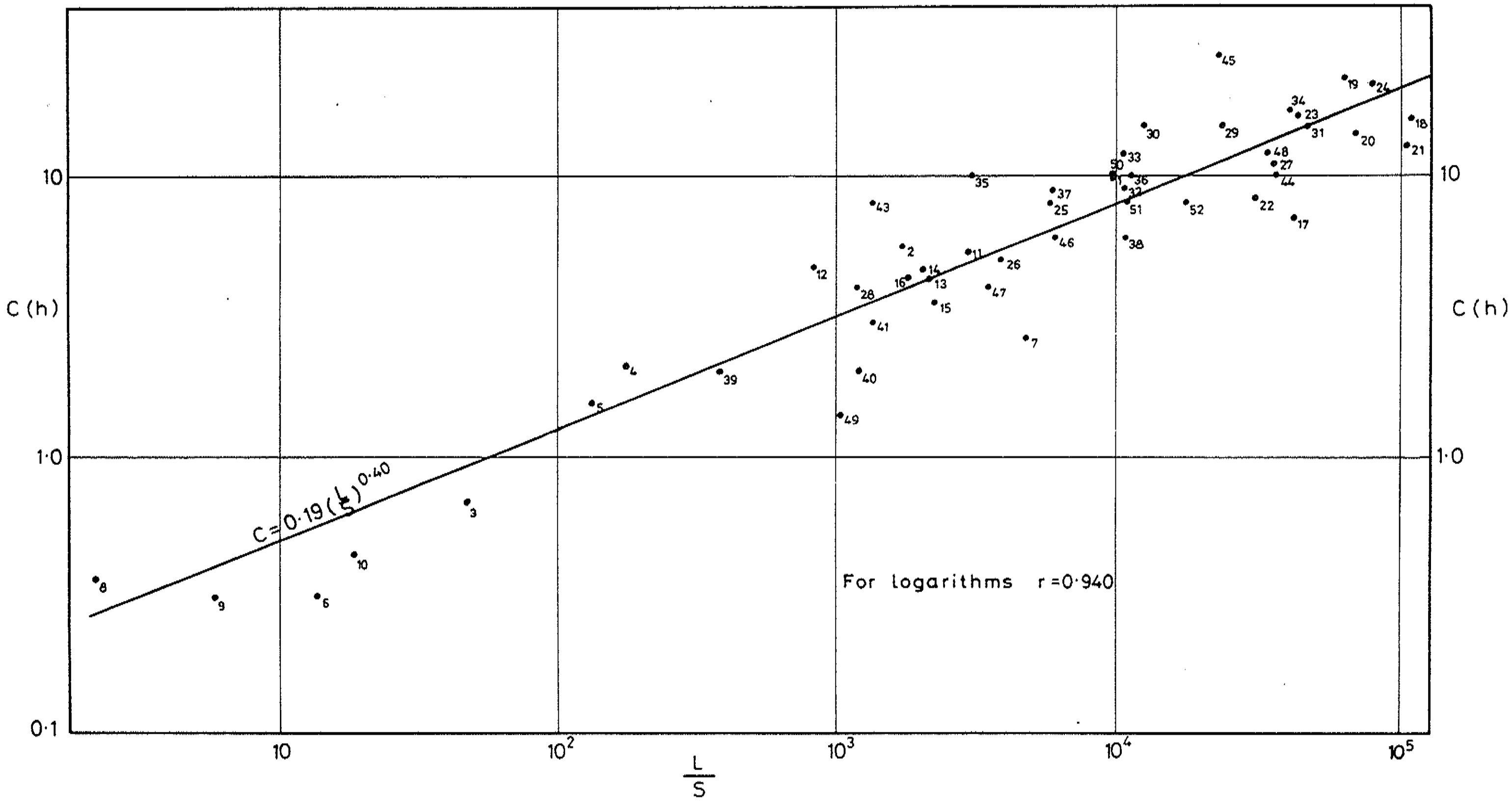


Fig. 4.1 Relation between Unit Hydrograph parameter C and catchment characteristics (Length/slope).

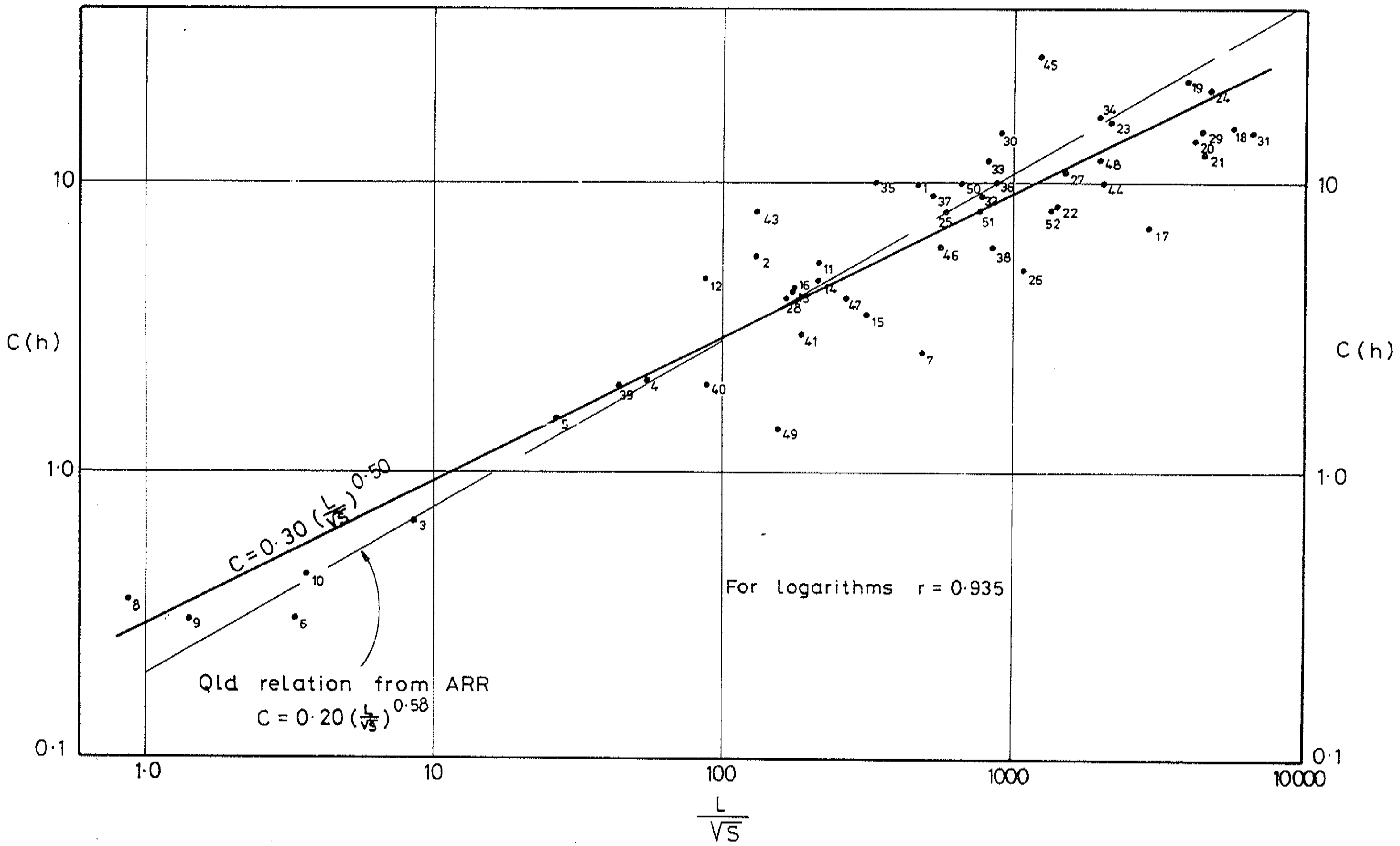


Fig. 4.2 Relation between Unit Hydrograph parameter C and catchment characteristics (Length/√slope).

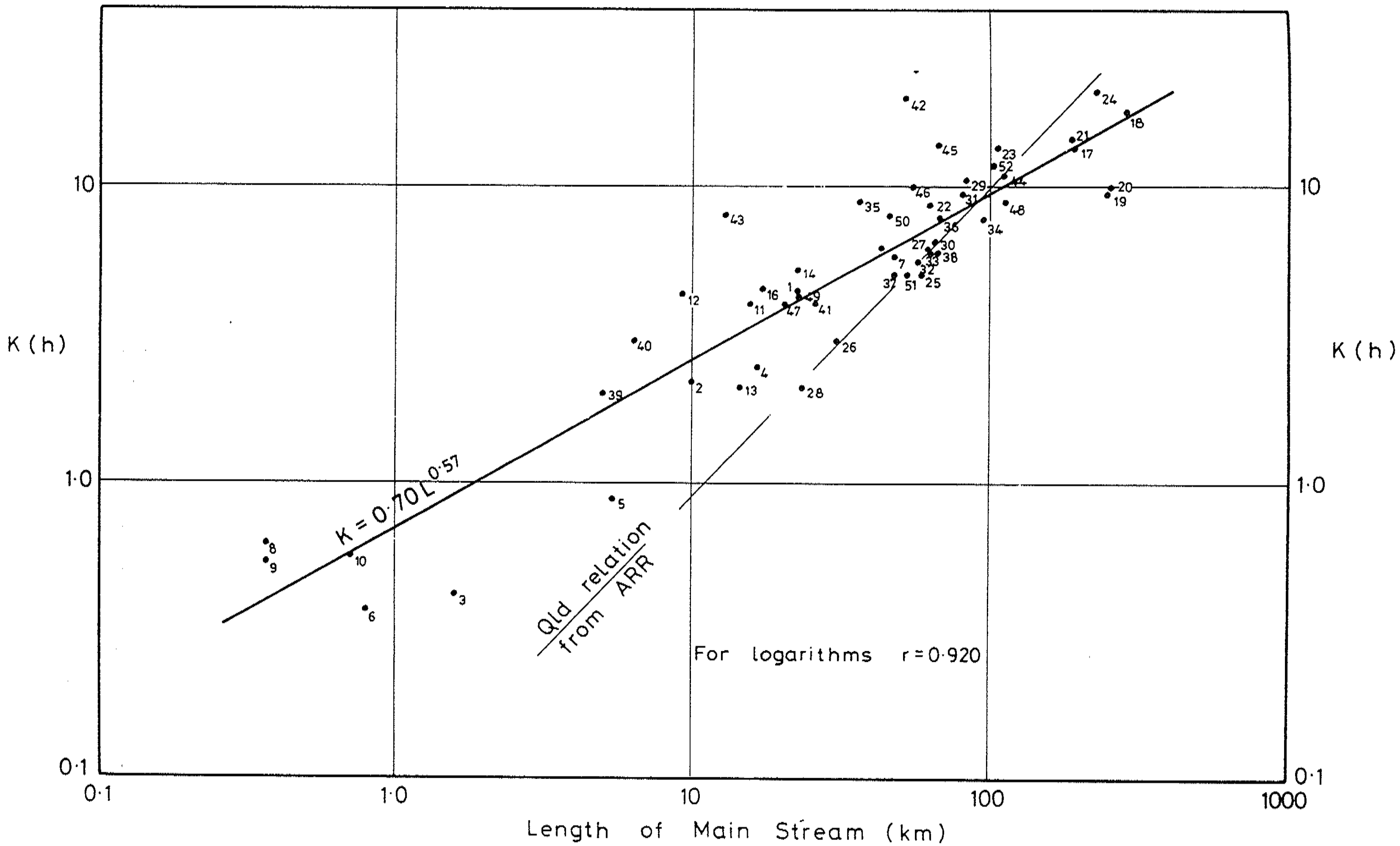


Fig. 4.3 Relation between Unit Hydrograph parameter K and catchment characteristic, length.

