AN ANALYSIS OF THE SURFACE WATER RESOURCES OF THE UPPER TAIERI RIVER, OTAGO

by

I. SIMMERS

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ABSTRACT

To plan a water resource survey data collection programme, it is vital to first establish the purpose for which the gathered data are to be used, and the degree of precision of the information at a particular confidence level that will be adequate. Purpose will determine the required data precision. Precision requirements will in turn dictate minimum record lengths of each variable necessary to estimate population parameters at a point, and the network density needed for parameter estimation over an area.

This study is concerned with the data requirements and analyses for the planning of an irrigation scheme in the Maniototo Plains and Styx Basin, Central Otago. The 95 percent confidence level is adopted for required data precision. Allowable standard errors of population parameter estimates are stated to be 10 percent for streamflow and precipitation and five percent for temperature.

Measured monthly, seasonal, and annual parameter values of these variables are summarised and discussed. Although the data collection networks are shown to be theoretically acceptable for most purposes, the measured data do not allow estimation of all the needed total - and sub-catchment population parameters at the required precision level. Record synthesis is necessary in order to increase the amount of information contained at this stage in the precipitation and streamflow data series.

Techniques chosen for time series extension and spatial extrapolation are linear, curvilinear and multiple regression analyses, water balance, conceptual and stochastic models. Each model is described, and limitations or advantages outlined. Also discussed are the theoretical aspects which concern precision of population parameter estimates from blended data, standard errors of prediction for synthetic records, and the relative simulation and prediction abilities of the models chosen. Split-record techniques are used to evaluate within and between model efficiencies.

Addition of synthesised records to the precipitation and streamflow data series still does not permit estimates of all required population parameters at the levels of precision stated as needed. In some instances, record extension results in a decrease in statistical information. For design of any irrigation scheme to proceed now, therefore, the chosen error criteria must be judged too stringent for the Upper Taieri data. If the calculated standard errors cannot be accepted, all precipitation and streamflow records from the study area will require extension by additional observations.

The study is also used as an opportunity to check the validity of commonly accepted concepts of 'regional hydrology', at least within the East Otago Region. It is concluded that for low flows, hydrological homogeneity cannot be assumed to equate with uniformity of basin characteristics. Regions are better defined in terms of allowable areal variation for stated hydrological parameters. The study area is not hydrologically homogeneous by the defined criteria. Further, the boundaries of hydrologically similar regions vary dependent on which streamflow parameter is considered.

Results are presented in British units throughout this study, since these are the units in which the basic data were measured and analysed.

ACKNOWLEDGEMENTS

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Many people have been associated with the project. In particular, thanks are due to Dr P. Hutchinson (Zambian Meteorological Department) for both his guidance and assistance with the large amount of computing; to Professor J. D. McCraw and Dr M. J. Selby (University of Waikato) and Mr D. L. Murray (University of Otago) for their helpful criticism and editorial review of the script; and to Professor R. J. Hosking, Mr J. C. Turner, Dr F. C. Durling and Dr R. A. Littler (University of Waikato) for their useful comments on the statistical techniques used. Thanks are also due to Mrs M. A. McLean for typing the script, and to other members of the University of Waikato staff for their help with the draughting and photographic printing.

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FRONTISPIECE: *Aerial panorama of part of the Upper Taieri River basin, looking north from near the headwaters down the Styx basin towards the Maniototo basin and the Hawkdun Range. (Photo by courtesy of A.R. Armstrong, Poolburn)*

CHAPTER 1: INTRODUCTION

TYPES OF DATA REQUIRED FOR WATER RESOURCE SYSTEM DESIGN

This project is concerned wtih the data requirements and analyses for the planning of an irrigation scheme in the Maniototo Plains and Styx Basin, Central Otago.

The general objective of water resource planning is to make the most effective use of the available water supply to meet all the foreseeable short- and long-term needs of a region. To this end, a survey of the water resources of a region is intended to provide an estimate of the sources, extent, characteristics, magnitude and dependability of this supply. From such a survey one can realise the advantages of multiple use, reconcile conflicting interests, and achieve optimum coordination between all interests concerned.

These objectives stated by Linsley (1958), Kuiper (1965) and Clark & Bruce (1966), are reflected in the water resources investigation and determination aspects of the New Zealand Water and Soil Conservation Act (1967). The Act also implies that a further objective of such investigations is to develop methods for water resources assessment. The present Upper Taieri study is an initial step towards achieving this goal, and gives attention to methods adopted in the absence of hydrological data. Simple standard or appropriately modified techniques are used to provide useful information with least cost in time and money.

The development of dependable water supplies from agricultural watersheds requires a knowledge of the runoff characteristics of the watersheds throughout the range of meteorological conditions that they can be expected to experience. For a few watersheds there exist stream gauging records of sufficient length to accurately assess the water yield characteristics. When these records are available, they are by far the best source of hydrological information for the basin (Haan, 1972(a)).

However, it is more than likely that some streamflow records in a drainage basin have missing years, or have unequal length, or should be extended backwards in time. There are two main approaches towards the extension or synthesis of streamflow records in such cases:

(a) the use of existing streamflow data from adjacent streams or other rivers in the region;

(b) the use of climatic data from weather stations in the area; these are often more numerous and have longer periods of record than flow stations.

Thus it becomes necessary to collect not only runoff data but also records of meteorological variables such as precipitation, temperature, wind movement, insolation and relative humidity. To achieve a satisfactory evaluation of water resources or determination of their use and management, any water resources survey requires an examination of the variation of all phases of the hydrological balance in space and time over the area concerned (Gibbs, 1964; Kuiper, 1965). It must be understood, however, that synthetic streamflow data derived from climatological or other hydrological records to augment a short actual streamflow record are only a substitute for measured streamflow values.

DATA PRECISION REQUIREMENTS FOR DESIGN APPLICATION

General:

To plan a data collection programme it is vital to first establish clearly the purpose for which the gathered data are to be used, and the degree of precision of the information at a particular confidence level that will be adequate (Montgomery & Hart, 1971). The purpose will ultimately determine the required data precision. Precision requirements will in turn dictate the minimum record lengths of each variable necessary to estimate population parameters at a point, and the network density needed for parameter estimation over an area. It is necessary to understand the relationship between precision and the data required to obtain it if a sampling programme is to be established at a point or over an area on a sound scientific basis. Quantitatively, the precision is defined as equal to half the range between two limits, and defines the extent of uncertainty that is acceptable in the value of the parameter measured. The confidence level is the percentage of occasions on which individual measured values will be between these limits.

The suggested approach in this study is to use the existing data to statistically establish the network design and period of sampling which would be needed to estimate parameters of the populations with stated precision at a stated level of confidence. It should be noted that regardless of the record length, there is still some finite probability that an unacceptable error will occur. A numerical statement as to what data precision is required for water resource system design may be different for each parameter and may refer to any number of variables over whatever time period.

The precision and confidence level required of a result must be chosen with care. Confidence is often set somewhat arbitarily at 95 percent, and this will be satisfactory for most purposes. However, a higher level of confidence might be required in connection with disputes, or in other critical situations. In accord with many other hydrological studies the 95 percent confidence level is adopted in this study as regards required data precision. The specified value of precision is critical in deciding the data required and should not be made smaller than necessary; an excessive data collection programme will result. For instance, if there is a need to know mean annual runoff to within plus or minus 20 percent, there is no need to have extremely long records. On the other hand, if an estimate that is five percent too high can result in severe water shortages because a reservoir is too small, many years of records may be needed (Haan, 1972(b)).

Streamflow:

To make a numerical statement or statements as to what data precision is required for this study is not simple. The primary purpose for which the gathered water resources data are to be used is the design of an irrigation scheme, operating on either a 'run-of-river' or storage reservoir basis. No firm commitment as to required data precision could be offered by planners of the proposed irrigation scheme and neither was such a statement located in a survey of the literature.

A solution suggested here is to consider the problem from two points of view:

(i) The maximum degree of precision likely to be achieved irrespective of either record length or network density, because of random and systematic errors inherent in the basic data measurement and processing.

(ii) The minimum acceptable precision as deduced from logical consideration of the design criteria (Murray, 1972).

A range of acceptable precision is thus proposed. The lower limit is determined by the design criteria and the upper value is that beyond which it is either impossible or impracticable to proceed in point or areal estimation of the required population parameters.

Records of streamflow provide the basic information for most water supply studies and should be continuous for a period of time sufficient to include conditions which are likely to be met in operating the project. The longer the record of streamflow, the smaller will be the sampling error (Clark & Bruce, 1966). For adequate estimation of streamflow characteristics Yevdjevich (1963) suggests that the minimum length of continuous records from all stations should be 30 to 40 years. This conclusion is confirmed by Hardison (1969) and Hidore (1963). Hidore further concludes that for most rivers he has studied with a 50-year record, the true mean annual runoff deviates less than 10 percent from the sample mean, and in many cases by only five or six percent, at the 95 percent confidence level. However, it is also shown that no particular length of record will produce a reliable indication of the true mean for all streams, and that even a 50-year record may be insufficient to give an estimate of the mean annual runoff to within 10 percent.

Such results are no surprise when the likely sources of error listed by Yevdjevich (op.cit) and Jackson & Aron (1971) are considered. There is a 95 percent probability that discharge measurement errors will be less than 5 percent for optimum conditions (Carter & Anderson, 1963). However additional errors from rating table and other causes in deriving daily flow values, can give a total error of the order of five to 15 percent (Veitch & Shepherd, 1971).

It therefore appears unlikely that station estimates of streamflow parameters from measured data in the study area could be expected to be within 10 percent of actual at the 95 percent probability level.

Although records of streamflow provide the basic information for most water resources studies, the planning and development of these resources often cannot be delayed for a long period of observation and record accumulation. The hazards of poor design cannot be ignored, but hydrologists are often required to provide design criteria for rivers with few years of discharge data, or none at all. Since information may be increased by use of the information contained in related series, estimates of streamflow parameters may therefore need to be determined by analytical methods used to extend or translate discharge data (Matalas & Langbein, 1962). If the correct model is chosen, the principal sources of error will be the incorrect estimation of the input parameters, regardless of the type of model (Haan, 1972b). The required precision of measured temperautre and precipitation data must therefore also be considered, assuming for the present that temperature is an index of evapotranspiration.

Evapotranspiration:

Little information was located in the literature on the maximum degree of precision likely to be achieved from measured temperature data. However, as a guide to the likely effects of random and systematic errors in evapotranspiration data input to models of streamflow synthesis, reference may be made to Parmele (1972) and Ibbitt (1972). Both conclude that random errors of the size normally encountered in hydrological records would have a negligible effect on estimates of the true streamflow parameter values. However, Parmele (op.cit) concludes that a constant bias in the evapotranspiration input data has a cumulative effect and results in considerable error in hydrograph peaks and recession characteristics. As a general rule estimates of evapotranspiration to better than 20 percent may not be necessary when total annual yield of a basin is of the order 40 to 50 inches. For areas with considerably less runoff it may be necessary to estimate evapotranspiration to better than 10 percent to achieve good fit between simulated and observed water yields.

It is therefore suggested for this study that estimates of temperature parameters from measured data should be within 10 percent of actual at the 95 percent confidence level.

Precipitation:

For many purposes, and in particular the assessment of water resources, Hutchinson (1970(b)) considers that to work with less than monthly rainfall totals is unnecessary. As such, when considering in this study the required precision of measured precipitation data input to models of streamflow synthesis, monthly values are taken as the minimum time unit.

Point estimates of rainfall parameters from measured data are known to be affected by random and systematic errors and nonhomogeneity (Yevdjevich, op. cit); errors of rainfall measurement are the main causes of inaccuracy in most rainfall-runoff simulation studies (Dawdy & Bergmann, 1969). Likely causes and effects of such errors on parameter estimation in the Upper Taieri area are outlined by Hutchinson (1968, 1969(a), (b), 1970(a), (b)) and Hutchinson & Walley (1972). These studies form a useful basis for work in the present project.

For a small exposed site Hutchinson (1969(b)) shows that random errors of monthly rainfall can be up to plus or minus 4.2 percent of the sample mean for 95 percent confidence limits. Further, possible total inaccuracy of raingauges is stated as being of the order 20 percent or more at the same probability level (Hutchinson, 1968, 1969(a); Jackson & Aron, 1971). When the magnitude of likely total error is considered, it is not surprising to find a sample record length in excess of 30 years quoted as being the minimum necessary for stable parameter estimates from measured point rainfall data (Malone, 1951; McDonald & Green, 1960; Hutchinson, 1969(a)).

However, for most hydrological studies it is increasingly important to establish the mean rainfall over an area for particular periods of time. Methods of doing this from measurements at sample points vary from subjective to geometrical. Because rainfall measurement is a sampling method, estimates of the mean areal rainfall differ from the true mean due to the random and systematic errors of the point sample and the additional systematic errors attributable to extrapolation of point data to a 'representative' area (Clarke & Edwards, 1972).

It is essential, therefore, not only to be able to determine the mean rainfall over an area, but also to be able to estimate the precision of this determination from a given network (Hutchinson, 1970(b)). Conversely, if the required precision for an area is stated then it is possible to determine the minimum network density that will ensure that degree of precision. Gauge density will of course increase for a specified degree of precision as the sampling time interval decreases (Alvarez & Henry, 1970). Observations are not independent however, since correlations between adjacent gauges will usually be high. Normal methods to estimate the error of a mean therefore cannot be used. Several techniques have been proposed to overcome this difficulty (see Hutchinson, 1972) and these are considered further under network design.

In this study the preferred method for resolving the problems of network design and calculation of standard error is that developed by Czelnai *et al.* (1963), and used by Gandin (1970) in USSR and Cislerova and Hutchinson (1973) in Zambia.

To determine the order of maximum precision likely to be achieved in estimating monthly and annual mean areal rainfall in the Upper Taieri project area, reference was made to Sutcliffe (1966) and Cislerova & Hutchinson (op.cit). Both studies show that estimation of areal mean rainfall to within 17 to 20 percent of actual is often possible at the 95 percent confidence level. For some areas of Zambia however, it was not possible to use these values as criteria to determine optimum network density, since they also approximated the total errors at individual stations. This 'theoretical stringency limit' could be overcome by adopting a 95 percent probability allowable error of 30 percent, though this is considered unacceptably high for engineering and water resources purposes.

When the likely sources of total error in estimating point and areal values of mean monthly and annual rainfall are considered, it is suggested that in this study estimates of these parameters from measured data should be within 20 percent of actual at the 95 percent confidence level. However, this degree of precision is likely to be achieved only if the sampling network has uniform spacing (Sanderson & Johnstone, 1953; Gandin, 1970) and does not possess systematic errors due to altitudinal bias (Hutchinson & Walley, 1972). Further, the random and systematic errors associated with the catch at individual gauges will ultimately determine the limit of estimated parameter precision.

It must be remembered, however, that if the measured rainfall data are used to simulate mean streamflow values at less than monthly intervals, then considerably greater errors are probable. For example, Dawdy & Bergmann (1969) show that 'prediction of flood peaks cannot be made with better accuracy than about 20 to 25 percent standard error by rainfall-runoff simulation models which use data from a single raingauge whose records have been adjusted to be representative of mean basin conditions'.

Data precision required by the design criteria:

To determine the minimum acceptable precision of parameter estimates from measured or synthesised data requires logical consideration of the purpose for which the data are to be used and the associated design criteria.

Within any irrigation system of optimum design it is well known that water transmission and application losses can produce an overall 'irrigation efficiency' to the order of 60 percent, irrespective of available supply (Bolt, 1970). If this efficiency is assumed for the proposed irrigation scheme in the study area, then it is suggested that estimates of measured or synthesised parameters to within plus or minus 20 percent of actual at the 95 percent probability level could be accepted.

Although errors of such magnitude are undesirable no evidence was found to refute the belief that when necessary they could be largely offset by increased operating efficiency of the irrigation scheme. This belief is in essence reinforced by Basinski (1960), who concludes that for economic reasons it is generally impracticable to aim at water supplies sufficient to satisfy full requirements for more than 75 to 90 percent of years.

Summary:

It is now possible to make numerical statements as to what data precision is considered desirable for the design of the proposed Maniototo/Styx Basin irrigation schemes. These statements should not be assumed to be transferrable to other water resources projects, except in concept, and in the light of further experience may yet prove inappropriate even for the study area.

At this stage, therefore, it is proposed that:

(i) Estimates of measured or synthesised streamflow parameters to within 20 percent of actual at the 95 percent probability level would be acceptable. It appears unlikely, however, that station estimates of streamflow parameters, even from measured data, could be expected to have greater precision than plus or minus 10 percent at the same confidence level, irrespective of record length.

(ii) If estimates of streamflow parameters need to be determined by analytical methods which use measured precipitation and temperature input data, then errors in these variables need to be as small as possible. Errors of precipitation measurement will be the limiting factor; estimates of point and areal mean monthly and annual rainfall in this study should be within 20 percent of actual at the 95 percent confidence level. Estimates of temperature parameters should be within 10 percent of actual at the same confidence level.

STUDY OBJECTIVES

A statement of study objectives now follows automatically and may be given as a series of hypotheses:

(a) That the available measurements of precipitation, temperature and streamflow in the catchment permit estimates of the station, total and sub-catchment monthly, seasonal and annual mean, variability and extremes of the variables at the required level of precision. Should this hypothesis be rejected:-

(b) That the following techniques of data synthesis increase the information contained in the precipitation, temperature and streamflow data series, as compared with the measured series alone, and enable estimates of the population parameters from objective (a) to be derived at the required precision level:

- (i) Regression analysis for time series extension and spatial extrapolation of precipitation, temperature and streamflow data - linear, curvilinear and multiple regression.
- (ii) Alternative deterministic models for time series extension and spatial extrapolation of streamflow data - water balance and conceptual models.
- (iii) Stochastic model for time series extension of streamflow data.

The most appropriate geographical unit for water resources planning is the river drainage basin. It is thus suggested that the concepts and objectives of 'regional hydrology', as demonstrated by representative basins, are fundamentally similar in purpose to the regional assessment of water resources. The study area lies within the East Otago Region and accords in all respects with the general regional classification of $R_2P_2S_3$ given by Toebes & Palmer (1969). A further function of this study is thus the opportunity to test the within-catchment variations of yield and flow characteristics from a single 'representative' basin in a region which is supposedly hydrologically homogeneous. From this it is theoretically possible to check the validity of the basic concept of 'regional hydrology', at least within the East Otago Region. That is, by defining the hydrological characteristics of a region, to use these directly for data extrapolation within that region from the assumption of homogeneity. The third objective of this study may thus be stated as:-

(c) To define regional homogeneity as implied by the representative basin approach to areal water resource assessment, by stating permissable limits of areal variation in annual yield and low flow characteristics. Hence, to determine whether the study area is hydrologically homogeneous by the stated criteria, using the parameters annual yield, Lane & Lei (1949) variability index, base flow recession constant and unit area base flow. An assumed variation of precipitation with altitude is allowed for.

The principal objectives of this study are shown to be only partly achieved. However, the region's usable surface water resources are determined and analysed for their areal distribution and time variation, and provide information of both local and national importance. Results presented show that with some care and using readily available analysis techniques, considerable valuable information can be obtained which involves a wide spectrum of catchment climatic and flow characteristics. With the large amount of generally unprocessed basic hydrological data currently available in New Zealand, this study is most timely.

It is therefore postulated that although similar studies have in the past been stated to be precluded by a lack of sufficient data, or carried out with results of dubious benefit, two problems have been the paucity of overall project planning and a lack of awareness of the wide range of available analysis and synthesis techniques. By demonstrating here the value of some of these procedures, it is hoped that multipurpose planning and the use of a region's water resources by scientists and engineers can henceforth be achieved with less uncertainty.

CHAPTER II: GENERAL CATCHMENT DESCRIPTION

GEOLOGY

The Upper Taieri catchment study area covers 285 square miles and lies 40 miles northwest of Dunedin in Central Otago, New Zealand (Figure 1). The geology and associated structural features of the basin and surrounding areas have been well documented previously. For detailed descriptions reference may be made to Benson (1935), Williamson (1939), Cotton (1939(a),(b)), Raeside (1949), and more recently Mutch (1963), Wood (1963), McCraw (1965(a)), McKellar (1966) and Leslie (1966).

Major tectonic movements in late Cenozoic time have warped and faulted a cretaceous peneplain that has been partly covered with Tertiary sediments. The resulting fault angled depressions and tilted 'block' features give Central Otago its distinctive range and valley topography. The Upper Taieri and Maniototo plains together occupy one of these fault-angle depressions and dip to the northeast from the high schist plateau of the Lammerlaw Range.

The Upper Taieri portion of this larger Maniototo depression is bounded to the west by Rough Ridge, to the east by the Rock and Pillar and Lammermoor Ranges, to the south by the Lammerlaw Range, and to the north by a low ridge of schist basement rock which separates the Styx Basin from the extensive Maniototo plain. The area is one of accentuated relief and combines areas of swampy and poorly drained land around the Taieri River within the Styx Basin, deeply dissected hills, and the Lammerlaw Plateau (refer frontispiece and plates 1-10). Elevations range from 4756 feet on the Rock and Pillar Range to 1280 feet at the Patearoa-Paerau gauging site (Figures 2 and 3). Mean catchment elevation is 2807 feet, with the 1800 feet contour enclosing much of the low lying Styx Basin.

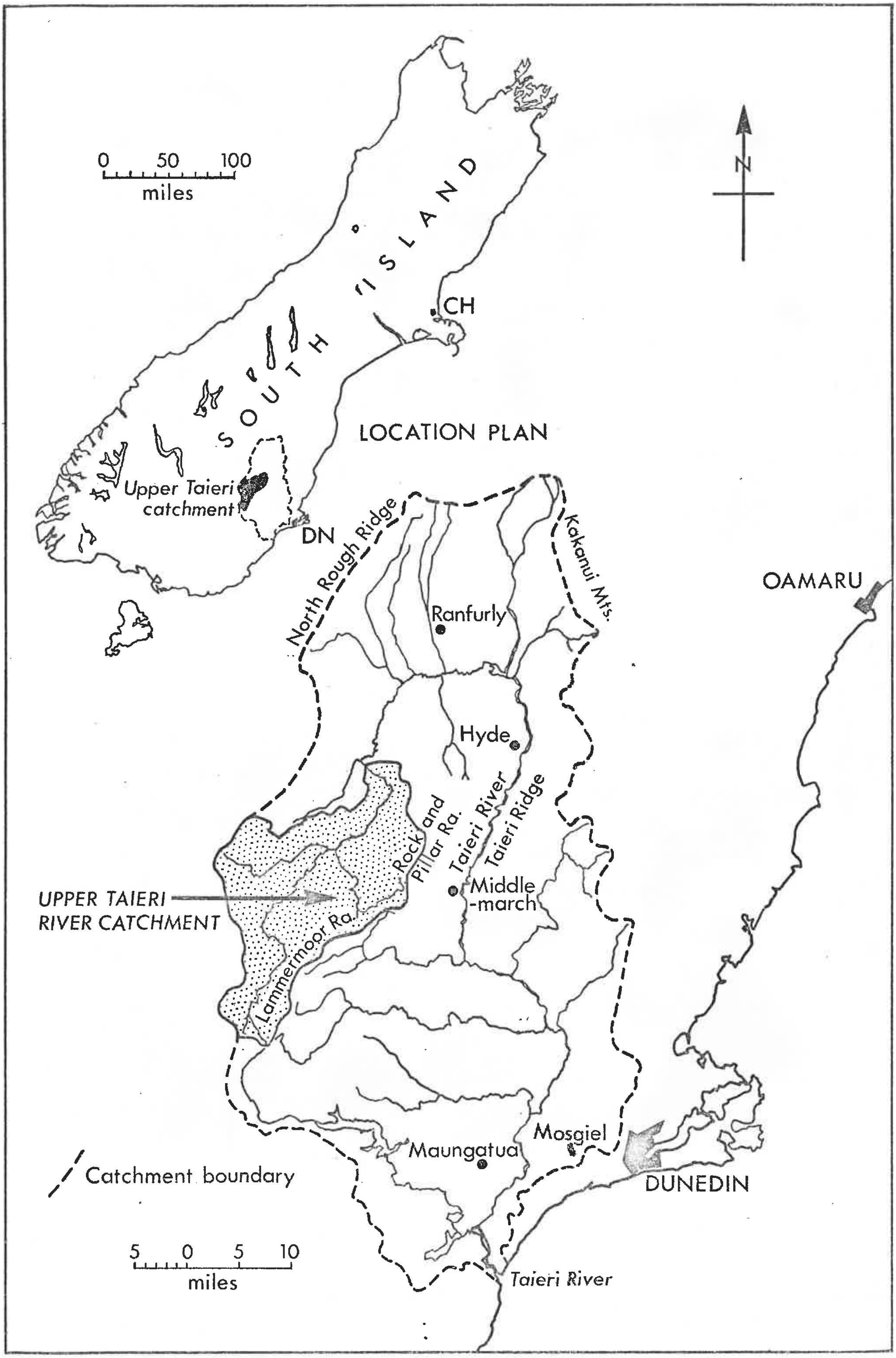


FIGURE 1: Upper Taieri catchment location

PLATE 1: Looking down the Taieri River towards the Paerau Gorge from the Paerau Rd. Br. gauging site

PLATE 2: Looking east up the Styx Ck. gorge from the bottom of the Old Dunstan Rd.

PLATE 3: Looking north from the Old Dunstan Rd. to the Paerau Gorge (Taieri River) and beyond to the Maniototo basin.

PLATE 4: Looking south-west across the Styx basin towards the headwaters from near the Paerau Gorge

PLATE 5: Looking north-east down the Styx basin towards the Paerau Gorge (far right), from the access track to Smith's raingauge

PLATE 6: Looking south-west across the upper end of the Styx basin towards Bottle Rock, from the access track to Smith's raingauge

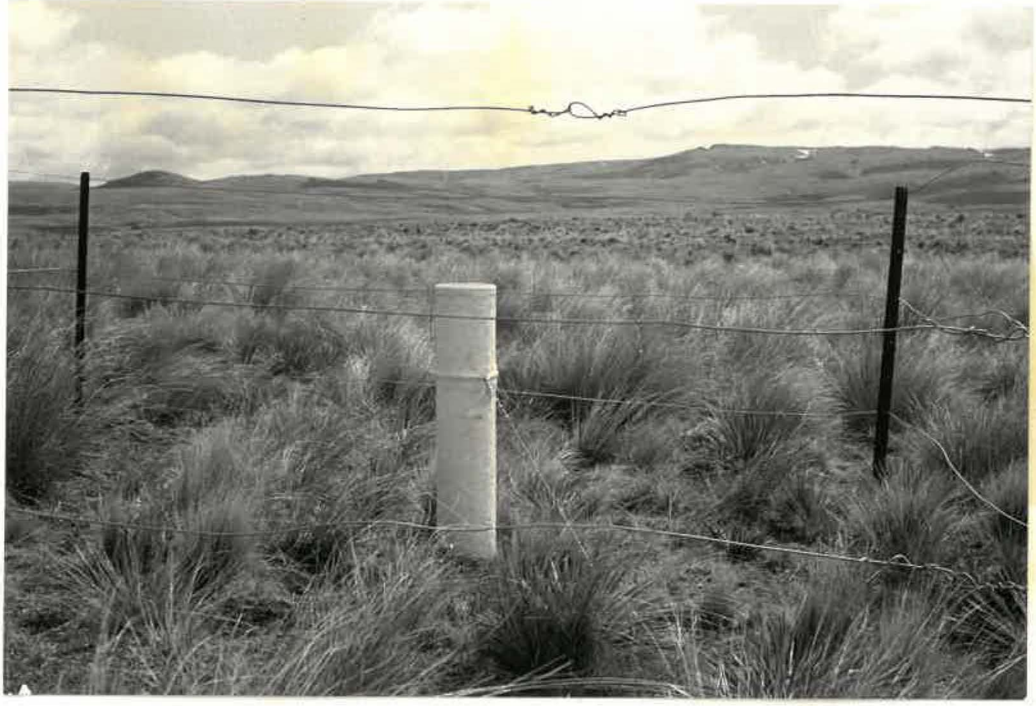
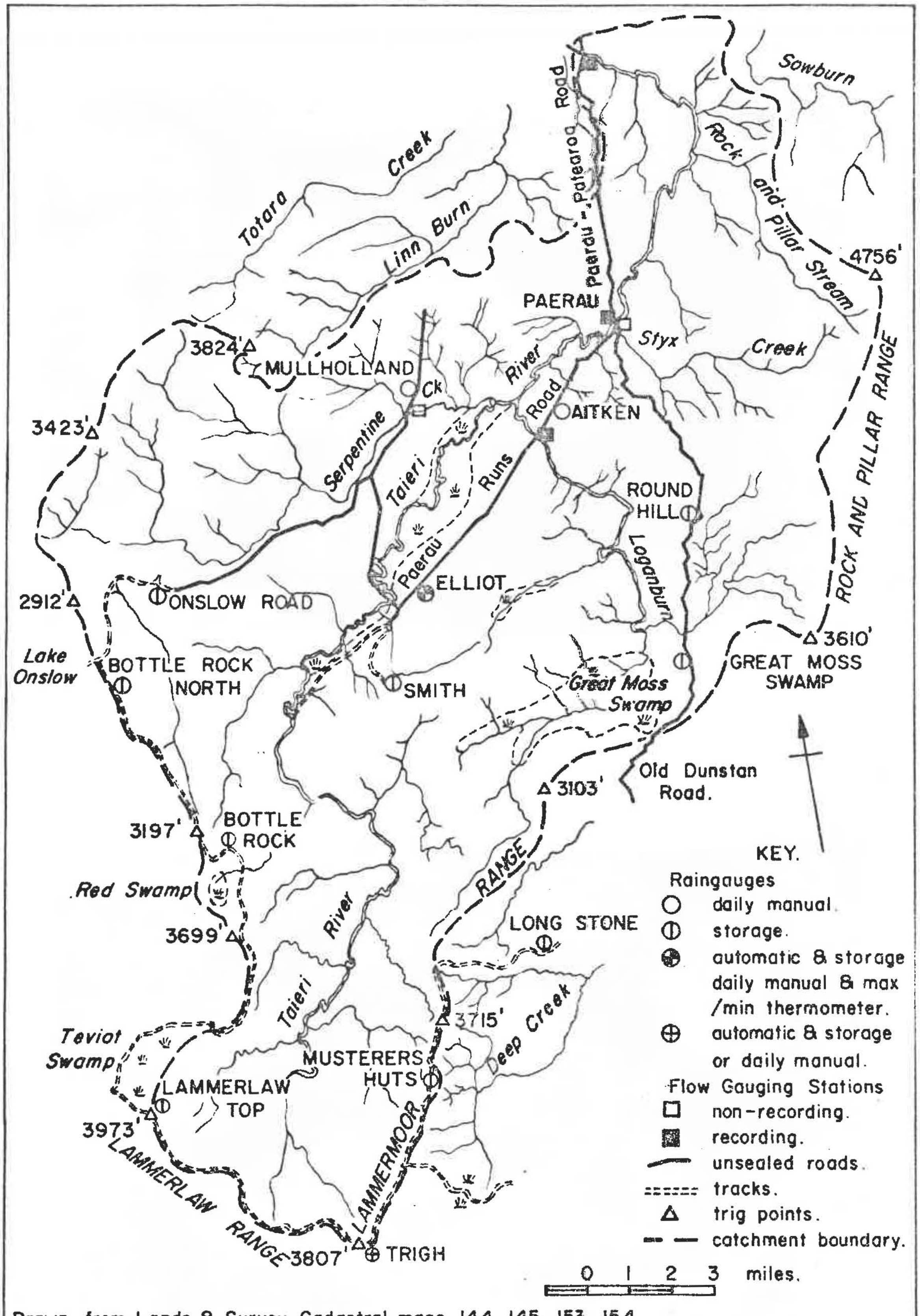


PLATE 7: *From the Great Moss Swamp raingauge looking north (Gauge 75 cm. capacity; fibreglass; 6 ins. diam. orifice; altitude 3050 feet)*

PLATE 8: *Looking south-west over the Great Moss Swamp from the Round Hill raingauge site*

PLATE 9: Looking east across the upper catchment and the Taieri River from Bottle Rock

PLATE 10: Looking south towards the headwaters, Lammerlaw Top and the Lammerlaw Range, from the Onslow Rd. raingauge (Gauge 75 cm. capacity; fibreglass, 6 ins. diam. orifice; altitude 2770 feet)



Drawn from Lands & Survey Cadastral maps 144, 145, 153, 154

FIGURE 2: Upper Taieri catchment hydrological installations

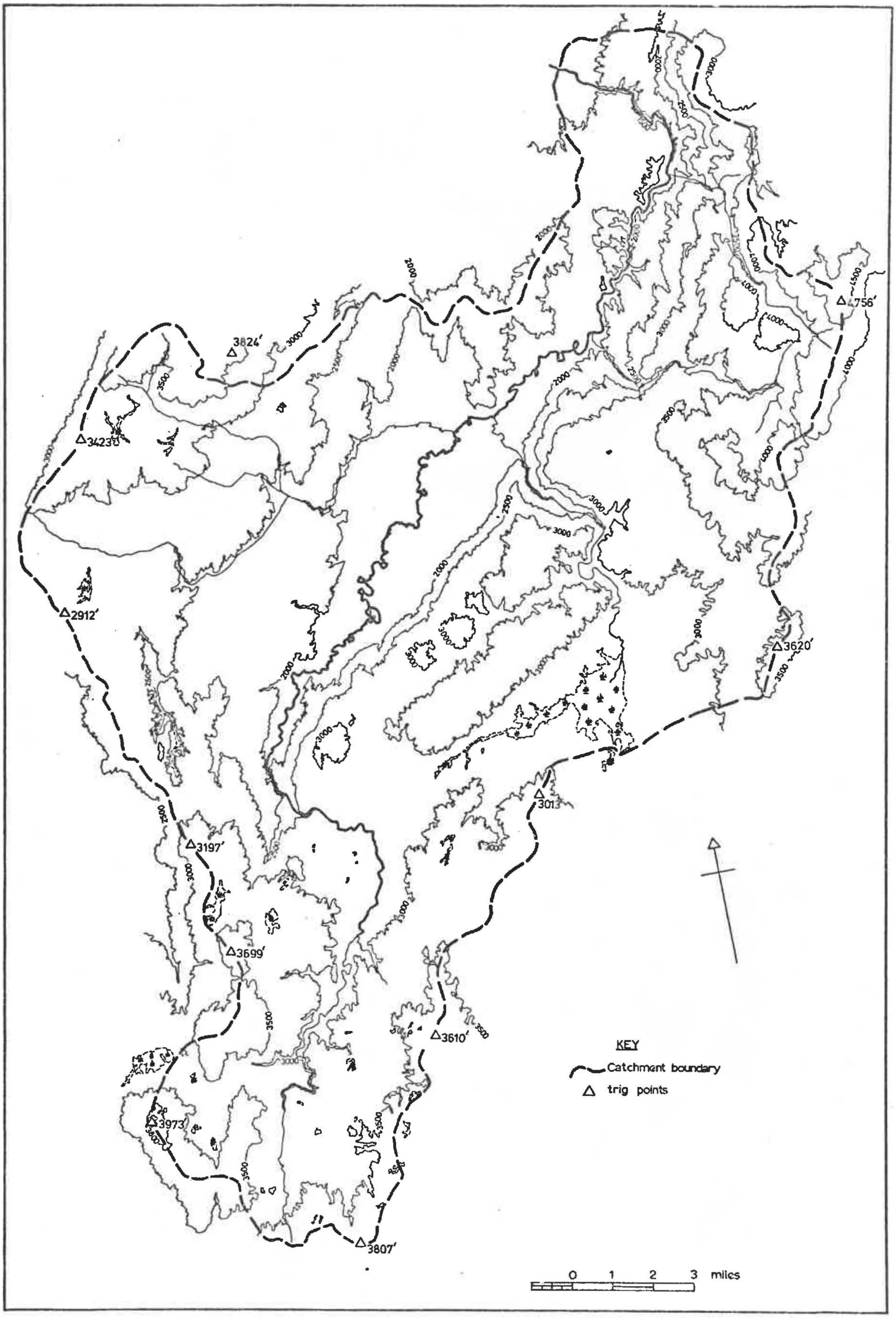


FIGURE 3: Upper Taieri catchment relief

Basement rocks are of the Haast schist group chlorite subzone IV, with the present Styx Basin and the Great Moss Swamp depressions subsequently infilled with Pleistocene and Recent gravels and swamp deposits (Figure 4). Other isolated patches of last, penultimate and earlier glaciation outwash gravels occur mainly in the south and west of the basin and lie unconformably on the planed schist undermass surface of the Cretaceous peneplain (Wood, 1963).

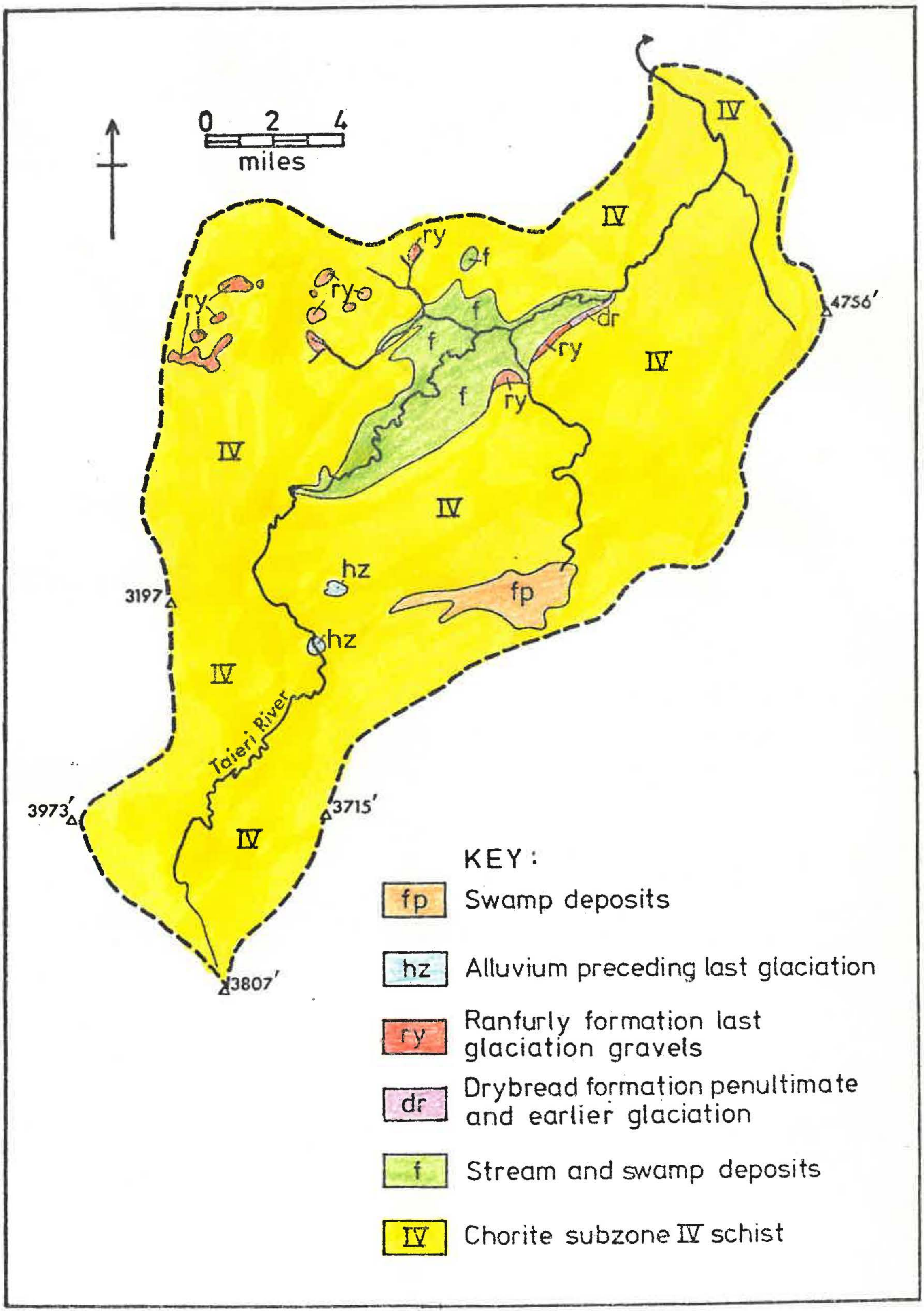
The distributions of the main formations shown on Figure 4 are derived from the "Geological Maps of New Zealand, 1:250,000" of Mutch (op. cit) and McKellar (op. cit) - Oamaru and Dunedin sheets.

For subsequent analysis or synthesis of the water resources of the Upper Taieri basin, it is assumed that the low ridge of schist basement rock which separates the Styx Basin from the Maniototo plain to the north acts to a large degree as an underflow barrier at the Patearoa-Paerau and Paerau gauging stations (McKellar, 1970). It is thus considered that the flows measured at these stations represent total outflow from the catchment, rather than surface runoff plus an unknown proportion of groundwater discharge.

SOILS

The pattern of soil formation in Central Otago is simplified by the wide distribution of parent materials derived from schist. Most soils are developed either on basement schist or on alluvium, loess, or solifluction debris derived from schist. Because of the similarity of parent materials it is possible to demonstrate in a striking fashion the effect of climate in soil formation.

A detailed description of the soils in the Upper Taieri catchment is unavailable, but generalised accounts of the major soil groups found



Source: Geological Map of New Zealand; Sheets 23 and 25, 1966.

FIGURE 4: Upper Taieri catchment geology

in the area have been given by McCraw (1965(b)), Raeside & Cutler (1966), Leamy (1966) and in Soil Bureau Bulletin No. 27 (1964). Figure 5 has been drawn from sheets 11 and 13 of this last publication.

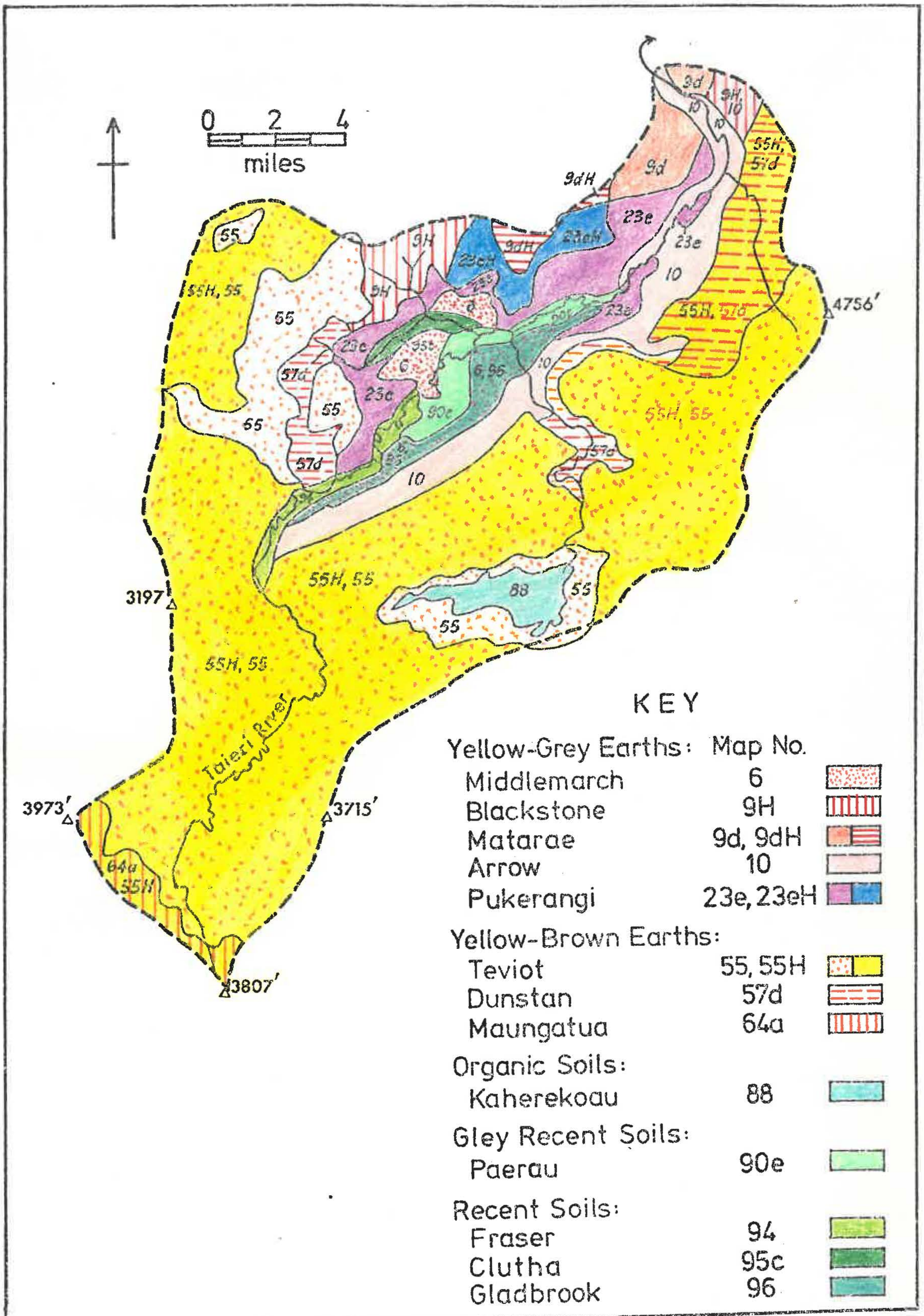
The soils of the Upper Taieri Basin may be divided into groups as follows:

Yellow-grey earths and related hill and steepland soils - dry subhygrous Middlemarch, Blackstone, Matarae and Arrow soil sets, and dry hygrous Pukerangi soils. The soils occur in a position peripheral to the brown-grey earths of the Maniototo Basin and are transitional from them. They cover some 20 percent of the total basin area and occur generally in areas where the mean annual rainfall is between 18-35 inches (Leamy, op. cit).

Yellow-brown earths and related alpine and steepland soils of the uplands and mountains - hygrous Teviot and Dunstan soils, and the hygrous to hydrous high country podzolised Maungatua soil. The soils essentially occupy the balance of the Upper Taieri catchment to the south, west and east above the low-lying Styx Basin, and cover some 72 percent of the total basin area. In general, yellow-brown earth features appear in the soils where the mean annual rainfall exceeds about 30 inches, and where the mean annual rainfall is greater than 40 inches they are dominant.

Upland organic Kaherekoau soil localised in and around the Great Moss Swamp.

Gley recent and Recent Paerau, Fraser, Clutha and Gladbrook soils, confined mainly to the floodplain of the Taieri River in the Styx Basin.



Source: Soil Map of South Island, N.Z., Sheets 11 and 13, 1964

FIGURE 5: *Upper Taieri catchment soils*

VEGETATION

Early botanical records of the Maniototo Basin and Upper Taieri catchment during the 1860s and 1870s show vegetation associations already modified by fire and grazing (Buchanan, 1868). The vegetation appears to have been tussock grassland dominated by *Festuca novae-zealandia* (fescue tussock).

Further deterioration or destruction of the tussock grasslands was evident by the 1920s, due to several decades of excessive burning and cultivation, cropping, stocking and rabbit infestation. By 1920 the healthy lowland tussock grasslands had vanished and with them nearly all palatable and burn-sensitive species of the former association. Early reports of the general vegetation associations of the area are well documented by Buchanan (op. cit) and Petrie (1896), with subsequent summaries and observations by Mark (1965), Raeside & Cutler (op. cit).

The extensive changes in the native grasslands over the past 100 years are aptly shown by the indigenous vegetation associations now found in the Upper Taieri catchment.

Low altitude fescue tussock grassland - dominated by *Festuca novae-zealandia* (fescue or hard tussock) and generally occurs between the cultivated areas on the valley floor and the 2500 feet contour. Almost all areas of fescue tussock in the catchment have exotic weeds and grasses present between tussocks.

Low altitude silver tussock grassland - dominated by *Poa caespitosa* (silver tussock) and found only on damper, well drained sites within the low altitude fescue tussock grassland.

Red tussock grassland - *Chionochloa rubra* (red tussock) dominates on several large areas within the Upper Taieri catchment where marshy conditions prevail; e.g. near the Great Moss Swamp and along the courses of small ephemeral streams where dainage is impeded. The association occurs at altitudes below 3500 feet.

Mixed snow/fescue tussock grassland - although this grassland occurs over wide areas in the catchment, it is essentially an artificial community created by management practices. The result is co-dominance of hard tussock on sites which, before European settlement, were probably completely dominated by the narrow leafed *Chionochloa rigida* (snow tussock). Mixed snow/fescue tussock grassland occurs above 2500 feet between the hard and snow tussock zones.

Snow tussock grassland - the association is characterised by complete dominance of *Chionochloa rigida* and remains only in areas where burning followed by heavy grazing has not occurred.

High altitude blue tussock grassland - blue tussock occurs near the summits of the Rock and Pillar, Lammerlaw and Lammermoor Ranges. The dwarf form of blue tussock (*Poa colensoi*) is dominant and snow tussock may be locally important.

Alpine cushion vegetation - the association occurs in places on the Rock and Pillar summit ridge and along the tops of the Lammermoor and Lammerlaw Ranges. It is dominated by low mat-forming plants. Tarns and boggy patches are common on the range summits so this association is apt to merge with the following communities.

Alpine bog - a common feature of the summit areas of the Lammerlaw Range. Many tarns are present and species around these have the same prostrate habit as the alpine cushion vegetation.

Alpine herbfield - herbfields occur when grasses relinquish dominance to the large mountain daisies (*Celmisia spp.*). They are found around Davidson's Top in association with snow tussock where grazing has followed fires, and also on the flat summit of the Rock and Pillar Range.

Swamp vegetation - there are quite extensive areas of swamp within the catchment, notably the Great Moss Swamp at the head of the Loganburn. These areas are dominated by sedges and rushes.

Subalpine scrub - a narrow, discontinuous zone of scrub dominated by *Hebe odora* is present between the snow tussock grassland and alpine vegetation on the Rock and Pillar Range.

The above 11 associations have been divided into eight classes of supposed hydrological similarity, with the areal distributions of each shown in Figure 6. Although no experimental work has been carried out to substantiate these divisions, it is suggested that plants of similar physiognomy will have similar effects on the hydrological regime. For example, silver tussock and fescue tussock are relatively similar in size and shape, so associations in which they dominate are classed as short tussock for the sake of simplicity. Similarly, snow tussock and red tussock associations are classed as tall tussock. The vegetation classes used in the map are cultivated areas with exotic pasture or crops, short tussock, mixed short and tall tussock, tall tussock and tall herbfield, swamp, subalpine scrub, short herbfield (*Celmisia viscosa*) and low alpine cushion.

Mark (1965) proposed that there is a close correlation between vegetation and climatic factors, as suggested by the distinct altitudinal zonation of the vegetation on the mountains of Central Otago. With the partial exception of the mixed short and tall tussock association this correlation is considered valid for the Upper Taieri area, when associated factors such as altitude, exposure and drainage are also considered. The mixed short and tall tussock association is undoubtedly expanding due to the activities of man. Snow tussock associations continue to degrade into mixed snow and fescue tussock, or even pure

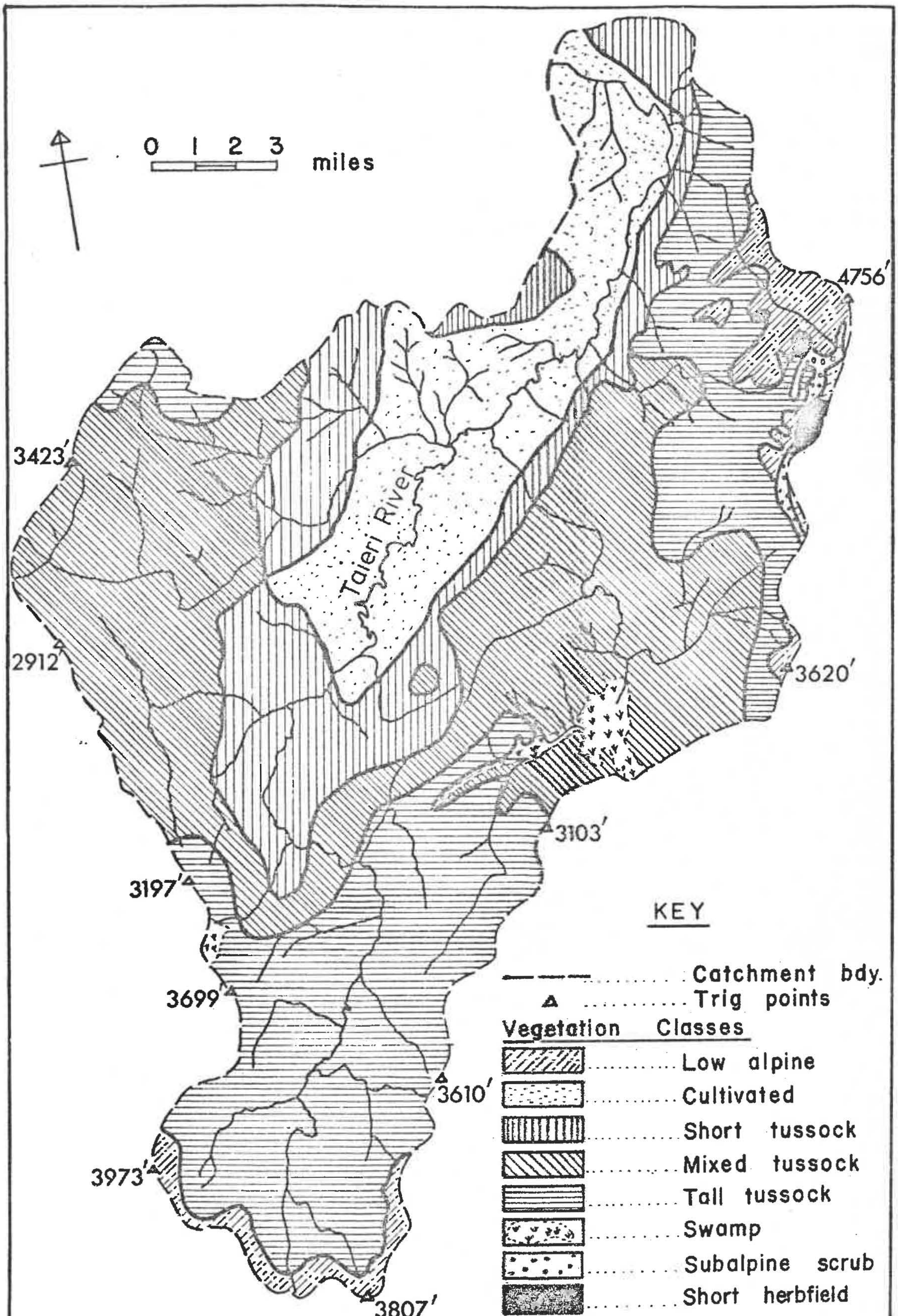


FIGURE 6: Upper Taieri catchment vegetation distribution

fescue tussock, as a result of repeated fires at altitudes below 2500-3000 feet. At higher altitudes where fescue tussock is not present to take over, snow tussock which has been killed by burning and grazing is replaced by herbfields of less palatable *Celmisia spp.*

CHAPTER III: NETWORK DESIGN AND BASIC DATA

PROBLEMS OF DATA COLLECTION IN THE STUDY AREA

The principal problems faced in the establishment and maintenance of a basic collection network in the Upper Taieri basin were limited finance, poor access and a severe climate.

Road access and all resident observers are limited to an altitude of up to about 2000 feet. Above this, access to the remainder of the catchment is by way of dry weather tracks which require a four-wheel drive vehicle. These tracks are subject to wash-outs, snow drifts and infrequent maintenance, and may be impassable for up to four months per year, particularly over the period June-September.

Of the flow measurement sites, none is ideal and all suffer from one or more of the problems: varying upstream or downstream controls; variable or irregular gauging section; too low or uneven velocity distributions; weed or other vegetative obstructions; bank overflow and site bypass through culverts. The relative importance of each factor at any station is dependent on stage.

However, the climate has created the most critical problems of data collection network establishment, maintenance, and operation in the study area. Access is seasonally sporadic and problems associated with discharge and water level measurements in frozen river channels are common in winter. Early solution has been necessary of such difficulties as frost protection of all precipitation gauges, interpretation of the effect of freeze-thaw cycles on automatic water level recorder charts, and the evaporation of raingauge catch.

BASIC DATA NETWORK DESCRIPTION - STREAMFLOW AND CLIMATE

General:

Hydrometeorological data are collected to provide information to develop and manage the water resources of a country, and also to serve research.

Networks for each type of data have historically been considered separately in the light of station density required to attain a suitable level of precision in describing the time and areal variations of the element under study. However, Linsley & Crawford (1965) and W.M.O. (1965) suggest that it is more rational to design a data acquisition network to provide a satisfactory solution to the specific needs for which the total network is being established. The inter-relations of the various elements of the hydrometeorological data should be considered. Such comments have particular relevance in this study of the Upper Taieri basin surface water resources.

There is also widespread agreement that a logical approach to network design is by means of primary and secondary stations, in which the long-term primary stations sample the time variability and the short-term stations the space variability (Rainbird, 1965; Uryvaev, 1965; W.M.O., op. cit). Improvements in the accuracy of information for individual areas usually results.

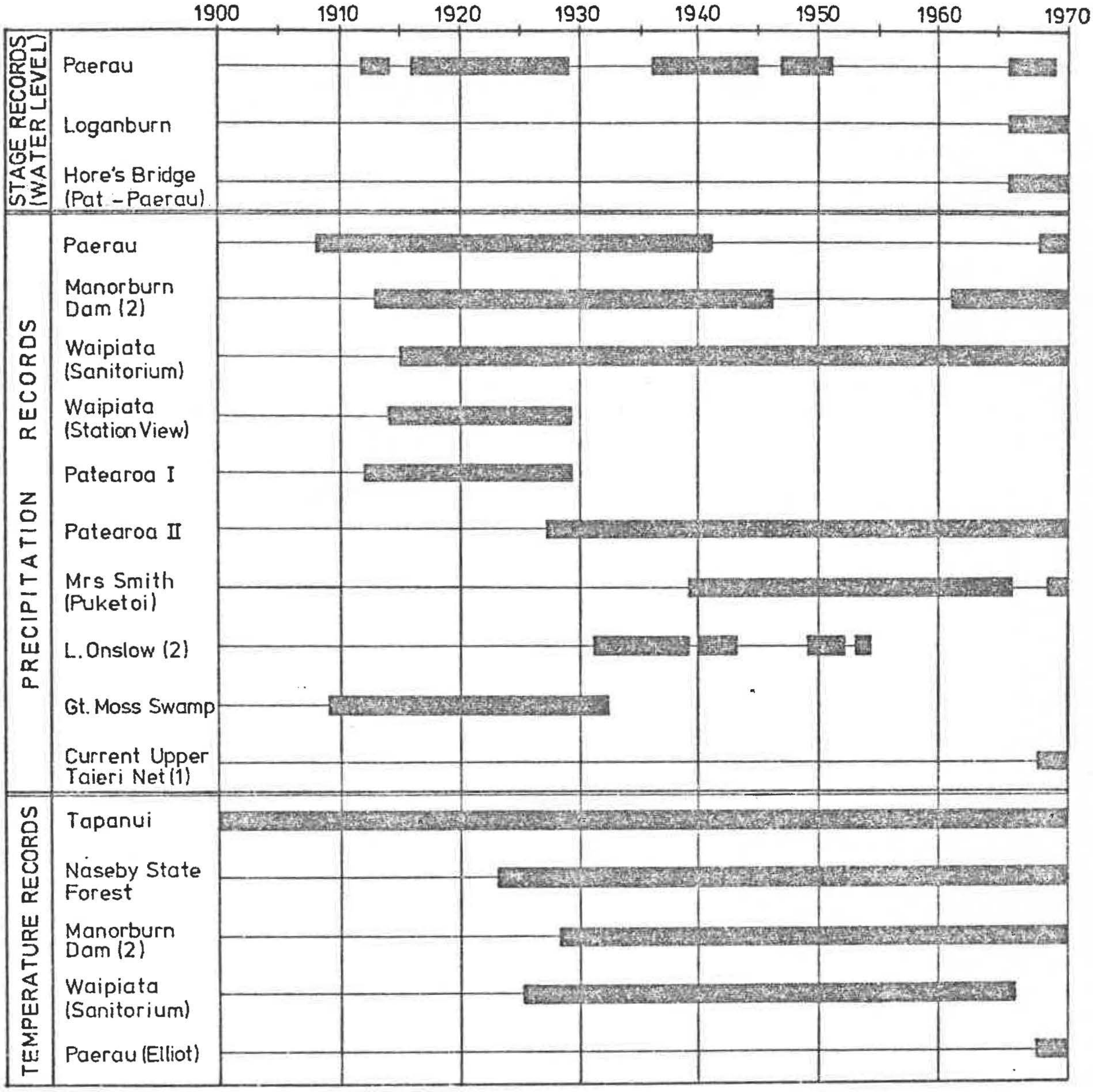
More specifically on the basic principles governing network design, Uryvaev (op. cit), Dawdy *et al.* (1970) and Gandin (1970) conclude that to design a data gathering system properly the relative value of alternative types of data should be assessed. The value of any type of data is measured in terms of its ultimate uses. The importance determines the precision required, and hence the period for which individual stations should be maintained, the network density, and the maximum feasible cost necessary to obtain that level of precision.

For a precipitation network, the rainfall catch is useful only to the extent that it represents the actual rainfall in the surrounding region. Rainbird (op. cit) and Alvarez & Henry (1970) conclude that it is impractical to derive a universally acceptable procedure for the design of precipitation gauge networks. The density of gauges required in any region will depend on the size of the area, the type of precipitation, the purposes to be served by the data, and whether the data requirements are for daily rainfall values, monthly, or long-term mean totals. Without a statement on such factors the problem of the number of gauges needed to determine the rainfall for an area within acceptable confidence limits thus remains.

However, for this study it is considered that there is sufficient information for a practical solution of the problem - the purpose for which the data are to be used, the minimum time unit, and the data precision required for design application have all been stated.

Upper Taieri network (pre 1966):

Records of precipitation and streamflow in the Upper Taieri basin to 1966 were sparse. They were limited to daily precipitation records at Paerau (N.Z. Meteorological Service Station I59491) for the period 1908-1940 and mean daily flow records for the Taieri River at the Paerau gauging station for the 27 year period 1912-13, 1916-28, 1936-39, part 1940, 1941-44, and 1947-50. No temperature records were available within the study area to 1966. Several records of precipitation and temperature, of varying length, were available outside this area provided by the N.Z. Meteorological Service and private observers (Figure 7).



(1) Current Upper Taieri research network - 2 automatic, 9 storage, 2 daily manual rain-gauges plus check manuals with autos.

(2) Incomplete record during period shown

FIGURE 7: Bar graph of available stage height, precipitation and temperature records - 1900 to 1970

These records form a basis for subsequent analysis. However, it is obvious from both the general principles and objectives of network design and the data requirements for the proposed irrigation scheme designs, that data available to 1966 for the Upper Taieri basin were insufficient for a water resources appraisal of the area. Consequently, the data collection network within the 285 square mile Upper Taieri basin was extended as shown in Figure 2. Confirmation of this decision has since been provided by Hutchinson (1970(b)) who, *inter alia*, demonstrates the inadequacy of the pre-1966 Upper Taieri precipitation network to estimate daily or monthly areal mean rainfall.

Post 1966 network - streamflow:

Flow observations in the area have been substantially expanded since 1966, with a series of routine gauging stations established on the Taieri River at Patearoa-Paerau Bridge, Paerau and Upper Styx Valley Bridge, and on the tributaries Styx Creek and Loganburn at Paerau and Serpentine Creek at McDonald's Bridge. Data from these stations are used to supplement a sporadic series of discharge measurements at various sites on the main river and principal tributaries made prior to 1966. Continuous water level recorders were also installed at Paerau and Patearoa-Paerau Bridges and on the Loganburn.

Post 1966 network - Precipitation:

The precipitation gauge network has been extended over the whole catchment since 1968 and now includes two automatic recorders and 13 storage or daily manual gauges (Figure 2). Individual gauges installed are identified in Table 1, and examples of the storage gauge stations are shown in Plates 7 and 10.

TABLE 1: Current Upper Taieri Precipitation Network

Gauge Name	Type	Altitude (feet)
Elliot	Casella weekly nat. siphon	2020
Elliot	'Marquis' daily manual	2020
Mulholland	" " " "	1880
Aitken	" " " "	1970
Onslow Rd.	75 cm capacity fibreglass storage	2770
Bottle Rock Nth.	" " " " " "	2950
Great Moss Swamp	" " " " " "	3050
Bottle Rock	" " " " " "	3200
Round Hill	" " " " " "	3370
Smith	100 cm capacity " " "	2950
Longstone	" " " " " "	3220
Musterer's Huts	" " " " " "	3500
Lammerlaw Top	" " " " " "	3970
Trig 'H'	" " " " " "	3750
" "	Fischer & Porter weighing	3750

With regard to eventual determination of catchment mean rainfall, the sampling network was distributed with spacing as uniform as allowed by available access (Sanderson & Johnstone, 1953). Care was also taken to minimise altitudinal bias in the network, in order to reduce the considerable systematic errors which are a feature of many general and particular networks at present. The validity of this approach has since been demonstrated by the work of Gandin (1970) and of Hutchinson & Walley (1972).

Post 1966 network - Temperature:

Maximum-minimum thermometers were installed at Elliot in 1968 and at Smith in 1969.

ADEQUACY OF NETWORK DESIGN - STREAMFLOW AND CLIMATE

General:

It is clear that any sampling network must serve the purpose for which the measured data are to be used.

For streamflow data, design requirements will dictate desirable measurement site locations and required data precision. The required precision is a function of the sample variance of the at point time series, and will in turn determine the record length necessary to estimate population parameters at a point.

In order to estimate population parameters of precipitation and temperature over an area, required data precision will dictate the optimum network density. However, to determine this optimum network density may require the assumption that at least one station in the network has a record of sufficient length to estimate total error at a point within allowable precision limits. Given an optimum network density therefore, it may be deduced that errors of areal population parameter estimates in excess of required precision limits, are the result of individual station sample variances and hence insufficient record length or inadequate measurement technique. The random and systematic errors associated with measurements at individual stations will ultimately determine the limit of estimated parameter precision over an area, even given an optimum network density.

Streamflow:

With flow observations at three sites on the main river and on each of the principal tributaries, it is concluded that sufficient sites are being sampled to satisfy the location requirements for design of the proposed 'run-of-river' or single storage reservoir irrigation schemes. However, whether or not the records from these sites are of sufficient length to give the data precision stated as required for design purposes will be discussed in subsequent chapters.

Precipitation: General

Statements in the literature of the type 'a general survey of water resources may be served by a relatively scanty multipurpose gauge network' (Linsley, 1958), are of little value to determine the adequacy of the present Upper Taieri precipitation network.

When hydrological networks are planned, it is essential to be able to determine for each specified purpose the raingauge network density required to assess the rainfall over an area to a given precision. General estimates based only on the area to be gauged have been suggested for the design of networks without adequate data (W.M.O., 1965). However, as in this study, the gauge network must usually be installed before sufficient data have been accumulated for objective statistical analysis.

The difficulty in estimating the errors and hence optimum network density, lies in the fact that observations are not independent. Earlier attempts, such as outlined by Sanderson & Johnstone (1953) and Sutcliffe (1966), were based on the assumption that the point measurements are random samples which independently assess the true mean. The error of estimate of the total rainfall is thus deduced from the variance of the point measurements - the standard error of the areal estimate is taken as the standard deviation of the individual observations divided by the square root of the number of gauges. There are objections to such a procedure and several methods have been used to overcome the difficulty.

McGuiness (1963) carried out an analysis of records from a dense network of gauges at Coshocton and suggested a tentative relationship between error, rainfall characteristics, and required gauge density. The method assumes that determination of mean rainfall from the dense network is liable to negligible error, and suffers from the practical difficulty of needing a dense network of gauges if the technique is to be applied elsewhere.

Sutcliffe (1966) has derived the formula $\sqrt{\frac{1-r}{n}} \cdot Sx$, (1)

for the standard error of estimate. Sx is the standard deviation; n, the number of gauges; and r the correlation coefficient between data from the gauge network for two independent time periods. The difficulty with this method, particularly for short time periods, is that no unique result can be arrived at, since r will vary according to which two time periods are chosen.

A third approach suggested by Hershfield (1965) and Hutchinson (1969(a)), is to arrange the raingauge density such that the product moment correlation coefficient between any pair of adjacent gauges is 0.9 or more. Since the method does not assess the errors of estimate of the mean, this correlation-distance relationship can only give a relative, rather than an absolute assessment of the standard error (Hutchinson, 1972). However, Zawadzki (1973) concludes that the 0.9 inter-gauge correlation seems to give a very high precision in area-averaged rainfall amounts. The method is based on the assumption of homogeneity between gauges. However, in a study on the effect of inhomogeneity on correlation estimates, McDonald & Green (1960) show that 20 percent record inhomogeneity is not serious for most purposes.

Precipitation: Upper Taieri network design by use of inter-station correlation

An acceptable lower coefficient limit of 0.9 is adopted in this study. It is thus deduced from the work of Hutchinson (1969(a); 1970(a)) on the decay of correlation with distance between adjacent gauges in the Otago area, that for annual data this value should be equalled or exceeded by all stations in the present network. In order to verify that Hutchinson's results may be applied in the Upper Taieri basin, correlation coefficients were derived for all stations in the present network, using Elliot as the primary station (Table 2).

TABLE 2: Upper Taieri Catchment Raingauge network correlation coefficients (base station Elliot)

Station Name	Correlation Coefficient (r) (significance level 99%)	Distance from Base station (miles)
Mulholland	0.858	4.4
Aitken	0.882	5.5
Onslow Rd.	0.974	6.4
Smith	0.911	2.4
Bottle Rock Nth.	0.977	7.6
Great Moss Swamp	0.987	6.4
Bottle Rock	0.983	7.6
Longstone	0.991	8.9
Round Hill	0.981	6.6
Musterer's Huts	0.971	11.7
Trig 'H'	0.943	15.9
Lammerlaw Top	0.979	13.8

Correlation coefficients are all significant at the 99 percent level, and with the marginal exception of Mulholland and Aitken accord with the adopted standard of r equals 0.9 or more.

The results are plotted in Figure 8, which also shows Hutchinson's correlation coefficient - distance relationship for annual data, derived from 465 data sets.

Hutchinson also demonstrates that for monthly and annual data altitudinal difference, or local relief, has a significant effect on between station correlation. However, he shows that for annual data and a correlation coefficient of 0.9, the maximum distance between stations in the Otago area is approximately 6.5 miles. This accords

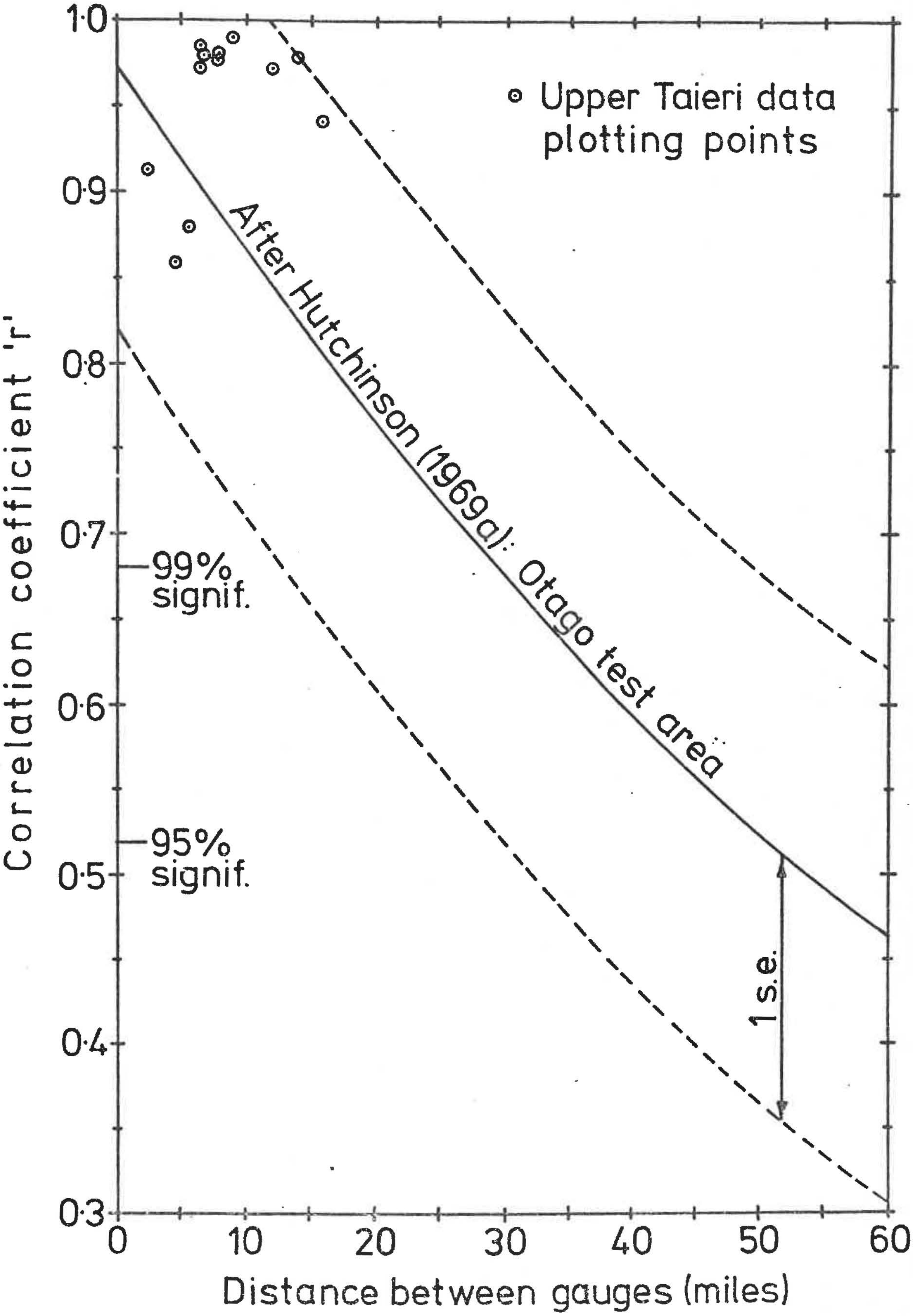


FIGURE 8: Decay of correlation with distance between gauges - annual data

with the average spacing of 5.3 miles for the present network as given by Figure 2.

Monthly correlation coefficients for the Upper Taieri-Maniototo area also follow in general the pattern of variability demonstrated by Hutchinson (1969(a)). If the results are accepted as applicable specifically to the Upper Taieri basin, it may be concluded that the present 5.3 mile station separation gives an insufficient gauge density to produce correlation coefficients of 0.9 or better for all months.

The results suggest that the present network density is quite adequate to satisfy the 0.9 inter-station correlation coefficient criterion for annual data and for 75 percent of months. For practical purposes however, it may not be feasible to establish a network of sufficient density to give estimates of mean areal rainfall to the required precision for every month.

Precipitation: Upper Taieri network design by use of the structural function

Hutchinson (1972) shows that although the correlation-distance relationship has its uses, the technique has now been superseded for determining mean or minimum grid distances. The preferred method to resolve the problems of network design and calculation of standard error is that developed by Czelnai (1963), and involves the use of the structural function. The method is adopted by Gandin (1970) and by Cislerova & Hutchinson (1973), and is very similar to the serial variation function described by Hutchinson (1970(b)). In brief, the structural function is used to give minimum admissable distances between hydrometeorological stations for specified accuracies, for interpolation of areal quantities. It is further shown by Gandin (op. cit) that the minimum admissable distance between stations varies over a region in proportion to a function of the time variance at each station.

The basis of the theory is that the estimate of the random error at any ungauged point increases with the distance between the ungauged point and any adjacent gauged point. In the simplest case, the error increases linearly from a value fixed for all gauges in the network, and the maximum error will occur at a point equidistant from any set of adjacent gauges. Hence the theory is first developed on this basis of linear interpolation, but since this overestimates the actual errors, is further developed on the basis of optimum interpolation. This last refinement provides a more convenient estimate of the errors. A basic assumption for the method is that of homogeneity and isotropy for the rainfall field.

Two types of error contribute to the random errors of estimation at any ungauged point. One is due to the distances between the point and the nearby gauges, and the other to the random instrumental and microclimatological errors at the gauges themselves. This latter type of error cannot be measured exactly, and must be estimated by the extrapolation of a standardised covariance function to zero distance. The standardised covariance function is recognised in the theory as the inter-station correlation coefficient.

If optimum instead of equal weighting is assumed, as recommended by Gandin (op. cit) for precipitation networks, then the standard error $\sqrt{E}$ will be reduced and is calculated as:

$$E = m_k \left[1 - \frac{2\mu^2 ({}^{L}/2)}{1 + \eta + \mu(L)} \right] \tag{2}$$

$$\text{or } E = m_k \, \varepsilon_{\text{opt}}. \tag{3}$$

m_k is the station sample variance; $\mu({}^{L}/2)$ and $\mu(L)$, the correlation coefficients between pairs of stations $({}^{L}/2)$ and (L) apart, determined directly from the correlation coefficient-distance relationship; and

η is the difference between 1.00 and the intercept of the correlation coefficient-distance function at zero distance, *i.e.* $1-\mu_o$.

Data used in the calculations for this study were taken from the combined Paerau and Elliot record of annual and monthly rainfalls for the years 1908-1940 and 1968-69. It is initially assumed that this combined 35 year record is of sufficient length to determine stable parameter estimates from the measured point data, and thus allow estimates of total error at a point in the present network to within permissable precision limits. It is also assumed from results shown thus far that the monthly and annual correlation coefficient-distance relationships given for the Otago area by Hutchinson (1969(a)) will also apply specifically to the Upper Taieri area. Figure 8 shows that the assumption of homogeneity is reasonably valid.

The monthly and annual correlation coefficient-distance relationships and values for η are shown in Figure 9. As reflected by the correlation coefficient, it was expected that the season would have affected the between station correlation due to the different atmospheric conditions and rain producing mechanisms. The degree of correlation should be less in summer, typified by a greater proportion of smaller, highly variable convectional rainstorms than in winter, in which more general rainfalls dominate. However, although wide differences do occur in the correlation coefficient from month to month, a well defined seasonal pattern is not evident. One answer to this apparent anomaly could lie in the use of monthly data. Such a time interval may mask the true convectional effect in summer, though be insufficient to minimise the areal variability of snowfall within the region in winter. Snowfall is common in and around the Upper Taieri basin between May and September. The degree of between station correlation in this period

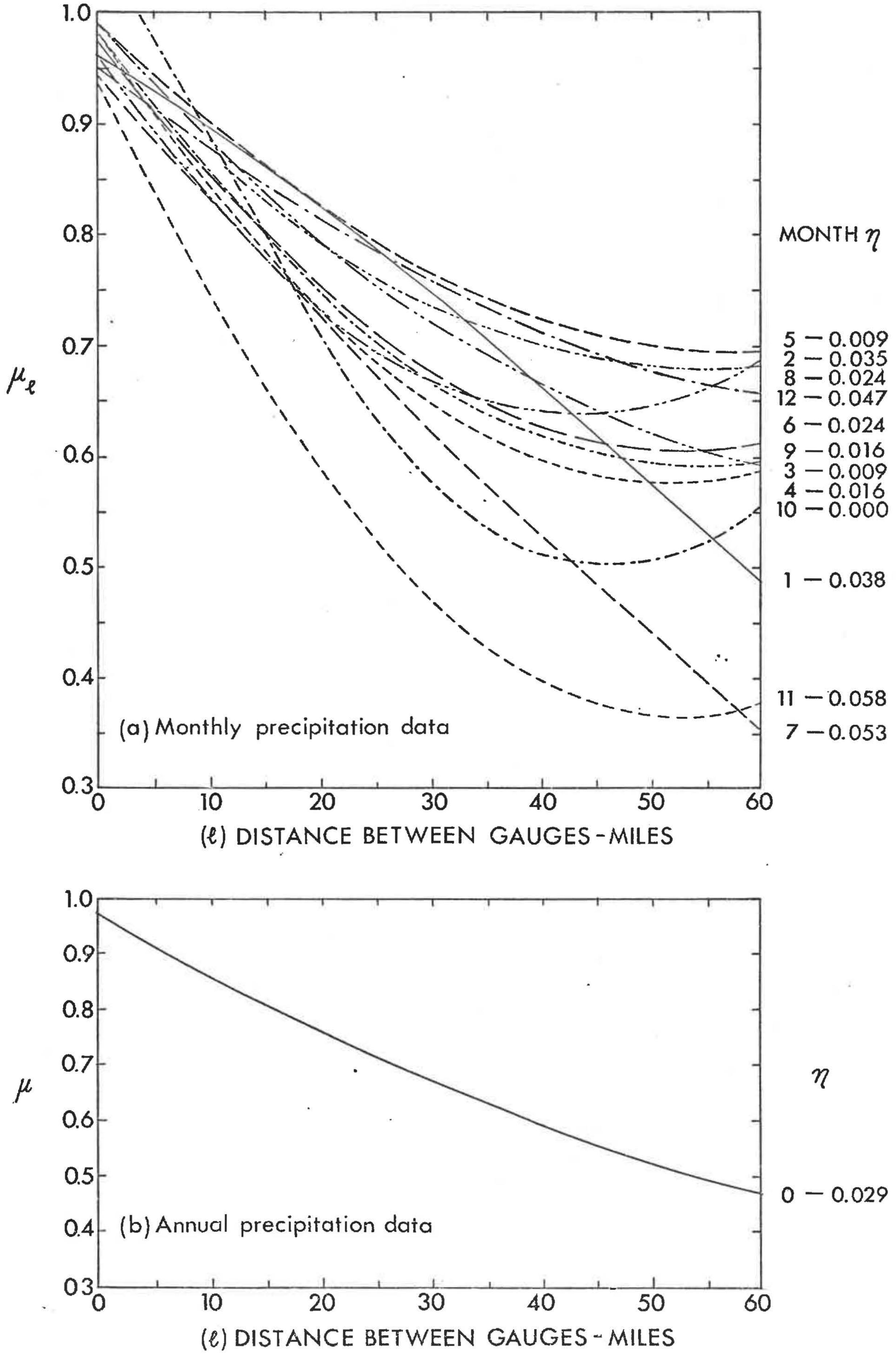


FIGURE 9: Standardised covariance function-distance relationship (monthly and annual precipitation data)

may also only reflect the relative ability of the gauges to sample precipitation of this type.

From equation (2) and Figure 9 it was thus possible to obtain the monthly and annual ε_{opt} function-distance relationships shown in Figure 10. The field of existing standard error of interpolation may be calculated, if the values of ε_{opt} and the derived monthly and annual rainfall sample variances (m_k) given in Table 3 are combined by way of equation (3).

TABLE 3: Monthly and annual mean rainfall and sample variance (m_k) for stations I59491 Paerau (1908-40) and Elliot (1968-69) combined.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mean Rainfall (ins.) :	2.99	2.37	2.62	2.50	2.28	2.13	1.43	1.89	1.77	2.53	2.60	3.15	28.28
n(years):	33	33	33	33	33	33	33	34	34	35	35	35	33
m_k(ins.):	2.76	2.82	2.85	2.07	1.77	2.12	0.72	2.19	0.88	1.88	1.53	2.66	36.91

$$\left[\quad m_k = \sum_{i-1}^{n} (x_i - \bar{x})^2 / n-1 \quad \right]$$

These standard errors of interpolation were recalculated as percentages of mean monthly and annual rainfall and are shown in Table 4 for varying between station distances.

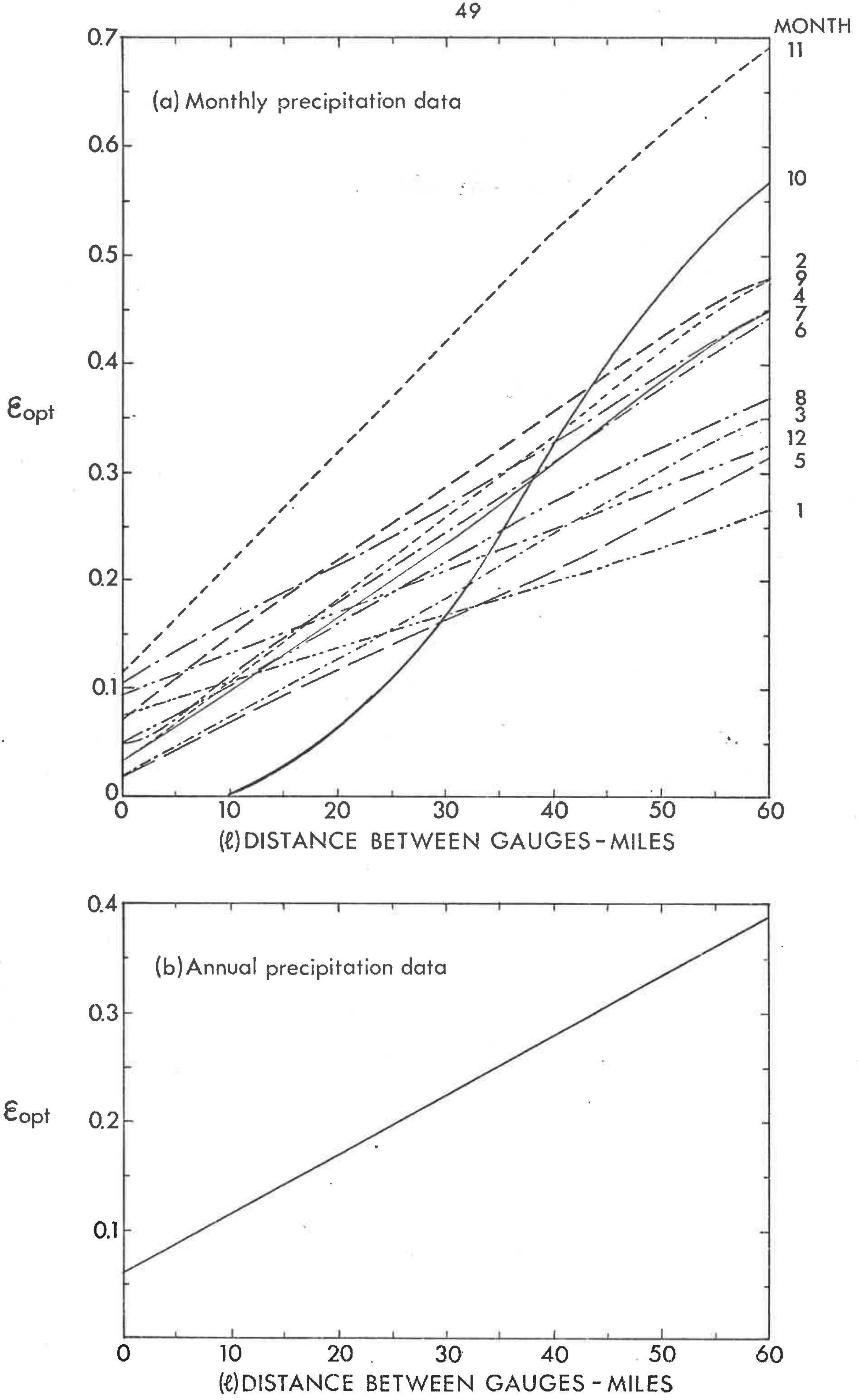


FIGURE 10: Relative error function-distance relationship (monthly and annual precipitation data: Otago test area)

TABLE 4: Values of standard error of interpolation ($\sqrt{E}$) as a percentage of mean station rainfall, for distance L (miles)

	0	5	10	20	30	40	50	60 (miles)
January:	15	16	17	20	22	24	26	28
February:	18	23	27	31	37	42	46	49
March:	8	13	16	22	27	31	35	38
April:	10	15	18	24	29	33	36	39
May:	7	12	14	20	23	26	29	32
June:	14	18	22	28	33	37	31	45
July:	19	21	24	27	31	33	37	39
August:	17	21	23	31	36	40	44	47
September:	9	13	16	21	25	29	32	35
October:	0	0	0	14	22	31	36	40
November:	15	19	22	26	30	34	37	39
December:	15	17	18	21	23	25	27	29
Annual:	5	6	7	8	10	11	12	13

For network design purposes it is not sufficient to show the distribution of errors. The basis of network design is to select the density and placement of the gauges such that for no part of the area does the error estimate exceed a predetermined value or design criterion (Cislerova & Hutchinson, 1973).

For the stated error criterion for point and areal mean monthly and annual rainfall - $\sqrt{E}$ less than 20 percent of mean at the 95 percent confidence level - the results in Table 4 suggest that the present network density is quite adequate for annual data. Maximum admissable distances between gauges of up to 30 miles would satisfy the design criterion.

Results for the monthly data are less promising. Seven months of the 35 year combined record contain relative standard errors of interpolation in excess of 10 percent. These errors are the random instrumental and microclimatological errors at the gauge. In only 42 percent of months, therefore, would it be possible to interpolate to values of less than 20 percent of actual at the 95 percent confidence level, no matter how dense the network. Further, by this method, in no month does the present network density allow parameter estimation to within the design criterion. On this basis the chosen allowable error appears to be too stringent a criterion for the study area, though as concluded by Cislerova & Hutchinson (op. cit) a higher value would be unacceptable for engineering and water resources purposes.

To lower the calculated values of $\sqrt{E}$ for the measured monthly data requires either a decrease in the values of sample variance m_k through an increase in record length, or increases in the values of μ with corresponding decreases in η. For example, if ε_{opt} is assumed to be at an optimum value for January with a 10 mile gauge spacing, a reduction in $\sqrt{E}$ to the stated criterion would require a record length of 103 years. Similarly, it may be shown that the existing network density would require a January record of about 88 years.

Precipitation: Conclusions

With a mean gauge density of approximately one for each 22 square miles of catchment area, the present network more than adequately complies with the WMO (1965) minimum density requirements for this climate and relief type. Although the network has known deficiencies due to poor access, network designs by use of inter-station correlation and the structural function confirm that the established gauges are within the bounds of acceptable density and location to satisfy the allowable error criterion of project design for annual data. Between gauge distances of up to 30 miles could be tolerated.

The results are less conclusive for monthly data. Although the correlation-distance relationship can only give a relative assessment of the standard error, analysis shows that the present network density is adequate to satisfy the 0.9 inter-station correlation coefficient criterion for only 75 percent of months. From structural function analysis using sample variance for one long-term station, in no month does the existing network allow mean areal rainfall estimation to within 20 percent of actual at the 95 percent confidence level. However, although Figure 8 shows that the assumption of homogeneity is reasonably valid for the general Otago area and the Upper Taieri basin, the plotted points suggest that in the test area the mean Otago curves have a tendency to underestimate μ for small distances. This increases ε_{opt} and hence the calculated value of $\sqrt{E}$. Unfortunately insufficient data are available to statistically verify this conclusion.

It is therefore deduced that although it may not be feasible to establish a network of sufficient density to give estimates of mean areal rainfall to the required precision for every month, the present 5.3 mile average station separation may be adequate to satisfy the allowable error criterion for some months.

Temperature: Upper Taieri network design by use of the structural function

Use is again made of structural function analysis in order to determine the network density that will ensure estimation of monthly and annual mean temperature parameters over the study area to within the required 10 percent of actual at the 95 percent confidence level. Optimum interpolation is again used to calculate the rational distance between stations, as recommended by Gandin (1970), rather than the less accurate linear interpolation.

Data used in the calculations were taken from the records of monthly and annual mean temperatures for stations I50001 Naseby State Forest, I59361 Manorburn Dam, I50212 Waipiata Sanatorium, I59921 Tapanui, and Elliot. With the exception of the Elliot data, monthly records vary from 25 to 43 years in length and annual records from 16 to 39 years. It is initially assumed that these records are of sufficient length to determine stable parameter estimates from the point data, and thus allow estimates of total error at any point in the general region to within permissable precision limits.

Although distances between stations vary from 11 to 76 miles, the necessary basic assumption of homogeneity and isotropy for the mean temperature field is considered valid. The N.Z. Meteorological Service show that temperature departures from normal do not vary greatly over distances of 50 to 100 miles for inland Otago and Southland (Finkelstein, 1969). The long-term data from Tapanui were included in the analysis since the record is known to be satisfactory and homogeneous, has the advantage for this study of an inland location, and has no known station site changes for the complete period 1900-1970.

Monthly and annual correlation coefficient-distance relationships and values for η were calculated from the available data. The results are shown in Figure 11. Correlation coefficients are all significant to at least the 95 percent level. Of immediate interest is that the illustrated decay of correlation with distance is considerably less than that shown previously for the monthly and annual precipitation data.

From equation (2) and Figure 11, monthly and annual mean temperature ε_{opt} function-distance relationships were determined and are shown in Figure 12. The field of existing standard error of interpolation was

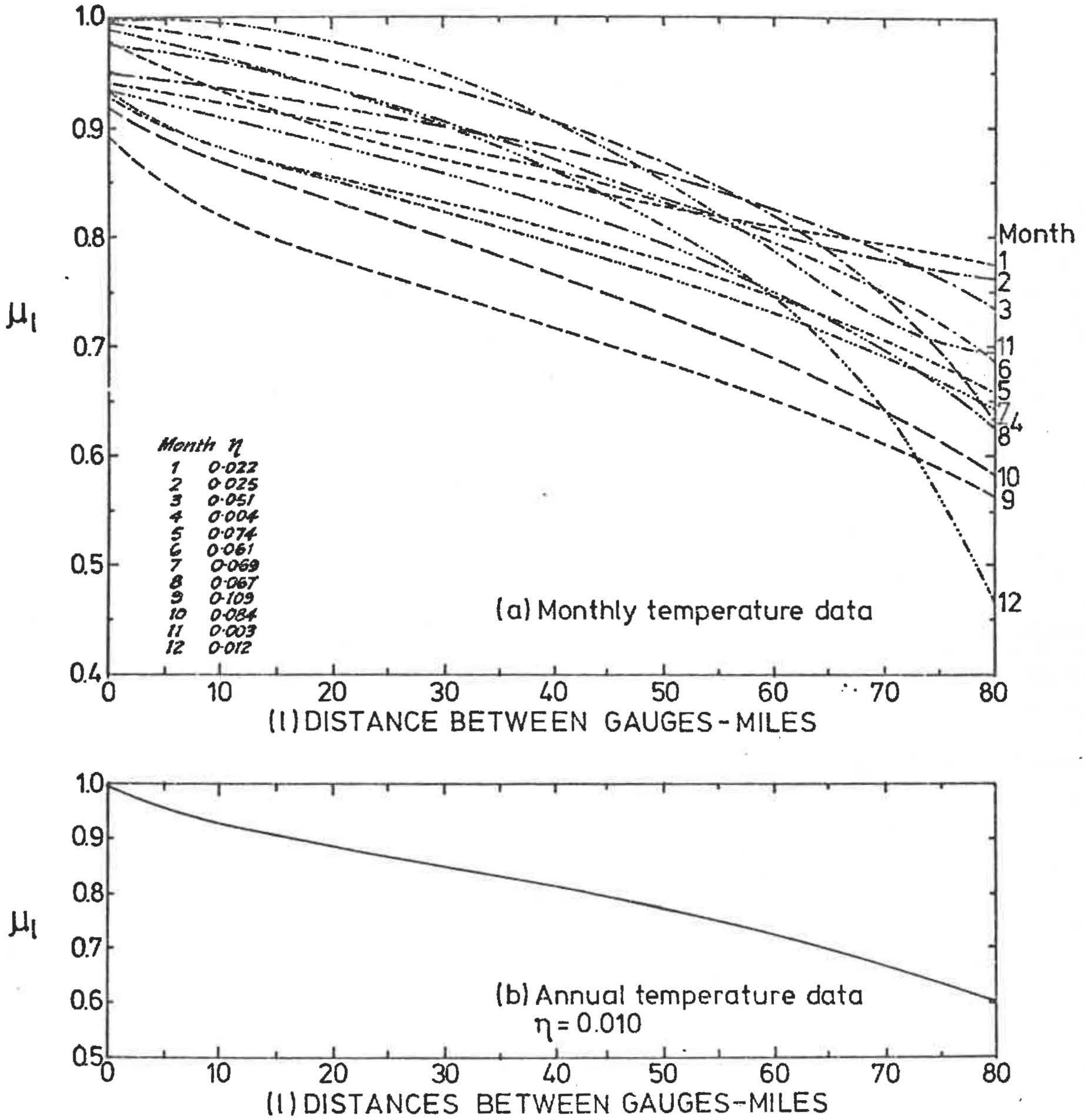


FIGURE 11: Standardised covariance function-distance relationship (monthly and annual temperature data)

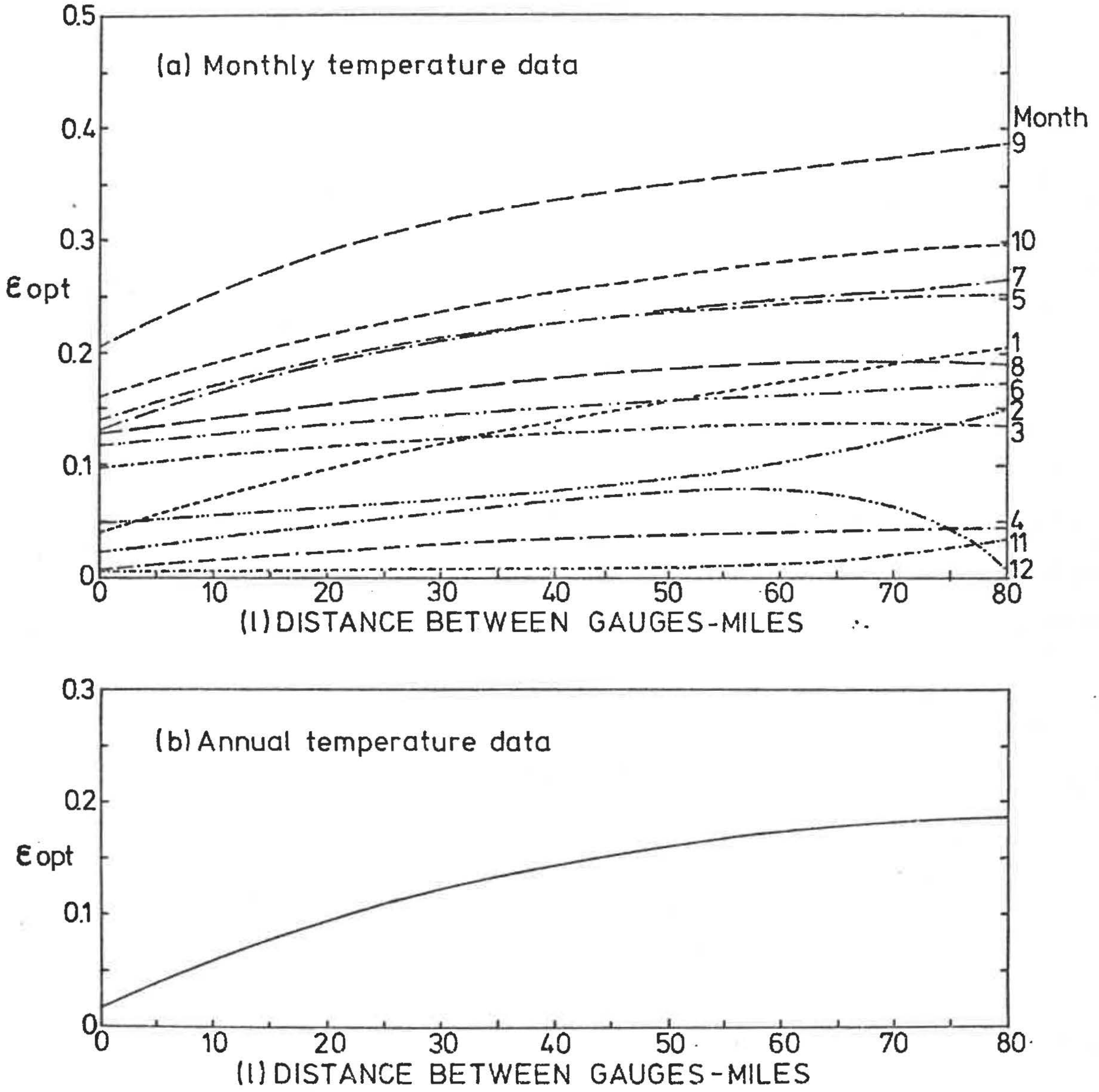


FIGURE 12: Relative error function-distance relationship (monthly and annual temperature data)

thus calculated by equation (3), from the combined values of ε_{opt} and derived monthly and annual mean temperature sample variances (m_k) given in Table 5. Records for Naseby State Forest were used to calculate the m_k values, since this station is located at the same altitude as Elliot and is the closest station to the Upper Taieri area with a long-term continuous record. Also, comparison of the post 1968 records for Elliot and Naseby State Forest show that the two stations have markedly similar characteristics with respect to mean monthly, monthly maximum and minimum, and mean daily maximum and minimum temperatures for each month.

TABLE 5: Monthly and annual mean temperature and sample variance (m_k) for station I50001 Naseby State Forest (1923-67).

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mean Temperature (°F):	56.1	55.9	52.5	47.3	40.8	36.0	34.7	37.6	42.7	47.4	50.4	54.1	46.3
n(years) :	45	45	45	45	45	45	45	45	44	45	45	44	43
m_k (°F) :	5.38	4.43	4.05	4.74	3.52	4.57	4.99	3.67	2.58	3.56	6.16	6.30	0.62

The standard errors of interpolation were recalculated as percentages of mean monthly and annual temperatures and are shown in Table 6 for varying between station distances.

TABLE 6: Values of standard error of interpolation ($\sqrt{E}$) as a percentage of mean station temperature, for distance L (miles)

	0	5	10	20	30	40	50	60	80 (miles)
January:	0.8	0.9	1.1	1.2	1.4	1.5	1.6	1.7	1.8
February:	0.8	0.9	0.9	0.9	0.9	1.0	1.1	1.2	1.4
March:	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4
April:	0.4	0.5	0.5	0.7	0.7	0.8	0.8	0.9	0.9
May:	1.7	1.8	1.9	2.0	2.1	2.1	2.2	2.2	2.3
June:	2.0	2.0	2.1	2.1	2.2	2.3	2.3	2.3	2.4
July:	2.3	2.4	2.6	2.8	2.9	3.0	3.1	3.2	3.3
August:	1.8	1.8	1.9	1.9	2.0	2.1	2.1	2.2	2.2
September:	1.7	1.8	1.8	2.0	2.1	2.1	2.2	2.2	2.3
October:	1.5	1.6	1.7	1.8	1.9	1.9	2.0	2.1	2.1
November:	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.9
December:	0.7	0.7	0.8	0.9	1.1	1.2	1.2	1.2	0.2
Annual:	0.2	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.7

Temperature: Conclusions

The results indicate that the existing Meteorological Service network is quite adequate to satisfy the study design criterion for point and areal estimates of monthly and annual mean temperature - $\sqrt{E}$ less than 10 percent at the 95 percent confidence level. Although the installation of an additional station at Elliot provides useful information on temperature parameters at less than monthly intervals in the Upper Taieri basin, the station is shown not to be needed when monthly or annual mean data are considered.

For a station separation of up to 80 miles, monthly values of $\sqrt{E}$ are still less than four percent of the mean, and the equivalent annual value is less than one percent. It is therefore concluded that for calculations which involve monthly and annual mean temperature data in the Upper Taieri area, the use of Naseby State Forest records will introduce only minor errors. For example, Table 6 shows that for Elliot, some 30 miles from Naseby State Forest, $\sqrt{E}$ has a maximum value of only 2.9 percent of the mean for monthly data, and for Trig 'H', $\sqrt{E}$ becomes 3.1 percent for a distance of 50 miles.

To estimate percentage errors at stations with elevations different from that at Naseby State Forest, it is of course necessary to first assume that mean temperature decreases with an increase in altitude, in accordance with known seasonal lapse rates. Such an assumption is basic to subsequent calculations of potential evapotranspiration in the study area.

Of further interest is the minimum length of record necessary to achieve the stated design criterion. The present Meteorological Service network is used to represent conditions in the Upper Taieri area. July is considered in this calculation since $\sqrt{E}$ is shown to be higher in this month than in any other, and will thus require the longest record to produce an acceptable value of station sample variance. If ε_{opt} is assumed to be at optimum values for 30 and 50 mile gauge spacing, record lengths for $\sqrt{E}$ to the stated criteria may be calculated as 17 and 19 years respectively. This corresponds well with the 15 to 25 years suggested as necessary by Malone (1951) in order to obtain a stable frequency distribution of temperature for a region such as the Upper Taieri.

RECORD HOMOGENEITY AND DATA CORRECTION

General:

Although for most hydrological purposes a long record is preferred to a short one, the user should recognise that the longer the record the greater is the chance that there has been a change in the physical conditions of the basin or in the methods of data collection. If these are appreciable, the composite record would represent only a nonexistent condition, and not one that existed either before or after the change. Such a record is inconsistent.

The use of a double-mass curve is a convenient way to check the consistency of a record, and such a check is one of the first steps in any analysis, except when the scarcity of other old records makes it impossible. The theory of the double mass curve is based on the fact that a graph of the cumulation of one quantity against the cumulation of another quantity during the same period, will plot as a straight line so long as the data are proportional. The slope of the line represents the constant of proportionality between the quantities.

As a prerequisite to subsequent analysis, all available streamflow, precipitation and temperature records from Ministry of Works, N.Z. Meteorological Service or private observer summaries for the area within and surrounding the Upper Taieri basin, were collated and examined for missing or inconsistent data. The records used are shown in Figure 7. Where possible, the test used for data consistency was the graphical double-mass curve technique illustrated by Searcy & Hardison (1960), with covariance analysis and the F statistic to test the significance of apparent breaks in slope (Scarf, 1971; Snyder, 1971).

Streamflow:

Records of streamflow to 1966 were sparse and limited largely to mean daily flow records for the Taieri River at Paerau for the 27 year period 1912-13, 1916-28, 1936-39, part 1940, 1941-44 and 1947-50. The only other data available were records of infrequent discharge measurements made at various other sites in the study area. Since 1966 the flow network has been expanded, with regular data collection stations established on the main river at the Patearoa-Paerau, Paerau and Upper Styx Valley Bridges, and on the tributaries Styx Creek, Loganburn and Serpentine Creek.

However, with the exception of the Paerau Bridge record, a lack of measured streamflow data over an extended period within the study area precludes application of the chosen record consistency test. The records are by necessity thus assumed to be consistent and homogeneous.

Temperature:

Records included for analysis were monthly mean temperatures for Elliot (1968-70), Tapanui (1900-70), Naseby State Forest (1923-70), Waipiata (1925-65), and Manorburn Dam (an incomplete record over the period 1928-70).

A lack of data over an extended period in the general study region again precludes the use of double-mass curve techniques to test the available record consistency. The data must therefore be assumed consistent and homogeneous, though Finkelstein (1969) suggests that such an assumption is valid for the data used.

Precipitation:

The records included initially were monthly and daily falls for I59491 Paerau (1908-40), and monthly totals for I59361 Manorburn Dam (an incomplete record for 1913-65 and 1961-70), I50112 Waipiata Sanatorium (1915-70), I50213 Waipiata Station View (1914-28), I59391 Patearoa No. I (1912-28), I50201 Patearoa No. II (1927-70), a private observer, Mrs B. Smith, at Puketoi (1939-65 and 1969-70), and I59581 Great Moss Swamp (1909-31). A sporadic record from Lake Onslow (1931-38, 1940-42, 1949-51, 1953) was also collated, but was subsequently rejected on the grounds of inadequacy for further analysis. Necessary corrections to data from the present Upper Taieri basin research network are considered separately.

As an initial test for homogeneity of regional precipitation patterns throughout a year, mean monthly rainfalls for each station were calculated for the periods indicated and the results plotted in Figure 13.

Since the records presented in this way may cover time intervals which vary, it could be argued that such a comparison is invalid on the grounds that one station may have operated during a period of high precipitation, while another covered a particularly droughty period. However, it is maintained that since each record is 15 years or greater in length, the use of mean monthly data gives an adequate indication of the climatic regime at each station irrespective of time interval. It is assumed that on a long-term mean basis, records of precipitation from stations of similar climatic regime will generally parallel each other as in Figure 13, irrespective of individual quantities and whether derived from a generally wet or dry period.

When the Paerau records are considered as a base for comparison, the Great Moss Swamp data are also excluded from subsequent analysis. Results from this station are shown to be atypical of the general Upper Taieri-Maniototo climatic pattern, particularly for the months

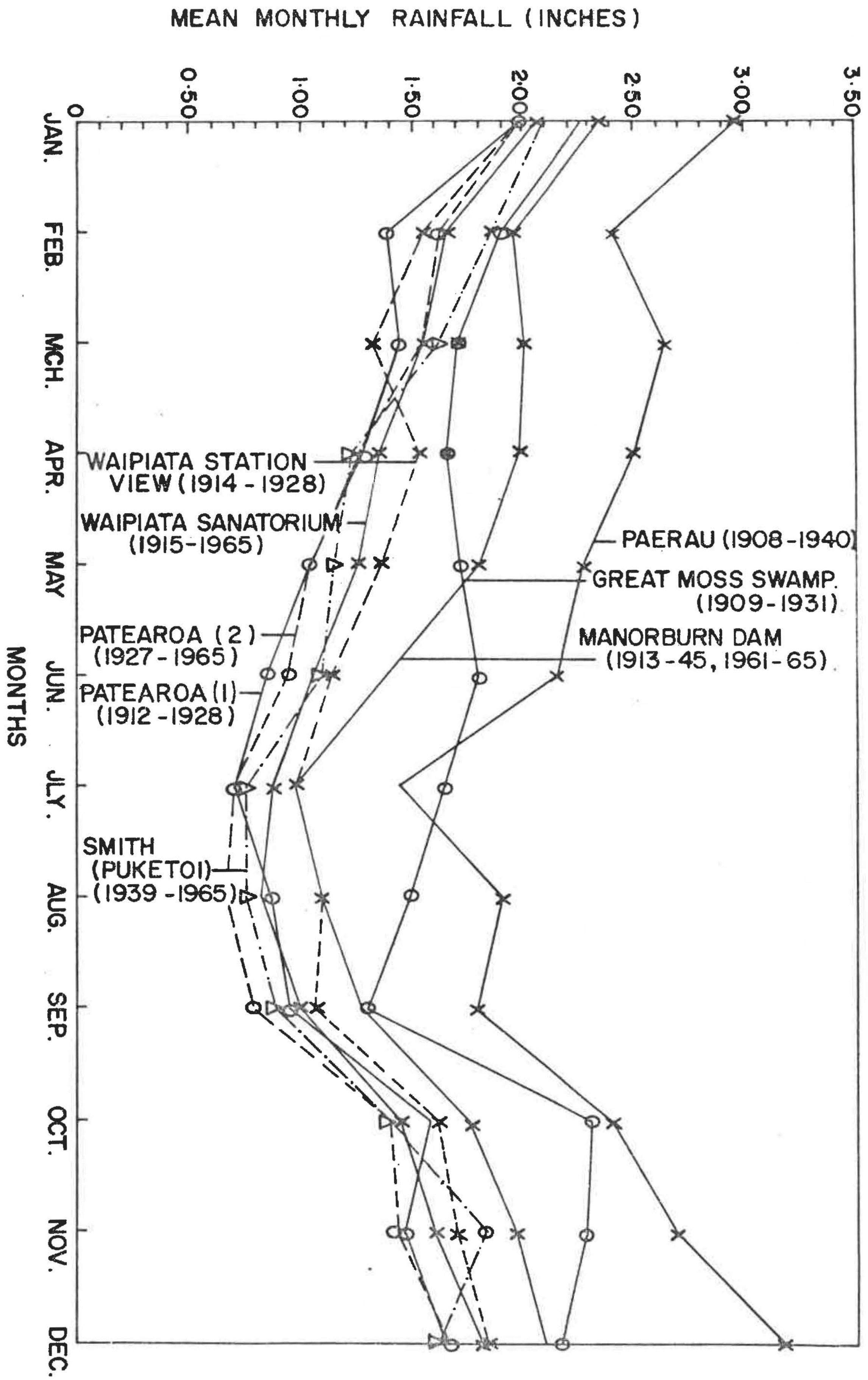


FIGURE 13: Mean monthly rainfall comparisons

April to August. Reasons for the differences are not known. All other stations tested accord generally with the Paerau mean monthly rainfall distribution.