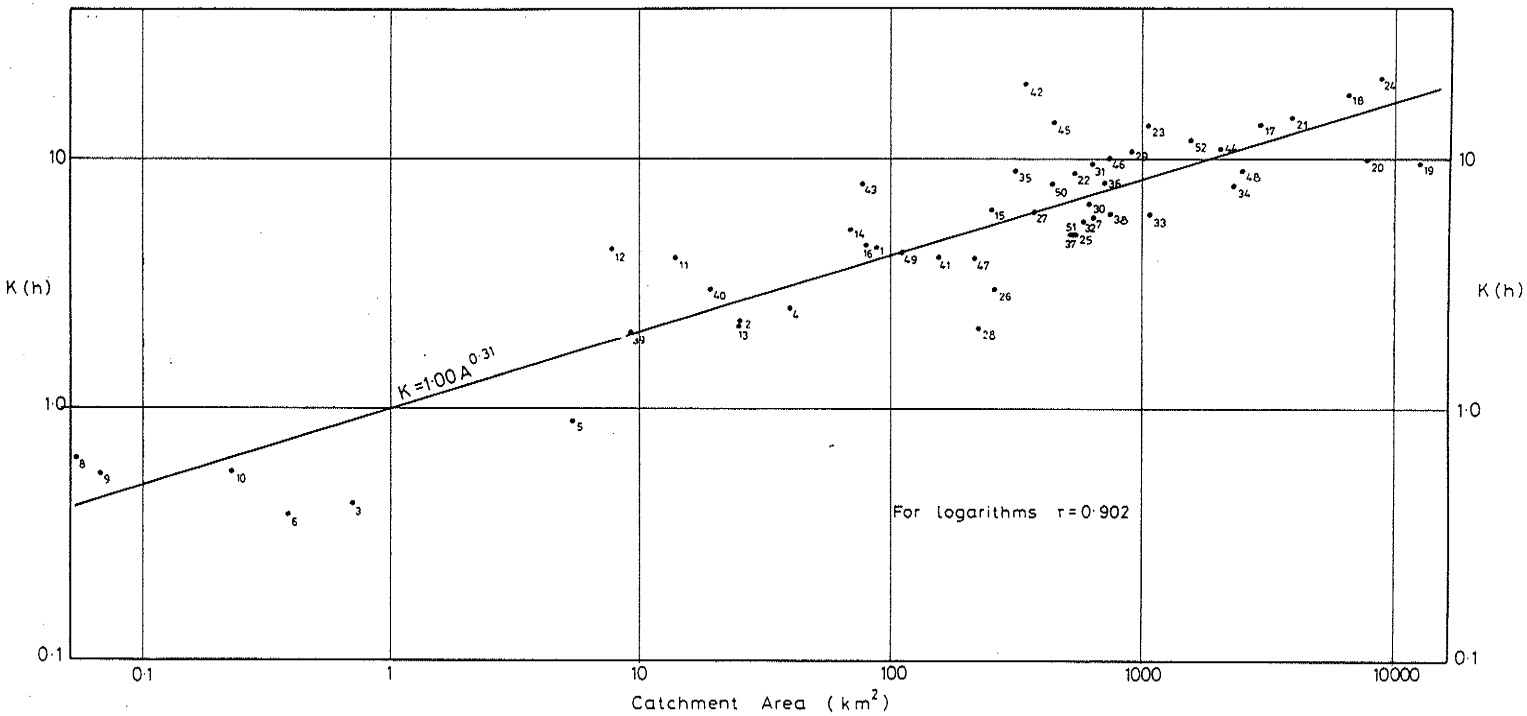


Fig. 4.4 Relation between Unit Hydrograph parameter K and catchment area.

5. EFFECTS OF AREA ON STORM LOSSES

The loss from gross storm rainfall on a catchment is an important consideration in a wide range of hydrological studies. The loss here is taken to mean the difference between the rain which falls on a catchment and the storm runoff which results from that rain. In many cases, such as flood estimation, the loss is the difference between the observed rainfall and the observed storm runoff. This latter definition is adopted here. As a practical approximation the loss can be divided into initial loss and continuing loss. As shown in Fig. 5.1, initial loss is assumed to be all rain in the initial period, which is the time from the beginning of rainfall until runoff is first generated on the catchment surface. Continuing loss rate (or simply loss rate) is the constant, relatively low rate of loss which is assumed to occur after initial loss is satisfied.

In this study we will examine the variation of loss rate with catchment area for eastern New South Wales. In an earlier study (Cordery, 1970), initial loss was investigated and found to increase with increasing catchment area for the region east of the Great Dividing Range in New South Wales. Figure 5.2 is a reproduction of Fig. 10 from Cordery (1970). No analysis of initial loss has been attempted in the current study because suitable data have not been available in an analysed form, and because insufficient time was available in the study. However, a large amount of loss rate data has been assembled and the analysis of this will now be discussed.

5.1 LOSS RATE STUDY

5.1.1 Introduction

Loss rate data have been derived and published for Australian catchments of various sizes (Laurenson and Pilgrim, 1963; Pilgrim, 1966b). No successful attempts have been reported to establish whether there is any relationship between loss rate and catchment size.

5.1.2 Definitions

In this report loss rate will be assumed to mean the constant rate of loss from gross rainfall during the supply period of a storm. It is also assumed that there is an initial loss, which accounts for all rain up to the beginning of the supply period, and that during the supply period the excess of rainfall over the loss rate is equal to the observed surface runoff from the catchment. During the supply period the loss rate is assumed to be the same at all points on the catchment. This loss model is based on Horton-type rainfall excess being produced over the whole catchment (see Section 2.2.2).

To determine the time at which the initial period ends and the supply period begins, the rainfall and runoff data for each catchment were examined to find short, intense storms which produced runoff. For these flood events it was found that the time between the short duration rainfall and the commencement of surface runoff was nearly constant from event to event. This constant time delay was assumed to be the typical time between the beginning of the supply period and the beginning of surface runoff at the catchment outlet. With larger duration storms this constant time delay was then used to measure back from the start of surface runoff to determine the time of the beginning of the supply period and end of the initial period. Definition sketches are shown in Fig. 5.1.

5.1.3 Derived Loss Rates

For this study loss rate data for eastern New South Wales were obtained from a number of sources. 207 values were derived in the School of Civil

Engineering of the University of New South Wales for 12 small catchments. 71 values on 9 catchments ranging from 450 km^2 to 7800 km^2 were provided by the Water Resources Commission of New South Wales. A further 58 values on 6 catchments of various sizes were obtained from Laurenson and Pilgrim (1963). Medians, means and standard deviations of derived loss rates, together with catchment areas, are shown for the 27 catchments in Table 5.1. A general condition for acceptance of data was that there should be at least 5 derived loss rate values for the catchment. A considerable amount of data was rejected because it did not meet this criterion. This minimum number was adopted so that the mean and median value for any catchment would not be unduly influenced by one exceptionally low or high value.

Table 5. 1

Summary of derived loss rate data for eastern New South Wales

Number shown on plot of data	Catchment	National No.	Area km^2	Loss rate -mm/h			No. of derived loss rate values
				Median	Mean	Std. Deviation	
1	Bobo R	204026	80	2.2	2.3	1.5	35
2	Badgery's Ck	212330	0.068	3.8	4.1	2.3	14
3	Cawleys Ck	214334	5.4	2.7	3.1	1.4	15
4	Blicks R at Dundurrabin	204020	252	3.3	3.4	0.9	17
5	Blicks R at Hernani	204021	70	2.0	2.2	1.2	9
6	Eastern Ck	212340	25	2.0	2.4	1.9	30
7	South Ck	212320	88	1.4	1.9	1.6	24
8	Lidsdale No.5	212305	0.062	3.0	2.9	0.4	7
9	Lidsdale No.9	212309	0.23	2.8	2.9	1.7	6
10	Pokolbin No.1	210064	14	3.0	2.7	1.1	8
11	Pokolbin No.3	210069	25	2.5	2.2	1.2	11
12	Research Ck	214330	0.39	2.3	2.7	1.5	31
13	Mt Vernon Ck	212333	0.70	3.2	4.4	4.1	18
14	Mann R	204004	7800	3.2	3.2	1.6	10
15	Gwydir R	418010	6650	1.4	2.0	1.6	11
16	Namoi R	419022	15043	2.0	2.6	1.4	7
17	Severn R	416006	3010	3.8	4.4	3.3	9
18	Belubula R	412056	1610	2.5	2.7	1.1	5
19	Manilla R	419020	2020	3.3	2.7	1.2	5
20	Brogo R	219013	453	2.3	2.1	1.3	6
21	Hunter R	210015	1295	4.3	5.7	4.8	7
22	Cudgegong R	421038	544	2.3	2.6	2.0	11
23	Eucumbene R	222503A	743	2.3	2.1	1.5	6
24	Lachlan R	412067	8290	1.1	1.6	1.5	14
25	Macquarie R	421002	14910	1.9	3.7	4.4	8
26	Macquarie R	421025	4580	3.3	3.5	2.5	5
27	Nymboida R	204001	1660	3.3	4.2	2.7	7

Examination of the distribution of values indicates that the derived values are not normally distributed, but as shown in Fig. 5.3 for Bobo R and for

Blicks R at Dundurrabin they can be either positively or negatively skewed. This can also be deduced from Table 5.1 where it can be seen that the mean is not usually equal to the median, but in most cases the differences are quite small. For non-normal distributions such as these the median is the best indicator value.

5.2 EFFECT OF CATCHMENT AREA ON DERIVED LOSS RATES

The median loss rate values shown in Table 5.1 have been plotted against area in Fig. 5.4. It can be seen that these median values are practically independent of catchment area. It appears that a median loss rate of 2.6 mm/h is applicable to all catchments in eastern New South Wales. The standard deviation of the points plotted on Fig. 5.4 is 0.80 mm/h.

The median loss rate values shown in Fig. 5.4 are approximately normally distributed about the value of 2.6 mm/h but it is evident that the standard deviation increases with increasing catchment area. This may be a function of sample size for the various ranges of catchment area, but from the data it does appear to be a real variation. Such a variation could result from the larger time periods used in the estimation of loss rates from large catchments which would cause considerable error in the estimation of intensity during each time period. For example, in a three hour period there may be little or no rain for two hours and high intensity rain for the third hour. The use of three hour periods for analysis would lead to the assumption of low, constant intensity rainfall for the whole period with a low value of loss rate.

The slightly larger median loss rates for the very small catchments, below about 1 km^2 may also be real or it may be due to sampling errors. For small catchments very short time intervals are used to define the hyetograph. Laurenson and Pilgrim (1963) showed that for most rainfall-runoff events, the more precisely the hyetograph is defined (ie, the shorter the time intervals used) the higher the derived loss rate will be. This could be the reason for the higher median values for the catchments of less than 1 km^2 area.

To examine whether or not the loss rate varies significantly (in a statistical sense) with area the total sample was divided into groups, depending on catchment area. Two tests were used - 1) the Mann-Whitney U test to examine whether or not the median loss rates in one group were larger than those in another group, and 2) the Kolmogorov-Smirnov test to examine whether or not the distribution of all derived loss rate values in one group was different from that in another group. The results are summarized in Table 5.2.

Table 5.2

Significance levels of differences between loss rate values in various catchment size groupings.

Range of catchment sizes grouped for statistical comparison (km^2)		Differences of medians, Mann-Whitney U Test	Differences of distribution, Kolmogorov-Smirnov Test
< 1.0	>1.0	significant at 9% level	significant at 2½% level
< 100	>100	not significant	not significant
< 1000	>1000	not significant	not significant
10-100	< 10, >100	significant at 3.5% level	significant at 1% level

It can be seen that all the loss rates for catchment areas greater than about 100 km^2 can be considered to have been drawn from the same population of data. However the values derived for catchments smaller than 1 km^2 are slightly different from all the rest and the values for areas between 10 and 100 km^2 are also different from values for catchments outside this size range.