A frequent problem in regional generalisation of hydrological data arises from the fact that stations have varying periods of records. To test the consistency of the historic records it was thus necessary to use two sequential time intervals in order to use an optimum period of record. The periods are 1916 to 1940 and 1941 to 1961. Results of the calculated double-mass curves are shown in Figures 14 and 15.

Figure 14 gives results for Paerau, Manorburn Dam, Waipiata Sanatorium and combined Patearoa No. I and No. II for the period 1916-40. With the exception of a discontinuity in the Manorburn Dam record in 1918 the data appear consistent and homogeneous. Brief changes in slope of double-mass curves could arise from chance. The W.M.O. (1965) thus suggests that no segment of less than about five points should be accepted as valid demonstration of inconsistency. A change in slope is generally only accepted as real if substantiated by other evidence or well defined for a long period. (For these reasons, the break in slope shown for the Manorburn Dam record in 1918 was not investigated further).

For the period 1941-61, Figure 15 shows results for Patearoa No. II, Smith (Puketoi), Waipiata Sanatorium, and a further station outside the study area, I59691 Deep Stream - located at Lat. 45° 40'S and Long. 169° 58'E. Except for Waipiata Sanatorium discontinuities in the records are evident, being slight for Patearoa No. II in 1952 and more marked for Smith and Deep Stream in 1954. Covariance analysis and F tests show that these breaks in slope are only marginally statistically

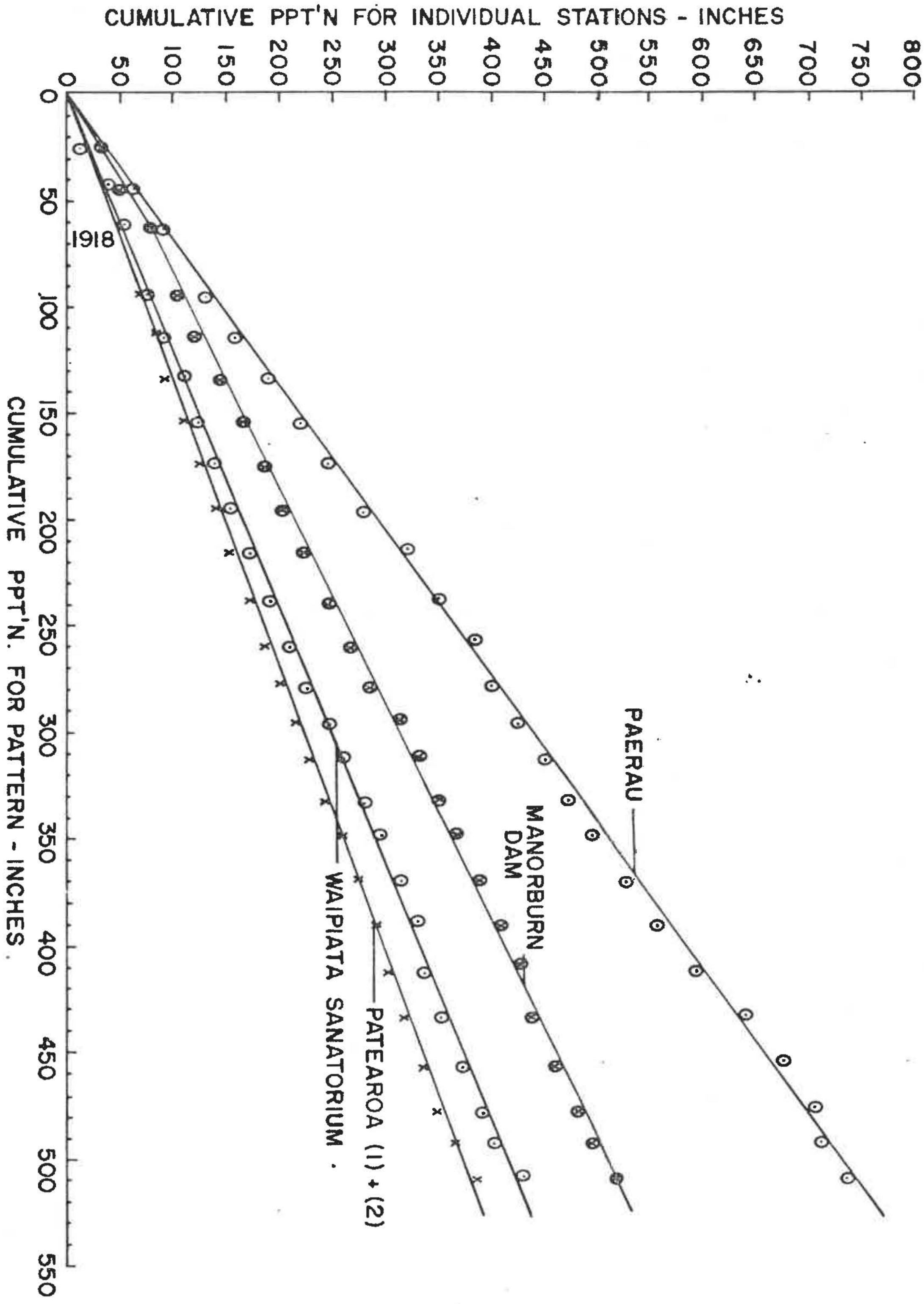


FIGURE 14: Double-mass curve of precipitation data (1916-1940)

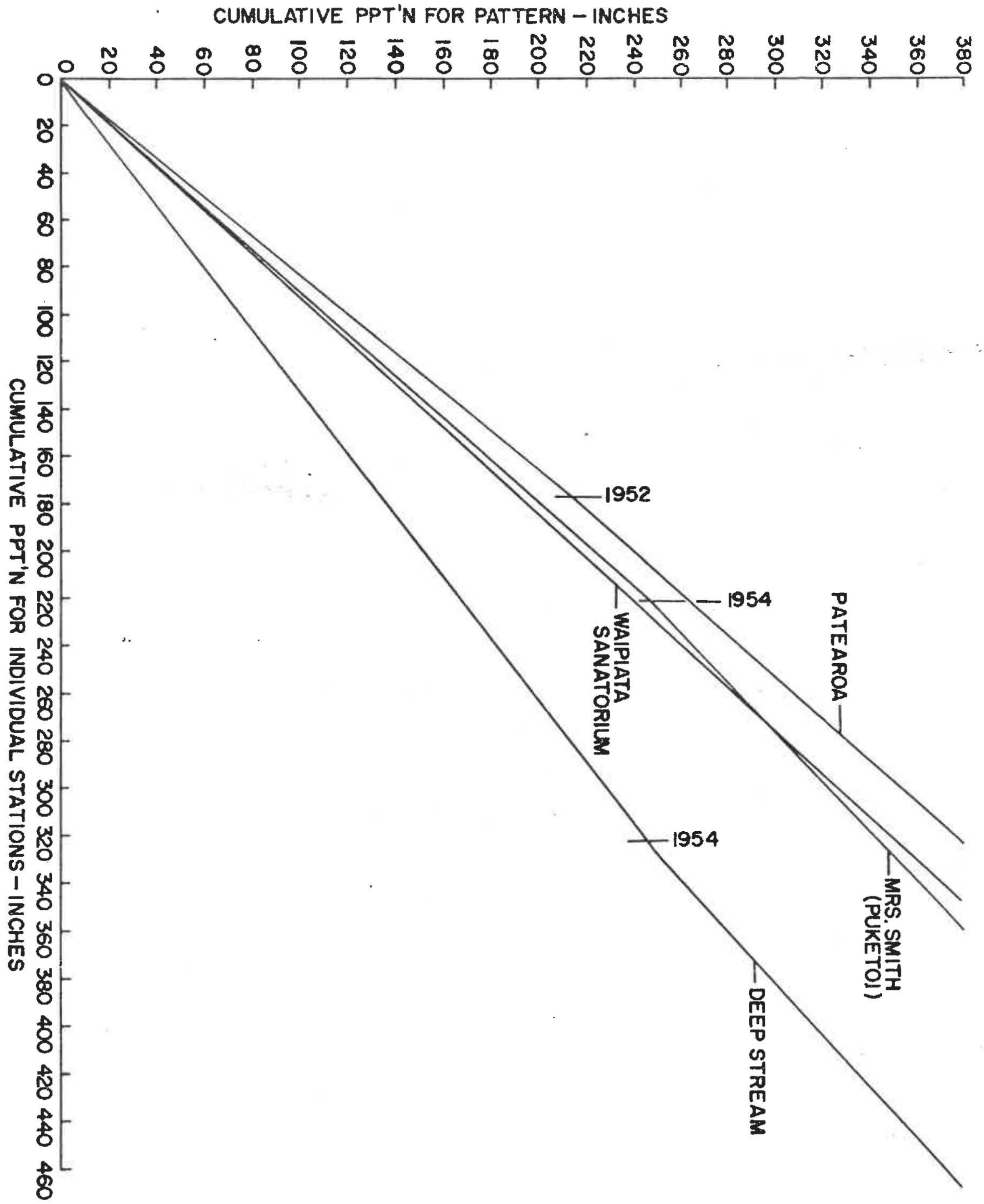


FIGURE 15: Double-mass curve of precipitation data (1941-1961)

significant at the 95 percent level. In the case of Patearoa No. II, the 1952 break in slope is a rather arbitrary choice.

Relative to the pattern, the breaks indicate an increase in precipitation for Deep Stream after 1954, and decreases for Patearoa No. II and Smith after 1952 and 1954 respectively. Trends and changes in slope of a double-mass curve may be caused by changes in exposure or location of the gauge, changes of procedure in processing data, etc. However, if similar breaks occur at several stations, their geographical location may indicate a regional climatic anomaly. The breaks due to this anomaly do not necessarily indicate inconsistent records, but may indicate which stations should be grouped in a pattern.

Although the discontinuities shown in Figure 15 occur in 1954, opposite in character, it is difficult to postulate whether the cause is climatic or statistical in origin. That is, either the area represented by the Deep Stream gauge is climatically anomalous with that surrounding Smith and Patearoa No. II, or, the results are indicative of insufficient stations to define the pattern and reflect compensating inhomogeneity from one or more of the data sets.

On the basis of insufficient evidence to warrant change, the original historical data are retained for subsequent analysis as necessary. The records from at least the Patearoa No. II and Waipiata Sanatorium stations are thus considered to be consistent.

Correction of present Upper Taieri network data:

Data from the post 1968 Upper Taieri basin precipitation network were also examined for missing or inconsistent records. Such a study served to highlight some of the sampling and operational problems associated with the field operation of storage raingauges under difficult conditions. The solution of these problems and resultant recommendations for future operation of such networks are worthy of further discussion.

Gauges first subjected to analysis were those located at Longstone, Musterer's Huts and Trig 'H' (Figure 2). Each had an approximately six month record. For initial evaluation purposes, each site was equipped with a standard five inch daily manual raingauge as well as the listed fibreglass storage gauge (Table 1). Each storage gauge contained kerosene as an anti-evaporant, as did the other storage gauges in the Upper Taieri network at that time.

A plot of cumulative manual versus cumulative storage gauge values disclosed two major anomalies. Firstly, significant discontinuities were recorded in the Longstone and Trig 'H' records on 31.3.69 and 22.4.69 respectively (Figure 16). These were isolated occasions, did not occur concurrently at the three stations, and are attributed to undercatching by the manual gauges during two autumn snow storms. It is concluded that since the storage gauges with an open orifice record a more realistic catch under these conditions, the manual gauge records are amended accordingly. No such discontinuities were observed in the Musterer's Huts records, and the cumulative curve is thus not plotted in Figure 16.

Secondly, the cumulative plots show that all three storage gauges were undercatching relative to the daily manual gauges. If the manual gauge records are assumed to be correct, leakage from the storage gauges may be discounted because the phenomenon is similarly recorded at all stations. The differences are thus attributed to catch evaporation even though kerosene was used in each storage gauge. For such differences to be entirely due to different orifice height was largely discounted because of the magnitude and non-uniformity of the effect over the time interval considered. Further analysis was thus carried out for the three stations. The results are shown in Table 7 and Figure 17.

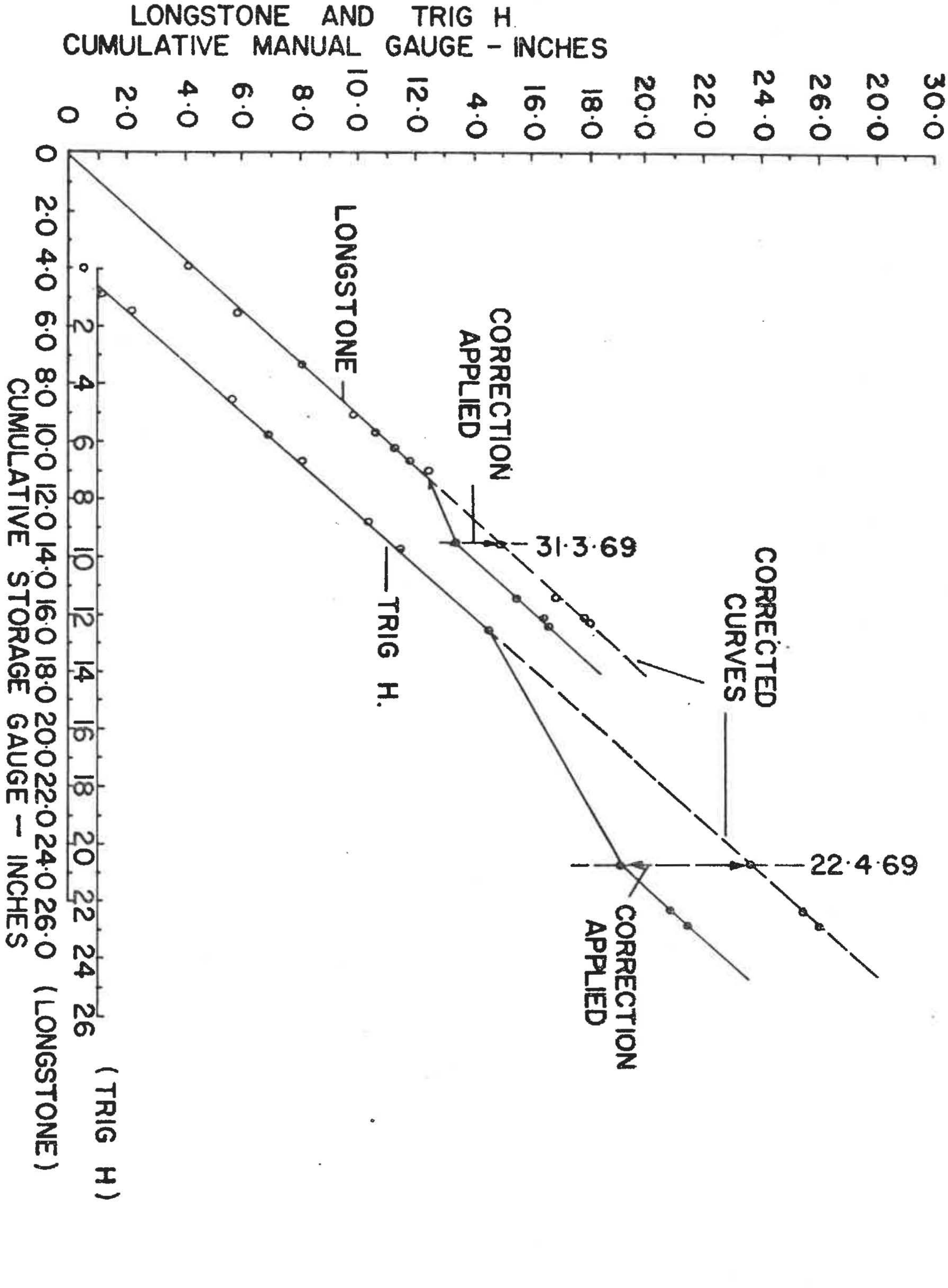


FIGURE 16: Manual/storage storm rainfall corrections (March-April 1969)

TABLE 7: Rainfall Loss Investigation - Longstone, Musterer's Huts, Trig 'H'

A. Longstone:

(1) Date	(2) Manual (ins.)	(3) ΣManual (ins.)	(4) Storage (ins.)	(5) ΣStorage (ins.)	(6) (2)-(4) (ins.)	(7) Period (days)	(8) (2)-(4) (ins./wk)	(9) Computed Storage (ins.)	(10) % Error (2)&(4)	(11) % Error (2)&(9)
10.10.68	0	0	0	0	-	-	-	-	-	-
28.11.68	4.15	4.15	3.86	3.86	0.29	48	0.042	3.86	-7.0	-7.0
2.1.69	1.67	5.82	1.65	5.51	0.02	35	0.004	1.57	-1.2	-6.0
16.1.69	2.29	8.11	1.79	7.30	0.50	14	0.250	2.17	-17.5	-5.2
12.2.69	1.77	9.88	1.75	9.05	0.02	27	0.005	2.41	-1.1	+36.2
18.2.69	0.80	10.68	0.62	9.67	0.18	6	0.210	0.74	-20.0	-7.5
6.3.69	0.65	11.33	0.51	10.18	0.14	17	0.058	0.88	-21.5	+35.4
12.3.69	0.63	11.96	0.51	10.69	0.12	6	0.140	0.65	-19.0	+3.2
17.3.69	0.49	12.45	0.27	10.96	0.22	5	0.308	0.39	-44.9	-20.4
31.3.69	*2.44	14.89	2.57	13.53	-0.13	14	-0.065	2.90	+5.3	+21.2
22.4.69	2.05	16.94	1.87	15.40	0.18	22	0.057	2.15	-8.8	+4.9
6.5.69	0.99	17.93	0.66	16.06	0.33	14	0.165	0.83	-33.3	-16.2
15.5.69	0.20	18.13	0.23	16.29	-0.03	9	-0.023	0.34	+15.0	+70.0

* Correct value - see double mass curve storage/manual (Fig. 16)

TABLE 7: Continued

B. Musterer's Huts:

(1) Date	(2) Manual (ins.)	(3) ΣManual (ins.)	(4) Storage (ins.)	(5) ΣStorage (ins.)	(6) (2)-(4) (ins.)	(7) Period (days)	(8) (2)-(4) (ins./wk)	(9) Computed Storage (ins.)	(10) % Error (2)&(4)	(11) % Error (2)&(9)
10.10.68	0	0	0	0	-	-	-	-	-	-
28.11.68	5.86	5.86	6.77	6.77	-0.91	48	-0.132	6.77	+15.5	+15.5
2.1.69	2.20	8.06	2.18	8.95	0.02	35	0.004	2.10	-0.9	-4.5
16.1.69	2.27	10.33	1.72	10.67	0.55	14	0.275	2.10	-24.2	-7.5
12.2.69	3.52	13.85	3.00	13.67	0.52	27	0.134	3.66	-14.7	+4.0
18.2.69	1.09	14.94	0.94	14.61	0.15	6	0.176	1.06	-13.7	-2.8
6.3.69	0.85	15.79	0.66	15.27	0.19	17	0.078	1.03	-22.3	+21.2
12.3.69	1.57	17.36	1.48	16.75	0.09	6	0.105	1.62	-5.7	+3.2
17.3.69	1.04	18.40	0.78	17.53	0.26	5	0.364	0.90	-25.0	-13.5
31.3.69	2.99	21.39	2.50	20.03	0.49	14	0.245	2.83	-16.3	-5.4
22.4.69	4.04	25.43	4.56	24.59	-0.52	22	-0.165	4.84	+12.8	+19.8
7.5.69	1.84	27.27	1.60	26.19	0.24	14	0.120	1.77	-13.0	-3.8
14.5.69	0.64	27.91	0.62	26.81	0.02	8	0.017	0.71	-3.1	+10.9

TABLE 7: Continued

C. Trig 'H':

(1) Date	(2) Manual (ins.)	(3) ΣManual (ins.)	(4) Storage (ins.)	(5) ΣStorage (ins.)	(6) (2)-(4) (ins.)	(7) Period (days)	(8) (2)-(4) (ins./wk)	(9) Computed Storage (ins.)	(10) % Error (2)&(4)	(11) % Error (2)&(9)
16.1.69	0	0	0	0	-	-	-	-	-	-
21.1.69	1.13	1.13	0.86	0.86	0.27	5	0.378	1.00	-23.8	-11.5
29.1.69	1.06	2.19	0.66	1.52	0.40	8	0.350	0.88	-37.7	-17.0
12.2.69	3.46	5.65	2.96	4.48	0.50	14	0.250	3.26	-14.4	-5.8
18.2.69	1.31	6.96	1.28	5.76	0.03	6	0.035	1.40	-2.3	+6.9
6.3.69	1.13	8.09	0.93	6.69	0.20	17	0.082	1.30	-17.7	+15.0
12.3.69	2.31	10.40	2.10	8.79	0.21	6	0.246	2.24	-9.1	-3.0
18.3.69	1.08	11.48	0.93	9.72	0.15	6	0.176	1.07	-13.9	-0.9
31.3.69	3.11	14.59	2.85	12.57	0.26	13	0.139	3.16	-8.4	+1.6
22.4.69	*9.13	23.72	8.07	20.64	1.06	22	0.337	8.35	-11.6	-7.7
6.5.69	1.72	25.44	1.64	22.28	0.08	14	0.040	1.81	-4.6	+5.2
15.5.69	0.60	26.04	0.51	22.79	0.09	9	0.069	0.62	-15.0	+3.3

* Corrected value - see double mass curve storage/manual (Fig. 16)

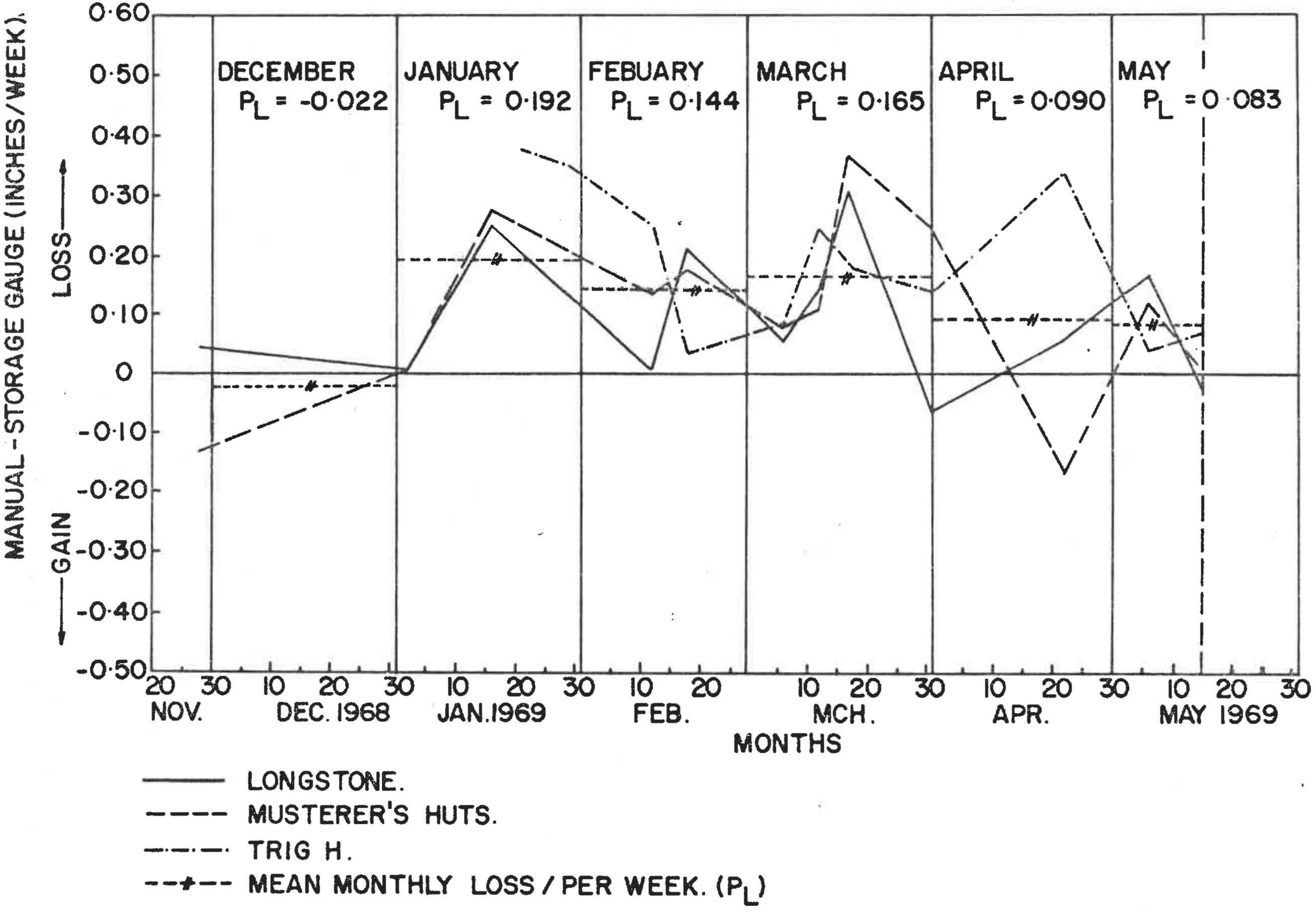


FIGURE 17: Rainfall loss analysis - Longstone, Musterer's Huts, Trig H

The daily manual gauge data are assumed as a base, and values of loss or gain per week are calculated from the differences between the individual manual and storage gauge readings at each site. Although the curves display some scatter, a logical seasonal pattern is described. The relationship for each station between loss or gain per week and altitude is not well defined, and mean monthly values are thus calculated from the combined data for all three stations (Figure 17). The four months January to April show loss values of 0.192, 0.144, 0.165, and 0.090 inch per week respectively. New values of storage gauge catch are hence calculated, and the initial and amended percentage errors between the storage and daily manual gauge values compared (Table 7).

An overall appraisal of the method and results obtained indicates that the approach is realistic. All Upper Taieri basin records from a four month period of storage gauge readings (January-April, 1969) were thus amended by these monthly factors before further analysis.

From these results and the conclusions of Hamilton and Andrews (1953), the use of kerosene as an anti-evaporant in the network storage gauges was discontinued, and was replaced by a light oil. The oil used is BP Energol WM2, and possesses the properties of flash point 365°F, specific gravity 0.845 at 60°F, pour point 10°F, and a kinematic viscosity of 15.7 at 100°F. Compared with an amount of 0.15 inch per gauge as suggested by Hamilton and Andrews (op. cit), the quantity added to each storage gauge in the Upper Taieri network is about one centimetre.

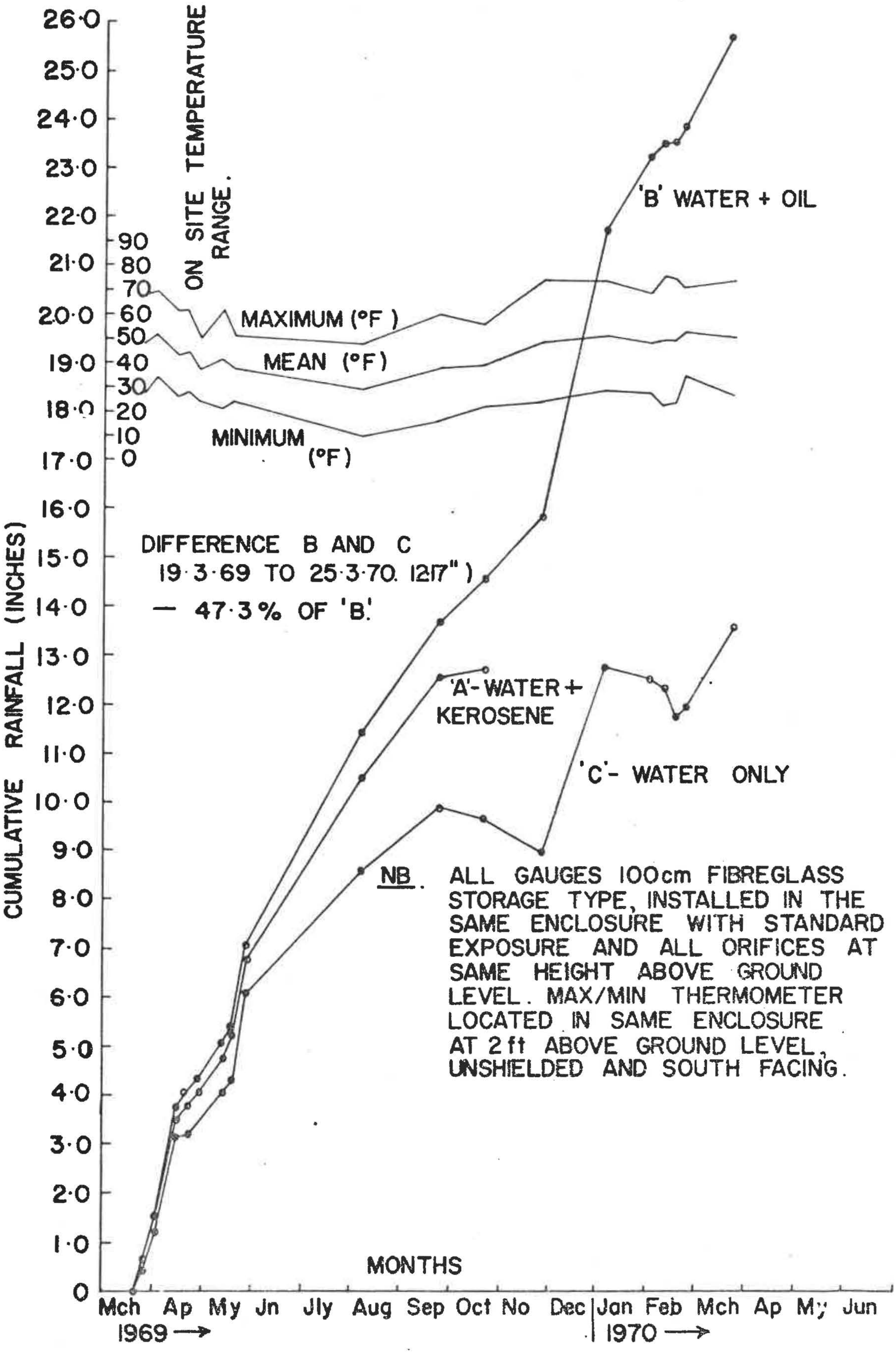
To test the validity of such a decision in the study area, a further controlled experiment was initiated at Smith (Figure 2) and maintained over a 12 month period from April 1969 to March 1970.

Three 100 centimetre capacity fibreglass storage gauges were installed in the same enclosure, with normal exposure and all orifices at the same height above ground. A maximum-minimum thermometer was also placed in the enclosure, two feet above ground level, unshielded and south facing. The three gauges, designated 'A', 'B' and 'C', contained respectively rainfall catch and one centimetre kerosene, catch and one centimetre WM2 oil, and rainfall catch only. Although gauge 'A' was withdrawn after only seven months' record, the cumulative plots of all readings showed marked differences (Figure 18). Losses from kerosene plus water are consistently intermediate between oil plus water and water only.

Over 12 months the water only catch was 52.7 percent of the water plus oil gauge catch. The remaining 12.17 inches were lost by evaporation. Also shown on Figure 18 are the site maximum, minimum and mean temperature readings.

A further loss analysis was thus carried out for gauges 'A', 'B' and 'C' by the same procedure as previously outlined. The gauge containing oil was used as a base, and was assumed to have no evaporation losses. Results of the analysis are shown in Table 8 and Figure 19.

A simple cyclic pattern over the 12 month period is evident, as expected, with a maximum loss for the water only gauge of 0.417 inch per week in February, 1970, and a minimum loss of zero for June, 1969. Although the evaporation losses show a similar cyclic pattern to that of the mean temperature record, attempts to predict these losses by correlation with on site or Elliot mean temperatures proved unsuccessful.



DIFFERENCE B AND C 19·3·69 TO 25·3·70. 12·17") — 47·3% OF 'B'.

NB. ALL GAUGES 100cm FIBREGLASS STORAGE TYPE, INSTALLED IN THE SAME ENCLOSURE WITH STANDARD EXPOSURE AND ALL ORIFICES AT SAME HEIGHT ABOVE GROUND LEVEL. MAX/MIN THERMOMETER LOCATED IN SAME ENCLOSURE AT 2 ft ABOVE GROUND LEVEL, UNSHIELDED AND SOUTH FACING.

FIGURE 18: Smith's Rd. storage gauges - cumulative rainfall

TABLE 8: Raingauge Loss Investigations - Smith's Road (2,950 ft)

('A' = Water and Kerosene; 'B' = Water and Oil; 'C' = Water only)

(1) Date	(2) Smith 'B' (ins.)	(3) Smith 'A' (ins.)	(4) Smith 'C' (ins.)	(5) (2)-(3) (ins.)	(6) (2)-(4) (ins.)	(7) Period B/A (Days)	(8) Period B/C (Days)	(9) (2)-(3) (ins./wk)	(10) (2)-(4) (ins./wk)
19.3.69	0.00	0.00	0.00	0.00	0.00	-	-	-	-
25.3.69	0.63	0.63	0.43	0.00	0.20	6	6	0.000	0.232
2.4.69	0.91	0.87	0.83	0.04	0.08	8	8	0.035	0.070
15.4.69	2.20	2.01	1.89	0.19	0.31	13	13	0.102	0.166
22.4.69	0.28	0.24	0.04	0.04	0.24	7	7	0.040	0.240
29.4.69	0.31	0.31	-	0.00	-	7	-	0.000	-
13.5.69	0.75	0.67	0.87	0.08	-0.12	14	21	0.040	-0.040
19.5.69	0.31	0.47	0.24	-0.16	0.07	6	6	-0.186	0.081
28.5.69	1.69	1.57	1.77	0.12	-0.08	9	9	0.093	-0.062
7.8.69	4.33	3.70	2.52	0.63	1.81	71	71	0.062	0.178
24.9.69	2.28	2.09	1.30	0.19	0.98	48	48	0.027	0.142
22.10.69	0.87	0.16	-0.28	0.71	1.15	28	28	0.177	0.287
27.11.69	1.30	(Gauge removed - leaking)	-0.67	-	1.97	-	36	-	0.383
7.1.70	5.87		3.86	-	2.01	-	41	-	0.343
5.2.70	1.54	-	-0.28	-	1.82	-	29	-	0.439
12.2.70	0.24	-	-0.20	-	0.44	-	7	-	0.440
19.2.70	0.04	-	-0.55	-	0.59	-	7	-	0.590
24.2.70	0.31	-	0.16	-	0.15	-	5	-	0.211
25.3.70	1.85	-	1.61	-	0.24	-	29	-	0.058

(All gauges 100 cms. Fibreglass storage type)

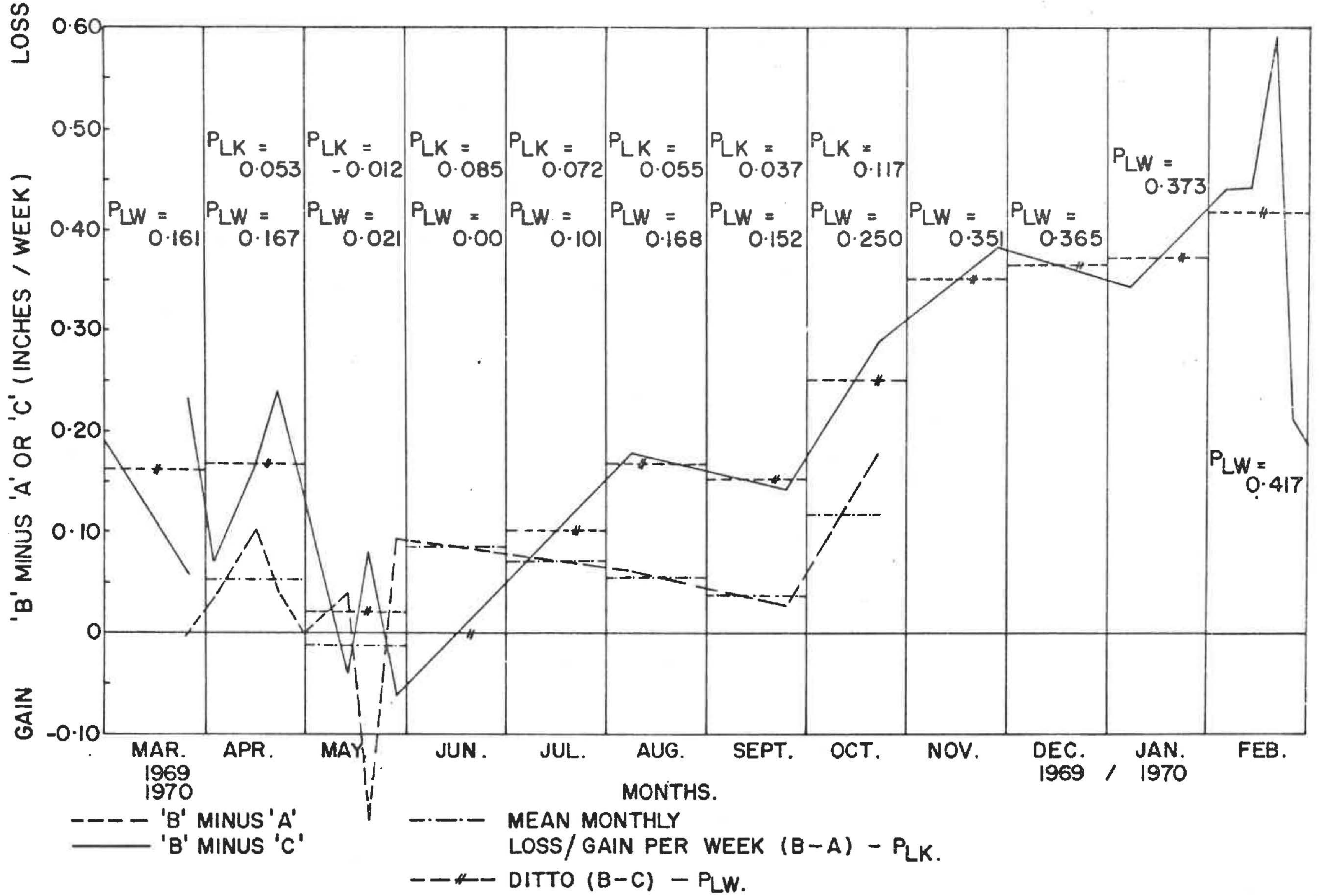


FIGURE 19: Storage gauge loss - Smith's Rd. (2950 feet)

Correlation coefficients were respectively -0.18 and +0.53 for the relationship between gauges 'B'-'A' and 'B'-'C' inches loss per week and mean temperature. No information on local wind run was available.

From these results at Smith it is concluded that open orifice storage gauges such as those used are most suitable for high country precipitation sampling. However, considerable doubt must be placed on the catches recorded if other than a light oil is used as an anti-evaporant in areas with a high potential evaporation. The oil chosen is also a useful additive in winter. Although the precipitation catch may freeze, an oil film stops the ice from adhering to the inside of the gauge, and hence prevents the gauge from splitting under frost action.

CHAPTER IV ESTIMATES OF POPULATION PARAMETERS FROM THE MEASURED DATA

MONTHLY, SEASONAL AND ANNUAL STATION MEANS AND VARIABILITY

Precipitation: seasonal distribution

Measured monthly, seasonal and annual data for the combined station records at I59491 Paerau and Elliot to cover the periods 1908-40 and 1968-69 are listed in Tables 9 and 10.

Equating the station at Paerau with that at Elliot proved to be a valid assumption. Although separated by a short distance, both stations show equivalence on a long-term mean annual rainfall isohyetal pattern derived for the area. Also, synthetic monthly and annual data derived by correlation and regression for Paerau from Manorburn Dam and Patearoa No. II, were essentially identical for 1968-69 with the catches concurrently recorded at Elliot.

Rainfall patterns and causes in Central Otago have been analysed by Browne (1958), who showed that three factors with their associated weather systems influence the rainfall patterns of the region. These are:

(i) Cold fronts which move across Central Otago from the west are the major single system causing daily rainfalls of 0.25 inch or more, with the rain heavier and more frequent in the northwest.

(ii) Cold fronts which cross Central Otago from the southwest and follow southwesterly airstreams, generally give little or no rain except to areas in the south, or southeastern areas if the flow is southerly or southeasterly.

(iii) Depressions which cross the South Island and are accompanied by southerly or easterly winds, give most rain in the south and east of Central Otago. The central, northern and western areas receive little rain.

TABLE 9: Paerau/Elliot measured monthly rainfall record (inches) - (I59491-Paerau-1908 to 1940; R.A.W. Elliot - October 1968 to 1969).

Year	J	F	M	A	M	J	J	A	S	O	N	D
1908	-	-	-	-	-	-	-	1.28	1.47	1.82	0.94	3.43
1909	4.43	1.39	3.88	2.50	0.60	2.59	0.95	1.69	1.01	3.35	2.11	1.68
1910	1.87	1.84	1.43	1.43	1.09	1.84	1.32	0.87	1.84	3.60	1.32	2.06
1911	2.32	0.37	1.31	1.52	0.68	2.08	1.36	1.12	1.36	0.74	4.40	2.51
1912	1.17	2.43	3.27	1.46	1.33	4.54	1.62	1.85	1.61	4.25	2.30	0.61
1913	3.55	1.48	3.29	1.49	1.71	0.97	2.56	5.00	1.50	2.04	3.19	4.83
1914	3.14	3.16	1.82	2.22	2.95	5.13	0.48	0.95	1.67	0.70	2.11	3.03
1915	2.06	4.16	2.02	1.40	1.70	2.82	0.47	0.37	0.75	3.19	3.14	2.46
1916	2.50	2.36	3.90	1.46	1.72	1.54	1.89	2.39	1.79	1.68	4.18	0.62
1917	1.32	1.05	2.25	1.78	5.08	0.84	0.69	0.88	2.74	4.44	1.74	4.01
1918	4.33	1.02	3.52	1.73	1.54	2.32	2.98	3.69	2.12	2.70	2.44	4.12
1919	8.84	0.55	0.87	5.25	1.86	3.97	2.00	6.96	5.11	1.04	3.51	4.56
1920	3.06	1.99	0.77	2.27	3.45	1.00	2.85	1.96	3.76	0.85	4.54	3.37
1921	2.63	1.49	4.44	2.03	1.44	3.09	2.47	1.49	1.31	3.04	1.01	5.18
1922	5.89	0.77	3.26	2.14	1.74	0.74	1.53	1.44	1.20	1.75	4.37	5.40
1923	2.81	2.96	3.53	5.95	6.12	1.56	0.00	1.60	1.03	1.32	1.95	2.25
1924	2.05	4.98	1.80	3.62	2.61	1.75	1.77	0.19	1.27	5.66	1.59	2.81
1925	1.27	2.09	3.95	2.60	1.64	0.76	2.47	5.85	2.60	3.89	3.39	3.14
1926	4.50	4.75	1.42	1.89	3.12	1.41	0.50	1.79	2.02	3.61	3.97	4.22
1927	2.45	2.78	4.43	3.10	1.73	0.59	1.40	1.98	2.39	1.87	4.35	2.35
1928	1.09	2.53	0.74	4.48	1.67	1.12	1.38	1.40	1.58	3.70	1.31	1.93
1929	2.62	0.57	3.36	0.65	0.62	3.79	3.26	0.66	1.12	0.05	3.61	2.70
1930	2.39	0.88	0.10	0.85	1.40	1.39	1.19	1.30	1.49	4.36	3.05	2.13
1931	5.88	5.58	0.55	0.73	1.26	1.78	0.94	2.54	1.81	2.74	1.49	2.25
1932	3.59	1.54	1.67	2.60	2.45	2.66	0.39	1.82	1.33	2.37	0.66	2.25
1933	1.90	1.85	1.48	6.12	3.60	1.71	1.25	1.71	0.77	3.71	3.39	5.80
1934	3.00	3.52	3.24	3.21	3.50	2.48	1.87	1.45	2.40	2.22	1.78	2.35
1935	3.98	3.36	6.35	1.90	4.11	6.72	0.21	1.91	0.74	0.70	4.89	2.48
1936	0.96	2.62	7.92	2.71	2.68	1.03	2.25	2.41	3.82	2.49	3.96	4.07
1937	3.26	7.90	3.09	4.16	3.22	1.58	1.33	1.85	1.17	0.43	1.41	6.15
1938	1.21	0.64	1.89	4.40	1.35	3.91	0.87	0.19	1.53	3.26	2.52	7.68
1939	2.08	1.20	0.85	1.63	1.32	1.89	2.11	2.42	2.87	1.15	2.26	0.95
1940	3.16	4.48	3.56	1.15	3.26	1.00	1.21	0.55	1.50	1.38	2.80	1.60
1968	-	-	-	-	-	-	-	-	-	2.60	1.60	1.30
1969	3.96	1.07	2.18	2.37	2.45	1.14	0.74	1.61	1.30	1.59	0.88	4.10
Mean:	2.99	2.37	2.62	2.50	2.28	2.13	1.43	1.89	1.77	2.53	2.60	3.15

TABLE 10: Paerau/Elliot measured seasonal and annual rainfall record (inches) - Paerau (1908-40); Elliot (1968-9).

Year	Summer (Dec-Feb)	Autumn (Mch-May)	Winter (Jun-Aug)	Spring (Sept-Nov)	Annual
1908	-	-	-	4.23	-
1909	9.25	6.98	5.23	6.47	26.18
1910	5.39	3.95	4.03	6.76	20.51
1911	4.75	3.51	4.56	6.50	19.77
1912	6.11	6.06	8.01	8.16	26.44
1913	5.64	6.49	8.53	6.73	31.61
1914	11.13	6.99	6.56	4.48	27.36
1915	9.25	5.12	3.66	7.08	24.54
1916	7.32	7.08	5.82	7.65	26.03
1917	2.99	9.11	2.41	8.92	26.82
1918	9.36	6.79	8.99	7.26	32.51
1919	13.51	7.98	12.93	9.66	44.52
1920	9.61	6.49	5.81	9.15	29.87
1921	7.49	7.91	7.05	5.36	29.62
1922	11.84	7.14	3.71	7.32	30.23
1923	11.17	15.60	3.16	4.30	31.08
1924	9.28	8.03	3.71	8.52	30.10
1925	6.17	8.19	9.08	9.88	33.65
1926	12.39	6.43	3.70	9.60	33.20
1927	9.45	9.26	3.97	8.61	29.42
1928	5.97	6.89	3.90	6.59	22.93
1929	5.12	4.63	7.71	4.78	23.01
1930	5.97	2.35	3.88	8.90	20.53
1931	13.59	2.54	5.26	6.04	27.55
1932	7.38	6.72	4.87	4.36	23.33
1933	6.00	11.20	4.67	7.87	33.29
1934	12.32	9.95	5.80	6.40	31.02
1935	9.69	12.36	8.84	6.33	37.35
1936	6.06	13.31	5.69	10.27	36.92
1937	15.23	10.47	4.76	3.01	35.55
1938	8.00	7.64	4.97	7.31	29.45
1939	10.96	3.80	6.42	6.28	20.73
1940	8.59	7.97	2.76	5.68	25.65
1969	6.33	7.00	3.49	3.77	23.39
Mean:	8.56	7.51	5.66	6.93	28.28

From the general aspects of Paerau rainfall distribution presented in Tables 9 and 10, and in Figures 20(a) and 21(a), precipitation shows a distinct seasonal character with a fairly marked summer maximum. Maunder (1965) concludes that this seasonal variation, at altitudes of less than 3,000 feet, is principally due to increased insolation in the summer months which results in an intensification of normal rain producing systems. Thus, cold fronts which cross Central Otago in the summer are subject to convectional uplift on a much larger scale than in winter. Similarly, rain producing depressions in the east are likely to produce more rain in eastern and southern areas of Central Otago in the warmer months than in the colder months.

Mean annual rainfall for Paerau is 28.28 inches. Although the summer maximum is evident, in no month is the average catch less than 1.43 inches. December, January and March are the wettest months, and the driest months on average are July, August and September. On average, 30 percent of the mean annual rainfall occurs in summer, whereas the comparable figure for the winter period is only 20 percent. For the months December to March, this value rises to 40 percent of the annual mean.

The Paerau results confirm trends shown by Coulter (1968), Leslie (1966) and the M.O.W. (1967) for other areas of Central Otago. Summer concentration of the low mean annual rainfall accentuates the dryness of the area, since a large proportion of the rain comes when temperature, insolation and evaporation are all high. Significant moisture deficiencies are thus produced within the lowland areas.

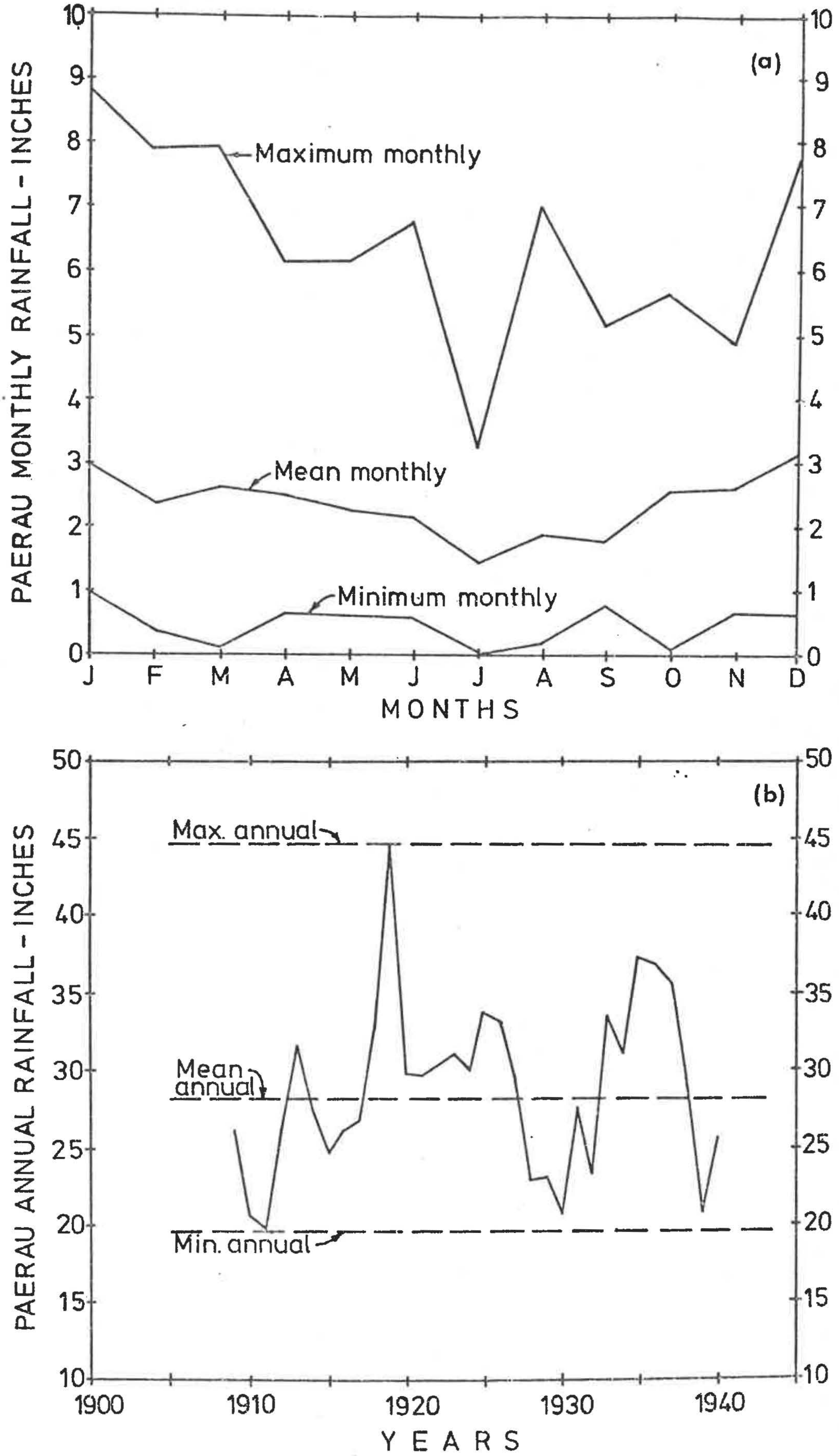


FIGURE 20: Paerau annual and monthly rainfall distribution (1908-1940)

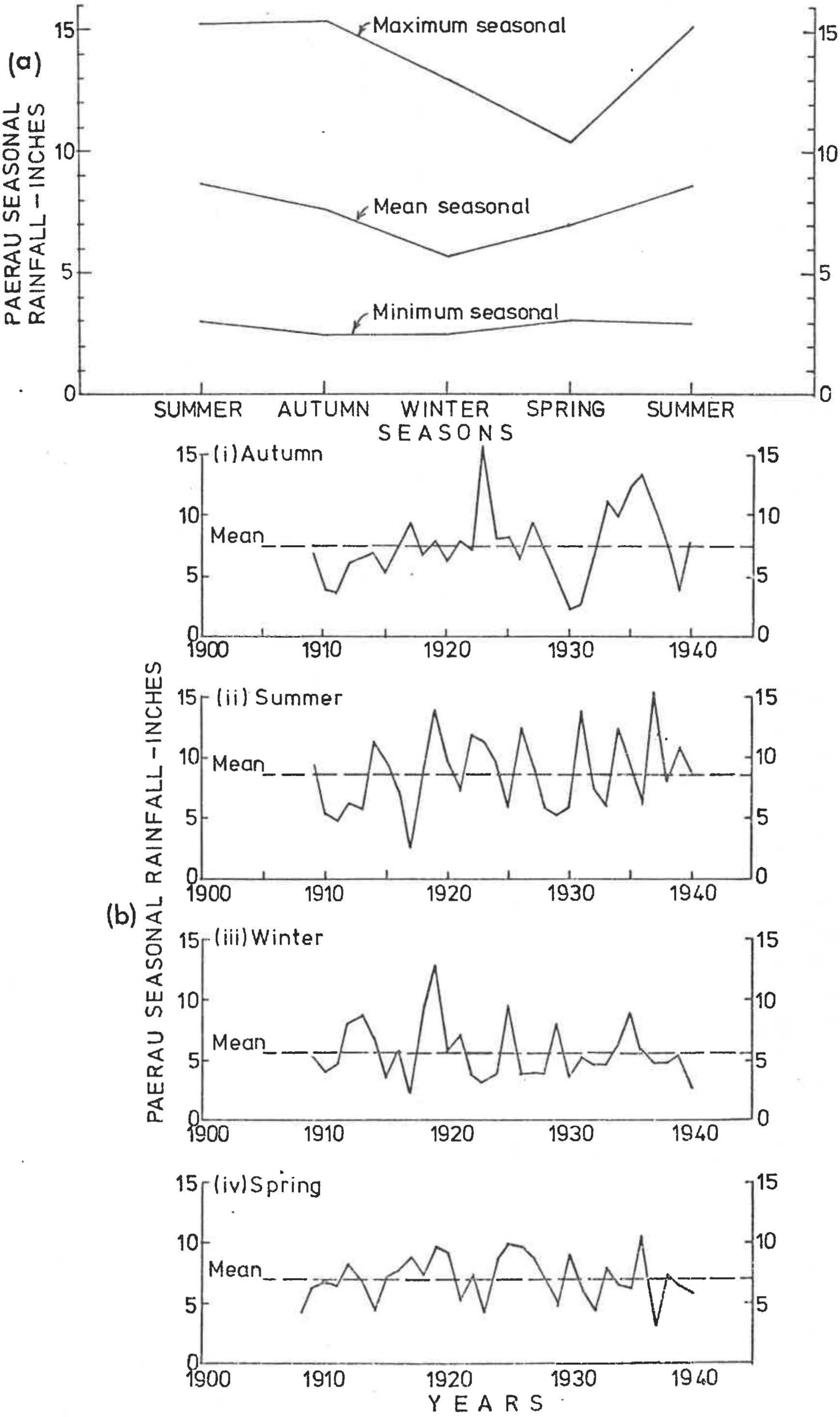


FIGURE 21: Paerau seasonal rainfall distribution (1908-1940)

Figures 20 and 21 also show the monthly, seasonal and annual extremes of both maximum and minimum falls for the period of record. The 1919 maximum annual rainfall is 57 percent above average and the 1911 minimum value is 30 percent below average. The highest monthly rainfall of 8.84 inches in January 1919 is equivalent to 31 percent of the average annual value, and the record shows that months occurred in which there was no precipitation.

Of interest from Figures 20 and 21, is that the 1919 annual rainfall maximum was caused by moderately above average summer conditions followed by an average autumn fall, the maximum recorded winter fall and above average spring total. The 1911 minimum annual total resulted from below average (though not minimum recorded) summer and autumn values, with the winter and spring rainfalls only slightly below average.

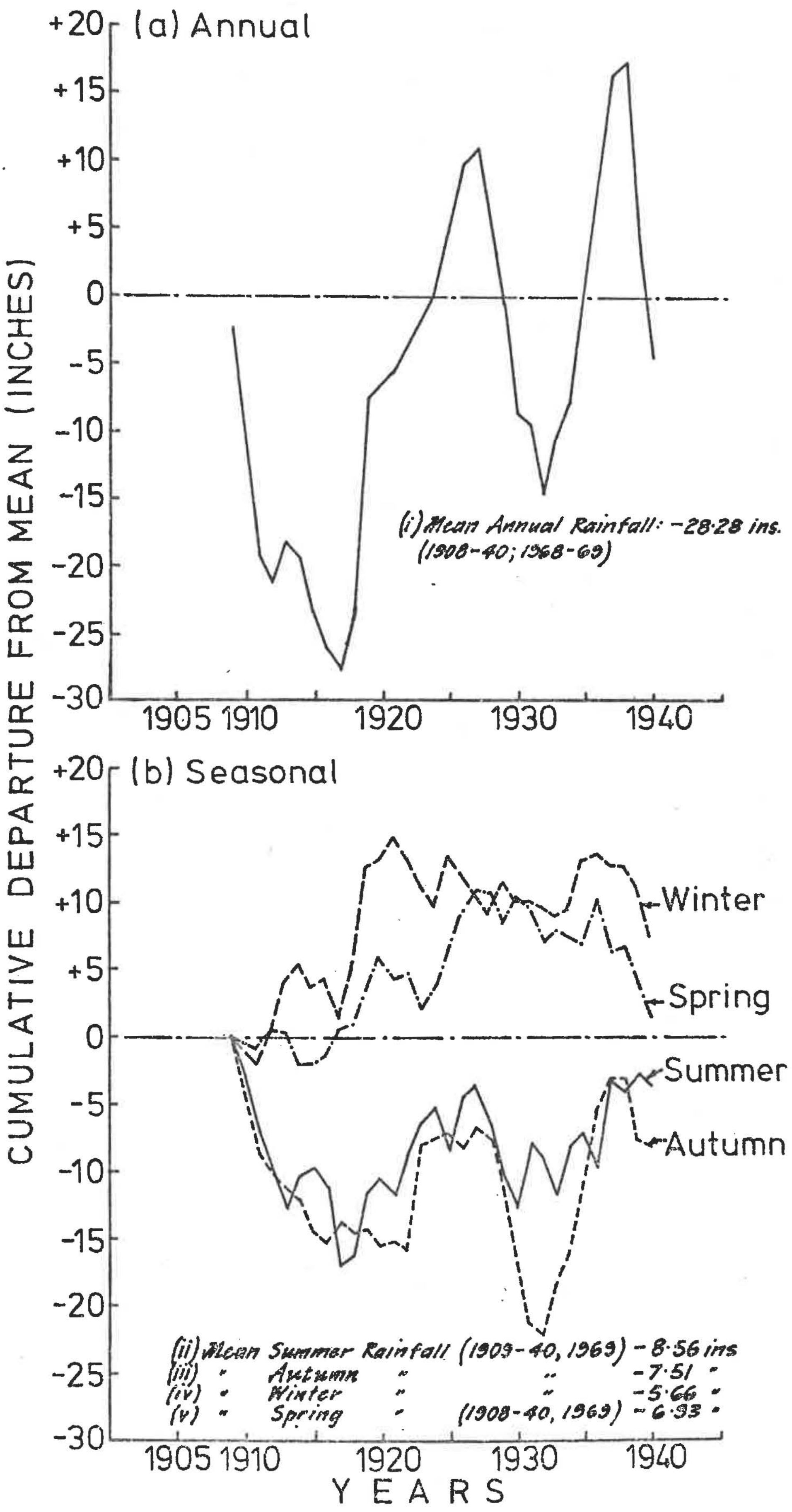
Precipitation: Variability

In association with mean and extreme values derived from the Paerau record, some indication is desirable as to the possible deviation from the mean in any one year. The simplest measure of these variations is the percentage variability. This is shown by Seelye (1940, 1946) to be the average departure of the monthly, seasonal or annual totals from their mean, expressed as a percentage of the mean.

Results of such an analysis are not given here, since the use of residual mass curves, or curves of cumulative departure from the mean, are considered of more value at this stage in a preliminary descriptive account of rainfall seasonal distribution and variability. Such curves appraise the long-term trends of precipitation and provide a more suitable presentation for purposes of comparison with long-term flow records. Residual mass curves developed for Paerau seasonal and annual rainfalls are shown in Figure 22. Successfully used by Grant (1969), and many other authors, the method is based on the principle that when the positive and negative departures from the mean are accumulated, a period of above average rainfall is indicated by an upward slope, while below normal falls correspond to a downward slope. A horizontal line between any two points represents a period of average rainfall.

With only minor variations, the trends shown in Figure 22 are similar to those derived by Finkelstein (1962) for Otago-Southland, by Seelye (1946) and by de Lisle (1961). Series of successive wet and dry years occur with an average fluctuation periodicity of approximately seven years, and thus demonstrate the expected persistence of type. Long-term fluctuations in the pattern of the annual mean are difficult to detect. However, precipitation data from nearby stations suggest that in recent years values to 1969 have gradually decreased since a minor maximum in the late 1950s. Estimates of earlier fluctuations in the long-term annual mean pattern would be only speculative from the data presented, and have not been attempted. However, it would appear that the range of variation between high and low water yield years has been smaller since 1946 than during the preceding recorded period - a conclusion also made by Grant (op. cit) for the Hawke's Bay area, though extending from 1940 in his case.

It is concluded that dry periods in the Upper Taieri were 1909-17, 1928-32, 1939-43, 1946-54, and more recently 1964-69. Subsequent data from the area indicates that the most recent dominant trend has further continued through 1970 to 1971. Periods of above average rainfall comprised the intervening years 1918-27, 1933-38, 1944-45 and 1955-63. Summer and autumn falls appear to have the major affect on



(i) Mean Annual Rainfall: -28·28 ins.
(1908-40; 1968-69)

(ii) Mean Summer Rainfall (1909-40, 1969) - 8·56 ins
(iii) " Autumn " " -7·51 "
(iv) " Winter " " -5·66 "
(v) " Spring " (1908-40, 1969) - 6·93 "

FIGURE 22: Departure from mean: Paerau annual and seasonal rainfalls (1908-1940)

the annual trends shown, particularly during dry periods. With figures 22(a) and (b) drawn to the same time scale, the relative importance of individual seasonal values can be readily determined. For example, during the dry period 1928-32, summer and autumn rainfalls shared the most significant decrease, while winter and spring values contributed to only a minor extent.

Precipitation: Monthly, seasonal and annual rainfall frequencies

In addition to the information already presented, of importance for engineering design purposes are the rainfall distributions depicted by "rainfall duration" curves. Such a graphical distribution of rainfalls is erroneously referred to as a "duration" curve, as the word "duration" implies a period of time (Hoyle, 1962). Since the curve describes a non-sequential distribution, it is more accurately a "cumulative exceeded frequency" curve.

The curves are a convenient way to indicate the variations in rainfall catch, and show the deviation of the rainfalls from the mean. When used with considerable caution and in realisation of the dominant affects of the extreme values on the distribution (Simmers, 1962), the curves may also be used to indicate possible return periods of known rainfall amounts.

Frequency curves have been calculated on a monthly, seasonal and annual basis for the measured Paerau/Elliot record, and are shown in Figures 23 and 24. The calculations were made as outlined by Searcy (1959) and Hoyle (op. cit), with the percentage exceedence axis plotted to a logarithmic scale for ease of curve determination.

In all but three months (July, August and September) there is a 50 percent chance that at least two inches of rain will be received per month. The chance of a monthly rainfall in excess of 2.5 inches

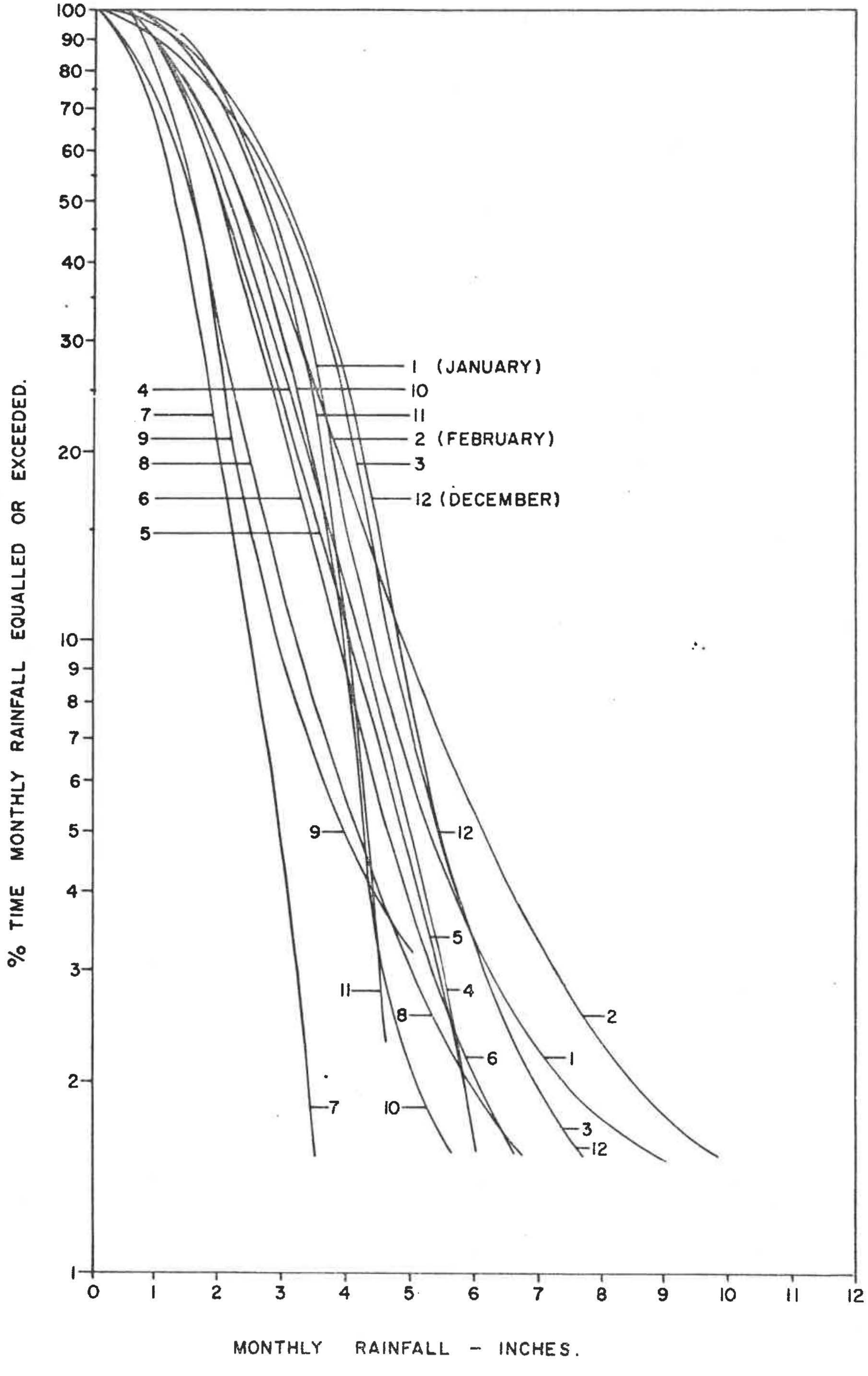


FIGURE 23: Percentage time Paerau/Elliot monthly rainfall equalled or exceeded (1908-40; 1968-69)

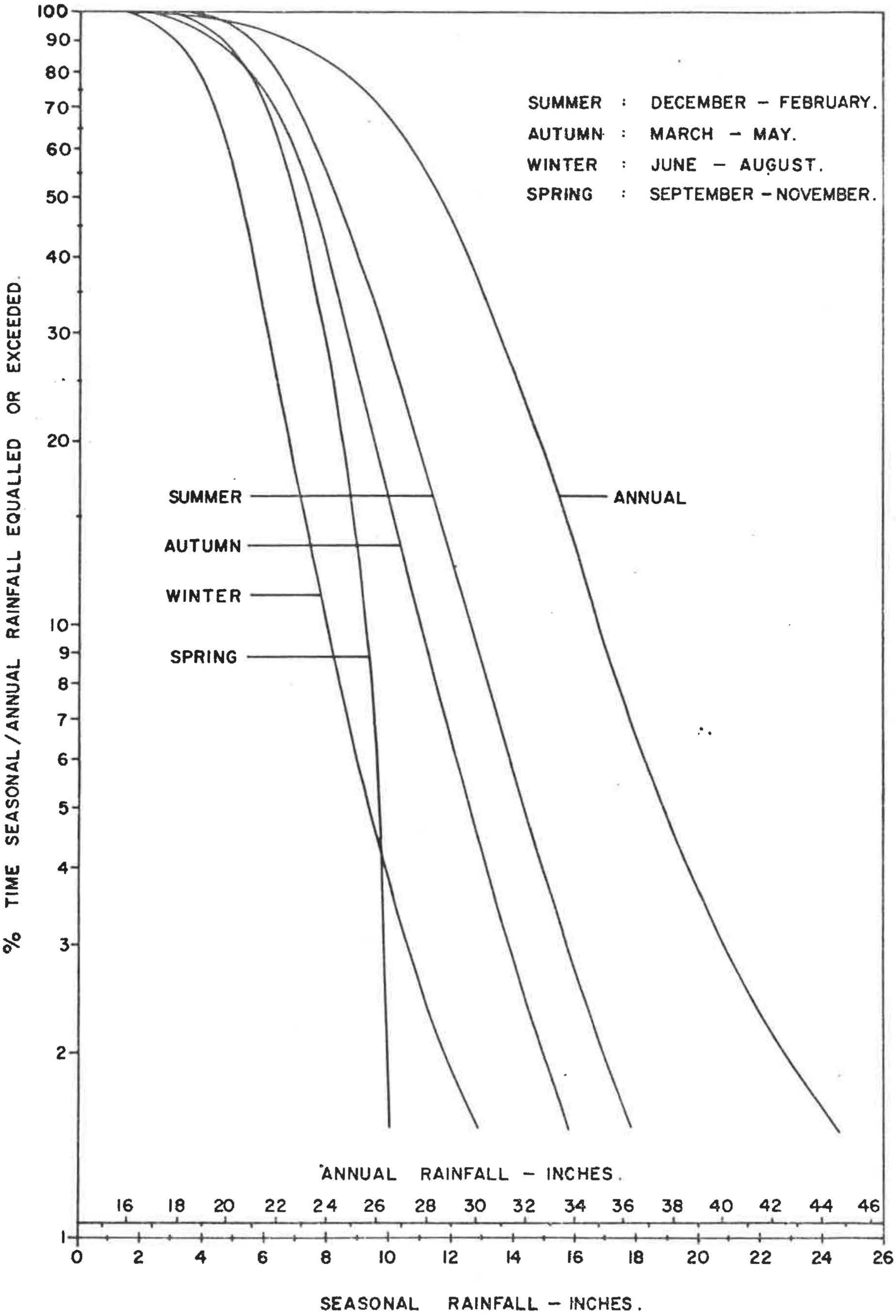


FIGURE 24: Percentage time Paerau/Elliot seasonal and annual rainfall equalled or exceeded (1908–40; 1968–69)

is much lower, although in all months this amount can be expected in 10 percent of years. Monthly totals in excess of six inches are seen to be rare. Only in February can such totals be expected more frequently than 5 percent of the time.

From the annual curve of Figure 24, it is of interest to note that in about 16 of the 33 years of record precipitation varies between 25.3 inches and 31.6 inches - a fluctuation range of 6.3 inches between lower and upper quartile values. Also, in 90 percent of years the rainfall exceeds 22.5 inches. Seasonal rainfall also fluctuates within moderate limits, and totals of less than three inches can be expected in only one year out of 11. In three-quarters of the years the winter rainfall can be expected to exceed 4.1 inches and the summer rainfall 6.7 inches. Other monthly, seasonal or annual values of either amount for a known occurrence frequency or frequency of a given amount can be derived as required from the Figures.

Precipitation: Significant Rainfall analysis

Any discussion of the rainfall regime of an area would be incomplete without some analysis of fall intensity values. To this end, the combined Paerau/Elliot records for 1909-37 and 1968-69, were subjected to further study on the basis of rain per wet day and rainfall received during a period of wet weather. The initial calculations made were similar to those presented by Slatyer (1960) and Osborn (1968). Summaries of the results are given in Tables 11 to 13.

Table 11 shows the monthly and mean monthly rain per wet day, with any precipitation in the form of snow recorded as equivalent rainfall. When expressed as rainfall per wet day, intensities increase from 0.17 inch in late winter to 0.32 inch in summer and early autumn. The overall

TABLE 11: Rain per wet day for Paerau/Elliot (inches) - 1909-1937, 1968-1969

Year	J	F	M	A	M	J	J	A	S	O	N	D
1909	0.23	0.35	0.43	0.25	0.15	0.17	0.16	0.14	0.10	0.24	0.18	0.19
1910	0.21	0.31	0.11	0.18	0.10	0.23	0.12	0.15	0.26	0.45	0.26	0.26
1911	0.39	0.12	0.33	0.17	0.17	0.15	0.17	0.22	0.15	0.07	0.31	0.16
1912	0.20	0.20	0.25	0.15	0.12	0.27	0.16	0.14	0.13	0.28	0.18	0.12
1913	0.27	0.19	0.33	0.19	0.13	0.14	0.20	0.56	0.17	0.19	0.20	0.51
1914	0.39	0.45	0.26	0.17	0.27	0.39	0.10	0.10	0.21	0.12	0.18	0.23
1915	0.17	0.38	0.29	0.14	0.21	0.28	0.07	0.19	0.15	0.40	0.26	0.22
1916	0.25	0.20	0.35	0.24	0.16	0.26	0.24	0.24	0.26	0.13	0.32	0.31
1917	0.15	0.10	0.32	0.22	0.42	0.17	0.12	0.15	0.30	0.30	0.44	0.33
1918	0.48	0.17	0.59	0.25	0.13	0.17	0.21	0.41	0.30	0.18	0.16	0.37
1919	0.59	0.18	0.15	0.40	0.19	0.40	0.20	0.50	0.57	0.09	0.22	0.38
1920	0.34	0.25	0.19	0.25	0.23	0.20	0.22	0.20	0.24	0.11	0.27	0.37
1921	0.29	0.37	0.32	0.23	0.21	0.39	0.22	0.14	0.12	0.34	0.13	0.52
1922	0.74	0.26	0.20	0.24	0.35	0.37	0.17	0.24	0.24	0.19	0.29	0.42
1923	0.23	0.33	0.39	0.99	0.68	0.26	0.00	0.40	0.26	0.22	0.65	0.32
1924	0.23	0.83	0.36	0.52	0.37	0.29	0.25	0.19	0.32	0.51	0.40	0.40
1925	0.42	0.35	0.49	0.37	0.33	0.19	0.41	0.73	0.22	0.43	0.31	0.39
1926	0.64	0.40	0.28	0.32	0.31	0.28	0.17	0.36	0.34	0.30	0.44	0.42
1927	0.31	0.46	0.40	0.31	0.22	0.12	0.13	0.17	0.30	0.17	0.23	0.21
1928	0.16	0.42	0.19	0.37	0.19	0.14	0.28	0.20	0.16	0.23	0.13	0.21
1929	0.37	0.10	0.48	0.13	0.10	0.32	0.25	0.09	0.10	0.05	0.28	0.14
1930	0.17	0.44	0.10	0.17	0.18	0.11	0.20	0.26	0.12	0.36	0.25	0.24
1931	0.35	0.56	0.09	0.09	0.11	0.25	0.19	0.21	0.36	0.39	0.21	0.38
1932	0.28	0.22	0.33	0.22	0.31	0.27	0.07	0.23	0.27	0.34	0.07	0.23
1933	0.17	0.14	0.25	0.47	0.33	0.17	0.14	0.21	0.13	0.27	0.48	0.36
1934	0.33	0.39	0.19	0.32	0.29	0.28	0.16	0.21	0.22	0.17	0.20	0.29
1935	0.31	0.42	0.79	0.17	0.41	0.52	0.05	0.19	0.09	0.09	0.31	0.31
1936	0.14	0.22	0.79	0.45	0.30	0.15	0.17	0.24	0.29	0.28	0.33	0.45
1937	0.27	0.56	0.21	0.35	0.36	0.18	0.33	0.26	0.13	0.11	0.20	0.47
1968									0.10	0.17	0.15	0.16
1969	0.40	0.18	0.18	0.15	0.18	0.10	0.06	0.16	0.13	0.13	0.18	0.27
Mean Rain per wet day	0.32	0.32	0.32	0.28	0.25	0.24	0.17	0.25	0.22	0.24	0.27	0.31

TABLE 12: Number of rain days per month at Paerau/Elliot on which falls of specified amount can be expected (1909-1937, 1968-1969)

Month	Amount of Rainfall (inches)						
	0.01-0.10	0.11-0.25	0.26-0.50	0.51-1.00	1.01-2.00	2.01-4.00	4.01-6.00
January:	3.37	2.87	2.13	1.13	0.53	-	-
February:	3.10	1.93	1.17	0.93	0.47	0.07	-
March:	2.93	2.47	1.60	0.90	0.47	0.07	0.03
April:	3.87	2.23	1.63	1.03	0.23	0.13	-
May:	3.73	2.93	1.57	0.83	0.23	0.07	-
June:	3.30	2.80	2.07	0.70	0.10	-	0.03
July:	4.20	2.37	1.20	0.40	0.10	-	-
August:	3.23	2.57	1.40	0.70	0.17	0.07	-
September:	4.16	2.48	1.16	0.81	0.13	-	-
October:	4.55	2.90	1.61	0.87	0.35	0.03	-
November:	4.58	2.81	1.87	1.32	0.19	0.03	-
December:	3.71	2.52	2.06	1.23	0.55	0.06	-

TABLE 13: Expected number of occurrences per month at Paerau/Elliot of wet periods of amount or duration equal to or exceeding that specified (1909-1937; 1968-1969)

Month	Amount of Rain per period (inches)									
	0.01	0.05	0.25	0.50	1.00	2.00	3.00	4.00	5.00	6.00
January:	4.63	4.23	2.86	1.96	1.03	0.16	0.06	0.06	0.03	0.03
February:	3.40	3.23	2.00	1.33	0.86	0.19	0.09	0.06	0.03	-
March:	4.12	3.79	2.26	1.63	0.90	0.33	0.10	0.03	0.03	0.03
April:	4.05	3.72	2.19	1.59	0.96	0.26	0.06	0.03	-	-
May:	4.15	3.62	2.29	1.39	0.66	0.23	0.13	0.03	-	-
June:	3.89	3.56	2.13	1.56	0.56	0.16	0.03	0.03	0.03	-
July:	4.00	3.63	1.70	1.20	0.30	0.03	-	-	-	-
August:	4.30	4.00	2.27	1.20	0.47	0.10	0.07	0.07	-	-
September:	4.40	3.95	2.08	1.15	0.51	0.03	-	-	-	-
October:	4.58	4.19	2.64	1.45	0.77	0.16	0.03	-	-	-
November:	4.39	4.10	2.94	1.84	0.87	0.16	0.03	-	-	-
December:	4.48	4.13	2.71	1.84	1.00	0.35	0.12	0.06	0.03	-

	Duration of period (days)									
Month	1	2	3	4	5	6	8	10	12	14
January:	4.64	2.57	1.67	0.97	0.57	0.34	0.07	-	-	-
February:	3.39	1.89	1.29	0.79	0.62	0.19	0.06	0.30	-	-
March:	4.13	2.13	1.30	0.87	0.54	0.27	0.10	-	-	-
April:	4.07	2.34	1.77	0.97	0.47	0.30	0.10	0.03	0.03	0.03
May:	4.16	2.33	1.83	1.00	0.60	0.30	0.03	0.03	-	-
June:	3.90	2.10	1.47	0.84	0.67	0.40	0.10	-	-	-
July:	4.00	2.47	1.40	0.53	0.30	0.23	0.03	-	-	-
August:	4.29	2.16	1.33	0.53	0.30	0.10	-	-	-	-
September:	4.41	2.35	1.22	0.77	0.29	0.13	0.03	-	-	-
October:	4.58	2.64	1.70	0.96	0.48	0.32	0.16	0.06	-	-
November:	4.38	2.64	1.77	1.45	0.80	0.48	0.16	-	-	-
December:	4.47	2.63	1.60	0.99	0.64	0.41	0.09	0.03	0.03	-

level of intensity is normal for this climatic zone, as are the higher intensity values from summer rainfall sources. The data are further amplified in Table 12 to show the number of daily falls of various amounts which can be expected in any one month.

The Table shows the general features apparent in Table 11. However, it should be noted that in the interests of simplicity the figures displayed in the bulk of the Table are discrete amounts and only relevant to the rainfall ranges under which shown. That is, a value shown in the 0.26-0.50 inch rainfall range is not included cumulatively under the 0.01-0.10 inch and 0.11-0.25 inch ranges, although such an amount would obviously have fallen to give the higher range total.

A high proportion of the daily rainfalls are less than 0.50 inch, particularly during winter. The higher mean rainfall per wet day in summer is caused by the greater number of falls in excess of 0.50 inch. The greatest number of falls in the range 0.01-0.10 inch occur in July and the spring months September to November. Daily rainfalls in excess of two inches in winter are very rare, a little more common in spring and summer months, and most common during autumn. Such a conclusion does not contradict that drawn previously on the reason for a higher mean rainfall per wet day during summer. Table 12 shows this to be valid, though only to the limit of 2.00 inch daily falls.

Summer ground surface temperatures are often high in the Upper Taieri area, vegetation and soil surfaces parched, and evaporation losses great. As a result, light showers in this period serve little purpose for the provision of excess moisture for plant growth. To show the likely affect of this, a daily value of 0.25 inch of rain is chosen as the minimum amount necessary to meet this provision for plant growth (Osborne, 1968). Table 12 thus shows that for the total number of rain days per month of all specified amounts, significant rainfall (in excess of 0.25 inch) was recorded on only 39 percent of the days in December as a maximum, with a minimum value of 21 percent in July.

However, expression of rainfall intensity as rain per wet day does not provide any indication of intensity within any one fall, or of the total received during a period of wet weather. Data on the first aspect are not available for the study area except for 1968-69, but for the latter can be obtained from the daily rainfall records. Basinski (1960) concludes that the total rainfall received in a wet period is the primary factor which influences water penetration and runoff, rather than the rainfall received per wet day within the period. To examine this feature, Table 13 has been constructed from the measured daily Paerau/Elliot records for 1909-37 and 1968-69.

The Table expresses the expected wet period amounts or duration occurrences per month which equal or exceed that specified. A wet period is defined as a period of persistent wet weather which is broken by two or more consecutive rainless days. A single dry day within a wet period is not regarded as terminating the period. In this instance the values given under both amount and duration are cumulative. That is, occurrences listed under an amount of 0.25 inch rain per period or three days duration, are also included in the 0.05 inch and 0.01 inch and the two and one day groups respectively. The reason is that the distributions presented are essentially "open ended". They are compiled on the basis of being equal to or exceeding the value specified, but less than the next highest group.

The number of wet periods increase from 3.4 per month in late summer to 4.6 per month in spring. In all months about one-half of these periods are of two or more days duration. Except for March, August and September approximately one-third are three or more days, and only in March and November are about one-quarter of the wet periods of four or more days duration. The likelihood of wet periods greater than six days is small, particularly in winter, and in no month can such periods be expected more than one year in five. The months in which the longest west periods occur are February, April, May, October and December. With the exception of May, in each of these months periods of eight days or longer can be expected at least one year in 10.

The amount of rain received per wet period varies widely but only rarely exceeds 4.00 inches. In general the amount of rain per wet period is highest in summer and autumn. However, in all months the rainfall in about one-half of the periods is less than 0.50 inch and in at least one-third of the periods comprises falls which total between 0.25 inch and 0.99 inch. In more than 90 percent of the periods the rainfall is less than 2.00 inches, but except for July is greater than 1.00 inch for more than 10 percent of the periods.

Temperature: Seasonal distribution

Until the installation of a maximum-minimum thermometer at Elliot in 1968, no temperature records were available from within the study area.

However, an assumption of Elliot and Naseby State Forest record equivalence is found to be valid. The stations are located at the same altitude and Naseby State Forest is the closest station to the Upper Taieri area with a long-term continuous record. Network design by structural function analysis demonstrates that for point and areal estimates of monthly and annual mean temperature to within 10 percent of actual at the 95 percent confidence level, the measured Naseby State Forest data quite adequately represent the Upper Taieri area. Comparison of the measured post-1968 records for Elliot and Naseby State Forest further shows that the two stations have markedly similar characteristics. The results are given in Table 14 for the years 1968 and 1969.

Although the mean monthly temperature regimes for both stations are very similar, some slight differences are apparent on closer examination of the other listed parameters. Maximum and minimum temperatures are in general a little higher in summer for Elliot than for Naseby State Forest, and lower in winter. Mean daily maximum and minimum temperatures are generally lower throughout the year for Elliot, though for the period September 1968 to January 1969 the reverse is true for mean daily minimum values. It is thus concluded that the characteristics of monthly mean temperature and range of mean daily temperature are very similar, though some differences are evident when the extreme ranges are considered. Greater variability of the extremes (as defined by the range) is suspected for Elliot than has been previously recorded for Naseby State Forest.

However, since the most extensive use likely for the long-term temperature data is for calculation of the evapotranspiration component in a water balance, it is on this basis that final comparison of data from the two stations is made. With similar mean monthly temperature characteristics, the minor variations displayed by the extreme values are of little consequence in this analysis, though are acknowledged to be present. Potential evapotranspiration was calculated for Elliot and Naseby State Forest by the Thornthwaite (1948) method for each month of 1968 and 1969. The technique used was not entirely standard, however, but contained a built-in option of altitudinal corrections dependent on

TABLE 14: Paerau-Naseby State Forest temperatures (^{o}F) (1968-1969)

(a) Maximum temperature: (1968)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau									58.0	63.0	69.0	78.0
N.S.F.	86.0	88.5	83.0	74.0	67.8	54.8	51.6	59.2	61.0	66.0	69.0	76.6

(b) Minimum temperature: (1968)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau									23.0	24.0	29.0	29.0
N.S.F.	31.0	29.4	36.0	26.0	24.4	20.4	11.5	19.8	23.0	20.6	28.0	28.0

(c) Mean daily maximum temperature: (1968)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau									49.7	54.4	59.0	66.7
N.S.F.	69.7	71.9	67.9	54.4	53.6	44.4	40.4	49.0	52.3	56.5	60.5	64.4

(d) Mean daily minimum temperature: (1968)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau									32.0	34.6	39.1	41.5
N.S.F.	43.9	44.8	46.1	35.0	35.3	27.1	23.6	29.5	31.4	33.6	37.4	39.5

(a) Maximum temperature: (1969)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau	80.0	83.0	77.0	72.0	65.0	54.0	51.0	59.0	66.0	70.0	79.0	79.0
N.S.F.	78.3	82.0	76.5	70.0	66.0	53.4	53.7	60.6	67.4	72.0	80.5	80.2

(b) Minimum temperature: (1969)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau	34.0	31.0	30.0	25.0	17.0	12.0	14.0	20.0	28.0	22.0	26.0	28.0
N.S.F.	31.5	29.5	30.0	26.0	23.5	13.0	16.0	22.0	29.0	23.2	28.5	35.0

TABLE 14: Continued

(c) Mean daily maximum temperature: (1969)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau	66.3	69.7	65.3	56.4	48.0	42.9	43.5	50.2	56.7	55.6	68.5	67.9
N.S.F.	67.3	68.4	66.0	56.7	49.5	43.6	44.5	50.4	57.2	56.5	68.5	68.5

(d) Mean daily minimum temperature: (1969)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau	43.1	40.0	40.0	33.5	28.3	23.0	24.0	28.0	34.9	32.4	40.1	42.1
N.S.F.	42.8	41.8	41.8	36.2	32.5	25.1	26.8	33.7	35.9	34.8	41.1	44.2

(a) Mean monthly temperature: (1968)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau								39.6	40.9	44.5	49.1	54.1
N.S.F.								39.2	41.8	45.0	49.0	52.0

(b) Mean monthly temperature: (1969)

	J	F	M	A	M	J	J	A	S	O	N	D
Paerau	54.7	54.8	52.7	44.9	38.2	32.9	33.8	39.1	45.8	44.0	54.5	55.0
N.S.F.	55.0	55.1	53.9	46.4	41.0	34.4	35.6	39.5	46.6	45.6	54.8	56.3

variable seasonal lapse rates (Coulter, 1967; Mark, 1965). Values of potential evapotranspiration could thus be computed for any specified altitude from one set of basic data at a known height above sea level.

Results of the analysis are given in Table 15. The Table shows calculated values of potential evapotranspiration for Elliot and Naseby State Forest for the months August 1968 to November 1969, and for the cumulative 12 month period December 1968 to November 1969. Also shown are the theoretical differences in derived potential evapotranspiration between the two stations, for altitudes which vary from 1,800 to 3,400 feet in 200 and 400 feet intervals.

Monthly calculated differences remain essentially constant with increases in altitude, and for the period of record range from 0.00 to 0.38 inch. Maximum differences occur in May and December. For the cumulative values over the period December to November, Elliot-Naseby State Forest differences vary from 0.25 to 0.51 inch (1.1 and 2.2 percent respectively of the calculated totals).

On this evidence, it is concluded that the direct use of Naseby State Forest data to represent Elliot conditions would produce only a very minor but acceptable error in the calculation of water balance potential evapotranspiration values.

Measured mean monthly, seasonal and annual temperature data for the combined station records at I50001 Naseby State Forest and Elliot to the period 1923-69, are thus presented in Tables 16 and 17 and in Figures 25(a) and 26(a).

The temperatures show a well defined seasonal character with a summer maximum. Mean annual temperature is 46.3°F. Comparable mean seasonal values are 55.4°F for summer, 47.0°F in autumn, 36.1°F

TABLE 15: Comparison of Naseby State Forest and Paerau (Elliot) monthly and annual potential evapotranspiration for parts 1968 and 1969 (inches) (P = Paerau; N = Naseby State Forest)

A.

Altitude	*Station*	A	S	O	N	D	J	F	M
1800'	P	1.57	1.47	2.70	3.54	4.49	3.69	3.09	2.79
1800'	N	1.53	1.58	2.80	3.56	4.24	3.64	3.04	2.85
2000'	P	1.49	1.45	2.68	3.52	4.51	3.70	3.10	2.77
2000'	N	1.45	1.56	2.78	3.55	4.26	3.65	3.06	2.83
2400'	P	1.35	1.38	2.62	3.49	4.49	3.63	3.04	2.72
2400'	N	1.31	1.51	2.74	3.53	4.25	3.58	3.00	2.79
2800'	P	1.18	1.30	2.57	3.48	4.50	3.56	2.98	2.68
2800'	N	1.12	1.45	2.69	3.52	4.25	3.51	2.94	2.74
3000'	P	1.07	1.26	2.54	3.48	4.51	3.53	2.96	2.66
3000'	N	1.01	1.41	2.68	3.53	4.27	3.48	2.91	2.72
3400'	P	0.77	1.15	2.48	3.49	4.57	3.48	2.92	2.62
3400'	N	0.66	1.33	2.64	3.56	4.32	3.42	2.87	2.68

		A	M	J	J	A	S	O	N	Dec.-Nov.
1800'	P	1.59	0.78	0.22	0.34	1.00	1.46	1.92	3.50	24.87
1800'	N	1.68	1.00	0.33	0.49	0.98	1.47	2.04	3.45	25.21
2000'	P	1.57	0.76	0.14	0.26	0.93	1.45	1.90	3.48	24.57
2000'	N	1.66	0.98	0.27	0.42	0.92	1.46	2.03	3.43	24.97
2400	P	1.52	0.68	0	0.04	0.81	1.40	1.83	3.42	23.58
2400'	N	1.61	0.92	0.11	0.27	0.80	1.42	1.97	3.37	24.09
2800'	P	1.46	0.57	0	0	0.67	1.36	1.75	3.37	22.90
2800'	N	1.56	0.85	0	0.04	0.67	1.38	1.90	3.32	23.16
3000'	P	1.43	0.51	0	0	0.58	1.33	1.71	3.35	22.57
3000'	N	1.54	0.81	0	0	0.58	1.35	1.86	3.30	22.82
3400'	P	1.37	0.34	0	0	0.33	1.28	1.62	3.31	21.84
3400'	N	1.48	0.72	0	0	0.37	1.31	1.78	3.25	22.20

B. Difference in potential evapotranspiration for Paerau and Naseby State Forest at altitude indicated:-

Altitude	A	S	O	N	D	J	F	M
1800'	0.04	0.11	0.10	0.02	0.25	0.05	0.05	0.06
2000'	0.04	0.11	0.10	0.03	0.25	0.05	0.04	0.06
2400'	0.04	0.13	0.12	0.04	0.24	0.05	0.04	0.07
2800'	0.06	0.15	0.12	0.04	0.25	0.05	0.04	0.06
3000'	0.06	0.15	0.14	0.05	0.24	0.05	0.05	0.06
3400'	0.11	0.18	0.16	0.07	0.25	0.06	0.05	0.06

	A	M	J	J	A	S	O	N	Dec.-Nov.
1800'	0.07	0.22	0.11	0.15	0.02	0.01	0.12	0.05	0.34
2000'	0.09	0.22	0.13	0.16	0.01	0.01	0.13	0.05	0.40
2400'	0.09	0.24	0.11	0.23	0.01	0.02	0.14	0.05	0.51
2800'	0.10	0.28	0	0.04	0	0.02	0.15	0.05	0.26
3000'	0.11	0.30	0	0	0	0.02	0.15	0.05	0.25
3400'	0.11	0.38	0	0	0.04	0.03	0.16	0.06	0.36

TABLE 16: Elliot/Naseby State Forest measured mean monthly temperature record (°F) - Naseby State Forest (1923-68); R.A.W. Elliot (1969)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1923	52.1	51.5	51.1	43.6	40.5	36.3	28.9	34.9	43.7	45.4	56.2	57.2
1924	58.6	57.6	52.3	51.7	42.0	36.3	36.3	38.1	46.6	49.9	52.8	53.0
1925	57.6	53.9	50.1	47.7	38.7	32.7	35.7	34.9	39.2	46.8	48.0	53.0
1926	56.1	52.9	52.0	51.9	39.1	37.7	35.9	37.1	43.6	44.9	46.6	52.2
1927	57.3	55.7	50.8	45.8	39.7	29.9	35.2	35.5	41.3	45.9	46.3	53.2
1928	56.9	57.9	54.1	49.2	40.2	36.0	37.5	38.3	42.4	46.5	49.7	52.5
1929	54.6	55.4	52.0	46.9	39.0	38.2	34.8	38.2	44.2	50.9	50.8	51.4
1930	52.7	57.2	50.0	47.3	41.6	35.2	32.3	35.1	40.3	43.8	46.3	54.3
1931	53.6	55.1	52.0	45.8	43.4	35.2	33.6	36.4	39.0	47.6	51.0	54.2
1932	52.6	54.6	52.2	48.7	40.8	36.6	39.0	35.8	41.8	47.4	50.4	52.5
1933	56.1	56.8	53.9	44.8	39.1	34.2	35.2	38.0	42.8	46.8	49.2	56.2
1934	53.6	57.5	51.1	49.3	39.8	37.4	33.2	37.6	43.0	47.4	53.4	60.6
1935	58.0	59.6	55.1	48.5	39.9	35.4	33.6	39.2	39.0	46.0	48.0	59.3
1936	56.2	55.0	47.0	49.8	41.0	39.2	35.7	41.0	43.0	48.4	49.2	53.9
1937	53.4	52.3	53.9	46.8	43.8	34.4	35.2	40.4	42.8	47.2	54.2	57.6
1938	60.0	62.1	57.0	51.8	43.2	36.4	30.1	38.6	44.0	49.5	51.0	51.7
1939	53.3	56.8	56.0	49.0	42.8	40.0	32.5	34.8	43.4	46.2	52.0	56.6
1940	57.6	52.3	52.3	45.0	40.8	38.0	36.8	40.2	43.7	47.6	49.2	56.6
1941	57.6	58.1	54.4	46.2	42.9	32.0	35.8	34.4	44.0	46.8	50.4	52.1
1942	55.5	53.6	51.7	48.4	42.1	38.8	35.9	39.8	44.5	49.6	50.8	52.6
1943	55.9	55.8	50.9	47.6	40.0	37.2	31.3	34.8	40.3	46.1	52.7	55.6
1944	56.8	54.6	51.0	48.6	39.4	36.5	36.8	38.5	42.2	46.9	49.3	50.8
1945	56.5	54.8	51.2	47.7	39.2	34.0	33.2	40.6	42.3	44.1	52.9	48.0
1946	55.4	56.6	54.3	47.6	42.2	36.7	38.4	40.0	43.7	45.8	44.0	51.8
1947	54.8	55.0	56.6	45.8	43.1	35.7	34.3	40.8	-	46.6	53.9	56.2
1948	59.8	56.5	53.2	45.6	41.2	35.5	37.2	39.2	42.4	46.8	48.7	55.9
1949	53.8	58.3	51.1	44.0	39.5	34.8	37.2	37.1	43.3	50.3	51.1	51.9
1950	56.4	55.4	50.8	45.7	43.8	35.0	36.6	35.4	44.2	49.1	52.0	53.8
1951	54.8	54.5	53.4	45.8	38.3	31.6	35.8	38.4	43.4	46.2	49.6	50.6
1952	53.6	56.4	51.4	47.3	40.0	34.6	32.7	39.0	44.2	48.4	48.0	-
1953	54.0	53.4	51.2	46.6	40.4	34.1	33.6	38.1	42.5	46.4	51.6	54.5
1954	56.3	58.7	52.8	44.0	42.6	39.4	33.5	36.0	42.3	47.6	54.5	54.6
1955	57.2	56.1	52.6	49.0	43.0	34.7	31.6	38.6	44.8	49.2	49.6	56.7
1956	62.2	55.4	51.9	52.6	39.6	37.5	34.1	37.2	43.6	47.4	49.5	53.2
1957	56.0	58.0	55.4	47.2	40.8	38.0	33.3	37.8	43.1	44.7	53.0	51.2
1958	53.5	56.8	53.7	44.6	40.3	38.1	31.2	38.0	42.1	50.0	53.4	54.6
1959	59.6	56.2	53.1	48.9	35.2	37.6	36.2	37.6	44.2	44.2	52.4	55.8
1960	58.9	55.2	49.4	46.4	40.8	35.8	37.4	37.4	41.8	48.8	49.8	53.0
1961	57.0	56.1	50.0	46.9	40.0	35.2	34.6	36.9	40.4	52.1	51.6	58.2
1962	59.8	54.9	53.6	45.6	44.5	39.0	36.9	39.2	42.8	49.0	51.0	54.8
1963	59.2	57.2	51.1	44.0	42.3	33.2	32.4	35.7	42.0	50.0	47.9	51.6
1964	53.4	55.9	51.9	46.2	38.6	35.9	36.7	38.2	43.4	46.7	50.1	56.6
1965	56.6	53.0	51.6	46.3	39.5	37.2	32.6	36.2	44.4	46.3	49.4	54.4
1966	54.9	59.6	55.6	49.0	38.8	36.6	34.2	37.1	43.0	48.0	49.3	53.3
1967	56.2	56.6	54.0	47.7	43.2	37.2	35.6	41.2	40.6	47.6	46.7	54.0
1968	56.8	58.3	57.0	44.7	44.4	35.8	32.0	39.2	41.8	45.0	49.0	52.0
1969	54.7	54.8	52.7	44.9	38.2	32.9	33.8	39.1	45.8	44.0	54.5	53.4
Mean:	56.2	55.8	52.4	47.3	40.8	36.0	34.7	37.6	42.8	47.4	50.5	54.2

TABLE 17: Elliot/Naseby State Forest measured mean seasonal and annual temperature record (°F) - Naseby State Forest (1923-68); Elliot (1969)

Year	Summer (Dec-Feb)	Autumn (Mch-May)	Winter (June-Aug.)	Spring (Sept.-Nov.)	Annual
1923	52.6	45.1	33.4	48.4	45.1
1924	57.8	48.7	36.9	49.8	47.9
1925	54.8	45.5	34.4	44.7	44.9
1926	54.0	47.7	36.9	45.0	45.8
1927	55.1	45.4	33.5	44.5	44.7
1928	56.0	47.8	37.3	46.2	46.6
1929	54.2	46.0	37.1	48.6	46.4
1930	53.8	46.3	34.2	43.5	44.7
1931	54.3	47.1	35.1	45.9	45.6
1932	53.8	47.2	37.1	46.5	46.0
1933	55.1	45.9	35.8	46.3	46.1
1934	55.8	46.7	36.1	47.9	47.0
1935	59.4	47.8	36.1	44.3	46.8
1936	56.8	45.9	38.6	46.9	46.6
1937	53.2	48.2	36.7	48.1	46.8
1938	59.9	50.7	35.0	48.2	48.0
1939	53.9	49.3	35.8	47.2	47.0
1940	55.5	46.0	38.3	46.8	46.7
1941	57.4	47.8	34.1	47.1	46.2
1942	53.7	47.4	38.2	48.3	46.9
1943	54.8	46.2	34.4	46.4	45.7
1944	55.7	46.3	37.3	46.1	46.0
1945	54.0	46.0	35.9	46.4	45.4
1946	53.3	48.0	38.4	44.5	46.4
1947	53.9	48.5	36.9	47.8	47.1
1948	57.5	46.7	37.3	46.0	46.8
1949	56.0	44.9	36.4	48.2	46.0
1950	54.6	46.8	35.7	48.4	46.5
1951	54.4	45.8	34.1	46.4	44.9
1952	53.5	46.2	35.4	46.9	45.8
1953	53.9	46.1	35.3	46.8	45.5
1954	56.5	46.5	36.3	48.1	46.9
1955	56.0	48.2	35.0	47.9	46.9
1956	58.1	48.0	36.3	46.8	47.0
1957	55.7	47.8	36.4	46.9	46.5
1958	53.8	46.2	35.8	48.5	46.4
1959	56.8	45.7	37.1	46.9	46.8
1960	56.6	45.5	36.9	46.8	46.2
1961	55.4	45.6	35.6	48.0	46.6
1962	57.6	47.9	38.4	47.6	47.6
1963	57.1	45.8	33.8	46.6	45.6
1964	53.6	45.6	36.9	46.7	46.1
1965	55.4	45.8	35.3	46.7	45.6
1966	56.3	47.8	36.0	46.8	46.6
1967	55.4	48.3	38.0	45.0	46.7
1968	56.4	48.7	35.7	45.3	46.3
1969	53.8	45.3	35.3	48.1	45.7
Mean:	55.4	47.0	36.1	46.9	46.3

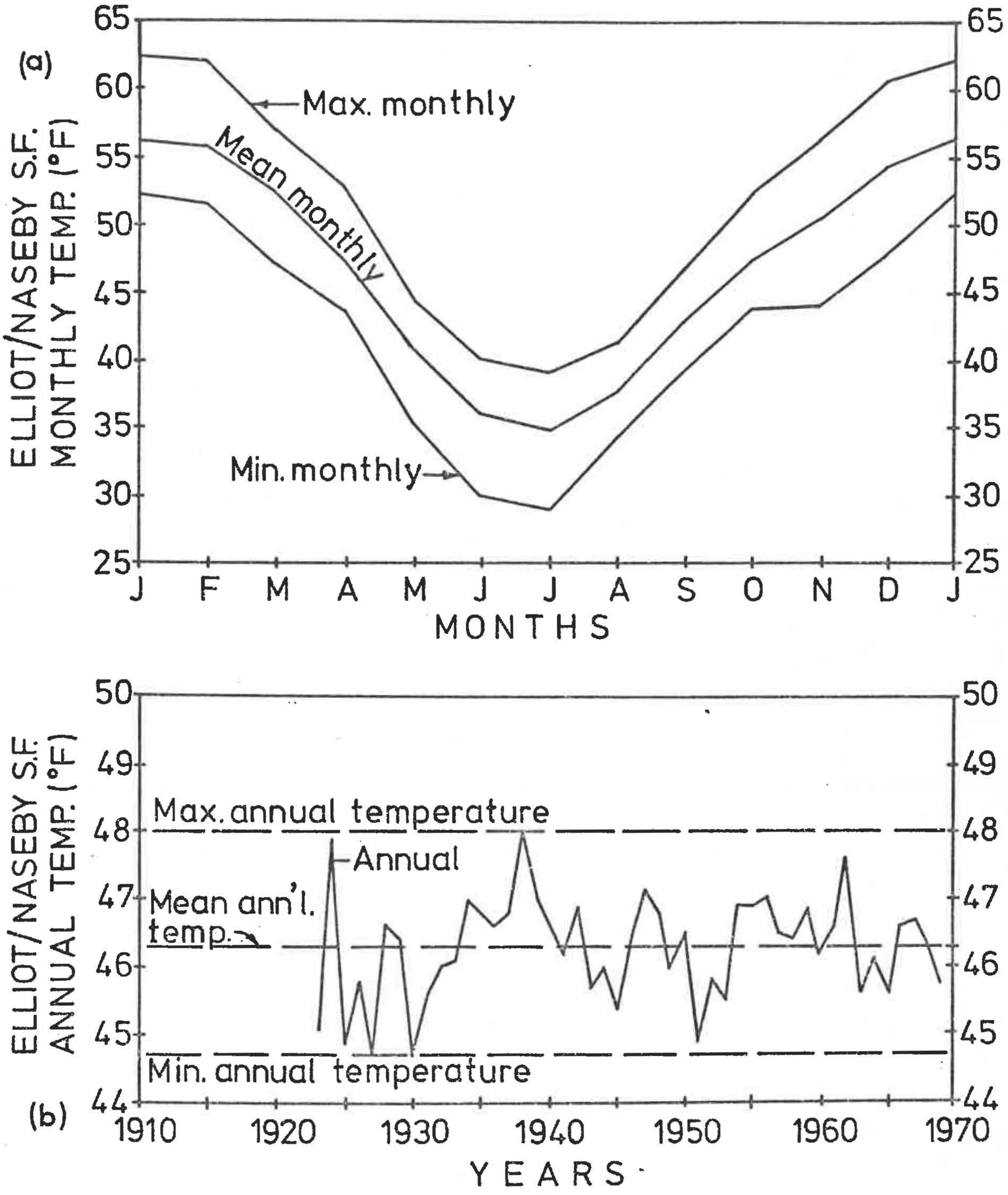


FIGURE 25: Elliot/Naseby State Forest annual and monthly mean temperature distribution - °F (1923-1969)

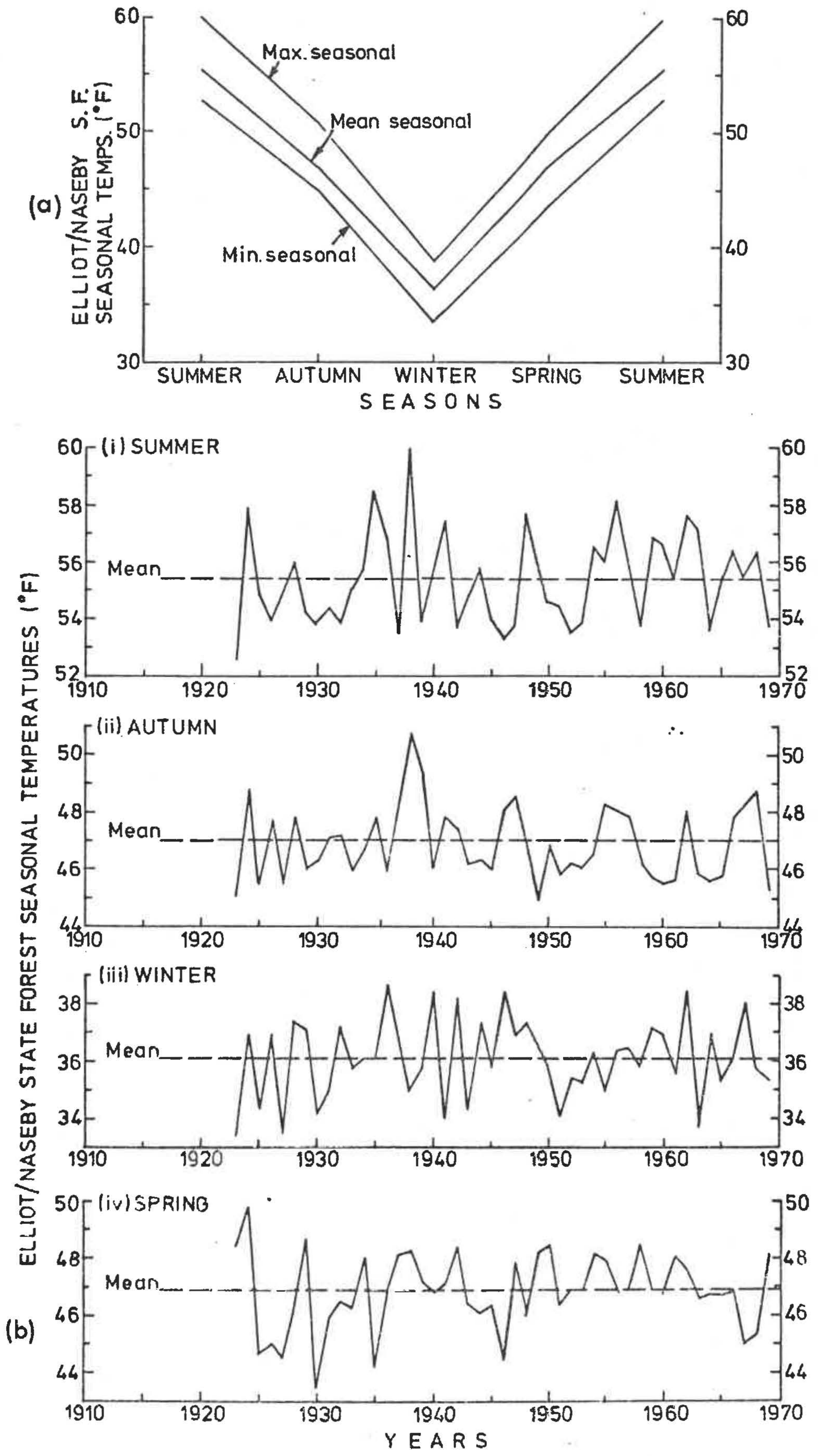


FIGURE 26: Elliot/Naseby State Forest seasonal mean temperature distribution - °F (1923-1969)

in winter and 46.9°F for spring. Figures 25 and 26 also show the mean monthly, seasonal and annual temperature extremes for the period of measured record. The maximum mean annual temperature occurred in 1938 with a value of 48.0°F - 1.7°F or 3.7 percent above average. The highest mean monthly temperature of 62.2°F in January 1956 is 10 percent above the mean figure for January. Similarly, the maximum mean seasonal value recorded in summer 1938 of 59.9°F is 7.7 percent above the mean summer figure.