The median values for catchments less than and greater than 1 km^2 are only different at the 9% significance level. This means that the chance of the small catchment values being from a population with a higher median than the population from which the values for the larger catchments are drawn is 91%, which gives only weak grounds for rejecting the hypothesis that both samples are from populations with the same median value. However the distribution of the values from catchments smaller than 1 km^2 is quite different from the distribution of the values for the larger catchments. Hence there is some evidence for assuming that loss rate values derived for very small catchments are slightly higher than those derived for larger catchments.

Both tests indicate that the loss rates for catchments between 10 and 100 km^2 are different from those for catchments of all other sizes. The Mann-Whitney test shows that the loss rate values for this size range are significantly lower than for catchments outside this size range. The reason for this is not known, but examination of Fig. 5.4 indicates that loss rates for very small catchments are slightly higher than for catchments greater than 100 km^2, and that values for catchments of between 10 and 100 km^2 are slightly lower than for the larger areas. Combining all the values for catchments of less than 100 km^2 provides a mean value between that for the catchments of less than 1 km^2 and the 10-100 km^2 catchments and this mean value is practically identical to the mean loss rate for catchments larger than 100 km^2.

5.3 CONCLUSION

From the data available there is some evidence that derived loss rate values vary with catchment area. However the evidence is not very conclusive and no clear trend is apparent. The slight differences in the values could easily be attributed to differences in the time periods used in determing loss rate values from the observed rainfall and runoff data. As a result it would appear that for practical application a median loss rate of 2.6 mm/h should be adopted for all catchments in eastern New South Wales. In practice a value of 2.5 mm/h would probably be used.

The major differences in expected losses that were discussed in Chapter 2 do not appear in these results. This is probably because the loss rate can be expected to be unresponsive to catchment differences, compared with initial loss. In a sense the catchment response measured by the loss rate is a stabilised response, since losses are only estimated from events where a significant volume of surface runoff is observed. Much more variation could be expected in initial loss or in the early portion of infiltration curves, but it was not possible to study initial loss or infiltration curves in this project.

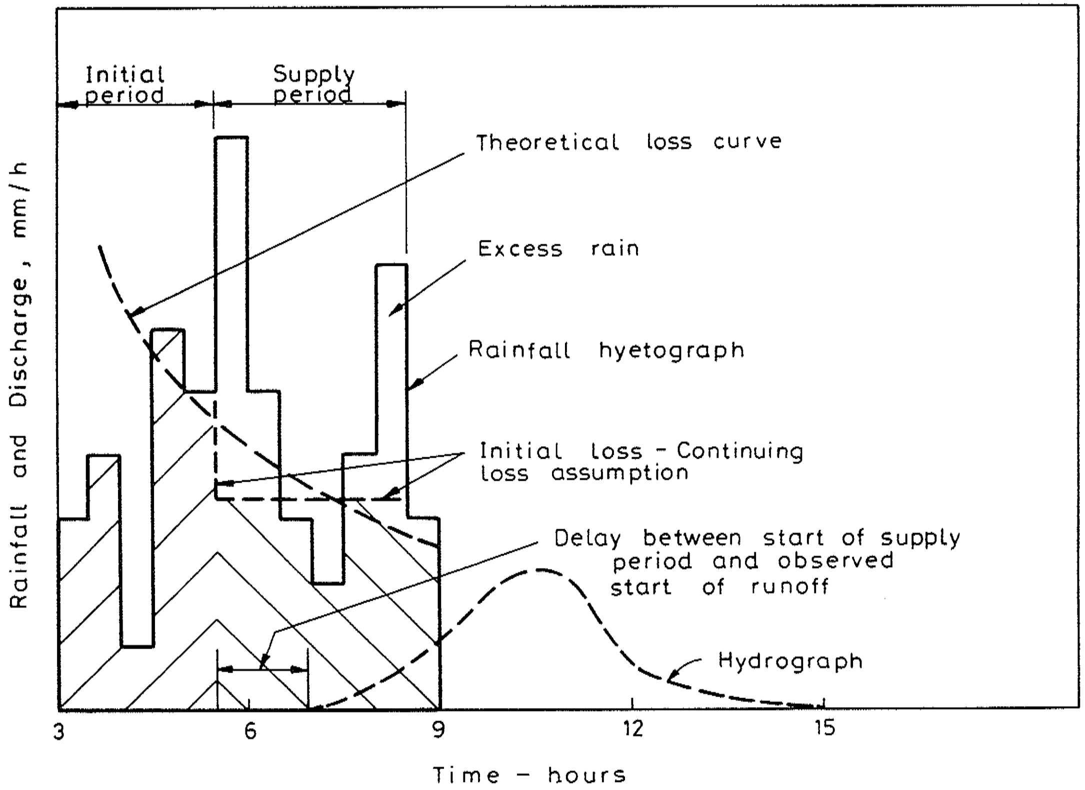


Fig. 5.1 Initial loss-continuing loss assumption.

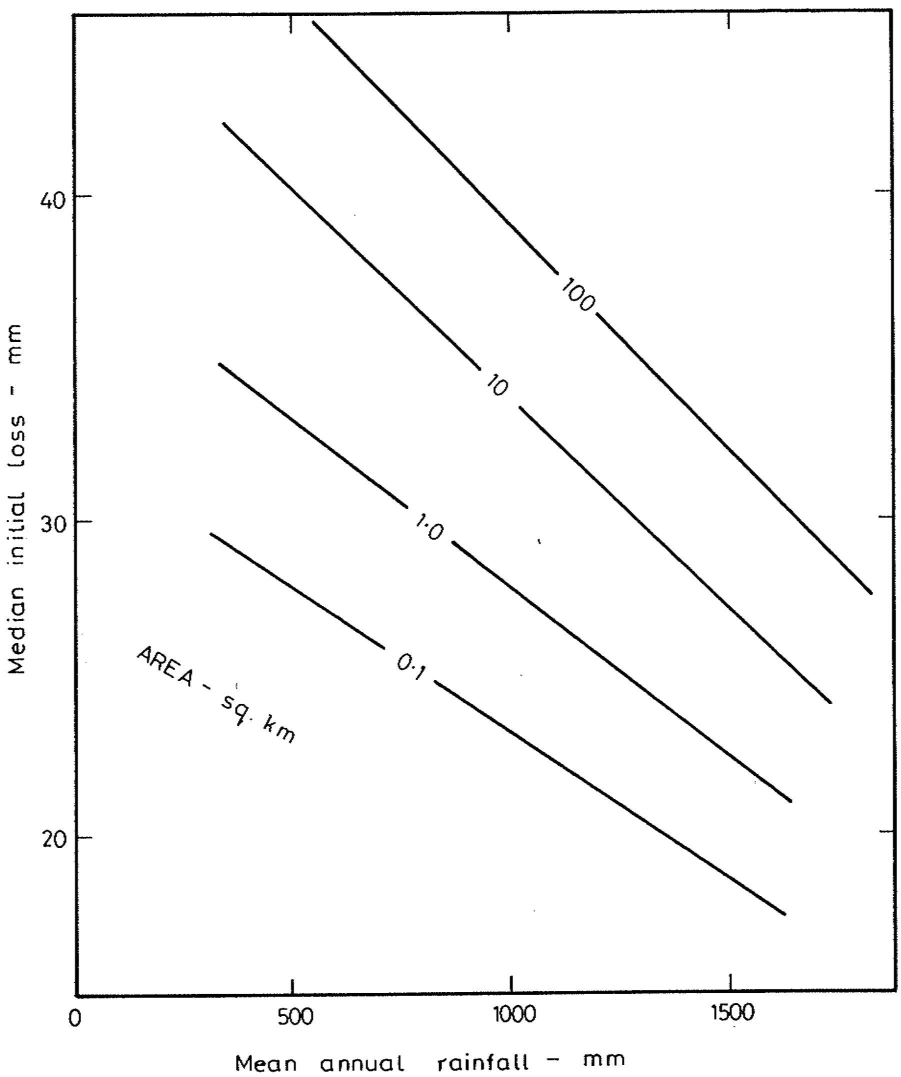


Fig. 5.2 Relation between median initial loss and catchment area. (After Cordery 1970).

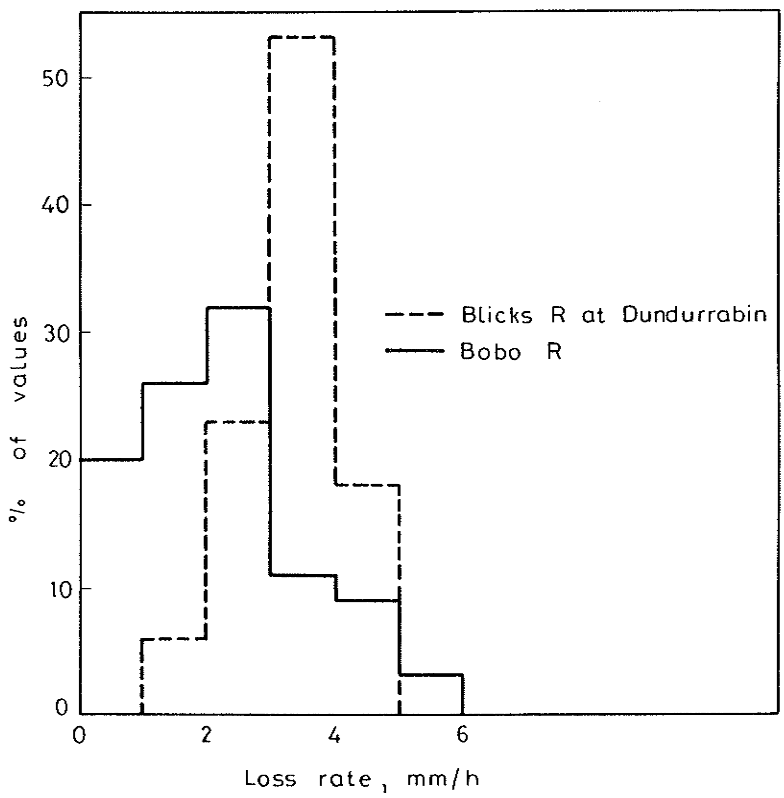


Fig. 5.3 Distribution of derived loss rate values.

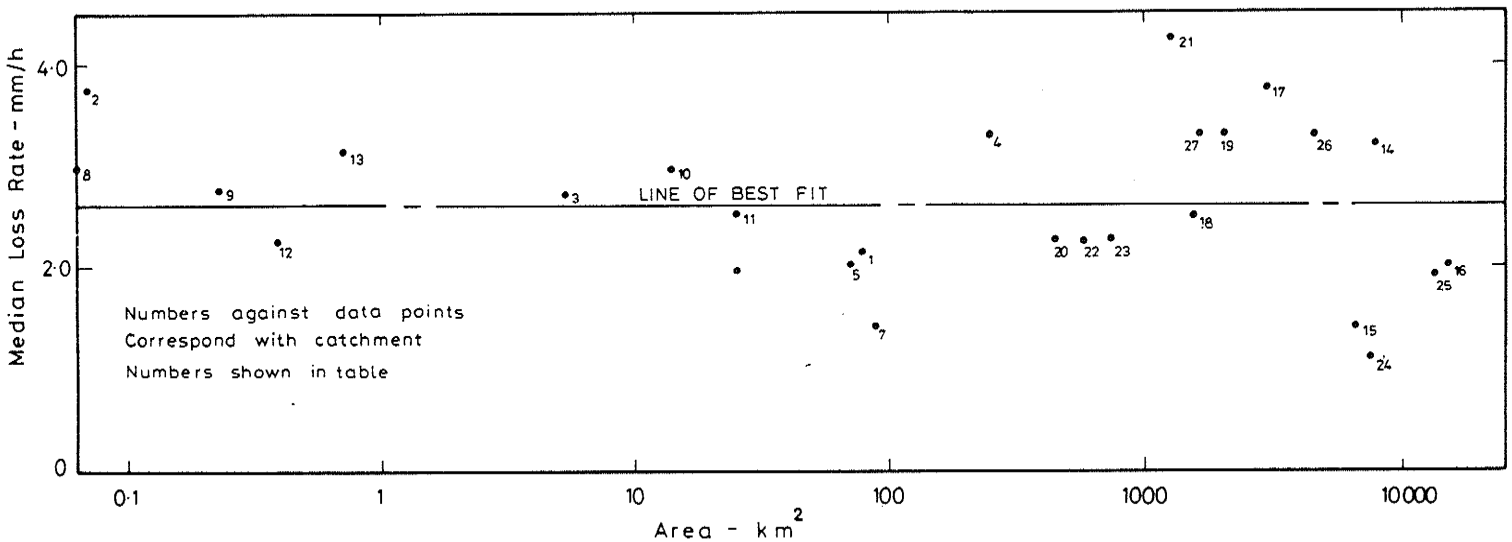


Fig. 5.4 Relation between median loss rate and catchment area.