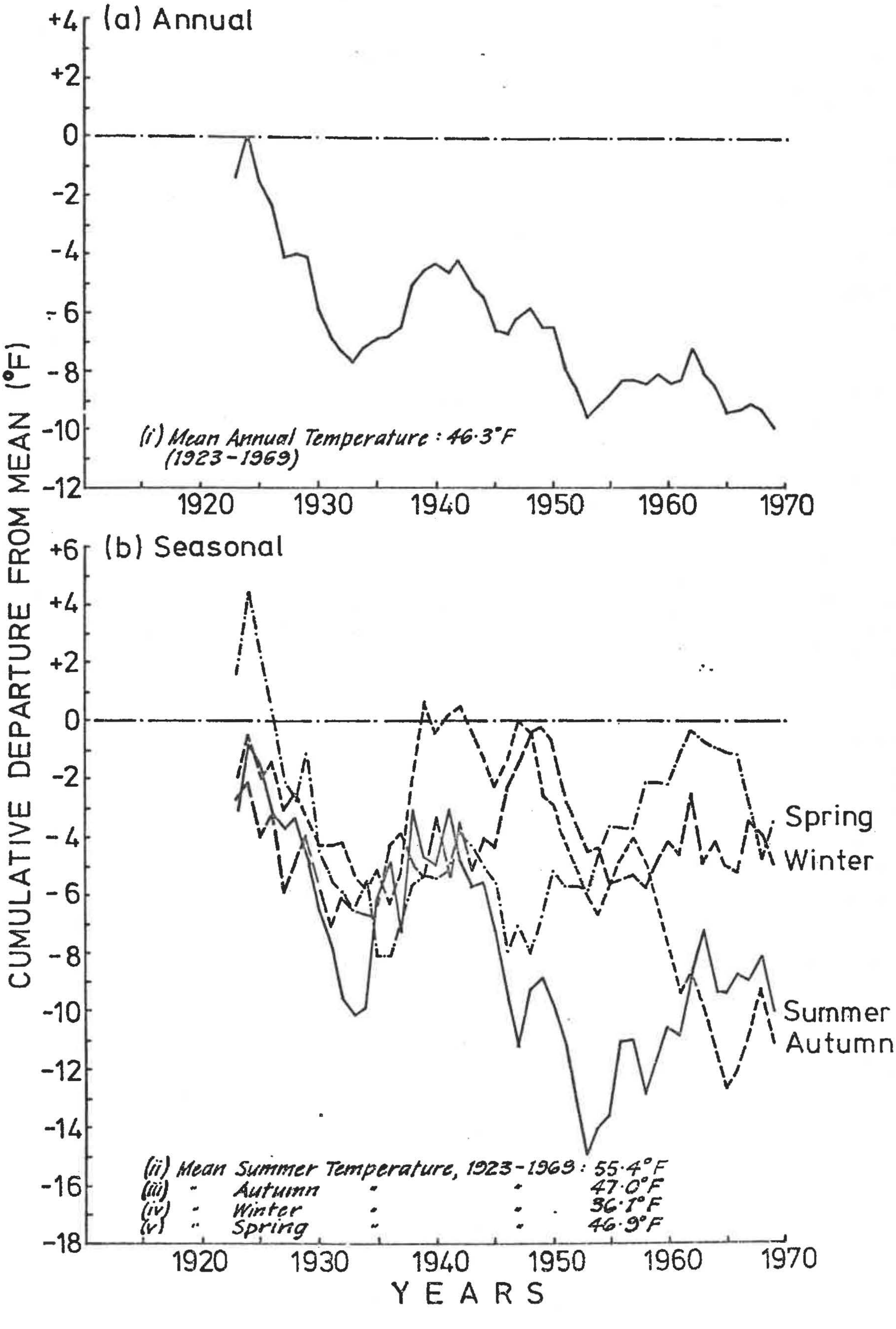
To consider the minimum mean recorded temperatures, the 1927 and 1930 mean annual value of 44.7°F is 1.6°F or 3.5 percent below average. On a monthly basis the lowest mean monthly temperature of 28.9°F in July 1923 is 17 percent below the July mean. The minimum seasonal value is 33.4°F, recorded in winter 1923.

The 1938 mean annual temperature maximum resulted from maximum recorded summer and autumn values, above average spring values, but below average winter temperatures. Similarly, the 1927 and 1930 minimum mean annual temperatures were a direct consequence of minimum or near minimum winter and spring values.

Although not discussed here, a comparison with the previously derived rainfall graphs (Figures 20 and 21) is of interest. The simultaneous study of such curves can be of assistance when attempting to define the relative significance of the major climatic elements which contribute to either events of high or low mean flow in an area, or climatic drought occurrences.

Temperature: Variability

Cumulative departure curves from the mean are shown in Figure 27 for the 1923-69 Elliot/Naseby State Forest mean annual and seasonal



(i) Mean Annual Temperature : 46·3°F (1923–1969)

(ii) Mean Summer Temperature, 1923–1969 : 55·4°F
(iii) " Autumn " " 47·0°F
(iv) " Winter " " 36·1°F
(v) " Spring " " 46·9°F

FIGURE 27: Departure from mean: Elliot/Naseby State Forest annual and seasonal temperatures (1923-1969)

temperatures. Their interpretation is as already described for similar precipitation curves.

The curves show an alternating series of years with above and below average mean annual temperature (46.3°F), with an average fluctuation periodicity of nine years for above average periods and 11 years for those years below average. Comparison of trends with those given by the precipitation data does not show any marked in or out of phase pattern. That is, for annual data at least, the association of either above or below average rainfalls with below average temperatures (or vice versa), is a matter of conjecture from the data presented. However, it is intended to continue this study at a later date though using data from the seasonal trends. A detailed investigation here of such an aspect is not considered relevant to the present study.

Long-term fluctuations in the pattern of mean annual temperature are difficult to define with any degree of accuracy. However, Figure 25 and temperature data from other stations in the same climatic region suggest that maxima have occurred in the early 1910s, late 1930s and early 1960s, with minima in the mid 1920s, and late 1940s. Over recent years these trends accord with those reported by Grant (1969), with the period 1963-69 of generally below average mean annual temperature and rainfall.

Warm periods in the Upper Taieri area were 1903-11, 1934-42, and 1954-62. Cooler periods of below average mean temperature comprised the intervening years 1912-33, 1943-53 and 1963-69. With Figures 27(a) and 27(b) drawn to the same time scale, the relative importance of seasonal values in the overall pattern of annual change can again be readily determined if needed.

Temperature: Frequency curves

Frequency curves derived for the 1923-69 Elliot/Naseby State Forest record are shown in Figures 28 to 31. Figures 28 and 29 display frequency curves calculated on a mean monthly, seasonal and annual basis for the 1923-69 record, while Figures 30 and 31 show monthly curves of maximum and minimum temperatures for the period 1930-69. The latter graphs are included since they display readily usable frequency distributions of the monthly extremes.

Of more immediate value to design problems would have been to plot the mean monthly, seasonal and annual evapotranspiration frequency curves instead of temperature. However, such a procedure would presuppose a preference for a particular method of evapotranspiration derivation for the Upper Taieri area, which could well be proved in error when additional data became available.

Temperature values for a stated occurrence frequency can be readily obtained from the presented curves, for subsequent use in any method of evapotranspiration derivation. This approach becomes of added importance for design purposes when the calculation of open water evaporation from known evaporation-potential evapotranspiration relationships is considered.

Streamflow: Seasonal distribution

Water resource investigations and studies involve a determination of the source, extent, magnitude and dependability of water resources, and an evaluation of opportunities for control and development (Clark & Bruce, 1966). The most direct measure of the surface water resources of a region are records of streamflow. Measured runoff from drainage basins thus establishes the best basis for comparison of runoff characteristics, provides a historic record for the station and furnishes a basis

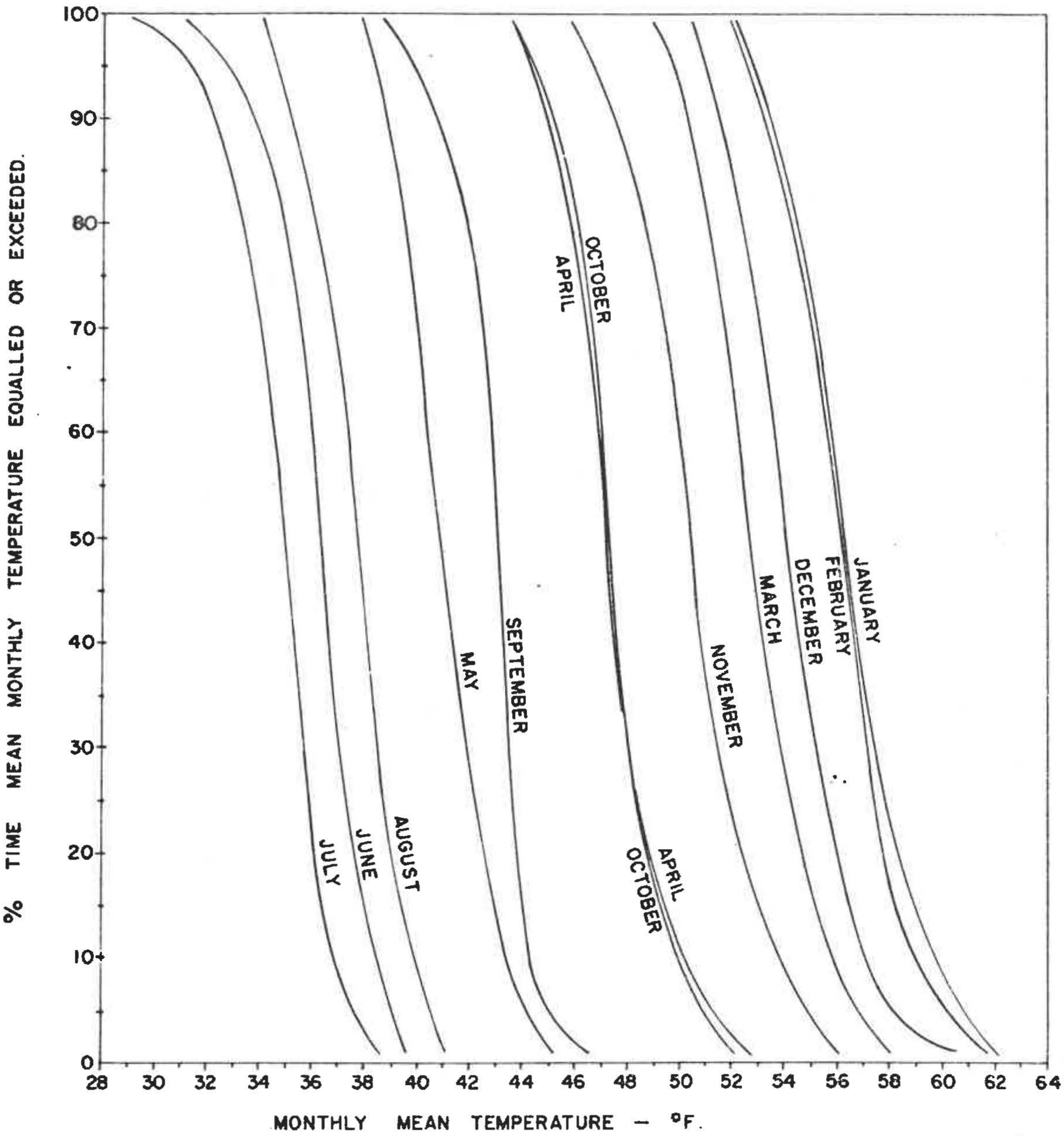


FIGURE 28: Percentage time Elliot/Naseby State Forest mean monthly temperature equalled or exceeded (1923-1969)

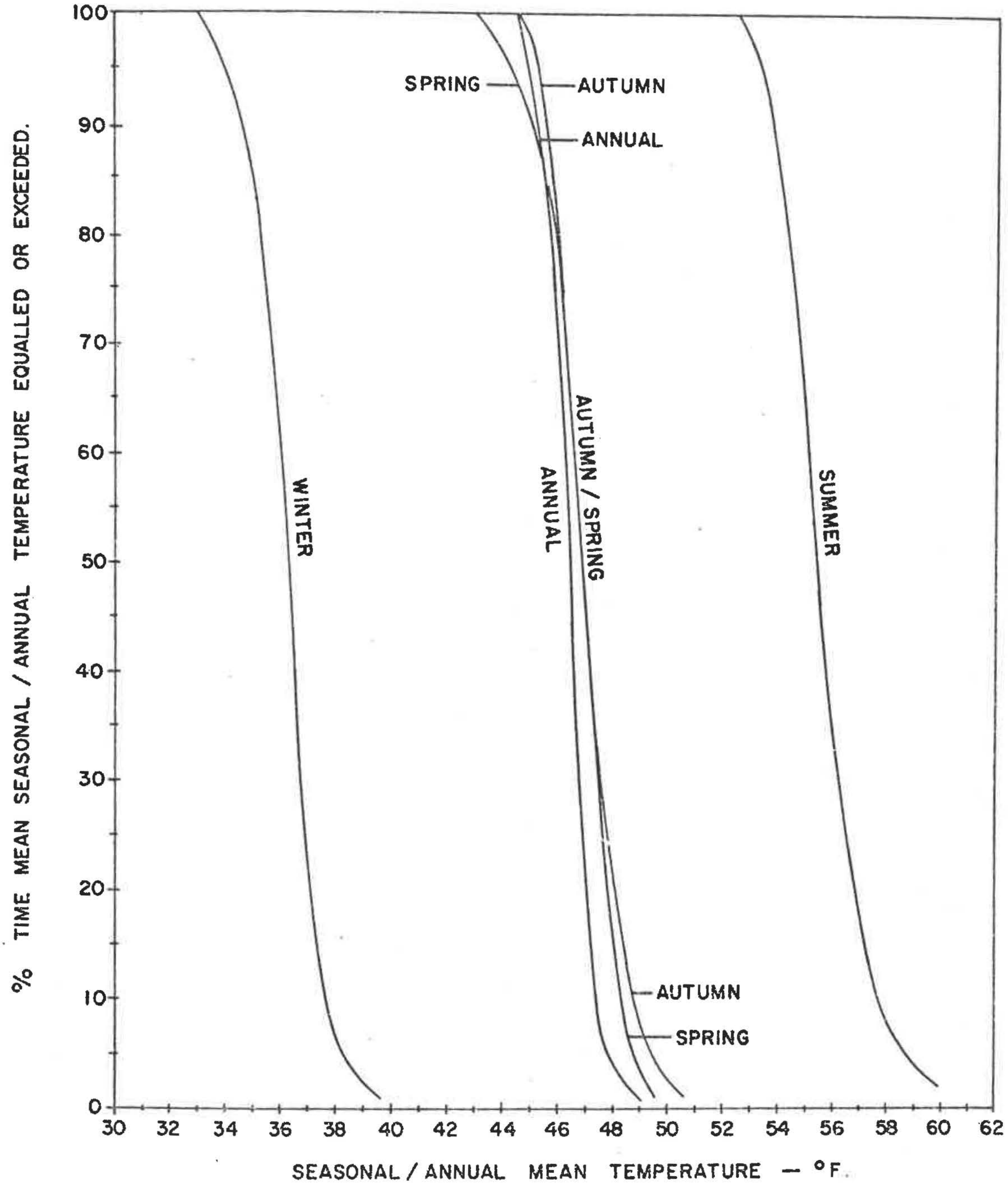


FIGURE 29: Percentage time Elliot/Naseby State Forest mean seasonal and annual temperature equalled or exceeded (1923-1969)

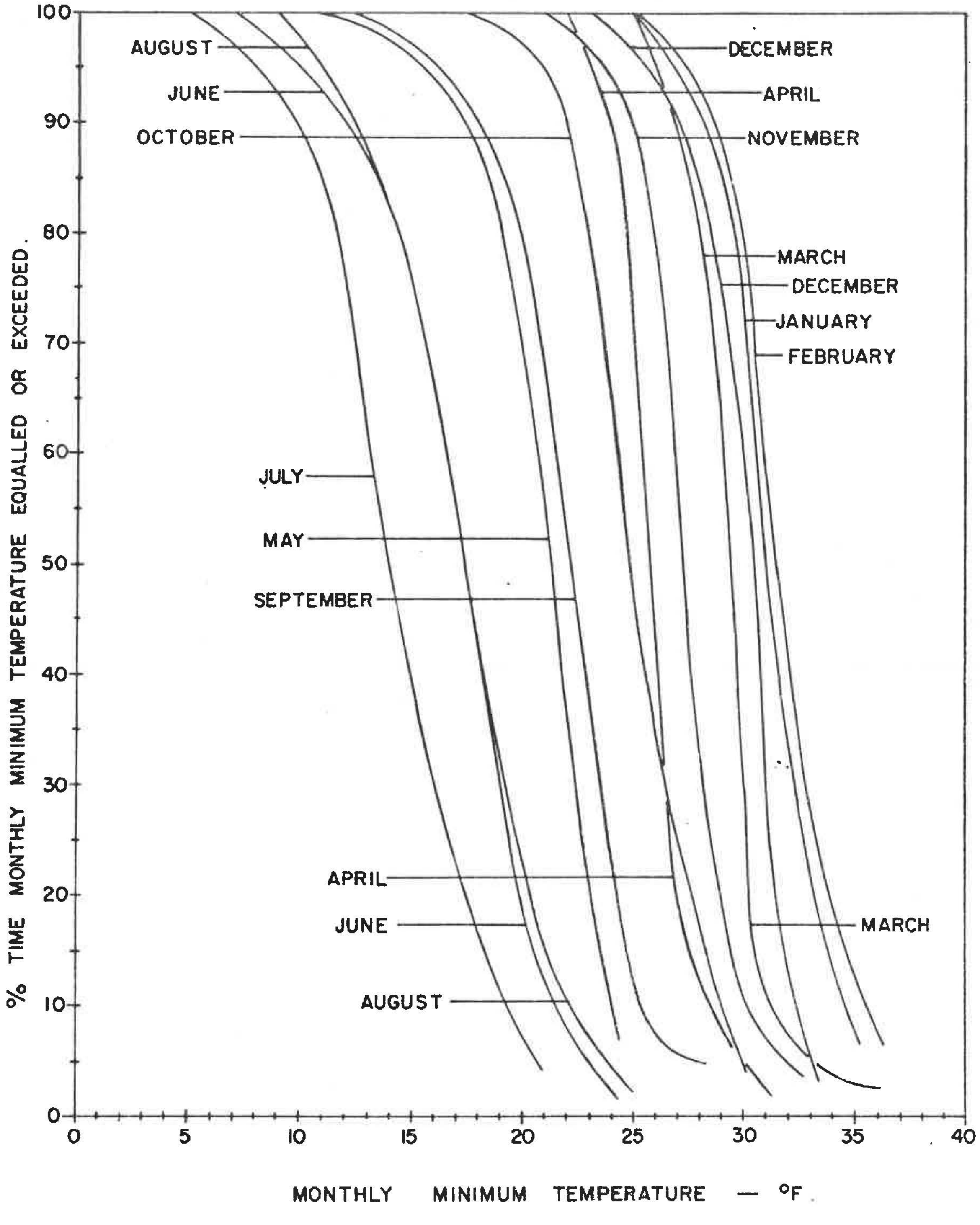


FIGURE 30: Percentage time Elliot/Naseby State Forest monthly minimum temperature equalled or exceeded (1930-1969)

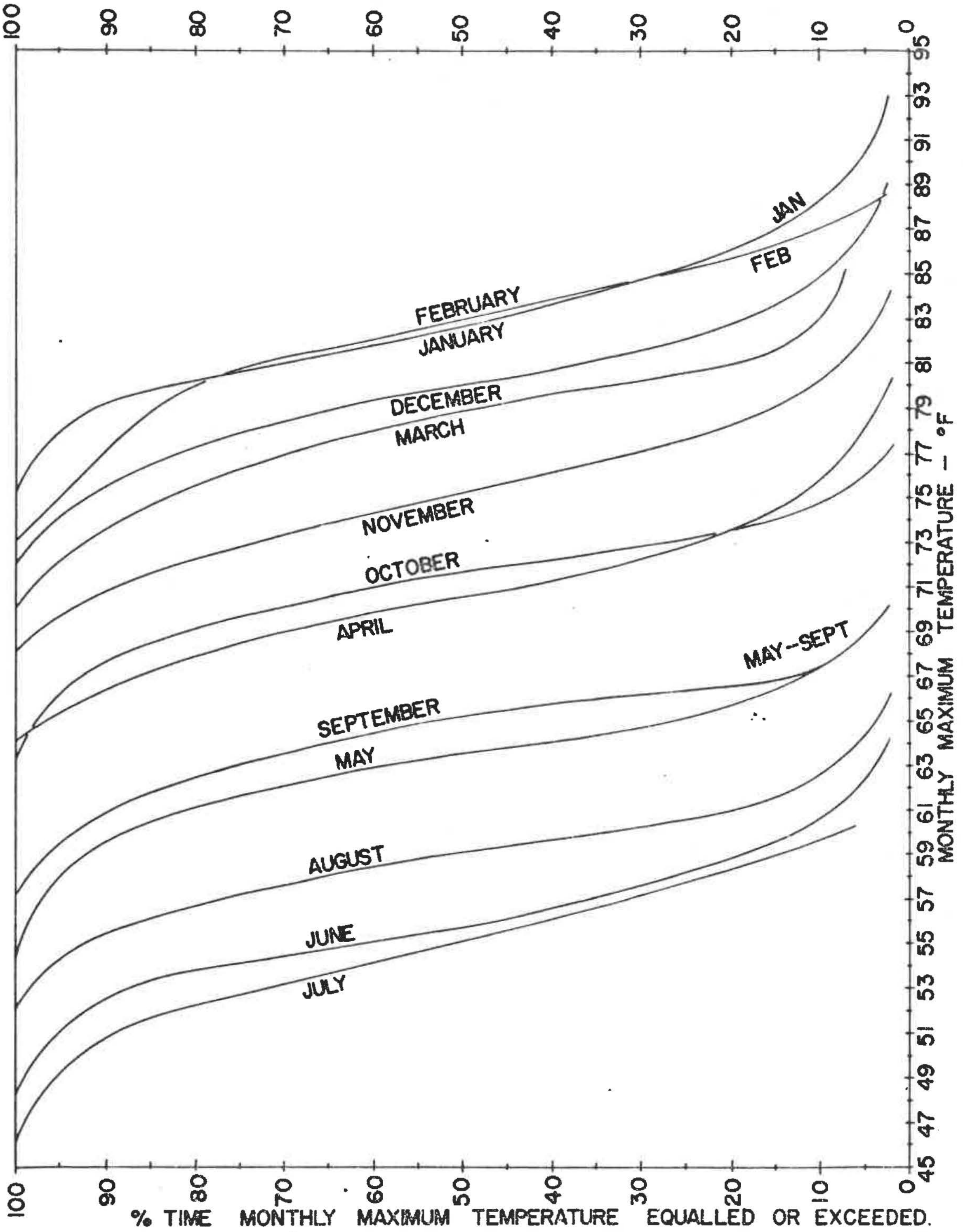


FIGURE 31: Percentage time Elliot/Naseby State Forest monthly maximum temperature equalled or exceeded (1930-1969)

on which to estimate the magnitude and distribution of future flows (Dawdy, *et al.* 1970).

All the available continuous flow records and discrete discharge measurements in the Upper Taieri area were collated from Ministry of Works summaries, and subjected to quality screening before analysis. Stage-discharge rating tables and other relevant site information for the six stations with measured data, are given in Table 18 and require no further discussion.

To plan the utilisation of streamflow, the first requirement is a quantitative description of the flow characteristics. The characteristics most indicative of the potential supply are the mean and variability of monthly and annual flows as obtained from continuous records at a gauging station (Riggs, 1969). Measured mean monthly, seasonal, January-March, October-March and annual mean discharges and yields for the Taieri River at Paerau and Patearoa-Paerau Bridges, and the Loganburn at Paerau, are presented in Tables 19 to 22. The periods of record available are 1912-13, 1916-28, 1936-39, 1941-44 and 1947-50 for the Taieri River at Paerau Bridge, and 1966-69 for all three stations.

Detailed discussion of the results is not intended at this point, though the data are important for engineering design pruposes. However, for the total catchment to Paerau Bridge average annual discharge is calculated as 288 cusecs. On a monthly mean basis streamflow varies between a minimum of 21.3 cusecs for March 1920 and a maximum of 1322 cusecs for September 1939. Annual mean discharge varies between 126 cusecs (1950) and 478 cusecs (1939). The general characteristics of total catchment mean flows to Paerau Bridge are further presented in Figures 32 and 33. Similar curves are not shown for Patearoa-Paerau Bridge and the Loganburn because of the small amount of measured data.

TABLE 18: Stage-Discharge Rating Tables - 1/10 ft by cusecs

1. *Taieri River 743000 at Paerau Rd. Br. (site No. 74316); Reference S145:667261; R.L. Zero 66.12 ft (Ass.)*

(a) Period 20.5.08 to 18.2.49: (R.L. Zero 68.12 ft Ass)

G.H. (Ft)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	13	18	23	28	35	43	52	62	73	84
1	96	109	123	138	155	174	194	215	237	260
2	284	309	335	362	390	419	449	479	509	539
3	569	599	629	659	689	719	749	779	810	842
4	874	906	938	970	1003	1036	1070	1105	1140	1175
5	1210	1244	1279	1315	1352	1389	1427	1466	1506	1546
6	1586	1626	1666	1707	1748	1789	1830	1871	1912	1953
7	1995	2038	2082	2126	2171	2217	2264	2312	2360	2408
8	2456	2504	2552	2600	2649	2698				

(b) Period 26.7.55 to 18.4.67: (R.L. Zero 66.12 ft Ass)

1										
2					38	43	51	61	73	87
3	102	118	135	153	172	192	212	233	254	276
4	298	321	344	368	392	416	441	466	491	516
5	542	568	594	620	647	674	702	730		

(Note: Staff gauge lowered 2.00 ft on 24.5.62. All gaugings for period 26.7.55 to 24.5.62 are plotted as G.H. + 2.00 ft)

2. *Taieri River 743000 at Patearoa-Paerau Br. (74314); M.R. S145:675374; R.L. Zero 1189.19 ft*

(a) Period 1.1.66 to 31.12.69:

0								15	23	32
1	43	54	65	76	88	100	112	124	137	151
2	165	180	196	213	231	250	270	291	313	336
3	360	384	409	434	460	486	512	539	566	594
4	622	650	678	707	737	768	801	836	873	912
5	953	996	1041	1088	1137	1188	1241	1296	1353	1413
6	1477	1545	1618	1695	1776	1860	1946	2034	2123	

3. *Taieri River 743000 at Upper Styx Valley Bridge (74317); M.R. S33:5518; R.L. Zero 92.87 ft Ass.*

(a) Period 24.5.62 to 31.12.66:

1		28	35	42	49	57	64	72	79	87
2	95	103	111	119	128	136	145	154	163	173
3	183	193	203	214	224	234	244	255	266	277
4	288	300	312	325	338	352	366	381	396	412
5	428									

TABLE 18: Continued

(b) Period 1.1.67 to 31.12.69:

G.H. (Ft)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0									16	21
1	26	32	38	44	50	56	62	69	76	83
2	90	98	106	114	122	130	138	146	154	162
3	171	180	189	198	207	216	225	234	244	255
4	266	278	291	305	319	334				

(Notes: (1) Change in gauging cross-section on 5.1.67;
(2) R.L. Zero changed to 92.73 Ft Ass. on 2.9.69. Rating Q equivalent to G.H. + 0.14 Ft from 2.9.69 to 31.12.69)

4. *Loganburn 743860 at Paerau Br. (74346); M.R. S144:624217;*
R.L. Zero 91.40 Ft Ass.

(a) Period 1.1.66 to 11.3.69:

0					1.0	2.5	6.0	11.5	18.9	28.1
1	39.0	51.6	65.8	81	97	115	135	157	181	206
2	232	259	287	316	346	377	409	441	473	505
3	537	569	601	633	665	698	731			

(b) Period 11.3.69 to 31.12.69:

0			0.9	5.0	9.7	15.2	21.6	29.2	38.0	47.8
1	58.6	70.6	84	99	116	135	156	179	204	232
2	262	292	323	355	388	422	457			

5. *Styx Creek 743840 at Paerau (74345); M.R. S33:6726;*
R.L. Zero 76.97 Ft Ass.

(a) Period 1.1.66 to 31.12.66:

1	6	9	14	20	27	35	43			

(b) Period 1.1.67 to 24.7.67:

1	5	7.5	10	15	21					

(c) Period 24.7.67 to 7.9.67:

1	6	9	14	20	27	35	43			

(d) Period 7.9.67 to 22.7.68:

0									3.5	6
1	9	12	16	22	28	36	45	55	65	75

(e) Period 22.7.68 to 31.12.69:

0									3.8	6.5
1	9.7	13.3	17.5	22.4	29.2	37.7	46.8	56.7	67.5	80.5

TABLE 18: Continued

6\. *Serpentine Creek 743870 at McDonald's Br. (74347); M.R. S33:5724; R.L. Zero 88.66 Ft Ass.*

(a) *Period 24.5.62 to 31.12.69:*

G.H. (Ft)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1										1.60
2	1.70	1.80	1.90	2.10	2.30	2.60	3.00	3.40	3.90	4.50
3	5.20	6.00	6.90	7.90	9.10	10.5	12.1	13.9	15.9	18.0
4	20.4	23.3	26.9	31.4	37.0	43.8	52.0	61.8	73.4	

TABLE 19: *Taieri River at Paerau Bridge measured mean discharge record (cusecs): 1912-1913; 1916-1928; 1936-1939; 1941-1944; 1947-1950; 1.6.66-31.5.69*

(catchment area above station - 233 square miles)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1912	158	151	296	157	408	625	395	324	620	831	549	175
1913	91.0	106	200	286	457	379	320	573	702	440	398	531
1916	106	79.4	105	124	141	193	230	373	584	302	287	95.9
1917	50.6	237	155	106	377	420	211	168	369	486	149	238
1918	222	61.9	242	196	321	476	177	548	647	616	511	375
1919	533	316	58.6	295	197	349	424	534	539	489	285	270
1920	145	27.8	21.3	39.5	103	361	610	279	458	557	484	131
1921	34.5	51.6	125	296	306	231	256	388	333	352	272	157
1922	286	86.9	169	234	199	105	143	204	332	173	266	355
1923	248	171	207	475	622	235	194	269	939	506	157	45.4
1924	54.0	31.6	27.1	35.1	137	170	180	305	258	325	185	67.0
1925	61.6	27.7	103	189	114	53.8	326	391	587	936	329	434
1926	118	281	220	131	496	250	198	263	612	586	456	405
1927	174	96.7	212	396	527	167	396	289	559	558	387	181
1928	78.3	44.6	34.4	234	215	107	443	198	322	831	354	112
1936	90.1	76.5	268	317	460	197	285	465	785	439	408	511
1937	358	641	670	468	873	430	214	603	559	437	256	129
1938	126	22.1	21.5	53.7	162	371	224	289	395	345	327	507
1939	426	199	102	90.8	204	328	320	345	1322	1100	951	343
1941	110	103	159	242	264	320	317	406	508	483	556	524
1942	406	221	269	376	290	219	253	379	374	461	487	304
1943	172	69.0	254	245	305	186	124	153	671	748	349	91.3
1944	25.9	187	171	436	227	452	450	568	458	458	355	440
1947	338	96.7	77.6	96.0	96.0	109	149	236	388	667	248	109
1948	96.0	96.0	96.0	95.6	111	120	149	116	151	367	220	177
1949	38.9	44.7	169	188	123	260	527	281	293	400	108	50.8
1950	74.0	66.7	48.7	98.0	40.9	93.1	242	154	286	153	102	151
1966	-	-	-	-	-	135	272	258	440	206	147	248
1967	68.6	44.6	52.3	85.8	484	301	168	173	283	190	226	111
1968	45.6	43.3	253	550	262	402	221	394	457	623	305	99.6
1969	66.0	79.6	86.8	338	379	-	-	-	-	-	-	-
Mean:	160	125	162	229	297	268	281	331	508	502	337	246
Mean: (inches)	0.792	0.559	0.801	1.097	1.469	1.283	1.390	1.638	2.432	2.484	1.614	1.217

(maxima and minima underlined)

TABLE 20: Taieri River at Paerau Bridge measured mean seasonal discharge record (cusecs): 1912-1913; 1916-1928; 1936-1939; 1941-1944; 1947-1950; 1.6.66-31.5.69

Year	Dec-Feb (Summer)	Mch-May (Autumn)	Jun-Aug (Winter)	Sept-Nov (Spring)	Jan-Mch	Oct-Mch	Annual* (Calendar yrs)
;1912	-	288	446	668	203	-	391
1912-13;1913	124	314	424	513	133	328	375
;1916	-	123	266	390	97.2	-	218
1916-17;1917	124	214	264	336	145	187	247
1917-18;1918	178	254	399	592	179	236	367
1918-19;1919	411	182	437	438	302	402	358
1919-20;1920	150	54.7	417	500	65.6	208	269
1920-21;1921	73.0	242	292	319	71.0	232	234
1921-22;1922	180	200	151	256	184	222	214
1922-23;1923	261	434	233	534	210	238	339
1923-24;1924	43.9	66.7	219	256	37.7	138	148
1924-25;1925	52.9	135	259	621	65.4	130	298
1925-26;1926	277	284	237	552	204	388	335
1926-27;1927	229	378	285	502	163	325	330
1927-28;1928	102	160	251	506	52.6	215	249
;1936	-	349	317	543	146	-	359
1936-37;1937	498	673	416	418	553	503	469
1937-38;1938	94.8	79.3	294	355	57.8	167	238
1938-39;1939	383	133	331	1124	244	320	478
;1941	-	221	348	515	124	-	334
1941-42;1942	389	311	284	441	301	412	337
1942-43;1943	185	268	154	591	168	294	281
1943-44;1944	99.6	276	490	424	127	262	352
;1947	-	89.8	165	437	173	-	218
1947-48;1948	100	101	128	248	96.0	220	150
1948-49;1949	88.4	160	357	268	85.5	171	208
1949-50;1950	63.7	62.1	164	180	63.0	126	126
1966/1967	123	209	223	264	55.5	129	205
1967/1968	67.0	353	213	233	116	145	217
1968/1969	81.8	267	338	463	77.4	212	288
Mean:	175	229	293	450	150	248	288
Mean (inches/ month):	0.856	1.122	1.437	2.177	0.717	1.245	1.398

(* 1966 to 1969 data from 1 June to 31 May)

(Maxima and minima underlined)

TABLE 21: Taieri River at Patearoa-Paerau Bridge measured mean discharge record (cusecs): 1.6.66-31.5.69 (Catchment area above station - 285 sq miles)

(a) Mean monthly data:

Year	J	F	M	A	M	J	J	A	S	O	N	D
1966	-	-	-	-	-	143	285	271	459	216	155	259
1967	73.3	48.4	56.5	91.4	50.6	315	177	182	297	200	238	117
1968	49.5	47.1	266	575	275	421	232	413	478	651	320	106
1969	70.7	85.0	92.5	354	396	-	-	-	-	-	-	-
Mean:	64.5	60.2	138	340	392	293	231	289	411	356	238	161
Mean(ins):	0.261	0.220	0.558	1.331	1.586	1.147	0.934	1.169	1.609	1.440	0.932	0.651

(b) Mean seasonal and annual data:

Year	Dec-Feb (Summer)	March-May (Autumn)	Jun-Aug. (Winter)	Sept.-Nov. (Spring)	Jan-Mar.	Oct.-Mar.	Annual*
1966/67	130	219	234	276	59.7	136	215
1967/68	71.7	370	223	244	122	153	228
1968/69	87.2	280	354	484	82.6	222	302
Mean:	96.3	290	270	335	88.1	170	248
Mean (ins/month):	0.377	1.158	1.083	1.327	0.346	0.677	0.984

(* Data from 1 June to 31 May)

TABLE 22: Loganburn at Paerau measured mean discharge record (cusecs): 1.6.66-31.5.69 (Catchment area above station - 58 sq miles)

(a) Mean monthly data:

Year	J	F	M	A	M	J	J	A	S	O	N	D
1966	-	-	-	-	-	28.2	41.4	45.0	74.2	51.2	20.1	30.4
1967	16.8	6.0	6.9	14.2	67.4	56.4	32.2	25.1	53.4	28.4	55.9	23.6
1968	7.2	4.7	78.0	120	56.5	125	58.9	102	70.6	102	37.5	11.9
1969	22.7	2.6	1.5	30.6	62.6	-	-	-	-	-	-	-
Mean:	15.6	4.43	28.8	54.9	62.2	69.8	44.2	57.4	66.1	60.5	37.8	21.9
Mean(ins):	0.310	0.080	0.572	1.055	1.235	1.341	0.878	1.140	1.270	1.201	0.726	0.435

(b) Mean seasonal and annual data:

Year	Dec-Feb (Summer)	March-May (Autumn)	Jun-Aug. (Winter)	Sept.-Nov. (Spring)	Jan-Mar.	Oct.-Mar.	Annual*
1966/67	18.2	29.7	38.3	48.5	10.1	22.2	33.7
1967/68	12.0	84.4	37.7	45.7	30.5	33.1	45.0
1968/69	12.8	31.6	94.7	70.5	9.2	30.2	52.6
Mean:	14.3	48.6	56.9	54.9	16.6	28.5	43.8
Mean (ins/month):	0.275	0.954	1.119	1.066	0.321	0.554	0.854

(* Data from 1 June to 31 May)

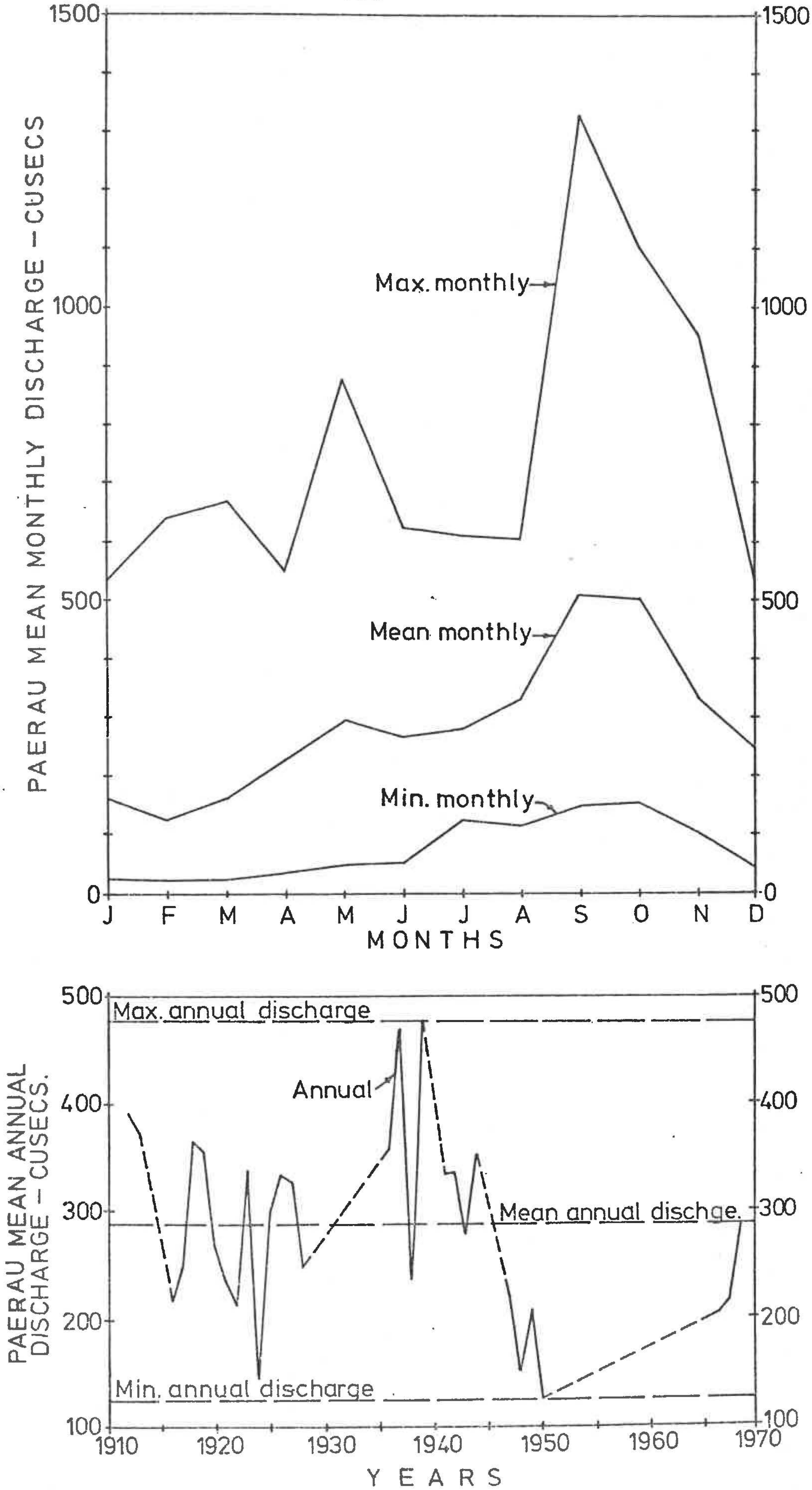


FIGURE 32: Paerau Bridge mean annual and mean monthly discharge distribution (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1966-69)

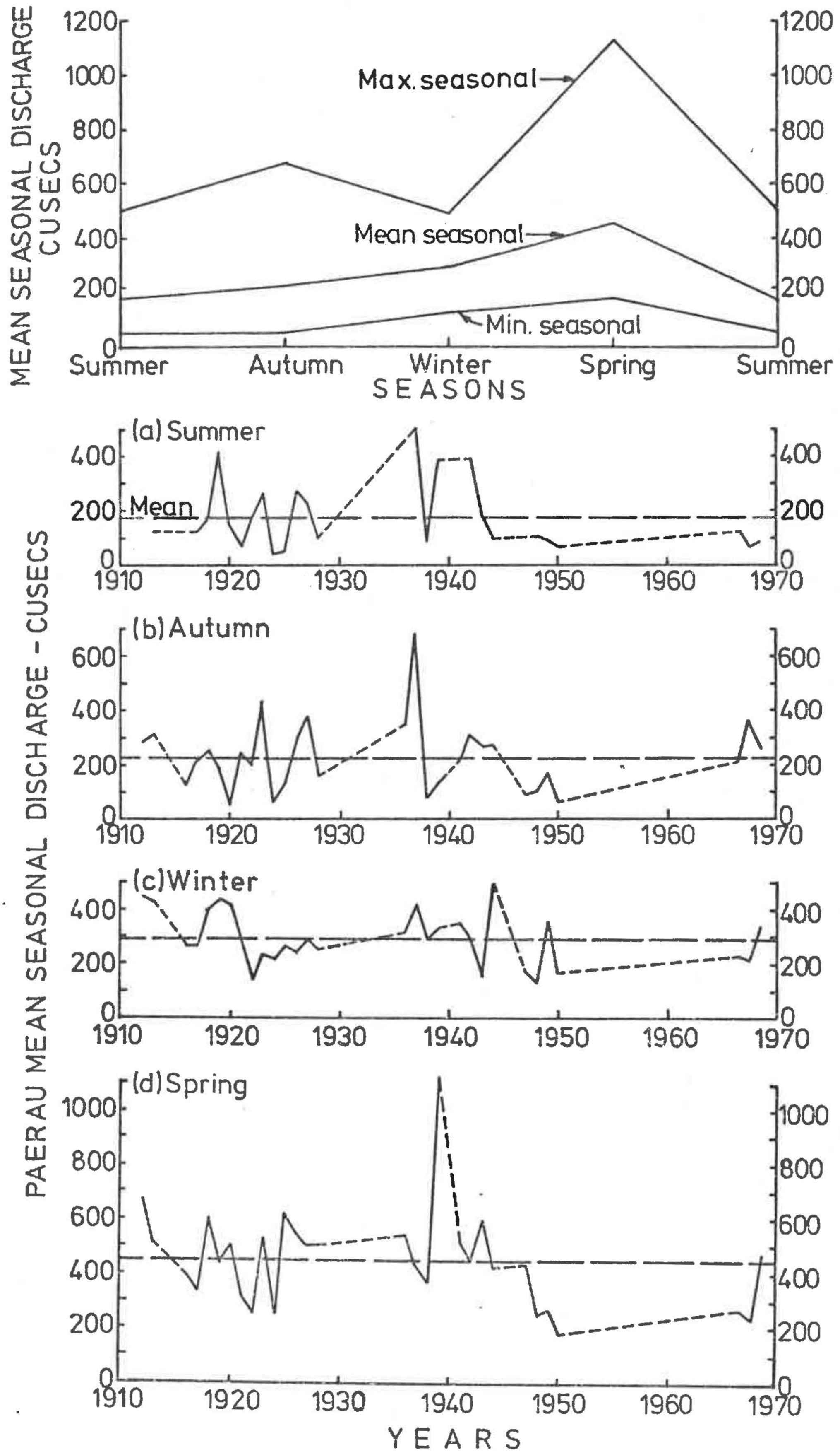


FIGURE 33: Paerau Bridge mean seasonal discharge distribution (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1966-69)

Streamflow shows a well defined seasonal pattern, though the marked spring maximum and summer minimum do not reflect the presented mean rainfall distribution for the area. Mean spring rainfall is only 0.80 of the summer mean rainfall, but mean spring runoff for the total basin is 2.6 times summer mean discharge. The spring maximum is undoubtedly the result of thaw and snowmelt from the upper catchment, releasing winter accumulated precipitation and moisture from surface storage. Kidson (1950) reports that snowfall frequency in the Upper Taieri area varies from above 15 to above 30 days per year dependent on altitude. Snowfall is mainly concentrated in the period May-September, though the frequency and amount vary considerably from year to year. However, contrary to the conclusion of Haupt (1960) from studies in Idaho, it cannot be concluded from the data available that rainfall at the time of spring thaw has created a more critical peak runoff condition than snowmelt alone in the Upper Taieri area.

Recent studies by Hutchinson & Simmers (1971) of individual flood hydrographs recorded at the Paerau Bridge gauging station reveal a further characteristic of total catchment outflows, which reflects the signigicant modifying influence on net system output imposed by catchment storage. From time of travel estimates, flood hydrographs are abnormally attenuated for a basin of this size. Peak discharges occur at the Paerau Bridge between two and four days after each rainstorm recorded at Elliot.

Figures 32 and 33 further demonstrate the runoff extremes for the period of record. The 1939 mean annual runoff maximum resulted from maximum recorded spring flows which followed above average mean winter discharges, though the basic causes are largely unexplained by the precipitation records already described. The causes could well have been a combination of an isolated rainfall event unrecorded by the Paerau gauge, the demonstrated above average winter precipitation accumulation, below average winter temperatures and above average spring temperatures (Figures 21 and 26).

The second highest maximum (1937), resulted from peak mean flows for summer and autumn, though the mean winter and spring values which followed were only average. Reason for the event is shown by Figure 21, where summer 1937 is seen to have had the second highest rainfall on record for that season. The annual rainfall maximum in 1919 produced high winter runoff, but only a secondary maximum in the mean annual discharge record. The maximum mean winter flow recorded in 1933 was caused by above average precipitation and temperatures, but on an annual basis produced a runoff value which was only moderately above average.

The 1950 minimum recorded mean annual discharge resulted from minimum or near minimum flows for all seasons, but although the rainfalls recorded for autumn, winter and spring were below average, the summer falls were slightly above average. Although not recorded, it is concluded from the general flow characteristics that the 1911 minimum annual rainfall would not have produced minimum flow values for the year. Rainfalls were lowest during the period of least mean flow and approximately average for winter and spring. Other comparisons which relate recorded flows to mean temperature and rainfall over the long-term record can be made as desired by reference to the presented graphs.

Careful study of such curves can give a valuable insight into the basic hydrology of any river basin, and in this instance gives some indication of the approximate likely magnitude of mean seasonal or annual flows not recorded. Figures 20 and 21 suggest that high flow conditions could be expected for 1945, 1955, 1957, 1958, 1961 and 1963. The existence of such conditions has been confirmed by downstream discharge records and flood reports.

Streamflow: Variability

The measured data for Paerau Bridge show that mean monthly runoff is more variable in the summer and autumn months than for the remainder of the year. Maximum variability generally occurs in the period December to March, doubtless due to the type of rainfall experienced during this period and the state of soil moisture levels at the time of runoff producing rains. There is a tendency for the variability to have a negative correlation with mean flow amount, in that months which show higher mean flows have the lower variabilities and vice versa.

Cumulative departure curves from the mean are given in Figure 34 for the Paerau Bridge mean seasonal and annual flows. The curve derivation and principles of their use are as described for the precipitation and temperature records. The curves show an alternating series of years with above and below average mean annual discharge, which generally reflects the trends already found for precipitation. The broken record limits the value of Figure 34 and as such the direct determination of short- and long-term fluctuation periodicities, without use of the rainfall data, has not been attempted.

However, it can be seen that periods of below average mean annual discharge occurred during the late 1940s to at least 1950 (c.f. below average annual rainfalls for the period 1946-54) and again from the middle to late 1960s. Some recovery of the most recent trend is evident during 1968, but current records indicate that the below average condition has subsequently resumed up to at least early 1971. 1968 provides only a temporary respite. With figures 34(a) and (b) drawn to the same time scale, the relative importance of individual seasonal values in the overall pattern of annual change can again be readily determined.

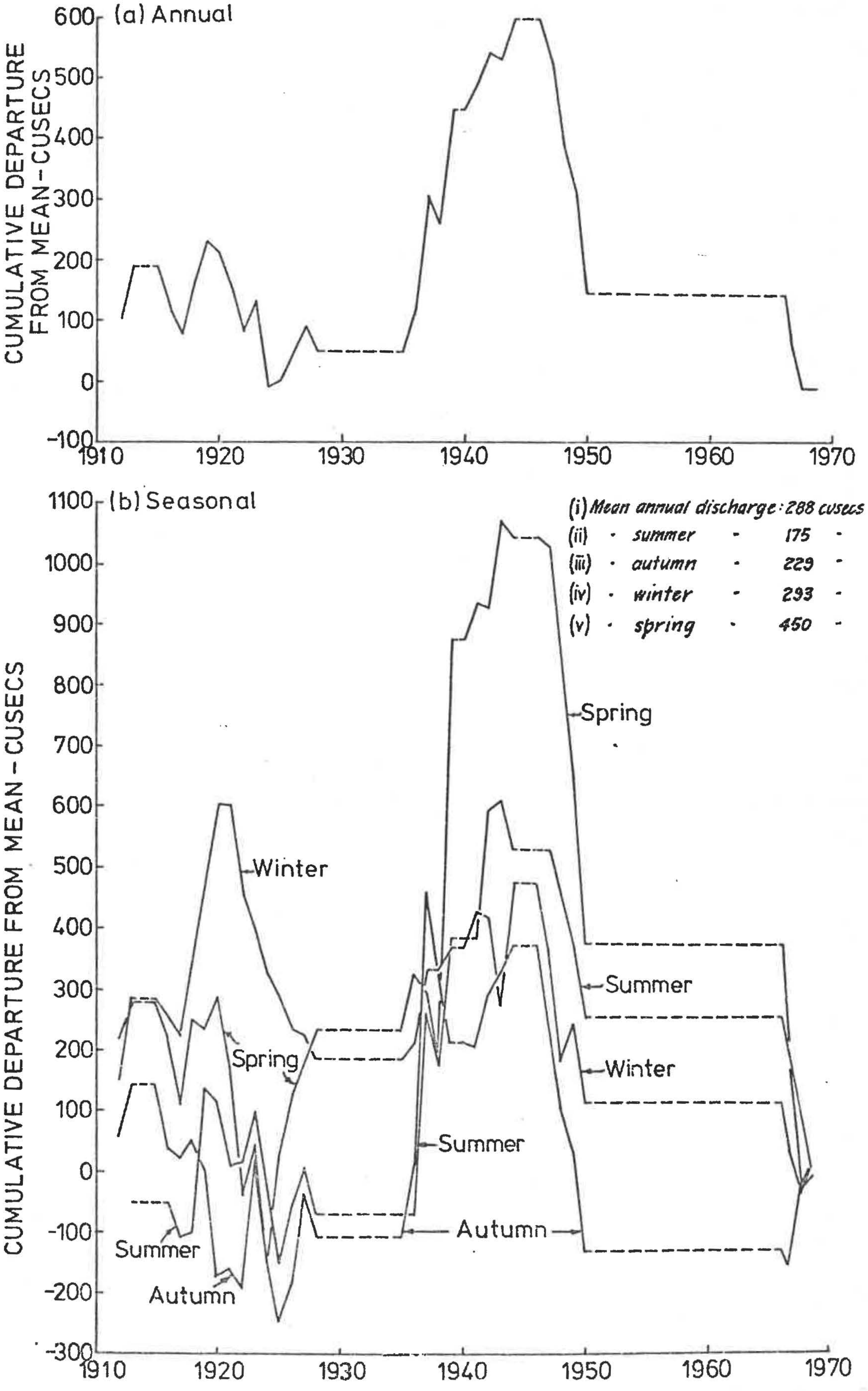


FIGURE 34: Departure from mean: Paerau Bridge mean annual and mean seasonal discharges - cusecs (broken record 1912-1969)

Streamflow: Frequency curves

Percentage exceedence curves of mean monthly, seasonal and annual discharges for the Paerau Bridge station are given in Figures 35 and 36. When used with caution the curves may be used to indicate possible return periods of known mean flows, or conversely, to determine the mean flow values for stated return periods.

In all but three months (January, February and March) there is a 50 percent chance that a total catchment mean monthly outflow of at least 200 cusecs will be recorded. The chance of recording mean monthly flows in excess of 300 cusecs is much lower, though in all months this amount can be expected in about 10 percent of years. Mean monthly flows in excess of 650 cusecs are infrequent, and occur only in September and October more often than 10 percent of the time. For the lower mean monthly flows, January-March record values of less than 100 cusecs for up to 35 percent of the time.

From the seasonal and annual curves of Figure 36, in approximately fifteen of the thirty years of record mean annual discharge varies between 250 and 350 cusecs - a fluctuation range of 100 cusecs between lower and upper quartile values. Further, in 90 percent of years the mean annual flow exceeds 200 cusecs. Mean seasonal discharges also vary between moderate limits, and values of less than 50 cusecs at the Paerau Bridge can be expected in only one year out of twenty. In three-quarters of the years the total basin mean summer flows can be expected to exceed 75 cusecs and spring mean flows 330 cusecs.