6. CONCLUSIONS

6.1 SPECIFIC CONCLUSIONS FROM THE STUDY

6.1.1. Review of Effects of Area on Runoff

(a) A large number of factors affects the relation of hydrological characteristics of small and large catchments. These factors have been reviewed in Chapter 2. Without consideration of these factors, study of relationships between small and large catchments cannot rise above mere empiricism, and cannot be more than site specific. Little is known about some of these factors and processes, particularly in the Australian context, including even the processes by which storm runoff occurs.

(b) The review of Chapter 2 indicates that general relationships can be expected to exist between most hydrological characteristics of small and large catchments. This applies particularly to flood characteristics, as many geomorphological variables active in forming the flood hydrograph from rainfall excess are related to area. However, the form of the relationship may be different from one region to another.

(c) Despite the preceding conclusion, the review also indicates that many factors affecting the hydrological relationships cannot be considered explicitly, and many may not even be capable of quantification. Closely defined relations are thus unlikely, and considerable scatter of data is inevitable in all relationships. Since many of the factors that cannot be considered explicitly vary from one region to another, transfer of relations to different hydrological regions is unlikely to be successful.

(d) Data errors will also cause scatter in hydrological relations. These errors are often relatively greater for small catchments.

(e) Many factors affect the hydrological characteristics of small, relatively homogeneous areas, but their effects over large areas tend to be masked as a result of averaging. These factors include land use, soil type, geology and climatological characteristics. The result is that the characteristics of small catchments exhibit greater variability than those of large catchments, and differences between the characteristics of the two types of catchments are likely.

6.1.2 Annual Rainfall-Runoff Relations

(a) McCutchan's method provides a good technique for deriving rainfall-runoff relationships. The derived relations are corrected for the effects of spatial variations of rainfall and hence scatter is reduced. The method estimates the relations at any point on a catchment, and eliminates the bias introduced in the conventional lumped relation derived as a mean curve through catchment average values of rainfall and runoff.

(b) Annual rainfall-runoff relations were found to vary consistently with catchment size within qualitatively defined hydrological regions.

(c) Losses defined as the difference between annual rainfall and runoff were found to increase, and the depth of runoff to decrease, with increasing catchment area in three of the four regions studied in the Clarence and Hunter River valleys. This is almost certainly due to channel transmission losses, which are apparently greater than any baseflow contributions, even though the Clarence and Hunter valleys are in humid and sub-humid regions respectively.

(d) The results obtained and the review of Chapter 2 indicate that channel transmission losses will have an important effect on the relation between hydrological characteristics of small and large catchments over much of Australia.

(e) The manner in which annual rainfall-runoff relations vary with catchment area differs for different regions. Thus before annual data from a small catchment could be transferred to a large catchment, the form of variation and the effect of transmission losses in that particular region would need to be determined. It would not be valid to transfer data from one region to another, and no comprehensive generalisations seem possible.

6.1.3 Effects of Area on Flood Hydrographs

(a) Consistent relations for the parameters C and K of the Clark unit hydrograph model were obtained for data from 52 catchments in Queensland, New South Wales and Tasmania. The catchments cover nearly six orders of magnitude of area, ranging from 0.05 to 15000 km^2.

(b) The consistency and high correlation of the relations probably reflect the dependence of the flood runoff process on geomorphological variables that are related to area. Also, all of the catchments are in humid regions, and the relations may not apply with as great accuracy to semi-arid and arid regions.

(c) Some scatter occurs in the relations, largely as a result of data errors and factors not explicitly included in the relations. However, the scatter is remarkably small, and the degree of correlation is adequate for practical application.

(d) The derived relationships for C and K provide greatly improved design data for unit hydrograph applications of flood estimation compared with data previously available. The ranges of catchment sizes and of the geographical regions covered are greatly increased.

6.1.4 Effects of Area on Storm Losses

(a) A total of 336 loss rates (rates of continuing loss during the supply period of a storm) has been derived or assembled for 27 catchments in New South Wales. Each catchment has at least five values. The catchments range in size from 0.06 to 15000 km^2.

(b) There is no clear trend of the loss rates with catchment sizes. Slight differences occur in the values for different ranges of area, but these could easily be attributed to the effects of different time periods used in analysis.

(c) For practical application, a median loss rate of 2.5 mm/h could be adopted for all catchment sizes. This design value is based on a much larger body of data covering a wider range of catchment sizes and conditions than previously available.

(d) The stability of the derived loss rates probably results from the fact that they are only derived from periods in which a significant amount of storm runoff is produced.

(e) It is likely that much greater variations would occur in values of initial loss or in the early portions of infiltration curves. There is evidence of variation of initial loss with catchment size. However, it was not possible to consider initial losses or infiltration curves in this study.

6.2 GENERAL CONCLUSIONS

Much research has been and is being carried out on relatively small catchments. The results of this project and the review of the processes and factors influencing the relation of catchment runoff to area indicate that while some results and relationships derived from small catchments may be able to be applied to large catchments, others may not. This is due to differences in the physical processes and in the factors affecting various aspects of runoff over the range of catchment sizes.

Individual studies based on observed data in a given region can generally produce consistent and usable relationships between specific hydrological characteristics and catchment area. Instead of area, one or more other catchment variables that are related to area may be used (such as length and slope), as these may be more directly related to the hydrological variable. However, the evidence indicates that the forms of the relationships may vary from region to region, and that they need to be evaluated for each region of application. Transferring relationships from one region to another may not be valid, and comprehensive generalisations of relationships between small and large catchments do not seem to be possible.

To provide a sounder basis for understanding hydrological relationships between small and large catchments, there is a great need for more information on basic hydrological processes. There is a surprising lack of knowledge about many processes, particularly in the Australian context, and this lack is only starting to be recognised. A need exists for more field programmes to obtain such information.

There is also a need for more long-term high-quality hydrological data, particularly for streamflow from small catchments and from nests of small and medium sized catchments within larger catchments. This study was delayed by a search for suitable data, and the analysis and results were restricted by the quantity and quality of data available in the most favourable regions that could be found. Problems of this type seem likely for most studies of a similar nature to that described in this report.

At a fundamental level, the aims of the project have been to review and investigate the processes and factors affecting the relationships between hydrological characteristics of small and large catchments, to identify problems in assessing and evaluating such relationships, and to apply and test some methodologies for developing relationships in a given region. Useful techniques have been demonstrated for developing relationships for annual or other rainfall-runoff relations, unit hydrograph parameters as measures of flood response, and storm loss rates. These by no means exhaust the hydrological characteristics of interest, but it was not possible to consider other characteristics in the time available in the project.

On a more practical level, the study has produced greatly improved design data for much of eastern Australia for unit hydrograph parameters for use in flood estimation, and for storm loss rates. Compared with previously available data, these relations are based on much more data and cover larger geographical regions and a much greater range of catchment sizes. The importance of channel transmission losses, even for humid regions in Australia, has also been demonstrated.

As well as being directed towards the relationships between small and large catchments, the results of the study also have important implications regarding the Representative Basins Program. The Program has been very beneficial in providing high quality data and in stimulating research and modelling developments. However, the results of the analyses and the review reported herein throw doubt on the very concepts of homogeneous hydrological regions and representative catchments. It is possible to develop relationships for transferring hydrological data from one catchment to another in a given region, but the form of these relations may vary from region to region. Unless greater understanding of fundamental hydrological processes can be obtained, it seems essential that the relationships be developed for each region from observed data on many catchments before transfer of data and results can be made with any confidence.

Although the direct transferability of results from small catchments and representative basins is very much open to doubt, it does not seem desirable to limit the gauging of these catchments or research using their results. They will continue to provide the data that are most suitable for the intensive analysis that will further understanding of hydrological relationships and processes. More effort will be required, however, to also analyse data from other types of catchments in any region of interest to indicate how the data from one type of catchment may be transferred to any other type.

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APPENDIX A: Program MQUAD for estimating areal rainfall using multiquadric surface fitting.

```
      PROGRAM MQUAD(INPUT=120,OUTPUT=150,TAPE5=INPUT,TAPE6=OUTPUT,
     $TAPE3,TAPE4)
C
C        MAIN PROGRAM FOR AREAL RAINFALL USING MULTIQUADRIC SURFACES
C
C     R.FALL DATA IS READ IN FROM UNIT 3.IT IS READ IN ON A YEAR BY YEAR
C     BASIS WITH UP TO 100 R.FALL STN. VALUES BEING ABLE TO BE HANDLED FOR
C     ANY ONE YEAR. NO CHECKS ARE MADE ON THIS DATA.                    C
C
      DIMENSION X(100),Y(100),XG(100),YG(100),RR(100),BB(100),CC(100),
     $LA(100),NI(100),NJ(100),SURF(21),NAME(6),X123(3),Y123(3),X13(3) ,
     $Y13(3),AVI(116),DATA(127),W(100,100),RFALL(165),GRAPH(100)
C         X AND Y ARE STATION COORDINATES, BB ARE THE DATA (RAIN)
C         CC = COMPUTED COORDINATES
C          W = INTERSTATION DISTANCE MATRIX
C     XMIN, XMAX ARE THE MIN & MAX RANGE IN X AXIS
C     YMIN, YMAX ARE THE MIN & MAX RANGE IN Y AXIS
      COMMON X,Y,XG,YG,RR,BB,CC,LA,NI,NJ,DATA,W,REALL,GRAPH
      COMMON /COM1/XMIN,XMAX,YMIN,YMAX,COSA,SINA
      EQUIVALENCE (DATA(1),NAME(1)),(DATA(7),IDATE),(DATA(8),NA),
     $(DATA(9),AVI(1)),(DATA(125),AVOLALL),(DATA(126),RMIN),
     $(DATA(127),RMAX)
      DATA NSIZE/100/
      REWIND 3
      REWIND 4
C-----------------------------------------------------------------------
C
      READ(5,2300)  (NAME(I),I=1,6)
 2300 FORMAT(6A10)
      READ(5,*)  (X123(I),Y123(I),I=1,3)
      WRITE(6,2400) (X123(I),Y123(I),I=1,2)
 2400 FORMAT(//,10X,'CO-ORDINATES OF BASELINE OF RECTANGLES',
     $/16X,*X1*,8X,*Y1*,8X,*X2*,8X,*Y2*,
     $//,10X,4F10.2)
C
C     CALCS BEGIN HERE FOR ROTATION OF AXES ON WHICH R.FALL STNS HAVE
C     BEEN LOCATED SO THAT THE NEW AXES ARE PARALLEL TO BASELINE OF THE
C     RECTANGLE ENCLOSING THE CATCHMENT.
C
      IF(X123(2).NE.X123(1)) GO TO 2500
      COSA=0.0
      SINA=1.0
      A=1.5708
      GO TO 2600
 2500 SLOPE=(Y123(2)-Y123(1))/(X123(2)-X123(1))
      A=ATAN(SLOPE)
      COSA=COS(A)
      SINA=SIN(A)
 2600 WRITE(6,2700)A
 2700 FORMAT(//,10X,'ANGLE OF ROTATION OF AXES IS =',F9.4,'  RADIANS')
      DO 2800 K=1,3,2
      X13(K)=X123(K)*COSA+Y123(K)*SINA
 2800 Y13(K)=-X123(K)*SINA+Y123(K)*COSA
      XMIN=X13(1)
      XMAX=X13(3)
      YMIN=Y13(1)
      YMAX=Y13(3)
```

```
      C
      C ****************************************************************
      C
            CALL SUB1
      C
      C ****************************************************************
      C
      C
      C  ROTATION COMPLETE
      C
            READ(3) ISTART,IFINISH,NS
            READ(5,*) ITIME1,ITIME2
            IF(ITIME2.GE.ITIME1) GO TO 2810
            WRITE(6,2805) ITIME1,ITIME2
       2805 FORMAT(//,10X,*ERROR...STARTING TIME PERIOD FOR CALCULATION OF ME
           $AN R,FALL .GT. END TIME PERIOD*/20X,*ITIME1 =*,I5,5X,*ITIME2 =*,
           $I5)
            GO TO 5200
       2810 IF((ITIME1.GE.ISTART).AND.(ITIME1.LE.IFINISH)) GO TO 2820
            IF((ITIME2.GE.ISTART).AND.(ITIME2.LE.IFINISH)) GO TO 2820
            WRITE(6,2815) ISTART,IFINISH,ITIME1,ITIME2
       2815 FORMAT(//,10X,*ERROR...ATTEMPTED CALCULATION OF MEAN R,FALLS OUTA
           $RANGE OF INPUT DATA*,/,20X,*ISTART =*,I5,3X,*IFINISH =*,I5,/,20X,
           $*ITIME1 =*,I5,3X,*ITIME2 =*,I5)
            GO TO 5200
      C
      C  READY FOR GENERATION OF SUB-AREA R,FALL VALUES
      C  LOCATE APROPRIATE R,FALL STN. DATA.
      C
       2820 KK=ITIME1-ISTART
            IF(KK.EQ.0) GO TO 2850
            DO 2840 J=1,KK
            READ(3) (RFALL(I),I=1,NS)
       2840 CONTINUE
       2850 NYRS=ITIME2-ITIME1+1
            RMIN = 10000.
            RMAX = -10000.
      C
      C ----------------------------------------------------------------
      C
            DO 5000 JJ=1,NYRS
            DO 2900 I=7,125
       2900 DATA(I)=0.0
            IDATE=ITIME1+JJ-1
            WRITE(6,3000) (NAME(I),I=1,6),IDATE
       3000 FORMAT('1',20X,6A10,/,20X,I4)
            DO 3100 KL = 1,NSIZE
            NI(KL)=1
            NJ(KL)=0
            XG(KL)=0.0
            YG(KL)=0.0
            X(KL)=0.0
            Y(KL)=0.0
            CC(KL)=0.0
            BB(KL)=0.0
       3100 RR(KL)=0.0
            NSTN=0
```

```
      READ(3) (RFALL(I),I=1,NS)
      DO 3450 I=1,NS
      IF(RFALL(I).GT.0.0) GO TO 3200
C
C  NO DATA FROM STATION I FOR TIME INTERVAL JJ.
C
      GO TO 3450
 3200 NSTN=NSTN+1
      IF(NSTN.LE.NSIZE) GO TO 3300
      WRITE(6,3250) IDATE
 3250 FORMAT(//,10X,*FOR R,FALL PERIOD *,I4,* THERE ARE TOO MANY R,FALL
     $STATIONS - MATRIX OVERFLOW*)
      GO TO 5200
C
C  UNPACK NO. FORMED IN DATA INPUT PROGRAM TO OBTAIN CO-ORDS. AND
C  R,FALLVALUE.  THIS IS DONE IN VECTOR CALLED 'RFALL'.
C
 3300 VALU=RFALL(I)/1.E04
      RR(NSTN)=1.E04*(VALU-INT(VALU))
      VALU=FLOAT(INT(VALU))/1.E04
      YG(NSTN)=1.E04*(VALU-INT(VALU))
      XG(NSTN)=FLOAT(INT(VALU))
      IF(NSTN.EQ.1) GO TO 3450
      NN=NSTN-1
C
C  CHECK FOR ZERO OR SMALL DISTANCES BETWEEN STNS.
C
      DO 3400 K=1,NN
      XDIFF=XG(NSTN)-XG(K)
      YDIFF=YG(NSTN)-YG(K)
      IF((XDIFF.GT.0.1).OR.(XDIFF.LT.-0.1)) GO TO 3400
      IF((YDIFF.GT.0.1).OR.(YDIFF.LT.-0.1)) GO TO 3400
      RR(K)=RR(K)+RR(NSTN)
      RR(NSTN)=-100000.0
      NJ(NSTN)=K
      NI(K)=NI(K)+1
 3400 CONTINUE
 3450 CONTINUE
C
C  AVERAGE THE R,FALL VALUES FOR STNS WITH ZERO OR SMALL
C  INTER-STATION DISTANCES.
C
      DO 3600 KI=1,NSTN
 3600 RR(KI)=RR(KI)/FLOAT(NI(KI))
C
C  FORM X,Y,BB
C
      NK=0
      DO 3700 KJ=1,NSTN
      IF(RR(KJ).LE.0.0) GO TO 3700
      NK=NK+1
      X(NK)=XG(KJ)*COSA+YG(KJ)*SINA
      Y(NK)=-XG(KJ)*SINA+YG(KJ)*COSA
      BB(NK)=RR(KJ)
 3700 CONTINUE
C
C ************************************************************
```

```
C
      CALL SECOND(T1)
      CALL PLOT(GRAPH,NK,X,Y,X13,Y13)
      CALL SECOND(T2)
      PRINT*,T1,'  PLOT   ',T2
C
C ******************************************************************
C
      N=NK
      DO 3800 I=1,N
      DO 3800 J=1,N
      AX=X(J)-X(I)
      AY=Y(J)-Y(I)
 3800 W(I,J)=SQRT(AX*AX+AY*AY)
C
C ******************************************************************
C
      CALL SECOND(T1)
      CALL MATINV(W,N,NSIZE,LA,PREC)
      CALL SECOND(T2)
      PRINT*,T1,'  MATINV  ',T2
C
C ******************************************************************
C
      DO 4000 I=1,N
      CI=0.0
      DO 3900 J=1,N
 3900 CI=CI+W(I,J)*BB(J)
 4000 CC(I)=CI
C
C  R.FALL STN. DATA IS PRINTED OUT LATER I.E. AFTER 4900.
C
C
C ******************************************************************
C
      CALL SECOND(T1)
      CALL SUB2(X,Y,CC,NK,NA,AVI,AVOLALL,RMIN,RMAX)
      CALL SECOND(T2)
      PRINT*,T1,'  SUB2   ',T2
C
C ******************************************************************
C
      WRITE(4)  (DATA(I),I=1,127)
      DELX=(XMAX-XMIN)/20.0
      DELY=DELX
      KKK=(YMAX-YMIN)/DELY + 2
      WRITE(6,4300)
 4300 FORMAT(///,50X,'RAINFALL SURFACE')
      DO 4400 L=1,21
      XX=XMIN+FLOAT(L-1)*DELX
 4400 SURF(L) = XX
      WRITE(6,4500)  (SURF(LL),LL=1,21)
 4500 FORMAT(1H/,'  Y//X  ',21(F5.0,1X))
      DO 4900 J=1,KKK
      YY=YMAX-FLOAT(J-1)*DELY
      DO 4700 I=1,21
      ZIJ = 0.
```

PROGRAM MQUAD FTN

```
      XX=XMIN+FLOAT(I-1)*DELX
      DO 4600 II=1,NK
 4600 ZIJ = ZIJ + CC(II)*SQRT((X(II)-XX)**2+(Y(II)-YY)**2)
      SURF(I) = ZIJ/1000.0
 4700 CONTINUE
      WRITE(6,4800) YY,(SURF(I),I=1,21)
 4800 FORMAT(1H0,//1X,F5.0,21(1X,F5.3))
 4900 CONTINUE
C
C PRINT OUT RAW AND CORRECTED R.FALL STN. DATA AND SOLVED VALUES OF CC.
C
      WRITE(6,4100)
 4100 FORMAT(//,10X,*RAINGAUGE CO-ORDINATES*,63X,*C  SOLUTION*,
     $//,16X,*XG*,9X,*YG*,8X,*RR*,8X,*X*,9X,*Y*,9X,*R*)
      WRITE(6,4200) (N,XG(N),YG(N),RR(N),X(N),Y(N),BB(N),NJ(N),CC(N),
     $N=1,NSTN)
 4200 FORMAT(5X,I2,3X,6F10.2,   I5,7X,'*',F20.5)
 5000 CONTINUE
      WRITE(6,5100) RMIN,RMAX
 5100 FORMAT(//,2X,'MIN. SUB-AREA AV. R.FALL =',F10.4,
     $//,2X,'MAX. SUB-AREA AV. R.FALL =',F10.4)
 5200 WRITE(6,5300)
 5300 FORMAT(//,120('0'),//,10X,'END OF PROGRAMME')
      STOP
      END
```

SUBROUTINE MATINV FTN

```
      SUBROUTINE MATINV(A,N,NDIM,LIG,PREC)
C
CC MATINV=INVERSION, PARTIAL PIVOT SELECTION ONLY
C     MATRIX INVERSION ROUTINE WITH PIVOT SELECTION OPTIMISATION
C     THE ORIGINAL -A- MATRIX IS DESTROYED
C     IF A PIVOT IS LESS THAN -PREC- THE ROUTINE PRINT AN ERROR MESSAGE A
C     GOES IMMEDIATELY TO RETURN
      DIMENSION  A(1),LIG(1)
      PREC = 1.E-11
      DO 5J=1,N
    5 LIG(J) = 0
      KN=N*NDIM
      DO4K=1,N
C     ORDERING THE PIVOTS
      KK= (K-1)*NDIM+K
      PVT =  ABS(A(KK))
      DO 15 L=KK,KN,NDIM
      P1 = ABS(A(L))
      IF(P1-PVT)15,15,16
   16 PVT=P1
      LIG(K)=(L-K)/NDIM+1
   15 CONTINUE
      IF(PVT.LT.PREC)GO TO 21
      IF(LIG(K).EQ.0)GO TO 6
      IX=(LIG(K)-K)*NDIM
      LM=(LIG(K)-1)*NDIM+1
      LL=LM+N-1
      DO 17L=LM,LL
      AP=A(L)
      LX=L-IX
      A(L)=A(LX)
   17 A(LX)=AP
C     INVERSION
    6 COM=A(KK)
      A(KK)=1.
      DO 1 J=K,KN,NDIM
    1 A(J)=A(J)/COM
      DO4I=1,N
      IX=I-K
      IF(IX)2,4,2
    2 IK=(K-1)*NDIM+I
      COM=A(IK)
      A(IK)=0.
      DO 3 J=I,KN,NDIM
      KJ=J-IX
    3 A(J)=A(J)-COM*A(KJ)
    4 CONTINUE
C     REORDERING THE ROWS AND COLUMNS
      K=N
   18 IF(LIG(K).EQ.0)GO TO 20
      L=LIG(K)
      DO 19 M=L,KN,NDIM
      AP=A(M)
      KM=M-L+K
      A(M)=A(KM)
   19 A(KM)=AP
   20 K=K-1
```

SUBROUTINE MATINV FTN

```
      IF(K.NE.0) GO TO 18                                              MQUAD4   311
      LIG(1)=0                                                         MQUAD4   312
      RETURN                                                           MQUAD4   313
   21 LIG(1)=1                                                         MQUAD4   314
      RETURN                                                           MQUAD4   315
   22 FORMAT (42H0DEGENERATED MATRIX - PIVOT IS LESS THAN  ,1PD9.2)    MQUAD4   316
   50 FORMAT (9H PIVOT = ,1PD13.6)                                     MQUAD4   317
      END                                                              MQUAD4   318
```