Comparison of the above data with the long-term average flow values given in Tables 19 and 20, demonstrates the dangers of accepting long-term average discharges for use in engineering design. The data in

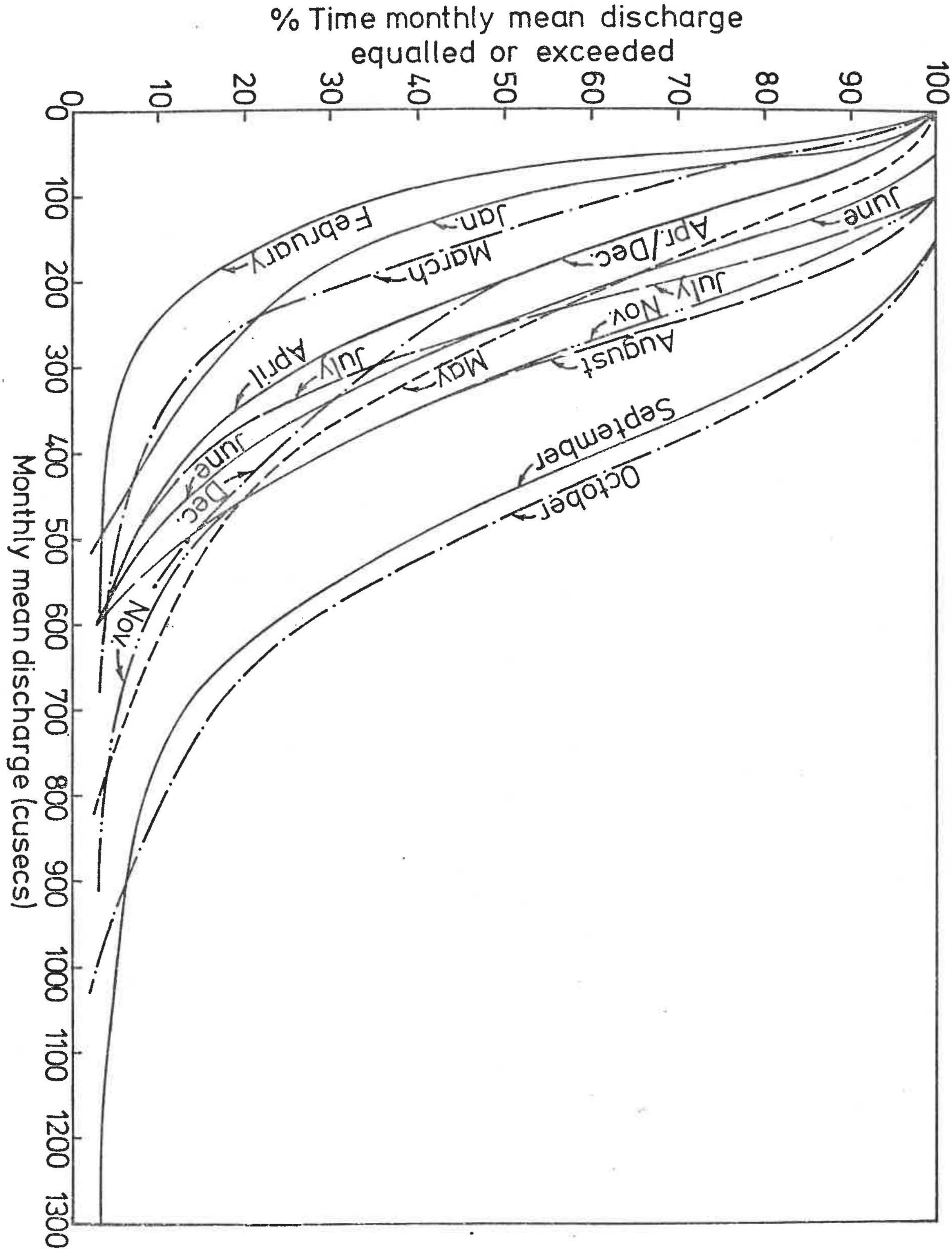


FIGURE 35: Percentage time Paerau Bridge monthly mean discharge equalled or exceeded (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1966-69)

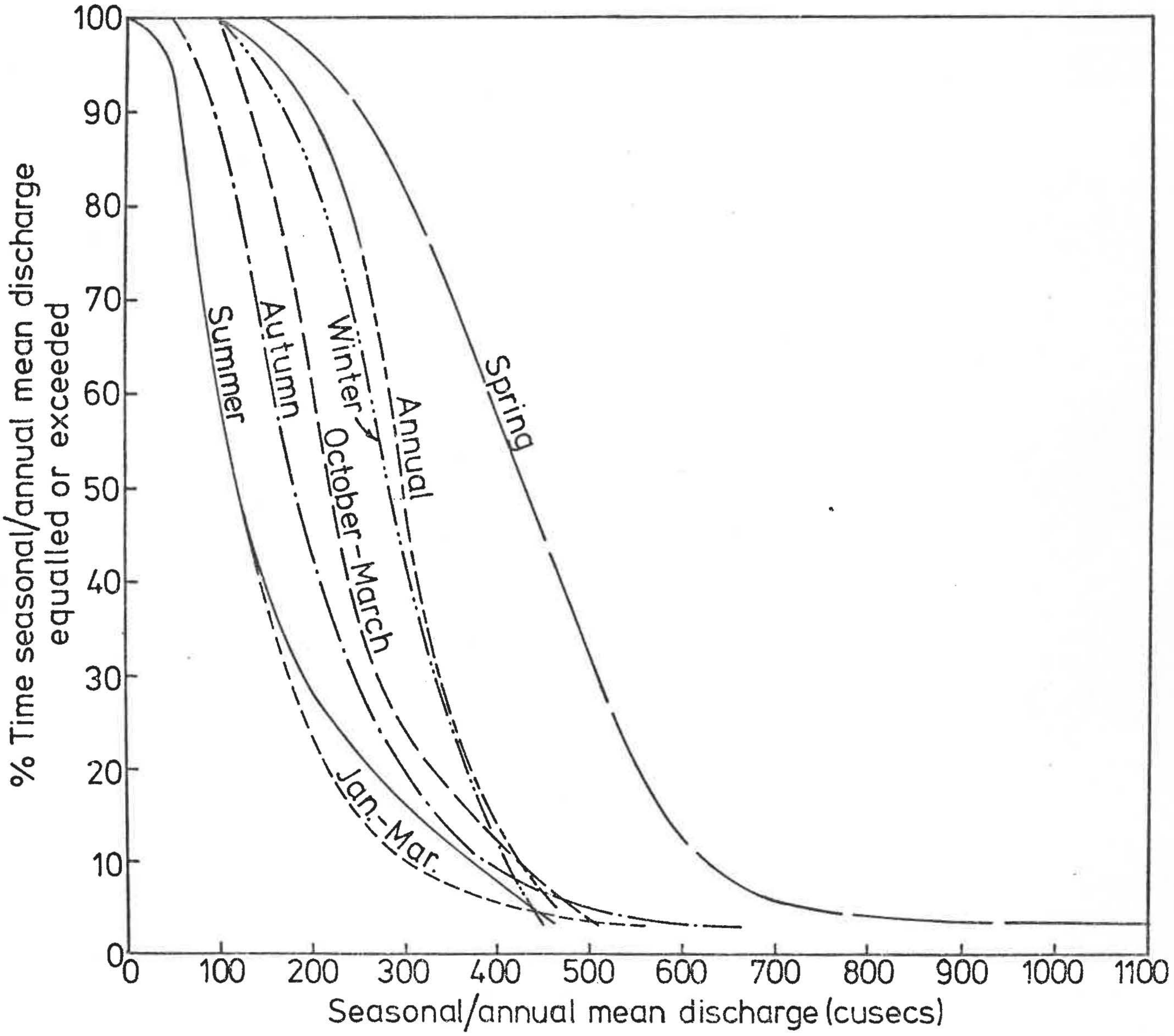


FIGURE 36: Percentage time Paerau Bridge seasonal and annual mean discharge record equalled or exceeded (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1966-69)

Figures 35 and 36 display skewed distributions about the long-term mean. Further, there is a tendency for a strong positive correlation between the degree of skewness and the data variability - months of greatest variability show the greatest departure from a normal distribution. The skewness decreases as the time interval increases, and is less for mean seasonal discharges than for the individual monthly values. The mean annual data display an almost normal distribution about the long-period mean.

From the results obtained it is thus suggested that the median discharge is a more meaningful statistic than the mean for purposes of engineering design and logical comparison of catchment flow characteristics. However, a major problem is that the median is not as readily calculated as the mean, and this tends to reduce its immediate value.

For example, Figure 35 shows that for mean February discharges at Paerau Bridge, the flow equals or exceeds 73 cusecs for 50 percent of the time. However, the average mean monthly discharge for February is calculated as 125 cusecs, and the Figure shows that this value is equalled or exceeded only 30 percent of the time over the period of record. That is, for 70 percent of the total period the mean February flow is less than the calculated long-term average. Other monthly or seasonal values may be calculated as required from Figures 35 and 36 and Tables 19 and 20, though the 40 percent negative departure of the median value from the long-term mean displayed by the February data is the maximum experienced for this station.

PRECISION OF PARAMETER ESTIMATES AND COMPARISON WITH REQUIRED PRECISION LEVELS

General:

The previous data presentation format provides valuable basic information on parameter estimates for design purposes and also gives a necessary insight into the general hydrology of the Upper Taieri area. However, if records are short the parameters may be poor estimates of the population parameters. Ultimate value for engineering design can thus only be achieved when the available measured data are considered in terms of the first study objective. That is, to what degree of precision are the parameters estimated, and how does this compare with the required precision levels?

Statistical parameters considered at this stage are the mean, standard deviation and coefficient of variation of measured monthly, seasonal and annual station precipitation, temperature and streamflow. Measured extreme values are considered separately. Also calculated for each variable is the number of samples required to achieve a stated precision level.

For the sake of simplicity the data are at this stage considered to be either normally or log-normally distributed and without serial correlation. Hutchinson (1969(a)) has concluded that monthly and annual rainfalls are distributed normally and follow the Central Limit Theorem. Similar results are also demonstrated for mean annual runoff by Haan (1972), Hardison (1969) and Fiering (1963). Analysis of the Upper Taieri data by the probability plotting technique outlined by Montgomery & Hart (1971), shows that the distributions of monthly, seasonal and annual precipitation and temperature data are normal. Distributions of mean seasonal and annual streamflows are also found to be normal, whilst the mean monthly flows are log-normally distributed. In all cases except for the mean monthly streamflows, the hypothesis of a normal distribution could not be rejected by a Chi-square test of normality (Snedecor & Cochran, 1969).

The assumption of true randomness in the data is of course incorrect. Consecutive values of the variables considered will usually not be independent, and to accord strictly with the laws of statistics it is not permissable to apply to such a population the calculations based on properties of random distributions of independent data. Nevertheless, it is probably justifiable in this instance to treat the data as if they were independent, since consecutive mean monthly values in each series are separated by an interval of 12 months and are therefore similar in nature to the annual series. Serial correlation coefficients for both the monthly and annual values are thus likely to be low - Yevdjevich (1961) shows that coefficients to the order of 0.2 are characteristic of mean annual streamflow series. For an account of the effects of autocorrelation on effective length of record and information content of the mean, reference should be made to Matalas & Langbein (1962).

A brief survey of the statistical formulae used at this stage to estimate the population parameters required by the first study objective, is as follows:

(i) The arithmetic mean of a sample of n items, each of which has a numerical value x_i, is given by $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ (4), and has a standard error ($SE\bar{x}$) of $s/\sqrt{n}$ (5). S is the sample standard deviation.

(ii) The variance of the sample is defined by

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad (6).$$

(iii) The sample standard deviation is given by $\sqrt{s^2}$, and has a standard error (SE_{sd}) of $s/\sqrt{2n}$ (7).

(iv) Another commonly used measure of variability is the coefficient of variation, defined as $Cv = s/\bar{x}$ (8), and has a standard error (SE_{Cv}) of $\frac{Cv}{\sqrt{2n}} \cdot \sqrt{1+2Cv^2}$ (9).

Although the above formulae assume stationary time series of independent, normally distributed data, they are used for each of the presented measured records including the mean monthly streamflows. Where interest lies principally in estimates of record variability and accuracy of the mean, Hardison (1969) shows that it is quite valid to assume normality for log-normally distributed data. He demonstrates, *inter alia*, that the relationship between Cv and $SE\bar{x}$ is independent of distribution type, and that the determination of $SE\bar{x}$ for monthly and annual streamflows can be achieved even if the data are assumed to be normally distributed. Further, if the logarithms of independent events are normally distributed, the coefficient of variation of the events can be estimated from Iv, the standard deviation of the common logarithms, by the expression $Cv^2 = \exp\left[(2.3026\ Iv)^2\right] -1$. This relationship is adapted from an equation given by Chow (1964).

(v) If sampling frequency is to be established on a sound scientific basis it is vital to understand the relationships between precision and the number of samples required to obtain it. The relationship is well established for normal and log-normal distributions. To estimate the mean of a normal distribution with precision P, at a stated level of confidence, the number N, of samples required is

$$({}^{ks}/P)^2 \qquad \text{———} \qquad (10).$$

k is a coefficient whose magnitude depends on the confidence level chosen. However, when n is less than about 30, the calculation should be made with t for (n-1) degrees of freedom instead of k, in order to correct for the error in estimating standard deviation from a small sample.

The value of N required to define the arithmetic mean of log-normally distributed data, with a stated precision and confidence level, is given by

$$N = \left[\frac{kfs}{\log q_4 - \log \bar{x}}\right] \qquad \text{———} \qquad (11).$$

f is a correction factor which depends on the percentile of the distribution at which the mean occurs (Table 23). Log $\bar{x}$ is the common logarithm of the arithmetic mean, and q_4 the upper confidence limit of a given percentile (Montgomery & Hart, 1971). Again t should be used instead of k when n is less than about 30.

TABLE 23: Values of f for given percentiles (After Montgomery & Hart, 1971)

Percentile	50 (median)	40	30	20	16	10	5	1
		60	70	80	84	90	95	99
f	1.25	1.27	1.32	1.43	1.52	1.71	2.09	3.67

The value of N is only an estimate whose accuracy depends on the accuracy with which s predicts the true dispersion of results for the sampling period. s cannot be expected to give a necessarily accurate prediction however well it represents the dispersion of the existing data. In general, the prediction will be best when s is calculated from as many results as possible. Another source of error is that the basic formulae used to calculate N are strictly only applicable when the data are independent.

Precipitation:

Results of the required statistical analyses on data listed in Tables 9 and 10 for Paerau/Elliot measured rainfalls, are shown in Tables 24 and 25.

The general seasonal characteristics shown in Figures 20 and 21 are again evident and need no further comment. For monthly and annual rainfalls, variabilities as given by the coefficient of variation

TABLE 24: Monthly mean rainfall parameters for stations I59491 Paerau (1908-40) and Elliot (1968-69) combined

	J	F	M	A	M	J	J	A	S	O	N	D
n (yrs):	33	33	33	33	33	33	33	33	34	35	35	35
Mean ($\bar{x}$) ins:	2.99	2.37	2.62	2.50	2.28	2.13	1.43	1.89	1.77	2.53	2.60	3.15
SE$\bar{x}$:	0.28	0.29	0.29	0.24	0.23	0.25	0.14	0.25	0.15	0.23	0.20	0.27
Std. Deviat'n (S):	1.66	1.67	1.68	1.43	1.33	1.45	0.84	1.47	0.93	1.37	1.23	1.63
SEsd:	0.20	0.20	0.20	0.17	0.16	0.17	0.10	0.17	0.11	0.16	0.14	0.19
Coeff. var. (Cv):	0.55	0.70	0.64	0.57	0.58	0.68	0.58	0.77	0.52	0.54	0.47	0.51
SEcv:	0.08	0.12	0.10	0.08	0.09	0.11	0.09	0.13	0.07	0.08	0.06	0.07
SE$\bar{x}$ as % $\bar{x}$:	9.36	12.2	11.1	9.60	10.1	11.7	9.79	13.2	8.47	9.09	7.69	8.57
N (yrs):	32	51	41	33	35	48	35	62	28	30	23	27

Notes: (i) see equations (4)-(10) for derivation of $\bar{x}$, SE$\bar{x}$, S, SEsd, Cv, SEcv, and N
(ii) N = (t0.05 s/p)^2, where p = 20% of $\bar{x}$ at 95% confidence level; t0.05 = 2.032 (34d.f.); 2.034 (33d.f.); 2.036 (32d.f.).

TABLE 25: Seasonal and annual mean rainfall parameters for stations I59491 Paerau (1908-40) and Elliot (1968-69) combined

	Summer	Autumn	Winter	Spring	Annual
n (yrs):	33	33	33	34	33
Mean ($\bar{x}$) ins:	8.56	7.51	5.66	6.93	28.28
Se$\bar{x}$:	0.51	0.49	0.39	0.31	1.05
Std. Deviat'n (S):	2.96	2.90	2.31	1.85	6.07
SEsd:	0.36	0.35	0.28	0.22	0.74
Coeff. var. (Cv):	0.34	0.38	0.41	0.22	0.21
SEcv:	0.04	0.05	0.05	0.03	0.02
SE$\bar{x}$ as % $\bar{x}$:	6.01	6.61	7.00	4.57	3.73
N (yrs):	12	15	17	7	5

Notes: (i) see equations (4)-(10)
(ii) N = (t0.05 s/p)^2, where again p = 20% of $\bar{x}$ at 95% confidence level; t0.05 = 2.036 (32d.f.); 2.034 (33d.f.)

accord with the pattern of percentage variabilities obtained by Seelye (1946) for the general area. On a seasonal basis, winter has the highest value of Cv and spring the lowest. There is a slight tendency for the variability to have a negative correlation with the average rainfall amount, in that the wetter months have lower variability than those in the drier season.

The degree of precision to which the parameters are estimated from the measured data is obtained from the calculated standard error values of the mean, and standard deviation or coefficient of variation. Discussion as to how the precision of these estimates compares with the required precision levels, is restricted here to consideration of the monthly, seasonal and annual means. Shown in Tables 24 and 25 are values of SE$\bar{x}$ in terms of percentage of the mean, and from equation (10) the number of years required to achieve the required precision level. If needed similar calculations may be made for the standard errors of standard deviation and coefficient of variation, by the transformation of equations (7) and (9).

The precision level suggested as necessary is for estimates of the mean to within 20 percent of actual at the 95 percent confidence level. The analyses confirm the overall results already presented during estimation of optimum network density by means of the structural function. Mean seasonal and annual station precipitation may be estimated from the measured data with standard errors of less than 10 percent. In fact the stated criterion could be satisfied by five year's records for an annual mean, and by up to 17 year's data for a seasonal mean.

Results for the monthly data are less promising. Table 24 shows that six of the twelve months from the 33 to 35 year record contain standard errors in excess of 10 percent. Further, calculations of N suggest that up to 60 years of record may be required to achieve the stated criterion for all months. Alternatively, the chosen allowable error must be considered too stringent a criterion with respect to estimates of population parameters of mean and variability at a point in the study area.

Temperature:

Results of analyses on data listed in Tables 16 and 17 for Naseby State Forest measured mean temperatures, are given in Tables 26 and 27. Again the previously demonstrated seasonal characteristics of the area are evident. Variability as given by the coefficient of variation has a winter maximum and spring minimum. Of interest is that the winter maximum is associated with the greatest seasonal rainfall variability, while the spring minimum occurs with the lowest seasonal rainfall variability.

Discussion on the degree of precision to which the required parameters are estimated from the measured data, and how the precisions of these estimates compare with the levels stated as necessary, is again largely restricted to consideration of the mean monthly, seasonal and annual values. The required precision for estimates of mean temperature is to within 10 percent of actual temperature at the 95 percent confidence level. Again the results of Tables 26 and 27 confirm the general conclusions drawn during estimation of optimum network density by means of the structural function.

Mean monthly, seasonal and annual station temperature may be estimated from the measured data with standard errors of less than five percent. In fact the calculated standard errors given by $SE\bar{x}$ are all

TABLE 26: Monthly mean temperature parameters for station I50001 Naseby State Forest (1923-67)

	J	F	M	A	M	J	J	A	S	O	N	D
n (yrs):	45	45	45	45	45	45	45	45	44	45	45	44
Mean ($\bar{x}$) °F:	56.1	55.9	52.5	47.3	40.8	36.0	34.7	37.6	42.7	47.4	50.4	54.1
SE$\bar{x}$:	0.34	0.31	0.29	0.32	0.27	0.31	0.33	0.28	0.24	0.28	0.36	0.37
Std. Deviat'n (S):	2.31	2.10	2.01	2.17	1.87	2.13	2.23	1.91	1.60	1.88	2.48	2.50
SEsd:	0.24	0.22	0.21	0.22	0.19	0.22	0.23	0.20	0.17	0.19	0.26	0.26
Coeff. var.(Cv):	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.05	0.04	0.04	0.05	0.05
SEcv:	0.004	0.004	0.004	0.005	0.005	0.006	0.006	0.005	0.004	0.004	0.005	0.005
SE$\bar{x}$ as % $\bar{x}$:	0.60	0.55	0.55	0.67	0.66	0.86	0.95	0.74	0.56	0.59	0.71	0.68
N (yrs):	0.7	0.6	0.6	1.0	0.9	1.4	1.7	1.0	0.6	0.6	1.0	0.9

Notes: (i) see equations (4)-(10) for derivation of $\bar{x}$, SE$\bar{x}$, S, SEsd, Cv, SEcv, and N

(ii) $N = (t0.05\ s/p)^2$, where p = 10% of $\bar{x}$ at 95% confidence level; t0.05 = 2.018 (42d.f.); 2.016 (43 d.f.); 2.015 (44d.f.)

TABLE 27: Seasonal and annual mean temperature parameters for station I50001 Naseby State Forest (1923-67)

	Summer	Autumn	Winter	Spring	Annual
n (yrs):	45	45	45	45	45
Mean ($\bar{x}$) °F:	55.4	46.9	36.1	46.8	46.3
SE$\bar{x}$:	0.25	0.19	0.21	0.20	0.12
Std. Deviat'n (S):	1.68	1.25	1.38	1.33	0.78
SEsd:	0.18	0.13	0.15	0.14	0.08
Coeff. var.(Cv):	0.03	0.03	0.04	0.03	0.02
SEcv:	0.003	0.003	0.004	0.003	0.002
SE$\bar{x}$ as % $\bar{x}$:	0.45	0.40	0.57	0.42	0.25
N (yrs):	0.4	0.3	0.6	0.3	0.1

Notes: (i) see equations (4)-(10)

(ii) $N = (t.0.05\ s/p)^2$, where again p = 10% of $\bar{x}$ at 95% confidence level; t0.05 = 2.015 (44d.f.)

less than one percent, and for all time intervals considered the stated criterion could be satisfied by only two years of records.

However, similar calculations for the station data variability estimates suggest that the complete measured record is needed to meet the required precision criterion. It is concluded, therefore, that the available measurements of temperature do permit estimates of the station monthly, seasonal and annual mean and variability at the required precision level.

Streamflow:

Results of analyses on data listed in Tables 19 to 22 for Paerau Bridge, Patearoa-Paerau Bridge and Loganburn measured discharges, are shown in Tables 28 and 29.

The well defined seasonal characteristics shown by Figures 32 and 33 are again evident. For the Paerau Bridge data, values of Cv suggest that mean monthly runoff is more variable in summer and autumn than during the remainder of the year. Again, Cv values show the tendency for the Paerau Bridge streamflow variability to have a negative correlation with mean flow amount.

Calculated values of mean and variability given for Patearoa-Paerau Bridge are obviously inconsistent with the long-term Paerau Bridge data. The differences doubtless arise from the small sample available for analysis. Results from both the Patearoa-Paerau Bridge and Loganburn stations must therefore be used with considerable caution - the likely errors involved are given by the listed standard errors of the mean, standard deviation and coefficient of variation.

Consideration of the precision of parameter estimates and comparison with required levels, is again centred around discussion of the mean

TABLE 28: Monthly mean discharge parameters for stations Paerau Bridge (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1.6.66-31.5.69), Patearoa-Paerau Bridge (1.6.66-31.5.69) and Loganburn (1.6.66-31.5.69)

A. *Paerau Bridge*

	J	F	M	A	M	J	J	A	S	O	N	D
n (yrs):	30	30	30	30	30	30	30	30	30	30	30	30
Mean ($\bar{x}$) cfs:	160	125	162	229	297	268	281	331	508	502	337	246
SE$\bar{x}$:	24.2	22.6	23.1	25.9	33.7	25.1	22.0	24.8	42.1	41.0	31.4	28.8
Std. Deviat'n (S):	133	124	127	142	185	138	121	136	231	225	172	158
SEsd:	17.1	16.0	16.3	18.3	23.8	17.8	15.6	17.5	29.8	29.0	22.2	20.4
Coeff. var. (Cv):	0.83	0.99	0.78	0.62	0.62	0.51	0.43	0.41	0.45	0.44	0.51	0.64
SEcv:	0.16	0.21	0.14	0.10	0.10	0.08	0.06	0.06	0.06	0.06	0.08	0.11
SE$\bar{x}$ as % $\bar{x}$:	15.1	18.1	14.3	11.3	11.3	9.40	7.86	7.50	8.30	8.18	9.31	11.7
N (yrs):	94	134	84	52	53	36	25	23	28	27	35	56

B. *Patearoa-Paerau Bridge*

	J	F	M	A	M	J	J	A	S	O	N	D
n (yrs):	3	3	3	3	3	3	3	3	3	3	3	3
Mean ($\bar{x}$) cfs:	64.5	60.2	138	340	392	293	231	289	411	356	238	161
SE$\bar{x}$:	7.56	12.4	64.6	139	66.4	80.8	31.1	66.9	57.4	148	47.6	49.2
Std. Deviat'n (S):	13.1	21.5	112	242	115	140	54.0	116	99.4	256	82.5	85.3
SEsd:	5.35	8.78	45.7	98.8	46.9	57.2	22.0	47.3	40.6	104	33.7	34.8
Coeff. var. (Cv):	0.20	0.36	0.81	0.71	0.29	0.48	0.23	0.40	0.24	0.72	0.34	0.53
SEcv:	0.08	0.16	0.50	0.41	0.14	0.24	0.09	0.19	0.10	0.42	0.15	0.27
SE$\bar{x}$ as % $\bar{x}$:	11.7	20.6	46.8	41.1	16.9	27.6	13.5	23.2	13.9	41.5	20.0	30.6
N (yrs):	25	77	400	306	52	139	33	97	35	313	73	170

C. *Loganburn*

	J	F	M	A	M	J	J	A	S	O	N	D
n (yrs):	3	3	3	3	3	3	3	3	3	3	3	3
Mean ($\bar{x}$) cfs:	15.6	4.43	28.8	54.9	62.2	69.8	44.2	57.4	66.1	60.5	37.8	21.9
SE$\bar{x}$:	4.52	0.99	24.6	32.8	3.15	28.7	7.85	23.0	6.41	21.8	10.3	5.40
Std. Deviat'n (S):	7.82	1.71	42.7	56.9	5.46	49.8	13.6	39.9	11.1	37.7	17.9	9.36
SEsd:	3.19	0.70	17.4	23.2	2.23	20.3	5.55	16.3	4.53	15.4	7.31	3.82
Coeff. var. (Cv):	0.50	0.39	1.48	1.04	0.08	0.71	0.31	0.70	0.17	0.62	0.47	0.43

TABLE 28: Continued

	J	F	M	A	M	J	J	A	S	O	N	D
SEcv:	0.25	0.18	1.40	0.76	0.03	0.41	0.14	0.40	0.07	0.34	0.23	0.20
SE$\bar{x}$ as % $\bar{x}$:	9.67	7.42	28.5	59.8	5.07	41.2	17.8	40.1	9.70	36.0	27.3	24.7
N (yrs):	152	90	1334	651	5	309	57	293	17	236	136	111

Notes: (i) see equations (4)-(11) for derivation of $\bar{x}$, SE$\bar{x}$, S, SEsd, Cv, SEcv, and N

(ii) N = (t.0.05.f.s./log q_4-log$\bar{x}$)^2, where p = 20% of $\bar{x}$ at 95% confidence level; t0.05 = 2.045 (29d.f.); 4.303 (2d.f.); f given by Table 23

TABLE 29: Seasonal and annual mean discharge parameters for stations Paerau Bridge (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1.6.66-31.5.69); Patearoa-Paerau Bridge (1.6.66-31.5.69) and Loganburn (1.6.66-31.5.69)

A. Paerau Bridge

	Summer	Autumn	Winter	Spring	Oct-Mar.	Jan-Mar.	Annual
n (yrs):	25	30	30	30	25	30	30
Mean ($\bar{x}$) cfs:	175	229	293	450	248	150	288
SE$\bar{x}$:	25.2	23.9	17.9	33.2	20.0	18.9	16.1
Std. Deviat'n (S):	126	131	98.4	182	100	104	88.2
SEsd:	17.8	16.9	12.7	23.4	14.1	13.4	11.3
Coeff. var.(Cv):	0.72	0.57	0.33	0.40	0.40	0.69	0.30
SEcv:	0.14	0.09	0.04	0.06	0.06	0.12	0.04
SE$\bar{x}$ as % $\bar{x}$:	14.4	10.4	6.13	7.38	8.06	12.6	5.59
N (yrs):	55	34	12	17	17	50	10

B. Patearoa-Paerau Bridge

	Summer	Autumn	Winter	Spring	Oct-Mar.	Jan-Mar.	Annual
n (yrs):	3	3	3	3	3	3	3
Mean ($\bar{x}$) cfs:	96.3	290	270	335	170	88.1	248
SE$\bar{x}$:	17.4	43.9	41.9	75.0	26.3	18.2	27.1
Std. Deviat'n (S):	30.2	76.0	72.7	130	45.5	31.5	46.9

TABLE 29: *Continued*

	Summer	Autumn	Winter	Spring	Oct-Mar.	Jan-Mar.	Annual
SEsd:	12.3	31.0	29.7	53.1	18.6	12.9	19.1
Coeff. var.(Cv):	0.31	0.26	0.27	0.39	0.27	0.36	0.19
SEcv:	0.14	0.11	0.12	0.18	0.12	0.16	0.08
SE$\bar{x}$ as % $\bar{x}$:	18.1	15.1	15.5	22.4	15.4	20.6	10.9
N (yrs):	45	32	33	70	33	59	16

C. *Loganburn*

	Summer	Autumn	Winter	Spring	Oct-Mar.	Jan-Mar.	Annual
n (yrs):	3	3	3	3	3	3	3
Mean ($\bar{x}$) cfs:	14.3	48.6	56.9	54.9	28.5	16.6	43.8
SE$\bar{x}$:	1.94	17.9	18.9	7.85	3.26	6.93	5.49
Std. Deviat'n (S):	3.37	31.0	32.7	13.6	5.65	12.0	9.51
SEsd:	1.38	12.6	13.3	5.55	2.31	4.90	3.88
Coeff. var.(Cv):	0.24	0.64	0.57	0.25	0.20	0.72	0.22
SEcv:	0.10	0.35	0.30	0.11	0.08	0.42	0.09
SE$\bar{x}$ as % $\bar{x}$:	13.6	36.8	33.2	14.3	11.4	41.7	12.5
N (yrs):	25	188	153	28	18	242	22

Notes: (i) see equations (4)-(9) and (11)

(ii) $N = \left(\frac{t_{0.05}.s}{p}\right)^2$, where again p = 20% of $\bar{x}$ at 95% confidence level; $t_{0.05}$ = 4.303 (2d.f.); 2.064 (24d.f.); 2.045 (29d.f.)

monthly, seasonal and annual discharge values. Although values of SE$\bar{x}$ in terms of percentage of the mean have been calculated for the monthly data from equation (5) for normal distributions, it should be noted that the equivalent values of N have been calculated from equation (11) for log-normal distributions.

The precision criterion suggested as necessary is for estimates of mean discharge to within 20 percent of actual discharge at the 95 percent confidence level. Results for the Paerau Bridge analyses are considered first. Mean annual, winter, spring and October-March discharges may be estimated from the 25 to 30 years of measured data with standard errors of less than 10 percent. For these time intervals the error criterion could be satisfied by no more than 17 years records. However, for summer, autumn, and approximately half the months, standard errors in estimating the mean exceed 10 percent.

For all seasons and for every month except February, the available measured data at Paerau Bridge would allow estimates of the mean to within 30 percent at the 95 percent confidence level. However, such errors are probably too high for normal acceptance in the engineering design of water resources projects (Cislerova & Hutchinson, 1973). Population estimates to within 20 percent at the 95 percent probability level could theoretically be achieved by an increase in record length. The calculated values of N in Tables 28A and 29A suggest that although such a solution is reasonable for the seasonal values and some months, it is quite impractical for the months December to March. For practical reasons it is evident that a less stringent error criterion must be accepted for these summer and early autumn months. As an alternative, the allowable error should perhaps be a stated discharge value, rather than a percentage of the mean.

Results from the Patearoa-Paerau Bridge and Loganburn analyses may be considered together. Reliable estimation of mean monthly, seasonal or annual discharge is not possible for either station to within the allowable error criterion given the available measured data. Although little reliance should be placed on the listed numerical values of N, the clear implication is that both records are of insufficient length. Standard errors of up to 42 percent are shown for the Loganburn mean seasonal discharges, and up to 22 percent for the Patearoa-Paerau Bridge data. Monthly standard error values are considerably higher, and reach 60 percent for the Loganburn and 47 percent for the Patearoa-Paerau Bridge record. In some instances the sample standard deviations exceed the value of the mean. It is thus concluded that only for Paerau Bridge do the available measurements of mean discharge allow estimates of at least some of the monthly, seasonal and annual parameters at the required precision level.

EXTREME VALUES - PRECIPITATION, TEMPERATURE, DISCHARGE

Precipitation: General

The occurrence frequency of various rainfall amounts is important in applications such as the assessment of the susceptibility of soils to erosion and in aspects of engineering design. Most commonly used in studies of this type is the annual series of extreme values. Data for such an analysis are more readily available than for a partial-duration series, and there is a good theoretical basis to extrapolate annual series data beyond the range of observation.

Limitations of annual series data are that each year is represented by only one event and the accuracy of any analysis of extreme values is determined by the length of available record. Extrapolation can involve considerable errors. For long return periods the short record has a large error and computations cannot be taken as precise estimates.

In this study, depth-duration-frequency curves have been calculated for Paerau using the available daily rainfall data for the period 1909-37. For comparative purposes, two methods have been used to derive the curves - as described by Seelye (1947) and Robertson (1963). Both are based on the theory of extreme values proposed by Gumbel (1958). The theory and calculation methods are well documented and need not be repeated here.

The limited nature of available data from the area precludes calculation of rainfall depth and frequency values with a duration of less than one day. Analysis is thus restricted to the maximum one, two and three day rainfalls for Paerau presented in Tables 30 to 32.

Precipitation: Seelye method (1947)

The method is a modification of Gumbel's theory of extreme values and involves the calculation of u and k values in the equation

$$X_T = (u \pm \delta u) + (k \pm \delta k) \log T \text{ ——————— } (12),$$

where X is the required rainfall, u and k are statistical parameters estimated from the annual rainfall maxima, δu and δk are the standard errors in u and k, and T the recurrence interval in years. Such an equation is suitable when T is at least unity, though to give results satisfactory for most purposes Robertson (1959) concludes that it is only applicable where records in excess of 20 years are available.

From the data presented in Tables 30 to 32, calculations on an annual and seasonal basis have been made of X_T for T equals, 1, 2, 5, 10, 20, 50 and 100 years for the durations (t) one, two and three days. Table 33 gives the results of this analysis, and shows computed values of X and klogT for the indicated recurrence intervals T, and also u, k,

TABLE 30: Maximum 1 day rainfalls - Paerau (inches) (1909-1937)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1909	0.70	0.72	1.30	0.59	0.39	0.70	0.45	0.53	0.22	1.45	0.54	0.74
1910	0.48	1.50	0.42	0.77	0.20	0.42	0.48	0.35	1.03	2.44	0.58	0.96
1911	1.30	0.22	0.41	0.40	0.47	0.58	0.40	0.79	0.60	0.15	3.02	0.53
1912	0.50	0.78	0.52	0.50	0.30	0.80	0.65	0.45	0.45	1.20	0.50	0.22
1913	1.11	0.37	1.25	0.63	0.50	0.29	0.82	1.76	0.70	0.95	1.27	2.17
1914	0.97	1.85	1.13	0.43	0.97	1.96	0.12	0.11	0.56	0.22	0.85	0.56
1915	0.42	1.38	0.63	0.50	0.80	0.61	0.13	0.13	0.31	1.06	0.75	0.91
1916	1.33	0.89	1.21	0.62	0.62	0.49	0.72	0.52	0.76	0.42	1.64	0.47
1917	0.44	0.30	0.96	0.77	2.31	0.40	0.39	0.29	0.71	1.07	0.91	0.96
1918	1.75	0.76	1.24	0.92	0.55	0.60	0.85	1.08	0.57	0.56	0.76	1.47
1919	1.95	0.31	0.27	2.63	0.49	1.17	0.56	2.38	1.53	0.24	0.79	1.57
1920	1.57	0.89	0.38	0.84	0.56	0.35	1.14	0.62	1.95	0.21	1.37	2.42
1921	0.55	0.89	0.82	0.53	0.39	0.83	0.46	0.56	0.37	0.86	0.31	2.00
1922	1.40	0.63	0.63	0.66	0.64	0.47	0.47	0.50	0.40	0.82	0.64	1.36
1923	1.04	0.82	0.96	2.85	2.22	0.73	0.00	0.68	0.64	0.40	0.89	1.13
1924	0.52	3.11	1.37	2.06	0.68	0.52	0.62	0.19	0.66	1.98	0.67	0.89
1925	0.82	1.20	1.88	0.92	0.66	0.37	1.14	2.94	0.85	1.46	0.94	0.93
1926	1.47	1.07	0.55	0.75	0.59	0.69	0.24	0.76	0.95	0.95	1.12	1.05
1927	1.05	1.25	1.90	1.05	0.90	0.20	0.41	0.43	0.94	0.64	0.80	0.53
1928	0.21	1.47	0.36	1.20	0.30	0.30	0.50	0.51	0.43	0.85	0.35	0.36
1929	0.60	0.18	2.05	0.24	0.19	0.61	1.30	0.16	0.30	0.05	0.46	0.48
1930	0.87	0.85	0.10	0.51	0.50	0.30	0.50	0.70	0.40	1.09	0.77	1.05
1931	1.12	1.84	0.17	0.25	0.47	0.50	0.50	0.92	0.92	0.93	0.53	1.15
1932	0.83	0.51	1.38	1.07	1.21	0.61	0.11	0.48	0.64	1.29	0.16	0.66
1933	0.79	0.41	0.75	2.10	1.58	0.35	0.37	0.58	0.39	1.85	1.08	1.77
1934	0.91	0.88	0.83	1.56	1.27	1.55	0.58	0.42	0.75	0.57	0.80	0.80
1935	1.24	1.55	4.31	1.03	1.90	4.41	0.08	0.45	0.22	0.20	0.85	1.10
1936	0.29	0.82	2.20	1.29	1.90	0.30	0.41	0.90	0.97	0.70	1.49	1.73
1937	0.85	2.12	0.50	0.76	1.35	0.71	0.56	0.53	0.31	0.37	0.54	1.41

TABLE 31: Maximum 2 day rainfalls - Paerau (inches) (1909-1937)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1909	0.90	0.72	1.59	1.11	0.39	1.20	0.55	0.77	0.32	1.81	0.59	0.74
1910	0.57	1.63	0.52	0.95	0.30	0.62	0.58	0.35	1.33	3.01	0.58	1.01
1911	1.32	0.22	0.79	0.49	0.47	0.88	0.46	0.79	0.66	0.21	3.32	1.03
1912	0.79	0.90	0.97	0.60	0.40	0.95	0.97	0.52	0.57	1.28	0.50	0.42
1913	1.41	0.45	1.71	0.69	0.55	0.52	0.82	2.46	0.70	1.05	1.32	3.44
1914	0.97	1.92	1.38	0.60	1.24	2.63	0.20	0.19	0.67	0.43	0.85	0.87
1915	0.56	2.10	0.90	0.56	1.09	1.07	0.13	0.25	0.31	1.06	0.84	0.93
1916	1.72	1.00	1.66	0.66	0.80	0.65	0.72	0.79	1.35	0.42	1.64	0.47
1917	0.44	0.40	1.20	0.86	2.40	0.61	0.39	0.36	1.36	0.39	0.91	1.54
1918	1.75	0.82	1.78	0.92	0.55	0.88	1.44	1.57	1.04	0.65	1.06	1.47
1919	3.82	0.31	0.30	2.79	0.76	2.11	1.01	2.57	1.75	0.24	0.93	1.66
1920	1.57	0.98	0.38	1.41	1.03	0.64	1.35	0.88	2.18	0.28	1.37	2.83
1921	1.01	0.98	1.32	0.85	0.39	1.21	0.78	0.69	0.37	0.93	0.36	2.00
1922	2.06	0.63	0.73	0.80	0.64	0.47	0.69	0.60	0.45	0.92	1.00	1.89
1923	1.17	0.87	1.19	4.48	3.68	0.73	0.00	1.21	0.64	0.40	1.06	1.13
1924	0.93	3.35	1.37	2.59	0.92	0.82	0.62	0.19	0.71	1.98	0.67	0.89
1925	1.08	1.43	2.03	1.05	0.73	0.56	1.19	4.11	1.08	2.21	0.94	1.20
1926	2.28	1.08	0.87	1.04	0.83	0.95	0.24	0.76	0.95	1.13	1.53	1.68
1927	1.35	1.25	1.90	1.36	0.99	0.20	0.52	0.69	1.03	0.94	1.11	0.53
1928	0.40	1.47	0.47	1.20	0.53	0.48	0.66	0.51	0.43	0.96	0.37	0.63
1929	1.04	0.32	2.63	0.30	0.23	1.51	1.99	0.22	0.40	0.05	0.86	0.88
1930	1.02	0.85	0.10	0.51	0.50	0.35	1.00	0.79	0.59	1.30	0.94	1.13
1931	2.07	2.20	0.25	0.35	0.63	0.55	0.53	1.16	0.92	0.93	0.53	1.38
1932	0.96	0.51	1.47	1.34	1.50	1.03	0.13	0.56	0.64	1.29	0.26	0.66
1933	0.92	0.78	0.75	2.10	2.36	0.60	0.72	0.93	0.40	1.86	1.83	2.65
1934	1.53	1.45	0.98	1.62	2.04	0.47	0.79	0.74	0.75	0.57	0.90	1.25
1935	1.60	2.76	5.63	1.09	2.00	5.01	0.15	0.80	0.39	0.20	1.53	1.57
1936	0.29	1.34	3.36	1.29	2.09	0.30	0.77	1.04	1.02	1.37	2.49	2.23
1937	0.85	2.24	0.65	1.42	1.35	0.90	0.67	1.04	0.31	0.39	0.55	2.21

TABLE 32: Maximum 3 day rainfalls - Paerau (inches) (1909-1937)

Year	J	F	M	A	M	J	J	A	S	O	N	D
1909	1.04	0.72	1.69	1.11	0.39	1.27	0.55	0.77	0.32	2.02	1.12	0.74
1910	0.57	1.63	0.52	1.06	0.45	0.62	0.68	0.35	1.53	3.01	0.58	1.36
1911	1.32	0.32	0.79	0.54	0.47	0.88	0.60	0.79	0.66	0.29	3.37	1.33
1912	0.79	0.96	1.02	0.60	0.40	1.10	0.97	0.52	0.67	1.64	0.70	0.50
1913	1.44	0.64	1.86	1.09	0.55	0.64	0.87	2.84	0.70	1.05	1.36	3.51
1914	0.75	1.95	1.38	0.60	1.43	2.72	0.20	0.28	0.99	0.47	0.85	0.87
1915	0.56	2.38	0.90	0.56	1.29	1.42	0.19	0.25	0.31	1.24	0.84	0.93
1916	1.79	1.31	1.66	1.13	0.86	0.79	0.80	1.00	1.44	0.45	1.76	0.47
1917	0.44	0.40	1.20	0.85	2.40	0.61	0.39	0.38	1.59	1.58	0.91	1.67
1918	1.75	0.86	2.41	0.92	0.83	0.88	1.62	1.57	1.34	0.81	1.09	1.47
1919	4.28	0.31	0.30	2.86	0.97	2.44	1.15	3.32	1.65	0.34	1.07	2.49
1920	1.57	0.98	0.38	1.62	1.21	0.64	1.35	0.88	2.43	0.24	1.76	2.83
1921	1.12	0.98	1.32	1.32	0.66	1.44	1.02	0.69	0.57	0.93	0.47	2.35
1922	3.46	0.70	0.76	0.80	0.64	0.47	0.81	0.98	0.56	0.92	1.26	2.22
1923	1.17	0.87	1.19	4.60	4.17	0.73	0.00	1.21	0.64	0.40	1.06	1.34
1924	0.93	3.48	1.37	2.70	1.03	0.82	0.62	0.19	0.71	1.82	0.67	0.89
1925	1.08	1.63	2.03	1.05	0.73	0.56	1.19	4.29	1.08	2.42	1.06	1.20
1926	2.28	1.43	0.87	1.04	0.83	0.95	0.24	0.97	1.32	1.38	1.53	1.99
1928	0.51	1.47	0.47	1.45	0.71	0.53	0.78	0.51	0.48	1.12	0.36	0.49
1929	1.04	0.32	2.63	0.30	0.39	1.90	2.23	0.33	0.40	0.05	1.31	0.88
1930	1.06	0.85	0.10	0.62	0.50	0.39	1.00	0.79	0.63	1.81	1.04	1.15
1931	2.53	2.29	0.25	0.35	0.63	0.71	0.70	1.16	0.77	0.94	0.53	1.38
1932	0.96	0.51	1.47	1.73	1.56	1.24	0.13	0.81	0.64	1.30	0.26	0.66
1933	0.94	0.89	0.75	2.10	2.48	0.65	0.76	0.93	0.40	1.86	1.83	3.67
1934	1.53	1.84	1.13	1.76	2.75	1.55	0.84	0.81	0.75	0.62	0.90	1.25
1935	1.91	2.86	5.73	1.09	2.89	5.02	0.15	0.92	0.50	0.35	2.03	1.57
1936	0.29	1.39	3.36	1.15	2.10	0.30	0.87	1.13	1.02	1.37	2.59	2.23
1937	1.66	2.30	0.85	2.07	1.35	0.99	0.67	1.04	0.31	0.39	0.55	2.21
1927	1.35	1.25	2.10	1.56	1.07	0.20	0.56	0.72	1.04	0.96	1.17	0.62

TABLE 33: Seelye depth-duration-frequency analysis for Paerau rainfalls ($X = u + k \log T$)

A. 24 hour rainfalls:

(1) Annual

T	k log T	X	1.14X
1	0.0	1.777	2.03
2	0.3811	2.158	2.46
5	0.8849	2.662	3.04
10	1.266	3.043	3.47
20	1.647	3.424	3.90
50	2.151	3.928	4.48
100	2.532	4.309	4.91

$u = 1.777$; $k = 1.266$
$\delta u = 0.1340$; $\delta k = 0.2045$

(2) Spring (September-November)

T	k log T	X	1.14X
1	0.0	0.933	1.06
2	0.311	1.244	1.42
5	0.721	1.654	1.89
10	1.032	1.965	2.24
20	1.343	2.276	2.60
50	1.753	2.686	3.06
100	2.064	2.997	3.42

$u = 0.933$; $k = 1.032$
$\delta u = 0.1092$; $\delta k = 0.1667$

(3) Summer (December-February)

T	k log T	X	1.14X
1	0.0	1.297	1.48
2	0.308	1.605	1.83
5	0.716	2.011	2.29
10	1.025	2.319	2.64
20	1.333	2.627	3.00
50	1.741	3.033	3.46
100	2.050	3.347	3.82

$u = 1.297$; $k = 1.025$
$\delta u = 0.1104$; $\delta k = 0.1685$

(4) Autumn (March-May)

T	k log T	X	1.14X
1	0.0	1.151	1.31
2	0.481	1.632	1.86
5	1.116	2.267	2.58
10	1.597	2.748	3.13
20	2.078	3.229	3.68
50	2.713	3.864	4.41
100	3.194	4.345	4.95

$u = 1.151$; $k = 1.597$
$\delta u = 0.1690$; $\delta k = 0.2580$

(5) Winter (June-August)

T	k log T	X	1.14X
1	0.0	0.703	0.80
2	0.428	1.131	1.29
5	0.995	1.698	1.94
10	1.423	2.126	2.42
20	1.851	2.554	2.91
50	2.418	3.121	3.56
100	2.846	3.549	4.05

$u = 0.703$; $k = 1.423$
$\delta u = 0.1506$; $\delta k = 0.2300$

TABLE 33: Continued

B. 48 hour rainfalls:

(1) *Annual*

T	k log T	X	1.06X
1	0.0	2.072	2.20
2	0.567	2.639	2.80
5	1.318	3.390	3.59
10	1.885	3.957	4.19
20	2.452	4.524	4.80
50	3.203	5.275	5.59
100	3.770	5.842	6.19

$u = 2.072$; $k = 1.885$
$\delta u = 0.200$; $\delta k = 0.305$

(2) *Spring*

T	k log T	X	1.06X
1	0.0	1.075	1.14
2	0.368	1.443	1.53
5	0.856	1.931	2.05
10	1.224	2.299	2.44
20	1.592	2.667	2.83
50	2.080	3.155	3.34
100	2.448	3.523	3.73

$u = 1.075$; $k = 1.224$
$\delta u = 0.1296$; $\delta k = 0.1977$

(3) *Summer*

T	k log T	X	1.06X
1	0.0	1.563	1.66
2	0.454	2.017	2.14
5	1.054	2.617	2.77
10	1.508	3.071	3.26
20	1.962	3.525	3.74
50	2.562	4.125	4.37
100	3.016	4.579	4.85

$u = 1.563$; $k = 1.508$
$\delta u = 0.1624$; $\delta k = 0.2479$

(4) *Autumn*

T	k log T	X	1.06X
1	0.0	1.389	1.47
2	0.581	1.970	2.09
5	1.350	2.739	2.90
10	1.931	3.320	3.52
20	2.512	3.901	4.14
50	3.281	4.670	4.95
100	3.862	5.251	5.57

$u = 1.389$; $k = 1.931$
$\delta u = 0.2044$; $\delta k = 0.3120$

(5) *Winter*

T	k log T	X	1.06X
1	0.0	0.956	1.01
2	0.516	1.472	1.56
5	1.198	2.154	2.28
10	1.714	2.670	2.83
20	2.230	3.186	3.38
50	2.912	3.868	4.10
100	3.428	4.384	4.65

$u = 0.956$; $k = 1.714$
$\delta u = 0.1814$; $\delta k = 0.2769$

TABLE 33: Continued

C. 72 hour rainfalls:

(1) Annual

T	k log T	X	1.05X
1	0.0	2.386	2.51
2	0.560	2.946	3.09
5	1.301	3.687	3.87
10	1.861	4.247	4.46
20	2.421	4.807	5.05
50	3.162	5.548	5.83
100	3.722	6.108	6.41

$u = 2.386$; $k = 1.861$
$\delta u = 0.1970$; $\delta k = 0.3007$

(2) Spring

T	k log T	X	1.05X
1	0.0	1.303	1.37
2	0.363	1.666	1.75
5	0.844	2.147	2.25
10	1.207	2.510	2.64
20	1.570	2.873	3.02
50	2.051	3.354	3.52
100	2.414	3.717	3.90

$u = 1.303$; $k = 1.207$
$\delta u = 0.1278$; $\delta k = 0.1950$

(3) Summer

T	k log T	X	1.05X
1	0.0	1.626	1.71
2	0.555	2.181	2.29
5	1.289	2.915	3.06
10	1.844	3.470	3.64
20	2.399	4.025	4.23
50	3.133	4.759	5.00
100	3.688	5.314	5.58

$u = 1.626$; $k = 1.844$
$\delta u = 0.1086$; $\delta k = 0.3031$

(4) Autumn

T	k log T	X	1.05X
1	0.0	1.501	1.58
2	0.596	2.097	2.20
5	1.385	2.886	3.03
10	1.981	3.482	3.66
20	2.577	4.078	4.28
50	3.366	4.867	5.11
100	3.962	5.463	5.74

$u = 1.501$; $k = 1.981$
$\delta u = 0.2097$; $\delta k = 0.3199$

(5) Winter

T	k log T	X	1.05X
1	0.0	1.012	1.06
2	0.548	1.560	1.64
5	1.273	2.285	2.40
10	1.821	2.833	2.98
20	2.369	3.381	3.55
50	3.094	4.106	4.31
100	3.642	4.654	4.89

$u = 1.012$; $k = 1.821$
$\delta u = 0.1927$; $\delta k = 0.2942$

δu and δk. Seasonal data are calculated as an extension to the standard method, since Simmers (1962) has concluded that such a parametric approach to the problem is of value for some design applications. In this way, the seasonal characteristics of the rainfall regime are not masked by the development of curves which use maximum rainfalls for each year, irrespective of time of occurrence.

From the one, two and three day values of X_T shown, a further adjustment is necessary to convert the figures to maximum 24, 48 and 72 hour falls (Robertson, 1963). As reported, the conversion factors are 1.14, 1.06 and 1.05 for $t = 24$, 48 and 72 hours respectively. Adjusted values of X_T are also shown in Table 33.

Depth-duration-frequency equations have not been derived for the data. For practical purposes it is usually more convenient and accurate to list the data as in Table 33 or to graph the calculated values of $X_{(T,t)}$ on log-log paper, one curve for each selected value of T.

The presented data need little discussion. Since the records used were only 29 years in length, the inclusion of extrapolated values for T equals 50 and 100 years is scarcely justified. If these latter results are to be used it should only be with due recognition of the possible errors involved. When maximised standard error values of δu and δk are assumed for the Seelye equation, possible standard errors in X_T may be calculated as listed in Table 34. The errors are shown in inches and as a percentage of X_T for the annual and seasonal series, with T equals 1, 2, 5, 10, 20, 50 and 100 years.

For maximum values of δu and δk, standard errors of X_T less than 10 percent generally occur only for estimates of the annual extreme values of one, two or three day rainfall at T less than about five years,

TABLE 34: Possible standard errors of X_T for Paerau rainfalls (1909-37) from Seelye equation: $X_T = (u \pm \delta u) + (k \pm \delta k) \text{ Log } T$. (Maximised values of δu and δk from Table 33 are assumed)

A. ONE DAY RAINFALLS:

	T	Annual	Summer	Autumn	Winter	Spring
Error in X_T (inches) for T equals:	1	0.13	0.11	0.17	0.15	0.11
	2	0.20	0.16	0.25	0.22	0.16
	5	0.28	0.23	0.35	0.31	0.23
	10	0.34	0.28	0.43	0.38	0.28
	20	0.40	0.33	0.50	0.45	0.33
	50	0.48	0.40	0.61	0.54	0.39
	100	0.54	0.45	0.68	0.61	0.44
Error in X_T (as % X_T) for T equals:	1	7.54	8.48	14.7	21.5	11.7
	2	9.08	10.1	15.1	19.5	12.8
	5	10.4	11.5	15.4	18.3	13.7
	10	11.1	12.1	15.5	17.9	14.0
	20	11.7	12.7	15.6	17.6	14.3
	50	12.3	13.2	15.7	17.3	14.6
	100	12.6	13.4	15.8	17.2	14.8

B. TWO DAY RAINFALLS:

	T	Annual	Summer	Autumn	Winter	Spring
Error in X_T (inches) for T equals:	1	0.20	0.16	0.20	0.18	0.13
	2	0.29	0.24	0.30	0.26	0.19
	5	0.41	0.34	0.42	0.37	0.27
	10	0.51	0.41	0.52	0.46	0.33
	20	0.60	0.48	0.61	0.54	0.39
	50	0.72	0.58	0.73	0.65	0.47
	100	0.81	0.66	0.83	0.74	0.53
Error in X_T (as % X_T) for T equals:	1	9.65	10.4	14.7	18.9	12.0
	2	11.1	11.7	15.1	17.9	13.2
	5	12.2	12.8	15.4	17.4	13.9
	10	12.8	13.3	15.5	17.2	14.3
	20	13.2	13.7	15.6	17.0	14.5
	50	13.6	14.1	15.7	16.8	14.8
	100	13.9	14.4	15.8	16.8	14.9

TABLE 34: Continued

C. THREE DAY RAINFALLS:

		Annual	Summer	Autumn	Winter	Spring
Error in X_T (inches) for T equals:	1	0.20	0.11	0.21	0.19	0.13
	2	0.29	0.20	0.31	0.28	0.19
	5	0.41	0.32	0.43	0.40	0.26
	10	0.50	0.41	0.53	0.49	0.32
	20	0.59	0.50	0.63	0.58	0.38
	50	0.71	0.62	0.75	0.69	0.46
	100	0.80	0.72	0.85	0.78	0.52
Error in X_T (as % X_T) for T equals:	1	8.25	6.67	14.0	19.0	9.80
	2	9.76	9.17	14.6	18.1	11.2
	5	11.0	11.0	15.0	17.4	12.3
	10	11.7	11.9	15.2	17.2	12.9
	20	12.2	12.5	15.4	17.0	13.3
	50	12.7	13.1	15.5	16.9	13.7
	100	13.1	13.4	15.6	16.8	13.9

and for very low recurrence intervals of the summer extremes. The higher return period values of annual X_T and the seasonal results which remain, show possible standard errors greater than the 10 percent proposed as acceptable. Annual values of up to 14 percent are evident for large values of T, and for the seasonal extremes 21 percent is the maximum shown by Table 34. Standard errors of the seasonal data are lowest for summer and greatest for winter.

It is thus concluded that the available measurements of daily rainfall allow estimates of X_T at the required level of precision for only annual values at T less than about five years and for summer with T generally two years or less.