SUBROUTINE SUB1 FTN

```
      SUBROUTINE SUB1
      COMMON /COM1/XMIN,XMAX,YMIN,YMAX,COSA,SINA
      COMMON /COM2/X(30),Y(30),YY(30),NN(30),NDIVX,NDIVY,N
C
C     READS IN AND ROTATES CO-ORDS. OF C.MENT BOUNDARY.
C
C
C     X IS THE X COORDINATE OF THE BOUNDARY
C     Y IS THE Y COORDINATE OF THE BOUNDARY
C     NN IS A WEIGHTING FACTOR FOR NODE POINT OF BOUNDARY
C     N IS THE NO. OF BOUNDARY PTS CHOSEN
C
      READ(5,*) N,NDIVX,NDIVY
      WRITE(6,50) N,XMIN,XMAX,YMIN,YMAX,NDIVX,NDIVY
   50 FORMAT(///,10X,'N=',I4,/,10X,          /,10X,'XMIN=',F8.3,3X,
     1'XMAX=',F8.3,/,10X,'YMIN=',F8.3,3X,'YMAX=',F8.3/,10X,'NDIVX =',I3
     $,/,10X,'NDIVY =',I3,//)
C
C     ROTATE CO-ORDS. OF BOUNDARY.
C
      DO 4530 I=1,N
      READ(5,*) XB,YB
      X(I)=XB*COSA+YB*SINA
      Y(I)=-XB*SINA+YB*COSA
 4530 CONTINUE
C
C     ADD  SMALL VALUE TO EACH NODE FOR OBTAINING THE NN FACTOR
C
      DO 106 I=1,N
      YY(I)=Y(I)+0.00001
  106 CONTINUE
C
C     COMPUTE THE WEIGHTING FACTOR NN FOR EACH BOUNDARY NODE
C
      DO 101 I=1,N
      NN(I)=0
      IP1=I+1
      IF(IP1.GT.N) IP1=1
      IF(Y(I).EQ.Y(IP1)) GO TO 102
      IF(YY(I).LT.Y(IP1).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      IF(I.EQ.1) GO TO 103
      IF(YY(I).LT.Y(I-1).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      GO TO 101
  103 IF(YY(I).LT.Y(N).AND.YY(I).GT.Y(I)) NN(I)=NN(I)+1
      GO TO 101
  102 NN(I)=1
  101 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SUB2(XO,YO,CC,NK,NA,AVI,AVOLALL,RMIN,RMAX)
C
C  FORMS GRID OF C.MENT SUB-AREAS  -INTEGRATES OVER EACH SUB-AREA TO
C  GIVE R.FALL VOLUME - CALCULATES AVERAGE C.MENT R.FALL.
C
      DIMENSION XO(1),YO(1),CC(1),AVI(1)
      COMMON /COM1/XMIN,XMAX,YMIN,YMAX,COSA,SINA
      COMMON /COM2/X(30),Y(30),YY(30),NN(30),NDIVX,NDIVY,N
      NA=0
      NR=0
      VOLALL = 0.
      SAREA = 0.
      DELX=(XMAX-XMIN)/NDIVX
      DELY=(YMAX-YMIN)/NDIVY
      AREA=DELX*DELY
      DO 4500 J=1,NDIVY
      YA=YMAX-FLOAT(J-1)*DELY
      YZ=YA-DELY
      YT=(YA+YZ)*0.5
      DO 4000 I=1,NDIVX
      VOLR=0.0
      IR=0
      IL=0
      X(N+1)=X(1)
      Y(N+1)=Y(1)
      XZ=XMIN+FLOAT(I-1)*DELX
      XA=XZ+DELX
      XT=(XA+XZ)*0.5
C
C  CALCULATE THE NO. OF INTERSECTIONS ALONG THE X AXIS
C
      DO 300 K=1,N
      IF(YT.EQ.Y(K).AND.XT.EQ.X(K)) GO TO 310
      IF(YT.EQ.Y(K).AND.YT.EQ.Y(K+1)) GO TO 10
      IF(YT.EQ.Y(K)) GO TO 20
      IF(Y(K).GT.YT.AND.YT.GT.Y(K+1)) GO TO 40
      IF(YT.GT.Y(K).AND.Y(K+1).GT.YT) GO TO 40
      GO TO 300
   10 IF(X(K).LT.XT.AND.X(K+1).GT.XT) GO TO 310
      IF(X(K).GT.XT.AND.X(K+1).LT.XT) GO TO 310
      IF(XT-X(K)) 11,310,12
   11 IR=IR+NN(K)
      GO TO 300
   12 IL=IL+NN(K)
      GO TO 300
   20 IF(X(K)-XT) 12,310,11
   40 XX=X(K)+(YT-Y(K))*(X(K+1)-X(K))/(Y(K+1)-Y(K))
      IF(XX-XT) 42,310,41
   41 IR=IR+1
      GO TO 300
   42 IL=IL+1
  300 CONTINUE
C
C  CHECK WHETHER     POINT. IS FALLING WITHIN THE BOUNDARY
C
      IF((IR-IR/2*2).EQ.0.OR.(IL-IL/2*2).EQ.0) GO TO 302
  310 NA=NA+1
```

```
      DO 4600 JJJ=1,NK
C
C     * * * COMPUTE THE VOLUME UNDER A CIRCULAR CONE * * *
C
C     * * * THE VERTEX OF THE CONE IS AT X0,Y0,0.0 * * *
C
C     * * * THE VOLUME IS BOUNDED BY THE RECTANGLE X = XZ
C                                                  X = XA
C                                                  Y = YZ
C                                                  Y = YA * * *
C     * * * *  COMPUTE THE LIMITS OF THE DOUBLE INTEGRAL
      XL = XZ - X0(JJJ)
      XU = XA - X0(JJJ)
      YL = YZ - Y0(JJJ)
      YU = YA - Y0(JJJ)
C
C     * * * DEFINE THE TERMS OF THE DOUBLE INTEGRAL * * *
C
      CA = CC(JJJ)
      XU2 = XU*XU
      YU2 = YU*YU
      XL2 = XL*XL
      YL2 = YL*YL
      YU3 = YU**3
      YL3 = YL**3
      XU3 = XU**3
      XL3 = XL**3
      XUYUS=SQRT(XU2+YU2)
      XUYLS=SQRT(XU2+YL2)
      XLYUS = SQRT(XL2+YU2)
      XLYLS=SQRT(XL2+YL2)
C
C     * * * *  IF Y+SQRT(X*X+Y*Y) = 0. REPLACE X BY A NONZERO CONSTANT *
      SHIFT = 10.E-5
      IF(YL.GT.0.0.AND.YU.GT.0.0) GO TO 50
      XL = SIGN(AMAX1(ABS(XL),SHIFT),XL)
      XU = SIGN(AMAX1(ABS(XU),SHIFT),XU)
C
C     * * * *  IF X+SQRT(X*X+Y*Y) = 0.0 REPLACE Y BY A NONZERO CONSTANT
   50 IF(XL.GT.0.0.AND.XU.GT.0.0) GO TO 70
      YL = SIGN(AMAX1(ABS(YL),SHIFT),YL)
      YU = SIGN(AMAX1(ABS(YU),SHIFT),YU)
   70 CONTINUE
C
C     * * * VLCONE IS THE VOLUME UNDER A CIRCULAR CONE * * *
C
      VLCONE=CA/2*(YU*(XU*XUYUS+YU2*ALOG(XU+XUYUS))/2-YL*(XU*XUYLS+YL2*A
     *LOG(XU+XUYLS))/2-YU*(XL*XLYUS+YU2*ALOG(XL+XLYUS))/2+YL*(XL*XLYLS+Y
     *L2*ALOG(XL+XLYLS))/2+XU3*ALOG(YU+XUYUS)/3-YU3*ALOG(XU+XUYUS)/6+XU*
     *YU*XUYUS/6-XU3*ALOG(YL+XUYLS)/3+YL3*ALOG(XU+XUYLS)/6-XU*YL*XUYLS/6
     *-XL3*ALOG(YU+XLYUS)/3+YU3*ALOG(XL+XLYUS)/6-XL*YU*XLYUS/6+
     *XL3*ALOG(YL+XLYLS)/3-YL3*ALOG(XL+XLYLS)/6+XL*YL*XLYLS/6)
C
C  END OF VLCONE
C
      VOLR = VOLR + VLCONE
 4600 CONTINUE
```

SUBROUTINE SUB2 FTN

```
      VOLALL = VOLALL + VOLR                                MQUAD4   482
      AVOL = VOLR/AREA                                      MQUAD4   483
      IF(AVOL.LT.RMIN) RMIN=AVOL                            MQUAD4   484
      IF(AVOL.GT.RMAX) RMAX=AVOL                            MQUAD4   485
      SAREA = SAREA + AREA                                  MQUAD4   486
      AVI(NA)=AVOL                                          MQUAD4   487
      GO TO 4000                                            MQUAD4   488
  302 NR=NR+1                                               MQUAD4   489
      AVOL=0.0                                              MQUAD4   490
 4000 CONTINUE                                              MQUAD4   491
 4500 CONTINUE                                              MQUAD4   492
      SUM=NA+NR                                             MQUAD4   493
      AF=NA/SUM                                             MQUAD4   494
      WRITE(6,7) AF                                         MQUAD4   495
    7 FORMAT(//2X,'RATIO OF AREA=',F10.6)                   MQUAD4   496
      AVOLALL = VOLALL/SAREA                                MQUAD4   497
      WRITE(6,9008) AVOLALL                                 MQUAD4   498
 9008 FORMAT(//,130('*'),//,10X,*C.MENT MEAN DEPTH =*,F6.0,//,130('*'))  MQUAD4   499
      RETURN                                                MQUAD4   500
      END                                                   MQUAD4   501
```

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SUBROUTINE PLOT FTN

```
      SUBROUTINE PLOT(GRAPH,NSTN,XS,YS,X13,Y13)
      DIMENSION GRAPH(100),X13(3),Y13(3),XS(NSTN),YS(NSTN)
      COMMON /COM1/XMIN,XMAX,YMIN,YMAX,COSA,SINA
      COMMON /COM2/X(30),Y(30),YY(30),NN(30),NDIVX,NDIVY,N
      DATA BLANK/' '/,DASH/'-'/,EYE/'I'/,EKS/'X'/,PLUS/'+'/,STAR/'*'/
C
C  EKS-X-DENOTES DIAGONALLY OPPOSITE CORNERS OF RECTANGLE CONTAINING
C           SUB-AREAS OVER CATCHMENT.
C  PLUS-+-CATCHMENT BOUNDARY POINT.
C  STAR-*-REPORTING STATION.
C
C
C  DETERMINE SIZE OF PLOT.
C
      BIGX=-10000.0
      SMALLX=10000.0
      BIGY=-10000.0
      SMALLY=10000.0
      DO 1500 I=1,3,2
      CALL RANGE(X13(I),BIGX,SMALLX)
      CALL RANGE(Y13(I),BIGY,SMALLY)
 1500 CONTINUE
      DO 1600 I=1,NSTN
      CALL RANGE(XS(I),BIGX,SMALLX)
      CALL RANGE(YS(I),BIGY,SMALLY)
 1600 CONTINUE
      SMALLX=SMALLX-0.03*(BIGX-SMALLX)
      SMALLY=SMALLY-0.03*(BIGY-SMALLY)
      BIGX=BIGX+0.03*(BIGX-SMALLX)
      BIGY=BIGY+0.03*(BIGY-SMALLY)
      XDIFF=BIGX-SMALLX
      YDIFF=BIGY-SMALLY
      DIFF=XDIFF-2.0*YDIFF
      IF(DIFF.GT.0.0) GO TO 1700
C
C  SIZE OF PLOT GOVERNED BY YDIFF.
C
      NY=50
      NX=INT((XDIFF/YDIFF)*64.8)
      GO TO 1800
C
C  SIZE OF PLOT GOVERNED BY XDIFF.
C
 1700 NX=100
      NY=INT((YDIFF/XDIFF)*77.16)
C
C  DIVIDE Y AXIS INTO NY INTERVALS.
C
 1800 DELY=YDIFF/FLOAT(NY)
      XRANGE=FLOAT(NX)/XDIFF
C
C-------------------------------------------------------------------------
C
C  PLOTTING STARTS HERE.
C
      DO 1900 I=1,100
 1900 GRAPH(I)=BLANK
```