Precipitation: Robertson method (1963)

In developing the mathematical theory of extreme values, Gumbel (1958) shows that when the number of independent observations is large, the distribution of the largest values tends to describe an asymptotic curve which may take one of three forms. In the present analysis of rainfall data concern is only with the exponential Gumbel Type I curve, with asymptotic probability given by an equation of the form $P(X) = \exp\left[-e^{-\alpha(x-u)}\right]$ ———————————— (13).
$\alpha(x-u)$ is the reduced variate and α and u are parameters estimated from the observed largest values. To estimate the parameters α and u, Robertson adopts the least-squares method based on the use of a special extreme value probability paper, whereas Seelye (1947) adopts the method of moments.

A limitation of the Gumbel method is that the annual rainfall maxima do not comply exactly with all the conditions upon which the distribution given by the equation for the Type I curve is based. When the annual extremes are plotted on extreme-value probability paper, the points may show some curvature or scatter and thus reveal little about the probable nature of the theoretical distribution. There is a problem to decide whether the departure from linearity is due to the records not being a representative sample of the long-term rainfall at the station, or whether there is some local climatic factor which influences the frequency distribution.

To compare this method with that described by Seelye (1947), the 1909-37 maximum daily rainfalls for Paerau listed in Table 30 were again analysed for the annual extreme series. A summary of results is given in Table 35, though the inclusion of rainfall amounts for the higher return periods is again hardly justified.

Although not illustrated, the observed maximum daily rainfalls show an increase in scatter about the theoretical curve above about T equals 10 years. Unadjusted values of X_T from the Seelye calculation lie within the two control curves and confirm the conclusions made by Simmers (1962) that both methods are equally acceptable and generally comparable in accuracy. However, there is a tendency for either overestimation of X_T for higher values of T by the Gumbel method, or, conversely, underestimation by the Seelye method in the same range. The reverse occurs with values of X_T for T less than about three years. An explanation of this trend is not attempted.

The standard errors of X_T given by the two control curves are listed in Table 36. Except for higher values above about T equals 10 years, the results are comparable with those already presented and discussed. No change of the previous conclusion is thus considered necessary.

TABLE 35: Summary: Maximum daily rainfall frequency analysis for Paerau (1909-1937) - Gumbel method

Rainfall in inches	Return period in years	Control Curves: Lower Limit	Control Curves: Upper Limit
0.63	1.01	0.35	0.92
0.83	1.03	0.61	1.05
1.11	1.10	0.94	1.29
1.32	1.20	1.16	1.49
1.47	1.30	1.30	1.64
1.68	1.50	1.51	1.85
2.02	2.00	1.82	2.21
2.84	5.00	2.54	3.14
3.39	10.00	2.93	3.85
3.70	15	3.13	4.27
3.91	20	3.26	4.57
4.08	25	3.37	4.79
4.59	50	3.76	5.43
5.10	100	4.27	5.93
2.17	2.33	Mean annual extreme	

TABLE 36: Standard errors of X_T for Paerau maximum daily rainfalls (1909-1937) from Gumbel analysis of annual extreme values

	T equals:-					
	2	5	10	20	50	100 (years)
Std. Error of X_T (inches):	0.20	0.30	0.46	0.65	0.83	0.83
Std. Error X_T (As % of X_T):	9.90	10.6	13.6	16.6	18.1	16.3

Temperature:

Temperature extremes do not feature prominently in analyses for this study, though for completeness some descriptive account of them is warranted.

Table 37 is given to show a summary of recorded Naseby State Forest and Elliot mean daily, monthly and seasonal maximum/minimum temperatures and ranges for the period 1923-69.

A marked seasonal variation in temperature extremes is apparent, from mean monthly maxima in the order of 80-83°F for summer to 55-60°F in winter. Corresponding minima are 30-31°F and 14-17°F for summer and winter respectively. An absolute maximum temperature of 93.3°F has been recorded for January, and the six months November-April all have maximum temperatures in excess of 80°F. Absolute minimum temperatures fall below 20°F in each of the months May-October. The range between the highest and lowest recorded values for the years 1930-69 has an absolute value of 88.3°F (93.3 to 5°F).

Average daily maximum readings in summer are between 67 and 69°F. Average daily minimum temperatures fall below 32°F during May-September, with a minimum in July (25.8°F). The greatest average daily range of temperatures occurs in January and February (25.3°F) and the least in June (17.3°F). The difference between the average daily maximum temperatures of the warmest and coldest months is 25.6°F and for the minimum values the figure is 17.7°F.

Streamflow: General

A knowledge of the magnitude of floods and minimum flows is important for engineering design. The problem here is to analyse present records and to forecast values of these extreme variates as a

TABLE 37: Summary: Paerau/Naseby State Forest measured mean daily, monthly, seasonal maximum/minimum temperatures and ranges (^{o}F) 1923-1969

A. *Mean Daily Maximum Temperatures (1923-1969:*

J	F	M	A	M	J	J	A	S	O	N	D	Year
68.8	68.6	64.8	58.3	50.5	44.6	43.2	47.3	53.6	58.8	62.3	66.5	57.3

B. *Mean Daily Minimum Temperatures (1923-1969):*

43.5	43.3	40.3	36.1	31.1	27.3	25.8	28.1	31.9	35.7	38.6	41.9	35.3

C. *Seasonal Mean Daily Maximum/Minimum Temperatures (1923-1969):*

		Summer	Autumn	Winter	Spring
(a)	Maximum	68.0	57.9	45.0	58.2
(b)	Minimum	42.9	35.8	27.1	35.4

D. *Mean Monthly Maximum Temperatures (1930-1969):*

J	F	M	A	M	J	J	A	S	O	N	D	Year
82.8	82.1	78.1	70.4	62.9	55.7	54.5	58.6	64.4	70.9	75.0	79.7	84.9

Highest Maximum:

93.3	88.5	85.6	80.2	70.0	64.0	60.5	66.0	70.0	77.0	84.0	89.0	93.3

E. *Mean Monthly Minimum Temperatures (1930-1969):*

30.8	31.1	28.9	25.6	20.4	16.7	13.8	17.0	21.6	24.4	26.9	29.7	12.6

Lowest Minimum:

25.0	25.1	25.0	22.2	10.8	7.0	5.0	9.4	12.0	17.0	21.0	23.2	5.0

F. *Seasonal Mean Monthly Maximum/Minimum Temperatures (1930-1969):*

		Summer	Autumn	Winter	Spring
(a)	Maximum	81.5	70.5	56.3	70.1
(b)	Minimum	30.5	25.0	15.8	24.3
		(Dec-Feb)	(Mar-May)	(Jun-Aug)	(Sept-Nov)

G. *Extreme Range of Temperatures (1930-1969):*

J	F	M	A	M	J	J	A	S	O	N	D	Year
68.3	63.4	60.6	58.0	59.2	57.0	55.5	56.6	58.0	60.0	63.0	65.8	88.3

H. *Average Daily Range of Temperatures (1923-1969):*

25.3	25.3	24.5	22.2	19.4	17.3	17.4	19.2	21.7	23.1	23.7	24.6	22.0

I. *Annual Range of Temperatures (1923-1969):*

Average daily max.	Range	Average Daily min.	Range
Jan. 68.8 July 43.2	25.6	Jan. 43.5 July 25.8	17.7

function of time. The statistical methods imposed by the irregularity of the phenomena are adequate under the limiting conditions of record homogeneity and stationarity. For probabilistic frequency analysis the records should be random, independent and homogeneous, without trend or periodicity. However, such conditions exist and are well known.

Floods and minimum flows are the extremes of the daily discharges and may be analysed by the statistical theory of extreme values by way of an annual extreme-value series. The theory and mechanics of the method are well documented and need not be reviewed here. Gumbel (1958) shows that annual maximum floods constitute a series which can be fitted to the Type I theoretical extremal distribution (equation (13)). The distribution holds for the condition of X lying between limits $-\infty$ to $+\infty$. For minimum flows there is no alternative. Since the discharges are positive variates, use of the Type III probability function of smallest values is required.

The Type III distribution has a finite lower limit, which may be zero, and takes the form of the equation

$$P(X) = \exp\left[-\left(\frac{x-\varepsilon}{u-\varepsilon}\right)^{\alpha}\right] \text{ ——————————— } (14).$$

x is the minimum flow, and ε, α and u are parameters estimated from one of several methods (Gumbel, 1958; Deininger & Westfield, 1969). The value of x equals u is the characteristic minimum flow, and ε is the smallest possible minimum or base flow and the lower limit of the distribution. The distribution thus holds for the conditions of x greater than or equal to ε, and u greater than ε.

To carry out frequency analyses of extreme values for the study area, annual maximum and minimum series were collated from the measured Paerau Bridge mean daily flow records for the periods 1912-13, 1916-28, 1936-39, 1941-44, 1947-50 and 1967-69. The possibility of similar calculations for the three year records at Patearoa-Paerau Bridge and Loganburn was not considered. Computer programmes used for the statistical calculations are listed in Appendix II.

Caution should be exercised in application of the results. Sources of error can arise in any of several ways. One possible error source for the Upper Taieri data is that except for 1967-69 the annual extreme values used were by necessity only mean daily rather than instantaneous discharges. However, this should not contribute a gross error to the maximum or minimum series, since the attenuated nature of the flow hydrographs should produce only small differences between the maximum or minimum mean daily and instantaneous extreme values.

Streamflow: Flood frequency analysis

As shown for the analysis of rainfall maxima, concern here is with the Type I extremal probability curve. Results of the computer analysis for the Paerau Bridge data are given in Table 38. Listed are values of X_T for specified return periods, the upper and lower control curve limits and the mean annual flood discharge defined by T equals 2.33 years. Values of X_T are given for T equals 50 and 100 years, though again the inclusion of these values is barely justifiable. Also shown are the flood discharges in terms of cusecs per square mile, which are of value for inter-catchment comparison.

Although not shown here, the observed flood discharges display a very reasonable scatter about the theoretical curve when plotted in accordance with the standard Weibull relationship. The standard errors of X_T given by the two control curves are listed in Table 39. Use of the data for return periods in excess of about 10 years should be in awareness of the possible errors involved.

TABLE 38: Annual flood frequency analysis (Gumbel) summary for the Taieri River at Paerau Bridge (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1967-69)

Return Period in years	Flow in cusecs.	Flow in cusecs/sq.ml.	Control Curves	
			Lower Limit	Upper Limit
1.01	306	1.31	131	481
1.03	420	1.80	288	552
1.10	586	2.51	479	692
1.20	710	3.05	609	811
1.30	796	3.41	695	897
1.50	919	3.94	815	1023
2.00	1116	4.79	1000	1233
5.00	1601	6.87	1420	1782
10	1922	8.25	1656	2187
15	2103	9.02	1782	2423
20	2229	9.56	1870	2588
25	2327	9.98	1938	2716
50	2628	11.3	2147	3108
100	2926	12.6	2438	3414
2.33	1206	5.17	(Mean Annual Extreme)	

TABLE 39: Standard errors of X_T for Paerau Bridge maximum daily discharges (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1967-69)

	T equals:-					
	2	5	10	20	50	100 (years)
Std. Error of X_T (cfs):	116	181	265	359	480	488
Std. Error X_T (As % X_T):	10.4	11.3	13.8	16.1	18.3	16.7

The available measurements of daily mean discharge do not allow estimates of X_T at the required precision level for any value of T. Calculated standard error is only 10.4 percent for T equals two, but values of up to 18 percent are evident for the higher recurrence intervals.

Streamflow: Minimum flow frequency analysis

Many theoretical probability distributions have been advanced to describe low flows, but the Gumbel Type III asymptotic distribution of smallest values has become the most commonly accepted (equation (14)).

Because of its engineering implications, estimation of the lower limit of the distribution (ε) is of particular concern. The estimate should be positive and should also be smaller than the smallest observed minimum flow. If the number of observations is large enough to ensure that the sampling error is small, the theoretical distribution curves obtained can be used to estimate the most severe minimum flows expected within a given number of years. Such information may be helpful in solving storage and irrigation problems. However, estimation of realistic values for ε is a problem since with limited available data, ε may vary markedly with additional information.

Results of the computed minimum flow frequency analysis for the Paerau Bridge data are given in Table 40. Shown are the values of X_T and their logarithmic transformations for specified return periods, the theoretical frequency and control curves, and minimum daily discharges in terms of cusecs per square mile.

Although not shown here, deviation of the measured discharges from the theoretical curve is marked beyond about T equals five years. The average standard errors of X_T given by the two control curves have been

TABLE 40: Annual minimum flow frequency analysis (Gumbel) summary for the Taieri River at Paerau Bridge (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1967-69)

Note: ε = 11.99 cusecs.

Return Period in years	Flow in cusecs.	Flow in cusecs/sq.ml.	Log Flow (= log e(Q-ε))	Control Curves	
				Log Lower Limit	Log Upper Limit
1.01	188	0.806	5.1701	4.7524	5.5878
1.03	136	0.585	4.8225	4.4431	5.2018
1.10	86.8	0.373	4.3154	3.9921	4.6387
1.20	63.2	0.271	3.9350	3.6471	4.2230
1.30	51.4	0.220	3.6734	3.3861	3.9607
1.50	39.0	0.167	3.2965	2.9995	3.5936
2.00	26.8	0.115	2.6953	2.3624	3.0282
5.00	15.4	0.066	1.2157	0.6987	1.7328
10	13.3	0.057	0.2362	-0.6173	1.0896
15	12.7	0.055	-0.3165	-1.4210	0.7880
20	12.5	0.054	-0.7035	-1.9838	0.5768
25	12.4	0.053	-1.0016	-2.4172	0.4141
50	12.13	0.052	-1.9198	-3.4089	-0.4306
100	12.05	0.0516	-2.8312	-4.3203	-1.3420

TABLE 41: Average standard errors of X_T for Paerau Bridge minimum daily discharges (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1967-69)

(After Hardison (1969) where Iv = 0.2738. Iv is the standard deviation of the common logarithms of the population of annual events)

T equals:-

	2	5	10	20	50	100 (years)
Std. Error X_T (As % X_T): (average)	11.1	13.5	15.0	17.1	19.4	21.3

calculated as shown by Hardison (1969) and are listed in Table 41. The results show that use of the data beyond the limit of T equals five years should be with caution.

Again the available measurements of daily discharge do not allow estimates of X_T at the required precision level for any value of T. Calculated standard error is 11.1 percent for T equals two years, and increases to 21 percent for higher return periods.

CATCHMENT MEAN PRECIPITATION AND YIELD

Precipitation:

It has become increasingly important for many hydrological purposes to accurately establish the mean rainfall over an area for particular periods of time. For example, the digital simulation of hydrological system performance is possible to a high degree of accuracy, yet the ultimate usefulness of such models depends on the accuracy of the input precipitation data.

Measured data available to determine estimates of monthly, seasonal and annual catchment mean precipitation for the Upper Taieri area, are limited to the 1908-40 daily record for I59491 Paerau and monthly values for 1968-69 at the thirteen stations listed in Table 1. However, Simmers (1970) and Hutchinson (1970(b)) have already demonstrated that considerable errors are involved when one gauge is assumed to represent the precipitation regime over the whole 285 square mile project area. Direct estimation of catchment mean precipitation is thus limited to the period 1968-69.

The first study objective is concerned with average catchment mean precipitation values. Calculation of the month by month areal mean values for 1968-69 is therefore not attempted at this stage. Justification for such a decision is found in the results presented for determination of optimum network density by means of the structural function. Gandin (1970) shows that if the precipitation stations are evenly distributed, the standard error of an areal mean depends on the statistical structure, the accuracy of observation, the distance between neighbouring stations, and on the area over which the averaging is carried out.

Standard errors of interpolation are given by equations (2) and (3). Average areal mean standard errors may thus be estimated for the Upper Taieri basin, by assuming the mean monthly and annual values of ε_{opt} from Figure 10, a measured mean gauge spacing of 5.3 miles, and a weighted mean station variance. That is, an equation of the form

$$\sqrt{\bar{E}} = [\bar{m}_k \; [1 - \frac{2\mu^2 \; (\frac{\bar{L}}{2})}{1 + \eta + \mu(\bar{L})}] \;]^{\frac{1}{2}} \qquad \text{———————} \quad (15),$$

where $\bar{L}$ is the mean interstation distance, and $\sqrt{\bar{m}_k}$ the mean station standard deviation given by $\sqrt{\bar{m}_k} = a_1 s_1 + a_2 s_2 + --- a_n s_n / A$. (Gandin, op. cit.; Sanderson & Johnstone, 1953). s is the standard deviation for each station, a the sub-area represented by each station, and $a_1 + a_2 --- + a_n = A$.

ε_{opt} would thus remain as previously calculated, but the station variance may change when the weighted mean derived from individual stations in the network is considered. Areal mean standard errors may thus vary from the values already shown, since the data on standard errors of interpolation presented in Table 4 have been calculated assuming variance from only the combined Paerau/Elliot record.

However, results presented show that even the combined 35 year record was not sufficient to give estimates for long-term areal mean rainfall to within 20 percent of actual at the 95 percent confidence level for all months. Further, in the initial calculations, the long-term record was also assumed to have statistical characteristics representative of all stations in the network.

It is therefore unlikely that the required parameters may be estimated from two year's data with a precision level greater than that already found unsatisfactory for other than annual values from a 35 year record. The present network density is shown to be in part theoretically acceptable. However, Table 4 and the discussion of Tables 24 and 25 suggest that all station records from the present network will require extension if estimates of the long-term annual, and at least some monthly, catchment mean precipitation values are needed to within the stated error criterion. It does not appear possible to estimate areal population parameters to the required precision with the measured data available.

Similar conclusions are reached for the sub-catchment estimates needed for the first study objective, and thus no attempt it made to calculate these values at this stage.

Yield:

Aspects of total catchment yield have already been considered in the discussion of Tables 28A and 29A for Paerau Bridge, and need not be reconsidered at length. Available yield measurements for the total area allow estimates of the annual and at least some of the monthly and seasonal parameters at the required precision level.

Only the Loganburn station has sufficient measured data to make any estimates of sub-catchment yield possible. However, Tables 28C and 29C show that the available records are of insufficient length to assure reliable estimation of mean monthly, seasonal or annual yield to within the allowable error criterion. The other stations on the major tributaries (Styx and Serpentine Creeks) and on the upper reaches of the main river (Upper Styx Valley Bridge), have insufficient available data to make any direct parameter estimates possible. Data for these sub-catchments are limited to sporadic discharge measurements prior to 1966, and regular gaugings since that time at approximately one to two weekly intervals.

It is thus concluded that the measured data available for the principal sub-catchments do not allow direct estimation of monthly, seasonal or annual yield parameters to within the stated error criterion. Sufficient sites are at present sampled to satisfy engineering design requirements as regards location. However, Tables 28 and 29 suggest that considerable extension of records on each of the major tributaries will be required, if recourse is not to be made to other ways of obtaining parameter estimates at the required precision level.

CONCLUSIONS

Summaries of measured monthly, seasonal and annual precipitation, temperature and streamflow data have been presented and discussed. The largely descriptive initial emphasis provides basic information of value for engineering design and gives an insight into the general hydrological characteristics of the Upper Taieri area.

Since parameters derived from short records may be poor estimates of the population parameters, the measured data are further analysed as required by the first study objective. That is, the degree of precision to which the parameters are estimated is calculated for each variable, and compared with the required precision levels. The statistical parameters considered are the mean, variability and extremes for time intervals which vary from daily to average annual values.

Although recognised as an approximation of actual conditions, the data are considered to be stationary time series of either normal or log-normal distribution, and without serial correlation.

It is suggested that estimates of point and areal average precipitation parameters for the Upper Taieri basin are required to be within 20 percent of actual parameters at the 95 percent probability level. The results show that mean seasonal and annual station precipitation may be estimated from the measured data with standard errors of less than 10 percent. The error criterion could be satisfied by five year's data for an annual mean and by 17 year's records for a seasonal mean. However, half of the months from the 35 year available measured record have standard errors in excess of 10 percent, and calculations show that up to 60 years of data may be needed to achieve the stated criterion for all months.

It is also deduced from the results that estimation of total and sub-catchment long-term areal mean precipitation to within 10 percent of actual precipitation is highly unlikely with the measured data. All station records from the post-1966 network would need considerable extension in order to allow direct estimation of areal population parameters with less than the allowable total error.

For maximum one, two and three day rainfalls, standard errors of less than 10 percent generally only occur for estimates of the annual extreme values at T less than about five years, and for very low recurrence intervals of the summer extremes. Higher return period values of annual X_T and the seasonal results which remain, show possible standard errors in excess of the 10 percent stated as acceptable.

Estimates of measured temperature parameters are required to be within 10 percent of actual parameters at the 95 percent confidence level. The results show that the available temperature data allow estimates of station monthly, seasonal and annual mean and variability at the required precision level. Calculated standard errors of the mean for the 45 year record are all less than one percent, and for the time intervals considered the stated criterion could have been satisfied by only two years of records.

Estimates of measured streamflow parameters are to be considered acceptable for design purposes if within 20 percent of actual parameters with 95 percent probability. The results show that total catchment mean annual, winter, spring, and October-March discharges may be estimated from the 25 to 30 year measured record at Paerau Bridge with standard errors of less than 10 percent. For these time intervals the error criterion could have been satisfied by 17 year's records. For the seasons which remain, and half the months, standard errors in estimating the mean are greater than 10 percent.

Streamflow population estimates with standard errors less than 10 percent may be possible with an increase in record length, though this is shown to be an impractical solution for the months December to March. It is evident that a less stringent error criterion must be accepted for the summer and early autumn months.

Available measured data for the principal sub-catchments do not allow direct estimation of monthly, seasonal or annual discharge parameters to within the allowable total error. Stations other than Loganburn have insufficient data of a type suitable for any direct form of parameter estimation. The continuous measured record for Loganburn is shown to be of insufficient length - standard errors of up to 42 percent are calculated for the mean seasonal discharges, and up to 60 percent for monthly values.

Available measurements of daily mean or instantaneous discharge do not allow estimation of total or sub-catchment annual flood or minimum flows at the required precision level for any return period. Standard errors of about 11 percent are calculated for both the flood and minimum flows at T equals two years, and values of up to 21 percent are evident for the higher recurrence intervals.

Although the precipitation, temperature and streamflow network design is judged to be theoretically acceptable for most purposes, it is evident that the first study objective has not been realised in full. The available measured data do not allow estimation of all the required population parameters at the required precision level. All precipitation and streamflow station records from the post-1966 network will need to be extended, unless indirect ways are used to obtain parameter estimates to within the stated precision level. Alternatively, the chosen allowable errors must be considered too stringent, though an increase may be unacceptable for the engineering design of water resources projects.

CHAPTER V BASIC DATA SYNTHESIS

NECESSITY FOR DATA SYNTHESIS

General

Although hydrological records are carefully kept with due attention to accuracy and the needs of consistency over the years, records are often either short, or scant, or both. Nearly every water development project requires some estimates or extension of available data.

For example, it would be ideal to have long-term records of streamflow which are continuous for a period of time sufficient to include conditions likely to be met in the operation of a specific project. This ideal is seldom met.

It is not possible to operate a gauging station with continuous flow records on every stream for which discharge data may be required. It is common practice, therefore, to define flow characteristics at one or more sites and transfer this information by one of several methods to the other stations. The many methods available are varied in their approach and degree of complexity, though most basically involve either some form of correlation, or make use of climatic data from the weather stations in the area. There should never be any doubt that such calculated values are only a substitute for measured data.

Upper Taieri Catchment:

It is obvious that the above comments have direct application to the Upper Taieri area. The first study objective has been only partially realised. Methods for data synthesis are now necessary in order to increase the amount of information contained at this stage in the precipitation and streamflow data series, as compared with the measured series alone. In this way, it may thence be possible to estimate the population parameters from the first objective at the required precision levels.

To determine the long-term runoff and mean flow characteristics for the total area and each principal subcatchment, it was initially assumed that the historic Paerau Bridge record was of adequate length to acceptably define the required parameters and hence be used for areal extrapolation. By the use of simple linear correlation and regression techniques and the available measured data, streamflow prediction equations could then be defined for the five stations which remain, and give records equivalent in length to that available for Paerau.

The above assumption is shown by Linsley (1958), Hidore (1963), Yevdjevich (1963), Ward (1968), and Moss (1970) to be generally valid for a 30 year record. However, results already presented show that the measured Paerau Bridge record is not of adequate length to satisfy the stated error criterion for all months or seasons. Extension of the Paerau Bridge record and synthesis of streamflows for the subcatchment stations are therefore necessary by way of techniques which use measured climatic data from within and peripheral to the study area.

Some extension of the measured temperature and precipitation data is also required in order to be fully effective for long-term streamflow synthesis, and to perhaps better satisfy the study objectives as regards precision of point and areal mean precipitation estimates. Basically, therefore, to satisfy the stated objectives of the study, it is considered necessary to develop long-term records of precipitation, temperature and streamflow from the available measured data to cover a common period of historic record. The periods of synthetic record to be derived are shown by Figure 37.

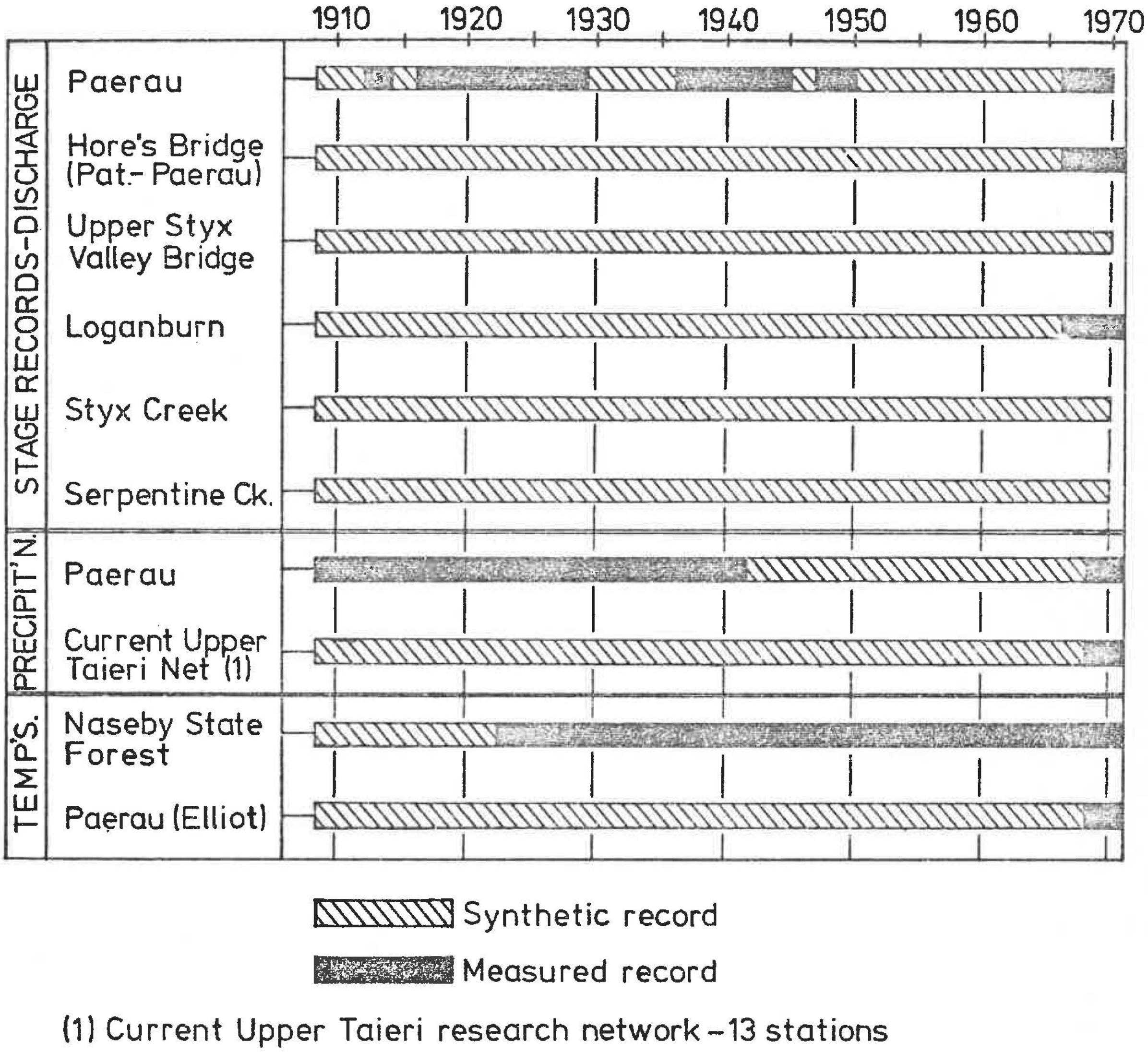


FIGURE 37: *Bar graph of measured and synthetic streamflow, precipitation and temperature records - 1908 to 1970*

Yet to be considered are theoretical questions of whether increased information in the statistical sense is added by such time extension and spatial extrapolation of the records. Also to be discussed are the factors:- precision of population parameter estimates from blended data, standard errors of prediction for the wholly synthetic records, and the relative simulation and prediction abilities of the models chosen. For example, Fiering (1963) showed that extension of a short record by correlation with data from another site may not always be desirable. Under certain circumstances, estimates of the population parameters mean and variance based on the extended record will be less reliable than those based on the unextended record.

OUTLINE OF MODELS USED

Parametric and Stochastic modelling: General

Regardless of the methods adopted for hydrological simulation, this study is based on the concept that the development of any relationship between elements of the hydrological cycle, however simple, may be classified as a model (Toebes & Ouryvaev, 1970). Further, as a basis for discussion of the various types of model available within the framework of hydrological system investigation, distinction must also be made between the terms 'system analysis' and 'system synthesis'. The study is conceptually guided by the approaches of Amorocho & Hart (1964), Dooge, (1968), Freeze & Harlan (1969), Dawdy & Kajinin (1970), and Clarke (1973).

The methods of system investigation fall into two principal categories - parametric and stochastic hydrology. Differences in the methods are evident, but two characteristics which theoretically limit the generality of the solutions are:

(i) the dependence of parameter values on historical records;

(ii) the assumption of stationarity or time invariance of the hydrological systems.

In brief, parametric hydrology is concerned with deterministic models, whereas stochastic hydrology is concerned with probabilistic models. A brief discussion of methods embraced by the two categories is desirable at this stage.

Parametric and stochastic modelling: Parametric hydrology

Among the earliest models used in hydrology were those of correlation analysis, or linear normal models. Multiple correlation methods have also been commonly used, though judgement is required to avoid the use of physically irrelevant parameters or parameters which possess strong interdependence. The methods of correlation analysis are powerful tools when used to test well grounded hypotheses in hydrology. Other less common methods are partial system synthesis with linear analysis and general non-linear analysis.

To establish quantitative relationships between streamflow and meteorological data, a technique currently receiving considerable attention is that of computer simulation of the hydrological cycle, or system synthesis. Model construction is based on the continuity equation. The principles and operation of conceptual models have been well described in the literature, and for further information on these aspects reference may be made to Kohler (1964), Crawford & Linsley (1966), Boughton (1965, 1966, 1967, 1968), Nash & Sutcliffe (1970), Hutchinson & Simmers (1971). Methods of parameter optimisation are described by Rosenbrock (1960), Boughton (1968(a)), Decoursey & Snyder (1969), Chapman (1970) and Clarke (1973).

Numerous modifications to the basic conceptual model of streamflow simulation have been proposed. The changes are demanded by factors such as different catchment size, and whether the model is intended exclusively for flow forecasts from a particular basin or for transfer in general form to ungauged catchments by way of the model parameters and basin characteristics (Wiser, 1966; Fenwick & Kingston, 1968). Conceptual models developed to date have generally proved reasonably reliable for general system synthesis, and are developing into a powerful tool with many applications in water resource investigations.

Catchment water balance techniques also have a very real place in the framework of parametric hydrology, and have been described by Edwards & Rodda (1970) as simplified conceptual models. Streamflow values may be determined from climatic data, and periods of moisture surplus and deficit derived. The method also affords the means to study the fundamental processes within the hydrologic cycle. Reference may be made to Thornthwaite & Mather (1955, 1957), McDonald (1963), or Raghunath *et al.* (1970), for details of water balance model principles and operation.

Parametric and Stochastic modelling: Stochastic hydrology

One of the most significant advances in recent years for generation of extended forecasts of basin yield, has been the use of probabilistic rather than deterministic concepts of simulation. Fundamental differences between parametric and stochastic models are described by Maas *et al.* (1962), Amorocho & Hart (1964), and Chow (1964).

Critical flow sequences may not be adequately represented by an observed record. However, mathematical statistics make possible the generation of hypothetical sequences of events which have the same probability characteristics of the past. Critical patterns of high and low flows are produced, which although not observed, could be expected on statistical considerations. An obvious limitation is that since the statistical parameters of the generated data population are the same as those estimated from the historical record, the new information is limited by the errors of measurement and sampling inherent in the observed data. The chief merits of the method are the extended information it provides beyond that of observed records, and the possible application to the design of multipurpose, multistructure systems (Payne *et al.* 1969; Young *et al.* 1969). Sequential streamflow generation by stochastic models yields hydrological information of practical use in water resources development and management, particularly when the system is relatively complex.

Thomas & Fiering (1962) introduced a widely accepted model which overcame weaknesses of earlier attempts. The model has sufficient flexibility to be used for either normally distributed or skewed weekly, monthly, seasonal or annual flow data, and incorporates serial correlation between successive flows to accord with an observed record (Boughton & McKerchar, 1968). The method has been extended by Harms & Campbell (1967). For a more comprehensive assessment of the theory, reference may also be made to Matalas (1967) and Pearson (1968).

More recent streamflow simulation methods which involve both single or multi-station flow generation and different time intervals, have been described by Yevdjevich & Roesner (1966), Young & Pisano (1968), Quimpo (1968), Payne (op. cit), Young (op. cit), Moreau & Pyatt (1970), and Chow & Kareliotis (1970).

Upper Taieri models:

In an attempt to satisfy the study objectives, the following techniques of data synthesis have been selected from the many available:-

(i) Linear, curvilinear, and multiple regression analyses for time series extension and spatial extrapolation of precipitation, temperature and streamflow data.

(ii) Alternative deterministic models for time series extension and spatial extrapolation of streamflow data - water balance and conceptual models.

(iii) Stochastic models for time series extension of streamflow data.

Other approaches of varying complexity are excluded for several reasons. The method outlined by Eakin *et al.* (1965), Riggs & Moore (1965) and Moore (1968), is precluded since there are insufficient streamflow records from a wide range of altitude and basin orientation. Methods which adopt an antecedent precipitation index (API) approach, as outlined by WMO (1965), Boughton (1968(b)), Moore (op. cit) and Sittner *et al.* (1969), are also not specifically considered in this study. Such methods are only a basic approximation of the conceptual model approach. Also, although the general method should apply to most streams, Moore (op. cit) concluded that exceptions would be those which are affected by regulation or snowmelt.

The technique proposed by Riggs (1969, 1970), is thought to have merit, but is precluded from this study since details of the method were not available in sufficient time to initiate a suitable data collection programme. However, it is considered desirable to test the value of this method under New Zealand conditions for future water resource studies.

Precision of new parameter estimates and comparison of models— Theory: Regression models

Statistical techniques may be utilized to examine the validity of using linear correlation analysis to augment data for any variable, when concurrent and additional data for the same variable are available at a nearby station.

Results from the theory of sampling give the variance of the first two statistical moments for a record of length n_1, taken to include only measured data. If correlation estimates are used to provide n_2 additional values, the result is a combined record which consists of n_1 measured values and n_2 estimated values. If the variance of a parameter computed from this blended record exceeds that computed from the record of size n_1 alone, the combined record provides a less precise estimate of the parameter. However, if the variance is less than that computed from the original record alone, the correlation technique has provided a more precise estimate and should be used.

For any particular parameter with known values of n_1, n_2 and ρ (population correlation coefficient), the relative information ratio, I, may be defined as the ratio of the variance of that parameter estimated from the original record, to that estimated from the combined record. I can vary from zero to infinity. When I exceeds unity, the variance of the estimate of a moment made from the original record alone is larger than that of the estimate made from the combined record, and thus the more precise estimate is computed from the combined data. When I is less than unity, the correlation analysis has introduced additional variance, or loss of precision. Correlation should not be used to augment the original data when I is less than 1.0.

For the above situation of n_1 measured values and n_2 additional estimated values, a weighted estimate of the mean of variable y is given by

$$\hat{\mu}_y = \frac{n_1\bar{y}_1 + n_2\bar{y}_2}{n_1 + n_2} \quad \text{———————} \quad (16);$$

$\bar{y}_1$ and $\bar{y}_2$ denote the estimates of the mean of y based on n_1 observations and n_2 regression estimates respectively. Matalas & Langbein (1962), Fiering (1963), and Frost & Clarke (1973) hence show that if the variables x and y in the array

$$x_1,\ x_2,\ \ldots\ x_{n_1},\ \ldots\ x_{n_1 + n_2}$$
$$y_1,\ y_2,\ \ldots\ y_{n_1}$$

are random and reasonably normally distributed, the variance of $\hat{\mu}_y$ from equation (16) is given by

$$\sigma_{\hat{\mu}y}^2 = \frac{\sigma_y^2}{n_1}\left[1 - \frac{n_2}{(n_1 + n_2)}\left[\rho^2 - \frac{(1 - \rho^2)}{(n_1 - 3)}\right]\right]. \quad \text{———————} \quad (17)$$

ρ is the coefficient of cross correlation of x and y.

The relative information ratio is given by

$$I = \left[1 - \frac{n_2}{(n_1 + n_2)}\left[\rho^2 - \frac{(1 - \rho^2)}{(n_1 - 3)}\right]\right]^{-1} \quad \text{———————} \quad (18)$$

For the case of I equals unity, the critical value of ρ^2 is calculated as $\rho^2 \geqslant {}^1/(n_1 - 2)$ ——————— (19).

If inequality (19) is not satisfied, the n_2 regression estimates will provide an unreliable estimate of the mean of y. Consequently, I will be less than 1.0, and additional information about the mean of y can only be obtained by an increase in n_1 (Matalas & Langbein, op. cit).

Clark & Bruce (1966) further show that the effective period of record of a combined short-term and extended record is approximately

$$N = \frac{n_1 + n_2}{1 + \frac{n_2}{(n_1 - 2)}\cdot(1 - \rho^2)} \quad \text{———————} \quad (20).$$

r may be substituted for ρ.

Correlation may also be used to improve estimates of the population variance. Fiering (op. cit) shows that the mean square error of the variance is given by

$$\mathrm{MSE}\ (\mathrm{Var}(y)) = \frac{2\sigma y^4}{n_1-1} + \frac{n_2\sigma y^4}{(n_1+n_2-1)^2}\left[2A + (n_2+2)B + (n_1+n_2-1)C - \frac{(n_1+1)(2n_1+n_2-2)}{n_1-1}\right] \tag{21}$$

in which $A = (n_1-1)\rho^4 + (n_1+4)\rho^2(1-\rho^2) + \frac{(n_1+1)}{(n_1-3)}(1-\rho^2)^2$,

$B = \rho^4 + \frac{6\rho^2(1-\rho^2)}{(n_1-3)} + \frac{3(1-\rho^2)}{(n_1-3)(n_1-5)}$, and

$C = \frac{2(n_1-4)(1-\rho^2)}{(n_1-3)}$.

The relative information ratio is given by

$$I = \frac{2\sigma y^4/(n_1-1)}{\mathrm{MSE}(\mathrm{Var}(y))} \tag{22}$$

The above solution shows that I exceeds 1.0 when ρ is of the order 0.8. Conditions for improved estimates of the variance are therefore more restrictive than those needed to improve estimates of the mean.

Tabular solutions of I are listed by Fiering (op. cit) for estimates of mean and variance given n_1, n_2 and ρ. The results show that the use of least squares regression can yield significant improvements in estimates of population parameters. Indiscriminant use of poor correlations may produce poorer estimates of parameters than could be obtained from the original data alone. However, the above equations apply only to data which may be, or are transformed to be, reasonably normally distributed and without serial correlation. Most hydrological sequences are serially correlated, and each observation repeats part of the information contained in past observations. Sequential correlation in hydrological series reduces the effective length of the series and also tends to impair the effectiveness of cross-correlation between series. Nevertheless, large values of cross-correlation can offset the loss of information due to autocorrelation.

For cross-correlated non-random series the variance of $\hat{\mu}y$ is given by

$$\sigma_{\hat{\mu}y^2} = \frac{\sigma y^2}{n_1}\left[\left(\frac{1+r_1}{1-r_1} - \frac{2.r_1}{n_1(1-r_1)^2}\right) - \frac{n_2}{n}\left[\rho^2\left(\frac{1+r_1}{1-r_1} - \frac{2(n+n_1)r_1}{nn_1(1-r_1)^2}\right)\right.\right.$$
$$\left. - \frac{(1-\rho^2)(1+r_1^2)}{n_1(1-r_1)^2}\right] + \frac{n_2(1-\rho^2)}{nn_1} . \left[\frac{3(1+r_1^4)+2r_1(1-r_1)^2}{n_1(1-r_1)^3(1+r_1)}\right.$$
$$\left.\left. - \frac{2r_1}{n_2(1-r_1^3)(1+r_1)} + \frac{n_1(1+r_1^2)\ \left[1-(1-r_1)(1+r_1)^3\right]}{nn_2(1-r_1)^4(1+r_1)^2}\right]\right] \text{——— (23).}$$

r_1 is the first-order autocorrelation coefficient and n equals $n_1 + n_2$. The value of I can be derived if $\frac{\sigma y^2}{n_1}$ is divided by $\sigma_{\hat{\mu}y^2}$ as given from (23).

However, as concluded previously, it is again proposed that assumptions of data randomness are probably justifiable, since serial correlation coefficients are likely to be low. The question of estimate precision for parameters derived from cross-correlation of non-random series is therefore not considered further in this study.

Equation (17) for the estimation of $\sigma_{\hat{\mu}y^2}$ applies to a blended record of any variable with n_1 measured values and n_2 additional values estimated by linear correlation and regression. However, regression theory affords a more general solution for correlation of either similar or dissimilar variables (e.g. precipitation versus streamflow), with application to linear, curvilinear, or multiple regression models.

The estimated standard error in prediction by linear regression of the population mean y, given x, is shown by Snedecor & Cochran (1969) to be

$$S\hat{\mu}_{y.x} = Sy.x\left(\frac{1}{n} + C_{11}\ (x-\bar{x})^2\right)^{\frac{1}{2}} \text{ ——————————— (24)}$$

with $(n-2)$ degrees of freedom. $Sy.x$ is the standard error of estimate from regression; n the number of items in the correlation; C_{11} is $^1/(n-1)(Sx)^2$, where Sx is the standard deviation of x values. For x equals $\bar{x}$, $S\hat{\mu}_{y.x}{}^2$ is given by $(Sy.x)^2/n$. Hence, if $S\hat{\mu}_{y.x}{}^2$ for n_2 regression estimates is added to $\frac{\sigma y^2}{n_1}$ given by n_1 measured values, the weighted average variance of the population mean for the blended data will approximate that given by equation (17).

Similar logic may be applied to estimate precision of $\hat{\mu}_{y.\bar{x}}$ for curvilinear and multiple regression models. However, for second and third order polynomials and multiple regression, equation (24) for $S\hat{\mu}_{y.x}$ becomes respectively, in matrix notation,

$$S\hat{\mu}_{y.x} = Sy.x,x^2 \left[(x-\bar{x},x^2-\bar{x}^2) \begin{bmatrix} C_{11}C_{12} \\ C_{21}C_{22} \end{bmatrix} \begin{bmatrix} x-\bar{x} \\ x^2-\bar{x}^2 \end{bmatrix} + \frac{1}{n} \right]^{\frac{1}{2}} \text{———} (25)$$

with $(n-3)$ degrees of freedom,

$$S\hat{\mu}_{y.x} = Sy.x,x^2,x^3 \left[(x-\bar{x},x^2-\bar{x}^2,x^3-\bar{x}^3) \begin{bmatrix} C_{11}C_{12}C_{13} \\ C_{21}C_{22}C_{23} \\ C_{31}C_{32}C_{33} \end{bmatrix} \begin{bmatrix} x-\bar{x} \\ x^2-\bar{x}^2 \\ x^3-\bar{x}^3 \end{bmatrix} + \frac{1}{n} \right]^{\frac{1}{2}} \text{—} (26)$$

with $(n-4)$ degrees of freedom, and

$$S\hat{\mu}_{y.x_1,x_2} = Sy.x_1,x_2 \left[(x_1-\bar{x}_1,x_2-\bar{x}_2) \begin{bmatrix} C_{11}C_{12} \\ C_{21}C_{22} \end{bmatrix} \begin{bmatrix} x_1-\bar{x}_1 \\ x_2-\bar{x}_2 \end{bmatrix} + \frac{1}{n} \right]^{\frac{1}{2}} \text{——} (27).$$

The degrees of freedom are $(n-3)$ for x_1,x_2 only in equation (27).

For 95 percent confidence limits, equations (24) to (27) must be multiplied by the appropriate value of $t_{0.05}$ given in standard statistical tables. In equations (24) to (26) for first, second and third order polynomials, $Sy.x,x^2,x^3$ is given by $S_{b_1}/\sqrt{C_{11}}$, where S_{b_1} is the standard error of the b_1 coefficient.

However, Osborn *et al.* (1971) and Hardison (1971) have suggested that interest may also be in the prediction standard error of an individual y, given x. The two prediction problems should not be confused. In this instance, equation (24) becomes, for the 95 percent confidence level,

$$\hat{Sy}_x = t_{0.05}\ Sy.x\ (1 + \frac{1}{n} + C_{11}(x-\bar{x})^2)^{\frac{1}{2}} \quad \text{———} \quad (28)$$

Similarly, equation (25) becomes

$$\hat{Sy}_x = t_{0.05}\ Sy.x,x^2 \left[(x-\bar{x}, x^2-\bar{x}^2) \begin{bmatrix} C_{11}C_{12} \\ C_{21}C_{22} \end{bmatrix} \begin{bmatrix} x-\bar{x} \\ x^2-\bar{x}^2 \end{bmatrix} + 1 + \frac{1}{n}\right]^{\frac{1}{2}} \quad \text{———} \quad (29)$$

etcetera. Dixon & Massey (1957) show that the confidence level is correct for a single prediction, but is not correct for repeated predictions from the same sample.

Sufficient theory has now been outlined to allow the second study objective to be tested, as far as is applicable to linear, curvilinear and multiple regression models.

Theory: water balance and conceptual models

Unlike the regression models just discussed, precision limits of parameter estimates derived by water balance or conceptual models are not readily quantifiable (Clarke, 1973). However, it is obviously desirable to establish objective numerical criteria for evaluating the goodness of fit of a model. An index of agreement or disagreement between the observed and computed values is required.

Linear regression analysis suggests a sum of squares criterion, such that the error function, or residual variance, may be defined as the cumulated sum of differences between computed and observed data. That is,

$$F^2 = \sum_1^n (x^1 - x)^2 \quad \text{———} \quad (30).$$

F^2 is the index of disagreement and x^1, x the computed and observed concurrent values (Nash & Sutcliffe, 1970). F^2 is analagous to the residual variance of a regression analysis. Alternatives to equation (30) are the mean squared error $F_m^2 = \frac{1}{n}\sum_{1}^{n}(x^1-x)^2$ ——————— (31), or the root mean squared error. All three forms are widely used in goodness of fit evaluation for simulation and prediction by a single model, or when the goodness of fit of several models is compared.

Theory: between model comparison

Clarke (op.cit) suggests, *inter alia,* that there is a need for comparison between the efficacy of conceptual models and simple regression models. In this study, the goodness of fit, or model efficiency measure proposed for comparative purposes is:

$$R^2 = \frac{\mathrm{var}(x) - F_m^2}{\mathrm{var}(x)} \qquad \text{———————} \quad (32).$$

var(x) is the initial variance given by $\frac{1}{n}\sum_{1}^{n}(x-\bar{x})^2$, where $\bar{x} = \frac{1}{n}\sum_{1}^{n}x$; n is the number of evenly spaced values in the record, and Fm^2 is as given by equation (31). R^2 is dimensionless and analagous to the coefficient of determination.

Other goodness of fit criteria are given by Nash & Sutcliffe (op.cit), March & Eagleson (1965), Jackson & Aron (1971), and Ibbitt & O'Donnell (1971).

If the relative behaviour of models is to be considered, it is insufficient to compare them on the grounds of how well they fit a given record. They should also be required to reconstruct a record, preferably preceding that to which the model was fitted. In this way the effect of serial correlation is minimised, and the "goodness of reconstruction" can be assessed independently of the goodness of fit. Objective comparisons of the reconstruction ability of the different models can then be made. Split record techniques such as described by Murray (1970), and Dickinson & Douglas (1972) are therefore used in this study to test the between and within model simulation and prediction abilities. Prediction results test the utility of the model.

REGRESSION ANALYSIS FOR PRECIPITATION AND TEMPERATURE TIME SERIES EXTENSION AND SPATIAL EXTRAPOLATION

Precipitation: Paerau record extension

In order to determine a long-term data series at each of the present stations in the Upper Taieri network, it is essential to extend the historic record for Paerau and assume equivalence of this station with that at Elliot. Provided acceptable correlation can be demonstrated, extension of the Paerau data is also proposed as a means to satisfy the study objectives as regards precision of parameter estimates at a point.

Two basic premises control any attempt to extend the 1908-40 Paerau record by correlation methods and hence to derive data for the period 1941-68. Any long-term station used in the correlation must have a record of sufficient length concurrent with Paerau to satisfy the demands of acceptable between-station correlation, and secondly, cover the period required for the extension.

Figure 7 shows that the only stations which could possibly satisfy both the above requirements for Paerau record extension are Manorburn Dam, Waipiata Sanatorium and Patearoa No. II. Of these, Manorburn Dam has a broken record for the period 1946-60 and is thus of limited value. Further, use of the Patearoa No. II record is dependent on the assumption that Patearoa No. I and No. II data can be combined for the initial correlation with Paerau without loss of consistency. The desirable requirements of record length for between station correlation studies proposed by McDonald & Green (1960) are satisfied. Also, the factors of between station distance and altitudinal difference lie within the limits shown by Hutchinson (1969) as theoretically allowable for this area, if monthly and annual correlations are to be significant at the 99 percent level.

Standard methods of simple linear and curvilinear correlation and regression are used, and involve no greater than third degree polynomials. Prediction equations for Paerau rainfall are developed for both monthly and annual data. The equations given in Table 42 and more fully defined in Appendix I(1), are derived with Paerau data as the dependent variables (Y) and in turn Manorburn Dam, Patearoa No. II, and Waipiata Sanatorium records as the independent variables (x). Record lengths used in the correlations are 1914-40 for Paerau-Manorburn Dam and 1916-40 for the remainder.

Monthly correlation coefficients follow the pattern of variability demonstrated by Figure 9. Maximum values occur in January and October with figures of 0.90 or better. Minimum coefficients are generally found for June, July and September, and it is only in these months that values of r fall below 0.60. With one exception, F tests show that correlations from the three sets of analyses are significant at the 95 percent level, and most are also significant at greater than the 99.9 percent level.

The three sets of correlations are considered satisfactory for record extension purposes. In all cases inequality (19) for the critical value of ρ^2 is satisfied, the relative information ratio I is greater than 1.00, and hence a more precise estimate of the mean may be computed from the blended data. However, conditions favourable for improved estimates of the variance are found for only January, May and October. In other than these months, therefore, poorer estimates are produced by the correlations than could be obtained from the original data alone. The question of obtaining increased estimate precision of population variance is hence not pursued.

TABLE 42: *Monthly and annual rainfall regression equations for Paerau record extension*

(Note: x = Manorburn Dam, Patearoa or Waipiata Sanatorium monthly or annual rainfall in inches.
Y = Paerau predicted monthly or annual rainfall in inches).

A. *Paerau-Manorburn Dam*

(i) January: $Y = 3.010 + 1.109 (x-2.400)$.
(ii) February: $Y = 2.574 + 0.179 (x-1.706) + 0.313 (x^2-3.907)$.
(iii) March: $Y = 2.638 + 3.074 (x-1.813) - 0.470 (x^2-4.642)$.
(iv) April: $Y = 2.660 + 1.385 (x-2.014)$.
(v) May: $Y = 2.500 + 1.805 (x-1.870) - 0.151 (x^2-5.320)$.
(vi) June: $Y = 2.111 - 4.134 (x-1.404) + 4.242 (x^2-2.499) - 0.924 (x^3-5.308)$.
(vii) July: $Y = 1.431 + 1.203 (x-0.999)$.
(viii) August: $Y = 1.879 + 6.129 (x-1.077) - 4.360 (x^2-1.501) + 1.109 (x^3-2.510)$.
(ix) September: $Y = 1.857 + 0.801 (x-1.294)$.
(x) October: $Y = 2.355 + 1.116 (x-1.757)$.
(xi) November: $Y = 2.755 + 1.071 (x-2.027)$.
(xii) December: $Y = 3.322 + 3.284 (x-2.011) - 0.448 (x^2-4.802)$.
(xiii) Annual: $Y = 29.092 + 6.004 (x-20.372) - 0.110 (x^2-430.794)$.

B. *Paerau-Patearoa*

(i) January: $Y = 3.042 + 1.291 (x-2.020)$.
(ii) February: $Y = 2.487 + 1.638 (x-1.386)$.
(iii) March: $Y = 2.695 + 6.729 (x-1.266) - 4.874 (x^2-2.061) + 1.318 (x^3-3.774)$.
(iv) April: $Y = 2.728 + 1.242 (x-1.405)$.
(v) May: $Y = 2.514 + 1.710 (x-1.058)$.
(vi) June: $Y = 1.962 + 1.125 (x-0.824)$.
(vii) July: $Y = 1.508 + 2.192 (x-0.860) - 0.532 (x^2-1.202)$.
(viii) August: $Y = 1.976 - 0.066 (x-0.859) + 3.543 (x^2-1.081) - 1.438 (x^3-1.675)$.
(ix) September: $Y = 1.909 - 1.518 (x-0.955) + 3.229 (x^2-1.241) - 1.047 (x^3-1.992)$.
(x) October: $Y = 2.388 + 1.994 (x-1.351) - 0.183 (x^2-3.075)$.
(xi) November: $Y = 2.765 + 2.837 (x-1.345) - 0.545 (x^2-2.329)$.
(xii) December: $Y = 3.368 + 1.512 (x-1.825)$.
(xiii) Annual: $Y = 29.344 + 150.475 (x-15.151) - 9.774 (x^2-233.389) + 0.209 (x^3-3657.175)$.

TABLE 42: (Continued)

C. *Faerau-Waipiata Sanatorium*

(i) January: $Y = 3.042 + 1.150\,(x-2.066)$.

(ii) February: $Y = 2.487 + 1.589\,(x-1.504)$.

(iii) March: $Y = 2.695 + 1.888\,(x-1.290)$.

(iv) April: $Y = 2.728 + 1.101\,(x-1.613)$.

(v) May: $Y = 2.514 + 1.236\,(x-1.303)$.

(vi) June: $Y = 1.962 - 17.434\,(x-1.020) + 17.281\,(x^2-1.314) - 4.572\,(x^3-2.052)$.

(vii) July: $Y = 1.508 + 1.333\,(x-0.972)$.

(viii) August: $Y = 1.976 + 5.115\,(x-1.040) - 4.969\,(x^2-1.525) + 1.597\,(x^3-2.724)$.

(ix) September: $Y = 1.909 - 2.814\,(x-1.124) + 3.800\,(x^2-1.638) - 1.039\,(x^3-2.893)$.

(x) October: $Y = 2.388 + 1.383\,(x-1.358)$.

(xi) November: $Y = 2.765 + 2.413\,(x-1.566) - 0.411\,(x^2-3.124)$.

(xii) December: $Y = 3.368 + 1.073\,(x-1.989)$.

(xiii) Annual: $Y = 29.344 - 4.284\,(x-16.845) + 0.150\,(x^2-289.336)$.

Results of the analyses are given by Table 43. New standard errors of the monthly and annual blended means are given by $\sigma_{\hat{\mu}_y}$ from equation (17), or for second and third order polynomials, from the weighted average of measured standard error of the mean (SE$\bar{y}$) and $S_{\hat{\mu}_y.\bar{x}}$ from equations (25) and (26). Results of standard error calculations from equation (24) were found to approximate those of equation (17), when weighted for n_1 and n_2 by SE$\bar{y}$. Although introducing a small additional error it was assumed that $\bar{x}$ for the n_2 regression estimates would equate with the $\bar{x}$ used in the original determination of equations (24) to (26).