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SUBROUTINE PLOT FTN

```
      DO 2000 I=1,NX
 2000 GRAPH(I)=DASH
      WRITE(6,2100) BIGY,GRAPH
 2100 FORMAT(//,20X,*DISTRIBUTION OF REPORTING STATIONS RELATIVE TO THE
     $ CATCHMENT UNDER CONSIDERATION*,//,6X,F9.1,3X,100A1)
      DO 2700 II=1,NY
C
C  CLEAR GRAPH.
C
      DO 2200 I=1,100
 2200 GRAPH(I)=BLANK
      GRAPH(NX)=EYE
      YNOW=BIGY-FLOAT(II)*DELY
      YB4=YNOW+DELY
      DO 2300 J=1,3,2
      CALL XY(GRAPH,X13(J),Y13(J),YNOW,YB4,XRANGE,SMALLX,EKS)
 2300 CONTINUE
      DO 2400 K=1,N
      CALL XY(GRAPH,X(K),Y(K),YNOW,YB4,XRANGE,SMALLX,PLUS)
 2400 CONTINUE
      DO 2500 L=1,NSTN
      CALL XY(GRAPH,XS(L),YS(L),YNOW,YB4,XRANGE,SMALLX,STAR)
 2500 CONTINUE
C
C  PRINT RESULTS.
C
      WRITE(6,2600) GRAPH
 2600 FORMAT(' ',16X,*I*,100A1)
 2700 CONTINUE
      DO 2800 I=1,100
 2800 GRAPH(I)=BLANK
      DO 2900 I=1,NX
 2900 GRAPH(I)=DASH
      WRITE(6,3000) SMALLY,GRAPH,SMALLX,BIGX
 3000 FORMAT(' ',5X,F9.1,3X,100A1,//,11X,F9.1,94X,F9.1)
      RETURN
      END
```

SUBROUTINE RANGE   FTN

```
      SUBROUTINE RANGE(A,BIGA,SMALLA)                                   MQUAD4   596
      IF(A.GT.BIGA) BIGA=A                                              MQUAD4   597
      IF(A.LT.SMALLA) SMALLA=A                                          MQUAD4   598
      RETURN                                                            MQUAD4   599
      END                                                               MQUAD4   600
```

SUBROUTINE XY   FTN

```
      SUBROUTINE XY(GRAPH,X,Y,YNOW,YB4,XRANGE,SMALLX,BCB)               MQUAD4   601
      DIMENSION GRAPH(100)                                              MQUAD4   602
      DATA ZERO/'0'/,BLANK/' '/                                         MQUAD4   603
C                                                                       MQUAD4   604
C     Y CO-ORD.                                                         MQUAD4   605
C                                                                       MQUAD4   606
      IF((Y.LT.YNOW).OR.(Y.GE.YB4)) RETURN                              MQUAD4   607
C                                                                       MQUAD4   608
C     Y IS WITHIN YNOW AND YB4.                                         MQUAD4   609
C     X CO-ORD.                                                         MQUAD4   610
C                                                                       MQUAD4   611
      REALX=(X-SMALLX)*XRANGE                                           MQUAD4   612
      INTX=REALX                                                        MQUAD4   613
      DELX=REALX-FLOAT(INTX)                                            MQUAD4   614
C                                                                       MQUAD4   615
C     ROUND - OFF FACILITY.                                             MQUAD4   616
C                                                                       MQUAD4   617
      IF(DELX.LT.0.5) GO TO 1500                                        MQUAD4   618
      INTX=INTX+1                                                       MQUAD4   619
C                                                                       MQUAD4   620
C     CHECK FOR POSSIBLE OVERWRITING.                                   MQUAD4   621
C                                                                       MQUAD4   622
 1500 IF(GRAPH(INTX).EQ.BLANK) GO TO 1600                               MQUAD4   623
      GRAPH(INTX)=ZERO                                                  MQUAD4   624
      GO TO 1700                                                        MQUAD4   625
 1600 GRAPH(INTX)=BCB                                                   MQUAD4   626
 1700 RETURN                                                            MQUAD4   627
      END                                                               MQUAD4   628
```

APPENDIX B: Program QR for deriving rainfall-runoff relationship using McCutchan's (1963) method.

```
      PROGRAM MAIN(INPUT=120,OUTPUT=150,TAPE1=INPUT,TAPE3=OUTPUT,TAPE2,
     $TAPE4)
C
C  PROGRAM DERIVES A RAINFALL - RUNOFF RELATIONSHIP BY A MODIFIED
C  MC. CUTCHAN,S APPROACH.
C  AV. R,FALL VALUES FROM EQUI-SIZED C,MENT SUB-AREAS ARE USED. THESE
C  VALUES HAVE BEEN PREVIOUSLY DERIVED AND ARE RECALLED UNDER TAPE2
C
      DIMENSION RC(20),QC(20),CATCHI(60),QCALC(60,2),QACT(60),DATA(127)
     $,NAME(6),AVI(116),ARRAY(187),JDATE(60),GRAPH(125),MAME(6),KN(4)
      COMMON RC,QC,CATCHI,DATA,JDATE,GRAPH,QCALC,QACT,MAME,N
      EQUIVALENCE (DATA(1),NAME(1)),(DATA(7),IDATE),(DATA(8),NA),
     $(DATA(9),AVI(1)),(DATA(125),AVOLALL),(DATA(126),RMIN),
     $(DATA(127),RMAX)
      EQUIVALENCE (QCALC(1,1),ARRAY(1))
C
C  READ IN AND PRINT OUT R,FALL CHANGE PTS AND CORRESPONDING DISCHARGES
C
      WRITE(3,1400)
 1400 FORMAT(* *,61X,*R,FALL*,6X,*CORRESPONDING*/58X,*CHANGE PTS*,6X,
     $*DISCHARGES*/63X,*(MM)*,8X,*(MM)*//)
      READ(1,*) NR
      DO 1430 I=1,NR
      READ(1,1410) (KN(J),J=1,4),KM,RC(I),QC(I)
 1410 FORMAT(4A10,A5,2F10.2)
      WRITE(3,1420) (KN(J),J=1,4),KM,RC(I),QC(I),I
 1420 FORMAT(* *,10X,4A10,A5,5X,F7.2,5X,F7.2,I5)
 1430 CONTINUE
C
C  READ IN LIMITS FOR PLOTTING.
C
      READ(1,*) XMAX,XMIN,YMAX,YMIN
C
C  POSITION TAPE2 AT BEGINNING OF REQUIRED TIME PERIOD.
C
      READ(1,*) ISTART,ITIME1,ITIME2
      NYRS=ITIME2-ITIME1+1
      IDIFF=ITIME1-ISTART
      IF(IDIFF.EQ.0) GO TO 1436
      DO 1434 J=1,IDIFF
      READ(2) (DATA(I),I=1,127)
 1434 CONTINUE
C
C  READ IN RECORDED DISCHARGES.
C
 1436 NQ = 0
 1440 READ(1,1450) K,B
 1450 FORMAT(30X,I4,6X,F10.2)
      IF(K.LT.0) GO TO 1470
      IF((K.LT.ITIME1).OR.(K.GT.ITIME2)) GO TO 1440
      NQ=NQ+1
      JDATE(NQ)=K
      QACT(NQ)=B
      GO TO 1440
 1470 WRITE(3,1480) NQ
 1480 FORMAT(// 5X,*THE NO. OF YEARS FOR WHICH THERE \RE RECORDED DISCHA
     $RGES =*,I6,//)
```

```
      C
      C  SET UP HEADING.
      C
           WRITE(3,1500)
      1500 FORMAT(* *,30X,*NAME*,26X,*YEAR*,
          $5X,*AV. C.MENT*,5X,*RUNOFF CALC.D*,5X,*RECORDED*,5X,
          $*RUNOFF CALC.D*
          $/70X,*R.FALL (MM)*,4X,*FROM AV. C.MENT*,3X,*RUNOFF*,7X,
          $*FROM C.MENT*
          $/85X,*R.FALL (MM)*,7X,*(MM)*,9X,*SUB - AREAS (MM)*/)
           N=0
           DO 2200 NN=1,NYRS
           N=N+1
           SUMQ=0.0
           DO 1600 I=7,127
      1600 DATA(I)=0.0
      C
      C  READ NAME,DATE,AV. R.FALL VALUES OF SUB=AREAS OFF TAPE2
      C
           READ(2) (DATA(I),I=1,127)
      C
      C  IS THERE A RECORDED DISCHARGE FOR THIS YEAR?
      C
           DO 1640 I=1,NYRS
           IF(IDATE.EQ.JDATE(I)) GO TO 1650
      1640 CONTINUE
      C
      C  NO RECORDED RUNOFF FOR THIS THIS YEAR.
      C
           WRITE(3,1645) IDATE
      1645 FORMAT(' ',30('*'),5X,*NO RECORDED DISCHARGE FOR YEAR*,I7)
           N=N-1
           GO TO 2200
      C
      C  CALC. DISCHARGE FROM AVI.
      C
      1650 DO 1700 J=1,NA
           CALL I2Q(NR,RC,QC,AVI(J),Q)
      1700 SUMQ=SUMQ+Q
      C
      C  END OF SUB-AREA AV. FALL DATA.
      C
           QCALC(N,2)=SUMQ/FLOAT(NA)
           CATCHI(N)=AVOLALL
      C
      C  ESTIMATE DISCHARGE FROM ANNUAL R.FALL.
      C
           CALL I2Q(NR,RC,QC,AVOLALL,QCALC(N,1))
      C
      C  PRINT RESULTS.
      C
           WRITE(3,2100) (NAME(I),I=1,6),IDATE,CATCHI(N),QCALC(N,1),QACT(N),
          $QCALC(N,2),N
      2100 FORMAT(' ',6A10,I4,F12.0,F14.0,F18.0,F16.0,I5)
      2200 CONTINUE
      C
      C  PLOT Q-I RELATION
```

PROGRAM MAIN

```
      C
            LEN=125
            ITYPE=0
            NV=2
            CALL PLOT(LEN,ITYPE,NV,CATCHI,QCALC,N,XMAX,XMIN,YMAX,YMIN,GRAPH)
      C
      C  PLOT MC CUTCHAN,S ESTIMATED RUNOFF .VS. RECORDED RUNOFF.
      C
            LEN=50
            ITYPE=1
            NV=2
            CALL PLOT(LEN,ITYPE,NV,QACT,QCALC,N,YMAX,YMIN,YMAX,YMIN,GRAPH)
      C
      C  PLOT RUNOFF DERIVED FROM AV. C,MENT R.FALL .VS. RECORDED RUNOFF.
      C
            LEN=50
            ITYPE=1
            NV=1
            CALL PLOT(LEN,ITYPE,NV,QACT,QCALC,N,YMAX,YMIN,YMAX,YMIN,GRAPH)
      C
      C  WRITE DATA FOR REGRESSION ANALYSIS OF MC CUTCHAN.S DERIVED Q AND
      C  RECORDED Q ONTO TAPE4.
      C
            DO 2300 I=1,6
            MAME(I)=NAME(I)
       2300 CONTINUE
            WRITE(4) (ARRAY(I),I=1,187)
            WRITE(3,2400)
       2400 FORMAT(///,135('0'),/ ,10X,*END OF PROGRAMME*)
            STOP
            END
```

SUBROUTINE I2Q FTN

```
      SUBROUTINE I2Q(NR,RC,QC,AVI,Q)
C     NR=NO. OF R,FALL DATA PTS.
C     RC=R.FALL CHANGE PTS.
C     QC=CORRESPONDING DISCHARGES TO RC.
C     AVI=R.FALL ARRAY.
C     Q=RESULTING DISCHARGES.
C     DERIVATION OF Q. BASED ON LIN. INTERPOL. OF A PLOT OF I.VS.Q
C
      DIMENSION RC(NR),QC(NR)
      IF((AVI.LT.RC(1)).OR.(AVI.GT.RC(NR))) GO TO 1800
      DO 1500 J=2,NR
      IF(AVI.LE.RC(J)) GO TO 1600
 1500 CONTINUE
 1600 Q=(QC(J)-QC(J-1))/(RC(J)-RC(J-1))*(AVI-RC(J-1))+QC(J-1)
 1700 CONTINUE
      RETURN
 1800 WRITE(3,1900) AVI
 1900 FORMAT(///,10X,'AV. SUB-AREA R.FALL VALUE =',F6.0,' IS OUT OF
     $RANGE OF R,FALL CHANGE POINTS ARRAY RC')
      STOP
      END
```

```
      SUBROUTINE PLOT(LEN,ITYPE,NV,XVEC,YVEC,NQ,XMAX,XMIN,YMAX,YMIN,     QR
     $GRAPH)                                                             QR
      DIMENSION GRAPH(LEN),ZUMBA(9),YVEC(60,2),XVEC(NQ)                  QR
      DATA BLANK/' '/,DOT/'.'/,ZUMBA/'*','2','3','4','5','6','7','8',    QR
     $'9'/                                                               QR
      XMN=XMAX-XMIN                                                      QR
      YMN=YMAX-YMIN                                                      QR
      XRANGE=LEN/XMN                                                     QR
      K=2                                                                QR
      IF(ITYPE.EQ.1) GO TO 260                                           QR
      WRITE(3,240)                                                       QR
  240 FORMAT('1',20X,*RUNOFF DETERMINED FROM SUB - AREA R.FALLS .VS. RAIQR
     $NFALL*)                                                            QR
      WRITE(3,250) YMAX                                                  QR
  250 FORMAT(//,1X,F6.0,3X,125('-'))                                     QR
      GO TO 290                                                          QR
  260 IF(NV.EQ.1) GO TO 264                                              QR
      WRITE(3,262)                                                       QR
  262 FORMAT('1',10X,*RUNOFF DETERMINED FROM SUB - AREA RAINFALLS .VS. RQR
     $ECORDED RUNOFF*)                                                   QR
      GO TO 267                                                          QR
  264 WRITE(3,265)                                                       QR
  265 FORMAT('1',10X,*RUNOFF DETERMINED FROM ANNUAL C.MENT RAINFALLS .VSQR
     $. RECORDED RUNOFF*)                                                QR
      K=1                                                                QR
  267 WRITE(3,268) YMAX                                                  QR
  268 FORMAT(//1X,F6.0,3X,50('-'))                                       QR
C                                                                        QR
C     SEARCH FOR VALUES OF YVEC OUTSIDE PLOTTING LIMITS YMAX OR YMIN.    QR
C                                                                        QR
  270 DO 280 I = 1,NQ                                                    QR
      IF(YVEC(I).LE.YMAX .AND. YVEC(I).GT.YMIN) GO TO 280                QR
      WRITE(3,275) I,YVEC(I)                                             QR
  275 FORMAT(//2X,30('*'),* YVEC(*,I3,*) = *,F8.4,* IS OUTSIDE PLOTTINGQR
     $ LIMITS OF EITHER YMAX OR YMIN*//)                                 QR
  280 CONTINUE                                                           QR
C                                                                        QR
C     DIVIDE Y AXIS INTO 50 INTERVALS                                    QR
C                                                                        QR
  290 DELY=(YMAX-YMIN)/50.0                                              QR
C                                                                        QR
C     PLOTTING STARTS HERE.                                              QR
C                                                                        QR
      DO 800 I=1,50                                                      QR
C                                                                        QR
C     CLEAR GRAPH                                                        QR
C                                                                        QR
      DO 300 J=1,LEN                                                     QR
      GRAPH(J)=BLANK                                                     QR
  300 CONTINUE                                                           QR
C                                                                        QR
C     INSERT GUIDE LINES IN GRAPH                                        QR
C                                                                        QR
      IF(ITYPE.EQ.1) GO TO 410                                           QR
      DO 400 J=5,105,25                                                  QR
      GRAPH(J)=DOT                                                       QR
  400 CONTINUE                                                           QR
```

```
      GO TO 440
  410 GRAPH(LEN-I+1)=DOT
C
C  SEARCH THROUGH YVEC FOR VALUES IN BETWEEN YNOW AND YB4
C
  440 YNOW=YMAX-FLOAT(I)*DELY
      YB4=YNOW+DELY
      DO 600 N=1,NQ
C
C  Y CO- ORD.
C
      IF((YVEC(N,K).LT.YNOW).OR.(YVEC(N,K).GE.YB4)) GO TO 600
C
C  YVEC IS WITHIN YNOW AND YB4.
C
C X CO- ORD.
C
      REALX=(XVEC(N)-XMIN)*XRANGE
      INTX=REALX
      XDIFF=REALX-INTX
C
C  ROUND-OFF FACILITY
C
      IF(XDIFF.LT.0.5) GO TO 445
      INTX=INTX+1
  445 IF(INTX.EQ.0) INTX=1
      IF((INTX.LE.LEN).AND.(INTX.GE.1)) GO TO 460
      WRITE(3,450) INTX
  450 FORMAT(//10X,*ANNUAL RAINFALL OUT OF RANGE OF PLOT*//15X,
     $*FOR GRAPH(N),N =*,I3)
      INTX=1
C
C  CHECK FOR POSSIBLE OVERWRITING.
C
  460 DO 550 NI=1,8
      IF(GRAPH(INTX).NE.ZUMBA(NI)) GO TO 550
      GRAPH(INTX)=ZUMBA(NI+1)
      GO TO 600
  550 CONTINUE
      IF(GRAPH(INTX).EQ.ZUMBA(9)) GO TO 600
      GRAPH(INTX)=ZUMBA(1)
      GO TO 600
  600 CONTINUE
C
C  PRINT GRAPH
C
      IF(ITYPE.EQ.1) GO TO 750
      WRITE(3,700) YNOW,GRAPH
  700 FORMAT(* *,F6.0,2X,*I*,125A1,*I*)
      GO TO 800
  750 WRITE(3,760) YNOW,GRAPH
  760 FORMAT(* *,F6.0,2X,*I*,50A1,*I*)
  800 CONTINUE
      IF(ITYPE.EQ.1) GO TO 1000
      WRITE(3,900)
  900 FORMAT(* *,8X,'+',25(4('-'),'+')/5X,*400*,4X,*500*,22X,*1000*,21X
     $,*2000*,21X,*2500*,14X,*2900*,
```

SUBROUTINE PLOT   FTN

```
     $//,* RUNOFF (MM)*,41X,*RAINFALL (MM)*)                           QR       281
      GO TO 1200                                                       QR       282
 1000 WRITE(3,1100)                                                    QR       283
 1100 FORMAT(* *,9X,50('-'),                                           QR       284
     $//,* CALCULATED*,20X,*RECORDED*/* DISCHARGE (MM)*,16X,*DISCHARGE QR       285
     $(MM)*)                                                           QR       286
 1200 RETURN                                                           QR       287
      END                                                              QR       288
```

APPENDIX C:- CATCHMENT DESCRIPTIONS

C.1 SOUTHERN REGION OF THE CLARENCE VALLEY - MANN RIVER AT JACKADGERY

C.1.1 PHYSIOGRAPHY

Topography: Elevations can exceed 1500m. Rugged terrain characterised by steep, dissected valleys. Fingers of flat terrain found along some streams. Plateau areas along the western and southern boundaries (900 - 1200m). East of Mt. Darkie (in the south) a steep escarpment divides the Clarence Valley from the Bellinger Valley.

Soil: Red podsolic soils and friable red earths subject to very high leaching - can be "excessively" porous despite high clay content. (Soil Conservation Service of New South Wales, (1975)).

Geology: High western plateau - granite; southern plateau - basalt; remainder dominated by silurian strata.

Groundwater Potential: Springs from badly jointed basalt around Dorrigo.

Vegetation: Mainly original land cover of heavily timbered forests, especially hardwood and brushwood. Rainforests found on range tops and there is some clearing for agriculture. Area of arable land 10-15%.

Land use: Mainly forestry with some grazing in the valleys.

C.1.2 CLIMATE

Rainfall: See Figure 3.1. Marked rainshadows due principally to topography. Annual median rainfall = 1025 mm.
Relative wet period: December to April (55% of total).
Relative dry period: May to September (27% of total).

Temperature: Warm to hot - October to April. Average winter minima about 12°C cooler than summer values.

Estimated Evaporation: (sunken pan).

Mean = 1176 mm
Standard deviation = 97 mm

C.2 UPPER HUNTER VALLEY - HUNTER VALLEY AT SINGLETON

C.2.1 PHYSIOGRAPHY

Topography: can be divided into 4 regions:-

C.2.1.1 North East Boundary: Mt. Royal Range and Barrington Tops. Greatest elevation in valley (greater than 1400m). Rugged terrain with deep narrow valleys which fall away to lower broken hills and eventually alluvial plains of the Hunter River.

Soil: Derived from basalt and limestone (highly leached) - of the Krasnozem family.

Vegetation: Higher elevations forested giving way to rich pastures near the Hunter River (Renwick (1968)).

Land use: Beef cattle grazing on rough upland pastures.

C.2.1.2 North Boundary: Liverpool Range. Elevations 600-1200m. Not as rugged as the North-East. Dominated by the wide valleys and rolling ridges of the Merriwa Plateau which is contained within the Liverpool Range, the Goulburn River and the Great Dividing Range.

Soil: Mainly derived from basalt with high variability especially in the Murrurundi District. Merriwa Plateau dominated by easily erodable cracking clays in the north and skeletal soils in the south (Renwick (1968)).

Vegetation: Merriwa Plateau cleared of original landcover and replaced with wheat and pastures.

Land use: Wheat and sheep grazing on Merriwa Plateau.

C.2.1.3 South Boundary: South of Goulburn River/Hunter River. Dissected sandstone plateau - valleys steep sided and often bordered by cliffs. Extremely rugged.

Soil: Poor, sandy skeletal soil with small areas of rich alluvial flats.

Vegetation: Woodland and scrub mainly with some pastures in the east.

Land use: Extreme west: Beef cattle grazing on small areas of undulating grassland.
East (Wollombi Brook): Grazing.

C.2.1.4 Hunter Valley Plain: Elevations down to 150m. Extends up the Hunter River to include Scone. Rich alluvial flood plain bordered by open undulating grassland. Varies in width from 3km near Scone to almost 25km near Singleton.

Soil: Rich alluvium, extremely fertile.

Vegetation: Grassland:

Land use: Grazing, dairying, fodder, vegetable and fruit growing, viticulture.

C.2.2 GROUNDWATER POTENTIAL: For all four regions - small yields from jointed rocks of Carboniferous and Tertiary Ages and from alluvium along major streams. Water quality is variable. (Wright (1977)).

C.2.3 CLIMATE

Rainfall: See Figure 3.8. Annual median rainfall = 650mm.
Relative wet period: December to April.
Relative dry period: June to September.
Temporal Rainfall distribution more uniform than for Clarence Valley. Rainfall variability increases westward with decrease in rainfall depths. (Wright (1977)).

Temperatures: Hot - October to April: average maximum 25-30°C. Rest of year - mild to warm. Average winter minima about 11°C cooler than summer values.

Estimated Evaporation: (Sunken pan).

Eastern section	mean	=	1176 mm.
	standard deviation	=	97 mm.
Western section	mean	=	1318 mm.
	standard deviation	=	152 mm.

N.B. Unless otherwise stated, the above data was derived from New South Wales Water Conservation and Irrigation Commission (various dates).