The data in column (6) (Table 43) correspond to the SE$\bar{x}$ values of Table 24, and suggest that the most precise parameter estimates will be obtained from the blended record derived from Manorburn Dam. Values of mean monthly and annual rainfall for the total period 1908-69 could thus be derived (Column (2)), and the new standard errors computed as a percentage of this blended mean, for comparison with Table 24 results.

Estimates of mean seasonal and annual station precipitation are now available to greater precision than for the measured series alone. Mean annual rainfall is estimated to within seven percent at the 95 percent confidence level. Results for the mean monthly data show that only August now has a standard error in excess of 10 percent. Months which previously indicated unacceptable errors were February, March, May, June, July and August. Further, for the monthly data derived by combining the measured values and linear regression estimates, equation (20) indicates that effective record lengths have increased by up to 20 years.

The second study objective is satisfied in part. Addition of regression estimates to the measured Paerau record now allows determination of the mean station rainfall at the required precision level for all months

TABLE 43: Paerau mean monthly and annual rainfall parameters for the blended measured and synthetic record 1908-69

				Parameter values as derived from:-								
				Manorburn Dam			*Patearoa*			*Waipiata Sanatorium*		
Month	1908-69 Mean Rainfall (inches)	n_1 (yrs)	n_2 (yrs)	d.f	$\sigma\hat{\mu}_y$ (ins)	(6) As % y col.(2)	d.f	$\sigma\hat{\mu}_y$ (ins)	(6) As % y col.(2)	d.f	$\sigma\hat{\mu}_y$ (ins)	(6) As % y col.(2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(5)	(6)	(7)	(5)	(6)	(7)
Jan.	2.95	33	27	25	0.24	8.13	23	0.23	7.80	23	0.24	8.13
Feb.	2.69	33	27	24	0.24	8.92	23	0.25	9.29	23	0.25	9.29
Mar.	2.96	33	27	24	0.25	8.44	21	0.27	9.12	23	0.25	8.44
Apr.	2.42	33	27	25	0.21	8.68	23	0.23	9.50	23	0.22	9.09
May	2.29	33	27	24	0.19	8.30	23	0.19	8.30	23	0.20	8.73
June	2.23	33	27	23	0.22	9.86	23	0.24	10.8	21	0.24	10.8
July	1.37	33	27	25	0.13	9.49	22	0.14	10.2	23	0.12	8.76
Aug.	1.69	33	27	23	0.21	12.4	21	0.23	13.6	21	0.21	12.4
Sep.	1.83	34	27	25	0.12	6.56	21	0.15	8.20	21	0.15	8.20
Oct.	2.37	35	27	25	0.18	7.59	22	0.19	8.02	23	0.19	8.02
Nov.	2.70	35	27	25	0.18	6.67	22	0.19	7.04	22	0.19	7.04
Dec.	3.08	35	27	24	0.24	7.79	23	0.25	8.12	23	0.25	8.12
Year	28.57	33	27	24	0.95	3.32	21	1.05	3.67	22	1.03	3.61

Notes: Column (2) - values derived from the combined 1908-40 and 1968-69 measured records, and the optimum synthetic record from regression analysis.

Column (3),(4) - years of measured data and additional estimated values respectively.

Column (5) - degrees of freedom available for determining $t_{0.05}$.

Column (6) - see equation (17). Also used are weighted values of $S\hat{\mu}_{y.\bar{x}}$ from equation (24) and the higher polynomial versions, equations (25) and (26). All values correspond to SE$\bar{x}$ of Table 24.

Column (7) - $\sigma\hat{\mu}_y$ as a percentage of the 1908-69 blended mean. Corresponds to SE$\bar{x}$ as %$\bar{x}$ in Table 24.

except August. Monthly, seasonal and annual Paerau data for the period 1941-68 are listed in Tables 44 and 45. The total record for 1908-69 is obtained by combining these data with those in Tables 9 and 10. It should be noted however, that the individual values in Table 44 are subject to the prediction standard errors defined by equations (28) and (29).

The data now available for Paerau are considered satisfactory, and a mass curve of precipitation versus time for 1908-69 shows no discontinuity at the end of the measured record in 1940. It is hence not necessary to derive the missing Paerau record by more sophisticated techniques.

Precipitation: Catchment mean precipitation

To define the long-term complete and sub-catchment mean rainfall for the Upper Taieri area, an initial step is to derive the long-term relationships between Elliot/Paerau and other gauges in the present network. Prediction equations are developed for all stations with Elliot as the independent variable, by way of simple linear correlation and regression and the corrected precipitation values from the network. Results of the analyses are given in Tables 46 to 48 and in Appendix I(2).

The correlation coefficients displayed are significant at the 99 percent level, vary from 0.86 to 0.99, and the relationships are considered satisfactory for spatial extrapolation of the Paerau data. If the 1908-69 mean monthly rainfalls for Paerau are substituted in the listed prediction equations for each station, long-term station rainfalls are determined as shown by Table 47.

Since the regression equations were developed from approximately monthly data, annual values are given by the sum of the monthly values. The derived 1908-69 mean annual precipitation varies from 22 inches at Mulholland in the north, to 63 inches at Lammerlaw Top and Trig H in the southern upland area.

TABLE 44: Paerau synthetic monthly rainfall record (inches 1941 to 1968

Year	J	F	M	A	M	J	J	A	S	O	N	D
1941	3.6	1.6	3.2	2.5	2.0	1.1	1.2	1.7	1.3	1.6	3.6	4.7
1942	2.9	3.5	2.4	1.1	2.3	1.4	1.7	1.4	1.8	4.1	1.9	3.8
1943	1.9	2.8	3.9	2.6	1.4	2.2	1.1	1.7	2.0	1.7	2.0	1.4
1944	1.9	7.9	2.6	4.4	1.6	3.8	1.2	2.0	1.8	1.7	2.1	4.8
1945	3.2	9.7	3.2	4.6	4.1	1.0	1.1	1.4	2.3	2.3	2.4	4.9
1946	4.2	1.7	0.8	1.5	2.1	2.2	1.5	1.5	5.3	2.3	1.5	3.1
1947	2.2	2.3	0.6	2.3	2.1	4.7	0.6	1.8	1.6	4.9	1.8	2.3
1948	2.4	2.6	4.6	1.6	1.4	1.9	1.1	0.0	2.0	2.7	3.5	2.2
1949	2.9	4.7	4.0	1.7	2.0	1.9	2.2	1.6	1.4	1.8	1.4	3.0
1950	3.3	3.8	2.1	1.6	1.0	1.5	1.4	1.6	1.4	2.2	3.3	2.7
1951	3.7	1.4	3.1	2.1	1.5	2.0	1.1	1.4	1.6	2.7	3.8	2.5
1952	2.2	2.6	1.8	1.9	2.1	1.9	1.1	0.7	2.7	4.1	3.1	3.2
1953	3.3	2.0	4.8	3.6	1.5	1.5	0.6	1.6	1.3	1.2	3.2	2.5
1954	2.0	2.0	5.0	1.2	2.0	2.3	1.5	1.4	1.3	1.6	2.3	2.3
1955	3.8	1.4	5.4	1.2	3.2	3.4	3.1	1.2	1.3	2.4	3.6	1.2
1956	3.0	0.6	0.4	3.2	5.2	1.9	0.7	1.2	1.2	2.3	3.3	4.1
1957	2.3	2.6	5.0	2.3	4.9	2.4	0.7	0.0	1.8	3.7	3.5	3.9
1958	5.0	5.7	4.6	3.3	3.5	1.6	0.6	1.0	1.6	2.0	1.9	4.3
1959	2.7	1.8	2.9	1.9	3.4	1.7	0.6	0.3	1.3	1.6	3.1	3.6
1960	2.3	3.6	5.5	1.3	1.9	2.6	1.0	1.6	3.1	1.5	3.7	1.8
1961	2.9	5.3	4.1	1.8	0.8	3.6	2.6	1.7	2.1	1.5	3.4	0.4
1962	3.2	2.8	4.1	2.9	1.7	3.9	1.7	2.2	1.4	3.2	2.1	2.4
1963	2.4	3.6	3.0	1.9	2.6	2.2	0.8	4.4	2.4	2.6	2.4	3.2
1964	1.8	1.1	4.1	1.0	2.0	1.3	0.7	2.0	1.3	1.8	2.6	4.8
1965	4.0	3.6	3.1	2.4	3.4	3.2	1.1	1.8	1.7	2.3	2.5	1.2
1966	5.0	2.0	3.8	1.4	1.1	4.1	0.6	0.5	1.5	0.9	3.3	2.2
1967	1.6	1.3	2.8	3.5	1.4	1.7	0.9	1.1	2.8	2.2	3.4	4.7
1968	1.8	2.0	2.8	4.2	2.3	2.7	4.0	1.7	1.5	2.6	1.6	1.3
Mean: (1908-69)	2.95	2.69	2.96	2.42	2.29	2.23	1.37	1.69	1.83	2.37	2.70	3.08

TABLE 45: Paerau synthetic seasonal and annual rainfall record (inches) 1941 to 1968

Year	Summer (Dec-Feb)	Autumn (Mar-May)	Winter (June-Aug)	Spring (Sep-Nov)	Annual
1941	6.8	7.7	4.0	6.5	28.1
1942	11.1	5.8	4.5	7.8	28.3
1943	8.5	7.9	5.0	5.7	24.7
1944	11.2	8.6	7.0	5.6	35.8
1945	17.7	11.9	3.5	7.0	40.2
1946	10.8	4.4	5.2	9.1	27.7
1947	7.6	5.0	7.1	8.3	27.2
1948	7.3	7.6	3.0	8.2	26.0
1949	9.8	7.7	5.7	4.6	27.6
1950	10.1	4.7	4.5	6.9	25.9
1951	7.8	6.7	4.5	8.1	26.9
1952	7.3	5.8	3.7	9.9	27.4
1953	8.5	9.9	3.7	5.7	27.1
1954	6.5	8.2	5.2	5.2	24.9
1955	7.5	9.8	7.7	7.3	31.2
1956	4.8	8.8	3.8	6.9	27.2
1957	9.0	12.2	3.1	9.0	33.1
1958	14.6	11.4	3.2	5.5	35.1
1959	8.8	8.2	2.6	6.0	24.9
1960	9.5	8.7	5.2	8.3	29.9
1961	10.0	6.7	7.9	7.0	30.2
1962	6.4	8.7	7.8	6.7	31.6
1963	8.4	8.5	7.4	7.4	31.5
1964	6.1	7.1	4.0	5.7	24.5
1965	12.4	8.9	6.1	6.5	30.3
1966	8.2	6.3	5.2	5.7	26.4
1967	5.1	7.7	3.7	8.4	27.4
1968	8.5	9.3	8.4	5.7	28.5
Mean: (1908-69)	8.70	7.68	5.29	6.92	28.57

TABLE 46: Upper Taieri catchment raingauge network regression equations (Base station Elliot (≡Paerau) is x)

Station Name	Regression Equation	Correlation Coefficient
Mulholland	Y = 0.805x - 0.049	0.858
Aitken	Y = 0.915x + 0.133	0.882
Onslow Road	Y = 0.887x + 0.031	0.974
Smith	Y = 0.909x + 0.321	0.911
Bottle Rock North	Y = 1.304x + 0.022	0.977
Great Moss Swamp	Y = 1.233x - 0.115	0.987
Bottle Rock	Y = 1.308x + 0.198	0.983
Longstone	Y = 1.130x + 0.227	0.991
Round Hill	Y = 1.141x - 0.076	0.981
Musterer's Huts	Y = 1.865x + 0.223	0.971
Trig H	Y = 2.018x + 0.471	0.943
Lammerlaw Top	Y = 2.079x + 0.303	0.979

Prediction standard errors of mean monthly and annual station rainfall, where x is the 1908-69 mean Paerau data, are given by Table 48. The listed data are values of $S\hat{\mu}y.\bar{x}$ from equation (24), and are given as a percentage of $\bar{y}$ from Table 47. The results indicate that for the stated Paerau values, the mean annual station rainfalls may be estimated by regression with standard errors of less than eight percent. Weighted average monthly and annual standard errors for the catchment are further shown by Table 48 to be as low as five percent.

Standard errors of the long-term station arithmetic means are not readily quantifiable for the derived data in terms of the second study objective. The Paerau/Elliot values used in the regressions are not error free, but are subject to the standard errors previously accorded to the data listed in Tables 43 and 44. However, provided the additional errors in the Paerau data are random and normally distributed, Snedecor & Cochran (1969) have suggested that equation (24) may still be used to determine standard errors of prediction. The standard errors listed in

TABLE 47: 1908-69 mean monthly and annual rainfall determination for the Upper Taieri raingauge network

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Paerau:	2.95	2.69	2.96	2.42	2.29	2.23	1.37	1.69	1.83	2.37	2.70	3.08	28.57
Mulholland:	2.32	2.12	2.33	1.90	1.79	1.74	1.05	1.31	1.42	1.86	2.15	2.43	22.42
Aitken:	2.83	2.59	2.84	2.34	2.23	2.17	1.39	1.68	1.81	2.30	2.60	2.95	27.73
Onslow Road:	2.65	2.42	2.66	2.18	2.06	2.01	1.25	1.53	1.65	2.13	2.42	2.76	25.72
Smith:	3.00	2.77	3.01	2.52	2.40	2.35	1.57	1.86	1.98	2.47	2.78	3.12	29.83
Bottle Rock North:	3.87	3.53	3.88	3.18	3.01	2.93	1.81	2.23	2.41	3.11	3.54	4.04	37.54
Gt. Moss Swamp:	3.52	3.20	3.53	2.87	2.71	2.63	1.57	1.97	2.12	2.81	3.21	3.68	33.82
Bottle Rock:	4.06	3.72	4.07	3.36	3.19	3.11	1.99	2.41	2.59	3.30	3.73	4.23	39.76
Longstone:	3.56	3.27	3.57	2.96	2.81	2.75	1.78	2.14	2.29	2.91	3.28	3.71	35.03
Round Hill:	3.29	2.99	3.30	2.68	2.54	2.47	1.49	1.85	2.01	2.63	3.00	3.44	31.69
Musterer's Huts:	5.72	5.24	5.74	4.74	4.49	4.38	2.78	3.37	3.64	4.64	5.26	5.97	55.97
Trig H:	6.42	5.90	6.44	5.35	5.09	4.97	3.23	3.88	4.16	5.25	5.92	6.69	63.30
Lammerlaw Top:	6.44	5.90	6.46	5.33	5.06	4.94	3.15	3.82	4.11	5.23	5.92	6.71	63.07
Weighted average basin rainfall:	3.40	3.11	3.41	2.80	2.66	2.59	1.63	1.99	2.14	2.75	3.12	3.54	33.13

Notes: (i) 1908-69 mean monthly and annual data for Paerau are as given by Table 43. Monthly values for the remaining stations are derived from the regression equations in Table 46, assuming x is the 1908-69 Paerau mean.

(ii) Mean annual values for other than Paerau are given by the sum of individual mean monthly data.

(iii) Weighted average basin rainfall derived from station mean monthly data and Thiessen weighting factors.

TABLE 48: Prediction standard errors of mean monthly and annual basin rainfall where x is the 1908-69 mean Paerau data

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mulholland:	7.99	7.73	7.99	7.49	7.39	7.34	7.43	7.02	7.06	7.44	7.66	8.08	7.55
Aitken:	6.67	6.44	6.68	6.18	6.02	5.97	5.16	5.36	5.50	6.12	6.45	6.77	6.11
Onslow Road:	4.01	4.04	4.00	4.14	4.21	4.25	5.92	4.97	4.71	4.17	3.80	4.01	4.35
Smith:	6.15	6.06	5.19	6.03	6.03	6.02	7.11	6.75	6.24	6.04	6.06	6.20	6.16
Bottle Rock North:	3.79	3.87	3.80	4.00	4.09	4.14	5.93	4.93	4.82	4.03	3.87	3.77	4.24
Great Moss Swamp:	2.93	2.98	2.93	3.07	3.13	3.17	4.46	3.72	3.55	3.09	2.98	2.92	3.24
Bottle Rock:	4.08	4.23	4.08	4.47	4.61	4.69	7.01	5.78	5.42	4.51	4.23	4.03	4.76
Longstone:	2.41	2.46	2.41	2.58	2.65	2.76	3.94	3.28	3.08	2.60	2.46	2.39	2.75
Round Hill:	3.24	3.29	3.24	3.38	3.43	3.47	4.79	4.04	3.83	3.39	3.29	2.72	3.51
Musterer's Huts:	4.54	4.67	4.54	4.95	5.04	5.12	7.66	6.31	6.02	4.94	4.66	4.49	5.25
Trig H:	5.75	5.79	5.75	5.90	5.97	6.02	7.79	6.78	6.50	5.92	5.79	5.73	6.14
Lammerlaw Top:	4.64	4.82	4.64	5.10	5.26	5.35	7.90	6.56	6.15	5.15	4.81	4.58	5.41
Weighted average standard error:	5.28	5.31	5.22	5.30	5.27	5.41	6.31	5.98	5.35	5.21	5.09	5.21	4.99

Notes: (i) The listed data are values of $S\hat{\mu}_{y.\bar{x}}$ from equation (24), and are given as a percentage of $\bar{y}$ from Table 47. x values for equation (24) are assumed to be the mean monthly rainfalls from Table 47, and error free.

(ii) Mean annual values are the average of summed individual mean monthly data.

(iii) Weighted average standard errors are derived from the station data and Thiessen weighting factors.

Table 48 will therefore be minimum values, since the true values of x are not directly known. If the values of x are maximised and minimised in accordance with the error distributions given in Table 43, a range of new rainfall data may be calculated for Table 47. The weighted average standard errors in Table 48 are in turn recomputed to be in the order of 25 percent.

Since the rainfall predictions for the 12 stations are unlikely to be improved, because of the Paerau/Elliot standard errors shown by Table 43, data derivation by alternative means are considered unnecessary. For example, Hutchinson's (1968) results show that multiple correlation techniques using topographic factors do not necessarily produce results of any greater accuracy than those derived above.

Techniques of areal integration of point rainfalls to establish the mean value over an area, rely largely on the Thiessen polygon, or arithmetic mean methods. When used with appreciation of their limitations, they generally give realistic results in most circumstances. Values of total and sub-catchment mean precipitation, and the relationship of these amounts to the long-term Paerau/Elliot record, are thus derived using the simple standard techniques. Although more sophisticated methods are not considered here, their importance is sufficient to warrant a separate study of relative merits.

Average basin mean monthly and annual rainfalls for the period 1908-69 have been calculated by three methods:

(a) Station mean annual rainfalls from Table 47 are plotted on a catchment outline map and isohyets for the period 1908-69 derived as shown on Figure 38.

(b) The Thiessen polygon technique applied to the plotted station mean annual rainfalls.

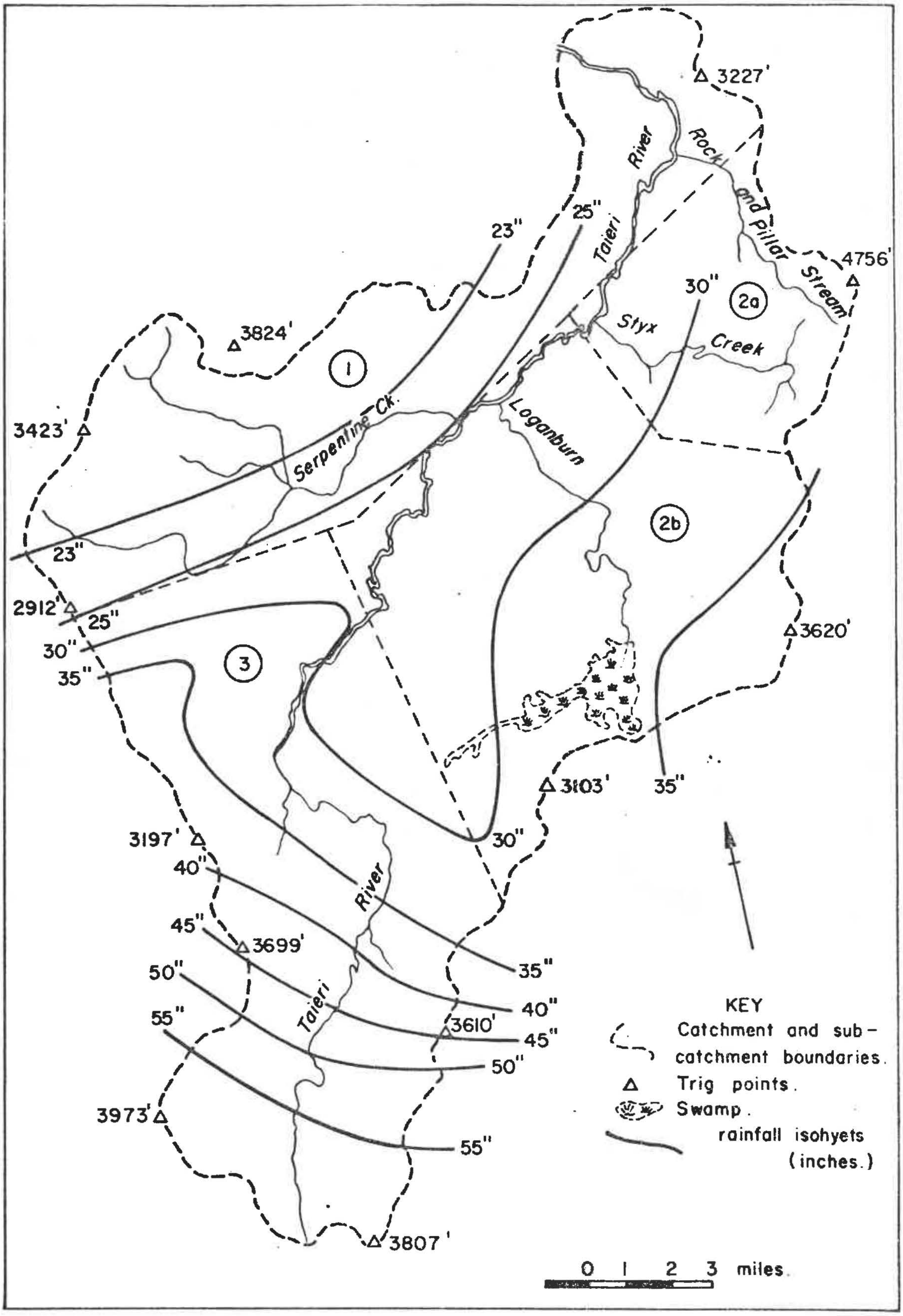


FIGURE 38: Upper Taieri catchment mean annual rainfall (1908-1969)

Calculation of the 1908-69 catchment mean annual rainfall by the above two methods gives a value of approximately 33 inches in each case (Table 47). The 1908-69 arithmetic mean value of 38 inches is not considered reasonable, since the station Thiessen weight factors suggest that undue emphasis would thus be given to the higher rainfalls for Lammerlaw Top and Trig H.

(c) Linear correlation of approximately monthly catchment mean rainfalls derived by the Thiessen polygon method, with equivalent period Elliot totals. Results of the analysis are given in Table 49. The table shows the calculations for 21 rainfall 'events', and the Thiessen weight factors appropriate to each gauge, dependent on the available records and hence variations of polygon used. The equation which relates average catchment 'event' values (Y) to the Elliot totals (x) is given as

$$Y = 1.28x + 0.004 \text{ inches} \quad \text{———————} \quad (33).$$

Other relevant statistics are d.f. = 19; $Sx = 1.84$ inches; $Sy.x = 0.42$ inches; $C_{11} = 0.0148$; $\bar{x} = 2.32$ inches; $r = 0.988$. The correlation coefficient is significant at the 99 percent level. Long-term average basin rainfalls and standard errors of prediction are thus derived in the same manner as described for Tables 47 and 48. The results are given in Table 50.

Catchment mean annual rainfall is calculated as 36 inches. The prediction standard errors show that for the given monthly Paerau data, mean values of average basin rainfall may be estimated by regression to within six percent. However, the above standard errors must again be considered as minimum values since x is not error free. If the calculated standard errors for $\bar{x}$ are again considered, it can be shown that the above error values may increase by up to 40 percent relative to $\hat{\mu}y$.

TABLE 49: Catchment mean rainfall - event Thiessen polygons

**Gauges included in Thiessen polygons for dates shown (points rainfall)*

Inclusive dates	(1)		(2)		(3)		(4)		(5)		(6)		(7)	
	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF
		10		33		10		4				8		3
2/3.1.69-15/16.1.69	220	022	180	059	240	024	279	011	-	-	227	018	229	007
		10		33		10		4				10		3
26/28.11.68-2/3.1.69	140	014	174	057	089	009	244	010	-	-	220	022	167	005
		8		19		10		4				10		3
26/28.11.68-15/16.1.69	360	029	354	067	329	033	523	021	-	-	447	045	396	012
		8		19		12		5		5				
15/16.1.69-21/22.1.69	031	002	021	004	013	002	113	006	051	002	-	-	-	-
		8		19		12		5		5				
21/22.1.69-12/13.2.69	082	006	134	025	100	012	452	023	514	026	-	-	-	-
		8		19		12		2		4		6		3
15/16.1.69-12/13.2.69	113	009	155	029	113	013	784	016	565	023	352	021	177	005
		12		19		12		2		4		7		4
12/13.2.69-18.2.69	068	008	030	006	000	000	131	003	140	006	109	008	080	003
		12		19		12		2		4		7		4
15/16.1.69-18.2.69	181	022	185	035	113	014	696	014	705	028	461	032	257	010
		12		19		12		2		4		7		4
18.2.69-5/6.3.69	025	003	027	005	010	001	066	001	075	003	085	006	065	003
		8		19		9		2		4		5		3
5/6.3.69-12.3.69	011	001	007	001	000	000	278	005	188	007	157	008	063	002
		8		19		9		2		4		5		3
12.3.69-17/19.3.69	026	002	034	006	033	003	107	002	098	004	104	005	049	001
		8		19		9		2		4		5		3
17/19.3.69-31/3.1/2.4.69	142	011	146	028	152	014	312	006	268	011	299	015	241	007
		8		19		9		2		4		5		3
5/6.3.69-31.3.1/2.4.69	179	014	187	035	185	017	679	014	554	022	560	028	353	010

TABLE 49: Continued

Inclusive dates	(1)		(2)		(3)		(4)		(5)		(6)		(7)	
	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF
		7		19		10		4				7		3
31/3.1/2.4.69-22.4.69	193	013	173	033	100	010	905	036	-	-	404	028	205	006
		7		19		10		4				7		3
5/6.3.69-22.4.69	372	026	360	068	285	028	1602	064	-	-	964	067	558	017
		8		19		10		4				10		3
22.4.69-13/15.5.69	088	007	051	010	085	008	232	009	-	-	248	025	261	008
		8		19		10		4				10		3
5/6.3.69-13/15.5.69	460	037	411	078	370	037	1834	073	-	-	1212	121	819	025
		9		19		12		4				10		3
12/13.2.69-13/15.5.69	553	050	468	089	380	046	2031	081	-	-	1406	141	964	029
		8		19		12		2		4		6		3
15/16.1.69-31/3.1/2.4.69	385	031	399	076	308	037	1459	029	1344	053	1106	066	675	020
		9		19		12		4				10		3
15/16.1.69-13/15.5.69	666	060	623	118	493	059	2417	079	-	-	1758	176	1141	034
		8		19		12		4				7		3
15/16.1.69-22.4.69	578	046	572	109	408	049	2364	095	-	-	1510	106	880	026

*Gauges included: (1) Elliot (4) Trig H (7) Longstone (10) Onslow Rd. (13) Great Moss Swamp
(2) Aitken (5) Lammerlaw Top (8) Bottle Rock (11) Smith
(3) Mulholland (6) Musterer's Huts (9) Bottle Rock Nth. (12) Round Hill

TABLE 49: Continued

Inclusive Dates	(8)		(9)		(10)		(11)		(12)		(13)		Catchment Mean Event Total (ins.)
	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	Tot. RF	WF RF	
2/3.1.69-15/16.1.69	199	9 018	207	3 006	156	12 019	190	9 017	-	-	-	-	2.01
26/28.11.68-2/3.1.69	-	-	225	5 011	120	12 014	086	13 011	-	-	-	-	1.53
26/28.11.68-15/16.1.69	-	-	432	5 022	276	11 030	276	12 033	350	12 042	391	6 023	3.57
15/16.1.69-21/22.1.69	078	10 008	043	11 005	-	-	067	11 007	055	12 007	065	6 004	0.47
21/22.1.69-12/13.2.69	105	10 010	120	11 013	-	-	127	11 014	137	12 016	100	6 006	1.51
15/16.1.69-12/13.2.69	183	8 015	163	11 018	-	-	194	9 017	192	12 023	165	6 010	1.99
12/13.2.69-18.2.69	066	10 007	038	11 004	-	-	-	-	031	12 004	062	6 004	0.53
15/16.1.69-18.2.69	249	10 025	201	11 022	-	-	-	-	223	12 027	227	6 014	2.43
18.2.69-5/6.3.69	025	10 002	025	11 003	-	-	-	-	025	12 003	025	6 001	0.31
5/6.3.69-12.3.69	051	8 004	043	3 001	047	12 006	098	9 009	008	12 001	011	6 001	0.46
12.3.69-17/19.3.69	043	8 003	031	3 001	040	12 005	028	9 002	028	12 003	024	6 001	0.38
17/19.3.69-31/3.1/2.4.69	385	031	183	005	148	018	151	013	079	009	058	003	1.71
5/6.3.69-31/3.1/2.4.69	479	8 038	257	3 008	235	12 028	277	9 025	115	12 014	155	6 009	2.62
31/3.1/2.4.69-22.4.69	175	9 016	222	3 007	113	11 012	245	9 022	150	12 018	175	6 010	2.11
5/6.3.69-22.4.69	654	9 059	479	3 014	348	11 038	522	9 047	265	12 032	330	6 020	4.80

TABLE 49: Continued

Inclusive Dates	(8) Tot. RF	(8) WF RF	(9) Tot. RF	(9) WF RF	(10) Tot. RF	(10) WF RF	(11) Tot. RF	(11) WF RF	(12) Tot. RF	(12) WF RF	(13) Tot. RF	(13) WF RF	Catchment Mean Event Total (ins.)
22.4.69-13/15.5.69	-	-	137	5 007	120	11 013	105	12 013	082	12 010	054	6 003	1.13
5/6.3.69-13/15.5.69	-	-	616	5 031	468	11 051	627	12 075	347	12 042	384	6 023	5.93
12/13.2.69-13/15.5.69	-	-	679	13 088	-	-	813	12 098	403	12 048	471	6 028	6.98
15/16.1.69-31/3.1/2.4.69	753	8 060	483	11 053	-	-	657	9 059	363	12 044	407	6 024	5.52
15/16.1.69-13/15.5.69	-	-	787	13 102	-	-	1007	12 121	595	12 071	636	6 038	8.76
15/16.1.69-13/15.5.69	928	9 084	705	11 078	-	-	902	9 081	513	12 062	582	6 035	7.71

*Gauges included:
(1) Elliot
(2) Aitken
(3) Mulholland
(4) Trig H
(5) Lammerlaw Top
(6) Musterer's Huts
(7) Longstone
(8) Bottle Rock
(9) Bottle Rock Nth.
(10) Onslow Rd.
(11) Smith
(12) Round Hill
(13) Great Moss Swamp

TABLE 50: 1908-69 average catchment rainfall determination and standard errors of prediction for the mean values, where x is the long-term mean Paerau data

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Average basin rainfall (ins.):	3.78	3.44	3.79	3.10	2.94	2.86	1.76	2.17	2.35	3.04	3.46	3.95	36.64
$\hat{S}\mu y.\bar{x}$ as % of $\bar{y}$:	2.57	2.72	2.64	2.96	3.12	3.21	5.89	4.47	4.04	3.01	2.71	2.52	3.32

Notes:
(i) Monthly rainfall values are derived from equation (33) with x the 1908-69 Paerau means from Table 43.
(ii) The annual value is the sum of all monthly values.
(iii) Standard errors are given by equation (24) and are shown as a percentage of average basin rainfall. x values are again taken as the 1908-69 Paerau means.

Average areal mean standard errors are thus still not readily calculable in terms of the second study objective. Although estimated catchment mean rainfall values are shown to be in close agreement from the three methods, standard errors will not be less than those given by Table 50.

It is therefore concluded that since the earlier extension of the Paerau record does not provide improved estimates of the station variance, weighted mean station variance required for equation (15) will not be reduced. Standard errors are thus unlikely to be less than those shown by Table 4 for network design by means of the structural function. It does not appear possible to estimate areal population parameters to the required precision with the data available.

If the value of 36 inches is assumed correct, the minor under estimation produced by methods (a) and (b) may be attributed to inadequate rainfall sampling in the headwater areas of the Rock and Pillar stream and Serpentine Creek. However, a lack of access precludes the installation and ready maintenance of additional gauges in these areas. Since the problem areas produce only a minor proportion of the available water in the Upper Taieri river system, the possible sampling errors may be accepted and the isohyetal map (Figure 38) used without further modification.

The data displayed by Table 47 suggest a strong positive correlation between mean annual rainfall and altitude in the study area. The equation which relates the 1908-69 mean annual station rainfalls (Y) and altitude is given as

$$Y = 0.0154x - 9.12 \text{ inches} \qquad (34).$$

Related statistics are d.f. = 11; Sx = 665 feet; Syx = 7.74 inches; C_{11} = 0.00; $\bar{x}$ = 2969 feet; r = 0.81; s.l.<0.01. Mean annual rainfalls of about 40-45 inches and 55-60 inches could thus be expected in the upper areas of the Serpentine Creek and Rock and Pillar Stream respectively.

95 percent confidence limits for the estimates are calculated by equation (24) to be plus or minus 10 percent.

It is thus concluded that mean annual rainfall varies from 23 to 63 inches over the 285 square mile area. Highest values occur to the south on the elevated plateau (35-63 inches), intermediate values in general on the eastern hill country (30-35 inches) and the lowest totals (generally less than 30 inches) to the north and west of the Taieri River and on the floor of the Styx Basin.

On the basis of these results and the vegetation distributions shown by Figure 6, the basin is divided into three zones (Figure 38). Area 2 is further divided because of suspected atypical yield characteristics produced by the Great Moss Swamp at the head of the Loganburn. Although not entirely coincident with drainage boundaries, these areas are subsequently considered as 'sub-catchments' of the whole basin.

Mean rainfalls for the sub-catchments are computed from the station mean values listed by Table 47 and the appropriate Thiessen weight factors. Results for mean annual data are given in Table 51. Also shown are the sub-catchment areas, mean altitudes, and the ratio of Elliot to sub-catchment mean rainfall. For an assumed total catchment mean rainfall for 1908-69 of 36 inches, sub-area figures for the same period are 25 inches for area 1, 29 inches for area 2a, 30 inches for area 2b, and 41 inches for area 3. Standard errors of estimate are again not less than those deduced for the total catchment.

Temperature: Naseby State Forest record extension

It has been shown that available measured data already allow estimates of station temperature parameters at the required precision level. However, for long-term water balance studies and for some models of streamflow synthesis, it is desirable to have long-term temperature data concurrent

TABLE 51: Subcatchment mean rainfall (1908-69)

Station Name	Station Mean Annual RF(ins) (1908-69)	Mean Annual RF(ins) x Thiessen weighting factor (%)			
		Area 1	Area 2a	Area 2b	Area 3
Mulholland:	22.42	7.55		0.23	
Aitken:	27.73	9.14	13.73	4.84	
Elliot:	28.57	0.63		5.99	0.85
Onslow Road:	25.72	8.01			2.30
Smith:	29.83			3.76	4.52
Bottle Rock North:	37.54				3.13
Great Moss Swamp:	33.82			6.97	
Bottle Rock:	39.76				8.99
Longstone:	35.03			0.98	2.18
Round Hill:	31.69		16.00	7.75	
Musterer's Huts:	55.97				9.16
Trig H:	63.30				4.15
Lammerlaw Top:	63.07				8.07
Total rainfall (inches):		25.33	29.73	30.52	43.35
Sub-catchment area (sq.mls):		77.2	29.8	81.1	97.0
Ratio Elliot: sub-catchment mean rainfall:		1: 0.887	1 :1.041	1:1.068	1 :1.517
Sub-catchment mean altitude (feet):		2400	3400	2800	3000

with the period of record available for other variables. Figure 57 shows that extension of the combined Naseby State Forest/Elliot record is thus necessary, in order to cover the period 1908-22.

Data considered initially for the analysis are the monthly and annual mean temperatures for Tapanui, Waipiata and Manorburn Dam. Only the Tapanui records are found to be suitable for Naseby State Forest data extension. Prediction equations are developed for mean monthly Naseby State Forest temperature, using linear and curvilinear correlation and regression. No greater than third degree polynomials are included, and the equations are given in Table 52 and more fully defined in Appendix I(3). Record length used in the correlations is 1923-65.

Correlation coefficients follow the pattern given by Figure 11. Maximum values of about 0.8 occur in January, February and March. Minimum values of 0.5-0.6 are found in September and December, and it is only in these months that the coefficients fall below 0.6. The correlations are significant at greater than the 99.9 percent level, and are considered satisfactory for extension purposes.

The critical value of ρ^2 is satisfied, the relative information ratio is greater than 1.00, and hence a more precise estimate of the mean may be computed from the blended data. However, poorer estimates of the variance are again produced by the correlations than from the original data alone.

Since interest lies principally in extension of the Naseby State Forest record, the calculations which demonstrate increased parameter precision are only needed to confirm that the statistical information content is not significantly reduced when the blended record is used.

TABLE 52: Monthly mean temperature regression equations for Naseby State Forest record extension

(<u>Note:</u> x is Tapanui monthly mean temperature ^{o}F;
Y is Naseby State Forest monthly mean temperature ^{o}F).

Tapanui-Naseby State Forest:

(i) January: $Y = 56.160 + 0.657\ (x-57.547)$.
(ii) February: $Y = 55.830 + 0.552\ (x-56.688)$.
(iii) March: $Y = 52.353 + 0.606\ (x-54.102)$.
(iv) April: $Y = 47.260 + 0.572\ (x-49.856)$.
(v) May: $Y = 40.807 + 0.530\ (x-44.579)$.
(vi) June: $Y = 35.981 + 0.620\ (x-40.100)$.
(vii) July: $Y = 34.670 - 73.283\ (x-39.535) + 1.907\ (x^2-1570.112) - 0.016\ (x^3-62618.7)$.
(viii) August: $Y = 37.567 - 7.077\ (x-42.172) + 0.091\ (x^2-1783.281)$.
(ix) September: $Y = 42.756 + 0.380\ (x-46.030)$.
(x) October: $Y = 47.379 - 10.464\ (x-49.798) + 0.110\ (x^2-2485.708)$.
(xi) November: $Y = 50.500 - 7.228\ (x-52.535) + 0.075\ (x^2-2767.287)$.
(xii) December: $Y = 54.156 - 4.984\ (x-55.133) + 0.051\ (x^2-3052.208)$.

TABLE 53: Elliot/Naseby State Forest synthetic mean monthly temperature record (^{o}F) - 1908 to 1922

Year	J	F	M	A	M	J	J	A	S	O	N	D
1908	59.3	58.1	54.4	46.7	41.3	37.5	34.6	37.2	44.0	48.7	51.3	54.9
1909	56.1	60.6	58.4	46.0	43.0	37.6	35.4	39.0	43.8	43.8	55.5	58.3
1910	59.9	61.4	56.2	49.1	45.2	39.4	34.7	39.6	43.9	48.7	54.5	56.5
1911	57.2	57.8	55.8	50.4	42.6	37.2	34.7	38.9	42.9	47.5	48.7	52.3
1912	55.2	55.0	51.1	47.3	40.3	35.7	35.1	38.6	43.3	47.1	50.2	55.0
1913	57.1	55.0	52.3	46.5	39.5	36.3	35.4	37.5	43.7	48.1	50.3	53.4
1914	58.8	55.2	53.7	47.3	39.3	35.9	35.3	38.0	42.9	47.7	49.0	52.4
1915	56.3	54.6	52.0	46.7	40.2	35.1	35.6	38.8	44.1	47.9	50.0	54.5
1916	55.9	56.4	55.1	48.4	41.1	38.6	34.4	37.1	43.1	47.9	51.5	56.0
1917	58.1	56.3	53.7	47.9	41.8	37.2	35.6	36.7	43.6	48.3	51.9	54.2
1918	57.5	58.6	53.9	46.9	41.2	36.0	33.5	36.4	41.4	47.2	48.0	52.6
1919	53.0	55.7	51.9	45.3	40.8	37.0	35.2	37.4	42.1	46.3	48.4	53.8
1920	55.7	57.3	52.8	47.2	39.6	37.9	35.9	35.7	42.7	47.5	47.9	53.6
1921	56.5	55.7	51.6	46.8	42.1	37.6	35.2	38.2	43.4	47.4	50.2	53.4
1922	56.9	57.7	49.9	47.1	40.4	34.9	33.9	37.4	42.9	46.5	50.3	54.2
<u>Mean:</u> (1908-69)	56.4	56.3	52.9	47.3	41.0	36.2	34.7	37.7	42.8	47.4	50.6	54.2

TABLE 54: Elliot/Naseby State Forest synthetic mean seasonal and annual temperature record (°F) - 1908 to 1922

Year	Summer	Autumn	Winter	Spring	Annual
1908	57.9	47.5	36.4	48.0	47.3
1909	57.2	49.1	37.3	49.4	48.5
1910	59.9	50.2	37.9	49.0	49.1
1911	57.2	49.6	36.9	46.4	47.2
1912	54.2	46.2	36.5	46.9	46.2
1913	55.7	46.1	36.4	47.4	46.3
1914	55.8	46.8	36.4	46.5	46.3
1915	54.4	46.3	36.5	47.3	46.3
1916	55.6	48.2	36.7	47.5	47.1
1917	56.8	47.8	36.5	47.9	47.1
1918	56.8	47.3	35.3	45.5	46.1
1919	53.8	46.0	36.5	45.6	45.6
1920	55.6	46.5	36.5	46.0	46.2
1921	55.3	46.8	37.0	47.0	46.5
1922	56.0	45.8	35.4	46.6	46.0
Mean: (1908-69)	55.6	47.1	36.2	46.9	46.5

Monthly, seasonal and annual Naseby State Forest data may thus be derived for the period 1908-22, and are listed in Tables 53 and 54. The total record for 1908-69 is obtained by combining these data with those given in Tables 16 and 17. However, it should be noted that the individual values of Table 53 are subject to the standard errors of prediction defined by equations (28) and (29).

REGRESSION ANALYSIS FOR TOTAL CATCHMENT STREAMFLOW TIME SERIES EXTENSION

Paerau Bridge record extension: simple rainfall-runoff correlation and regression models

It has been shown by Tables 28A and 29A that the available yield measurements for the total catchment allow estimates of the annual and at least some of the monthly and seasonal parameters at the required precision level. The measured Paerau Bridge record is not of adequate length to satisfy the stated error criterion for all months or seasons.

Population estimates to within 20 percent at the 95 percent probability level could theoretically be achieved by an increase in record length. Because of a lack of nearby long-term streamflow data, it is necessary to extend the Paerau Bridge record by way of techniques which use measured climatic data. The first of four such techniques to be used in this study is simple rainfall-runoff correlation and regression.

Simple linear or curvilinear regression models which correlate mean runoff and precipitation are convenient tools for flow prediction when rainfall records extend beyond the period of observed flow data (Diskin, 1970). The method is particularly applicable for prediction of annual or seasonal discharges in a basin where two or more distinct seasons are present. However, the value of the technique rapidly decreases in conditions where there is appreciable lag between rainfall and runoff.

Basic data used in this analysis comprise the measured mean discharge time series for Paerau Bridge and catchment mean precipitation. An initial requirement for correlation purposes is to convert the measured mean monthly and annual discharge records from Table 19 into equivalent yield. Results of this conversion are shown in Table 55.

Prediction equations for total catchment monthly and annual mean yield are thus developed, using no greater than third degree polynomials. The equations are given in Table 56 and are more fully defined in Appendix I (4). Poor correlations are found for the spring months September to November, and necessitate the use of cubic relationships. However, the other correlations are significant at between the 95 and 99 percent levels, and the coefficients vary between 0.61 and 0.76 with summer maxima. The poor spring correlation coefficients doubtless reflect the runoff lag condition described previously.

The correlations are considered overall as only marginally satisfactory for record extension purposes. However, results of combining the measured Paerau Bridge data with a synthetic record from regression analysis are given by Table 57.

Monthly and annual mean yield values do not differ markedly from the measured data listed in Table 55. Nevertheless, for the blended record, the estimated standard errors of $\hat{\mu}y$ given x equals $\bar{x}$ suggest that little information has been gained by the analysis. If the data in column (6) of Table 57 are compared with the SE$\bar{x}$ of Tables 28A and 29A, the standard error appears to have been reduced in all but three months. When the results are compared on the basis of standard error as a percentage of the mean, in only January, March and May is any improvement shown over that given by the measured record alone.

TABLE 55: Paerau Bridge measured mean yield (inches) 1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1.6.66-31.5.69

Year	J	F	M	A	M	J	J
1912	0.782	0.699	1.465	0.752	2.019	2.992	1.954
1913	0.450	0.474	0.990	1.369	2.261	1.815	1.583
1916	0.524	0.367	0.520	0.594	0.698	0.924	1.138
1917	0.250	1.059	0.767	0.508	1.865	2.011	1.044
1918	1.098	0.277	1.197	0.938	1.588	2.279	0.876
1919	2.637	1.412	0.290	1.412	0.975	1.671	2.098
1920	0.717	0.129	0.105	0.189	0.510	1.728	3.018
1921	0.171	0.231	0.619	1.417	1.514	1.106	1.267
1922	1.415	0.388	0.836	1.120	0.985	0.503	0.708
1923	1.227	0.764	1.024	2.274	3.078	1.125	0.960
1924	0.267	0.146	0.134	0.168	0.678	0.814	0.891
1925	0.305	0.124	0.510	0.905	0.564	0.258	1.613
1926	0.584	1.256	1.089	0.627	2.454	1.197	0.980
1927	0.861	0.432	1.049	1.896	2.607	0.799	1.959
1928	0.387	0.206	0.170	1.120	1.064	0.512	2.192
1936	0.446	0.354	1.326	1.518	2.276	0.943	1.410
1937	1.771	2.865	3.315	2.241	4.320	2.059	1.059
1938	0.623	0.099	0.106	0.257	0.801	1.776	1.108
1939	2.018	0.889	0.505	0.438	1.009	1.570	1.583
1941	0.544	0.460	0.787	1.159	1.306	1.532	1.569
1942	2.009	0.988	1.331	1.800	1.435	1.048	1.252
1943	0.851	0.308	1.257	1.173	1.509	0.891	0.614
1944	0.128	0.865	0.846	2.087	1.123	2.164	2.227
1947	1.672	0.432	0.384	0.460	0.475	0.522	0.737
1948	0.475	0.444	0.475	0.458	0.549	0.574	0.737
1949	0.192	0.199	0.836	0.900	0.609	1.245	2.608
1950	0.366	0.298	0.241	0.469	0.202	0.446	1.197
1966	-	-	-	-	-	0.646	1.346
1967	0.339	0.199	0.259	0.411	2.395	1.441	0.831
1968	0.226	0.200	1.252	2.633	1.296	1.925	1.094
1969	0.326	0.356	0.429	1.618	1.875	-	-
Mean:	0.792	0.559	0.801	1.097	1.469	1.283	1.390

TABLE 55: continued

Year	A	S	O	N	D	Annual
1912	1.603	2.969	4.112	2.629	0.866	22.842
1913	2.835	3.361	2.177	1.906	2.627	21.846
1916	1.846	2.796	1.494	1.374	0.475	12.750
1917	0.831	1.767	2.405	0.713	1.178	14.498
1918	2.712	3.098	3.048	2.447	1.856	21.414
1919	2.642	2.581	2.420	1.365	1.336	20.839
1920	1.380	2.193	2.756	2.317	0.648	15.690
1921	1.920	1.594	1.742	1.302	0.777	13.660
1922	1.009	1.590	0.856	1.274	1.757	12.441
1923	1.331	4.496	2.504	0.752	0.225	19.760
1924	1.509	1.235	1.608	0.886	0.332	8.668
1925	1.953	2.811	4.631	1.575	2.147	17.378
1926	1.301	2.930	2.899	2.183	2.004	19.516
1927	1.430	2.676	2.761	1.853	0.895	19.225
1928	0.980	1.542	4.112	1.695	0.554	14.546
1936	2.301	3.759	2.172	1.954	2.528	20.793
1937	2.984	2.676	2.162	1.226	0.638	27.323
1938	1.430	1.891	1.707	1.566	2.509	13.865
1939	1.707	6.330	5.443	4.553	1.697	27.847
1941	2.009	2.432	2.390	2.662	2.593	19.458
1942	1.875	1.791	2.281	2.332	1.504	19.633
1943	0.757	3.213	3.701	1.671	0.452	16.370
1944	2.810	2.193	2.266	1.700	2.177	20.564
1947	1.168	1.858	3.300	1.187	0.539	12.700
1948	0.574	0.723	1.816	1.053	0.876	8.763
1949	1.390	1.403	1.979	0.517	0.251	12.117
1950	0.762	1.369	0.757	0.488	0.747	7.340
1966	1.277	2.107	1.019	0.704	1.227	11.943
1967	0.856	1.355	0.940	1.082	0.549	12.642
1968	1.950	2.188	3.083	1.460	0.493	16.825
1969	-	-	-	-	-	-
Mean:	1.638	2.432	2.484	1.614	1.217	16.778

TABLE 56: Simple regression equations for Upper Taieri Catchment mean rainfall - Paerau Bridge monthly and annual mean yield (inches)

(Note: x = monthly or annual rainfall in inches;
Y = monthly or annual predicted yield in inches).

(i) January: $Y = 0.728 + 0.156\ (x-3.514)$.
(ii) February: $Y = 0.517 - 0.215\ (x-3.540) + 0.030\ (x^2-18.331)$.
(iii) March: $Y = 0.706 + 0.098\ (x-3.717)$.
(iv) April: $Y = 0.897 + 0.151\ (x-3.357)$.
(v) May: $Y = 1.220 + 0.258\ (x-2.783)$.
(vi) June: $Y = 1.094 + 0.146\ (x-2.476)$.
(vii) July: $Y = 1.231 + 0.231\ (x-2.104)$.
(viii) August: $Y = 1.462 + 0.176\ (x-2.738)$.
(ix) September: $Y = 2.126 - 11.187\ (x-2.541) + 4.055\ (x^2-7.534)$
$- 0.435\ (x^3-25.987)$.
(x) October: $Y = 2.197 - 1.869\ (x-3.302) + 0.575\ (x^2-13.819)$
$- 0.049\ (x^3-67.310)$.
(xi) November: $Y = 1.430 + 3.007\ (x-3.451) - 0.775\ (x^2-13.760)$
$+ 0.064\ (x^3-60.890)$.
(xii) December: $Y = 1.085 + 0.173\ (x-4.368)$.
(xiii) Annual: $Y = 14.641 - 5.183\ (x-37.712) + 0.072\ (x^2-1447.3)$.

TABLE 57: Paerau Bridge mean monthly and annual runoff parameters for the 1908-69 blended record

Month	1908-69 Mean Yield (inches)	n_1 (yrs.)	n_2 (yrs.)	d.f.	$S\hat{\mu}_{y.\bar{x}}$ (inches)	Col.(6) as % of Mean Yield Col.(2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
January:	0.800	30	31	22	0.109	13.7
February:	0.449	30	31	21	0.097	21.6
March:	0.764	30	31	22	0.106	13.9
April:	0.947	30	31	22	0.112	11.8
May:	1.379	30	31	22	0.152	11.0
June:	1.240	30	32	22	0.117	9.46
July:	1.279	30	32	22	0.112	8.76
August:	1.457	30	33	22	0.115	7.86
September:	2.038	30	33	20	0.252	12.4
October:	2.190	30	33	20	0.637	29.1
November:	1.606	30	33	20	0.492	30.7
December:	1.077	30	33	22	0.129	12.0
Year:	15.186	30	32	21	1.102	7.26

Notes:
(i) Column (2) - values derived from the combined measured records (Table 55) and the synthetic record from simple regression analysis.
(ii) Columns (3), (4) - years of measured data and additional estimated values respectively.
(iii) Column (5) - degrees of freedom available for determining $t_{0.05}$.
(iv) Column (6) - estimated standard error of $\hat{\mu}_y$ given x is error free and equal to $\bar{x}$ for the blended record; determined from the weighted values of $SE\bar{y}$ (Table 28, 29) and $S\hat{\mu}_{y.\bar{x}}$ from equations (24) to (26). Values correspond to $SE\bar{x}$ of Tables 28A, 29A.
(v) Column (7) - Column (6) as a percentage of the 1908-69 blended mean. Corresponds to $SE\bar{x}$ as a percentage of $\bar{x}$ in Tables 28A, 29A.

Standard errors of up to 31 percent of the 1908-69 means are shown for October and November, and in only three months is the value less than 10 percent. Calculations from equation (20) indicate that the maximum gain in effective record length is only 11 years.

The analysis does not satisfy the second study objective. Extension of the Paerau Bridge streamflow record by simple rainfall-runoff correlation and regression does not allow parameter estimation to markedly greater precision levels than for the measured series alone. As a result, synthetic monthly and annual data are not tabulated here for the period of missing record. Further, the standard errors shown by Table 57 must also be considered as minimum values, since the rainfall data used in the regressions are not error free.

Although the precision limits of the streamflow parameters are not readily quantifiable, it is concluded that with the exception of the spring months no marked loss of information results from the above record extension. The second study objective has not been realised, but a useful extension to the study is to now evaluate the model efficiency. Such a procedure can hence be applied to each model tested, and thus allow the deterministic models used in this study to be objectively compared for simulation and prediction ability.

Estimates of the population parameters may not be derived at the required precision level, but simulation of the missing flow records will be achieved with minimised errors of prediction. Subjective graphical studies of the measured and synthesised streamflow hydrographs are insufficient for between method comparison. The indices used, therefore, are as given by equations (31) and (32).

Split record techniques such as described by Murray (1970) are used in this study to test the between and within model simulation and prediction abilities. The period 1916-25 is taken for each model as a test interval for comparative purposes, and is the only occurrence in the measured Paerau Bridge record of an unbroken ten year data series. The first five years have been excluded from previous calculations to determine the runoff-climate relationships, and may thus be used to evaluate the "goodness of reconstruction" for each model. The period 1921-25 formed part of the original analyses, and is used to test the "goodness of fit" for each model.

Results of efficiency calculations for the simple rainfall-runoff regression models are summarised in Table 58. Monthly and annual values of var(x), F^2, Fm^2 and hence R^2 for the periods 1916-20 and 1921-25 are calculated from equations (30), (31) and (32).

Squared differences between computed and observed runoff values give a residual variance of 20.761 for the period 1921-25, with the mean square error thus calculated as 0.346. Overall simulation efficiency of the simple rainfall-runoff models is shown to be 58.7 percent for monthly yield data. However, the results for 1916-20 indicate that when the models are used for prediction purposes, the efficiency index falls from 0.587 to 0.507 for monthly data and from 0.221 to 0.005 for annual values.

Monthly and annual root mean square errors given in Table 58 further suggest that the simple rainfall-runoff regression models give somewhat unsatisfactory results. The calculated average monthly root mean square error for 1921-25 is 49 percent of the mean monthly yield, and ranges from 26 to 93 percent. Results for the mean annual data are lower, though the root mean square error is shown to be 23 percent for the interval 1921-25.

TABLE 58: Paerau Bridge residual variance and index of efficiency calculations for the simple rainfall-runoff regression models

squared differences between computed and observed runoff for:-

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1916	0.024	0.000	0.097	0.006	0.138	0.009	0.027	0.107	1.134	0.150	0.013	0.000	0.086
1917	0.037	0.311	0.020	0.051	0.097	1.256	0.009	0.120	1.996	0.064	0.472	0.001	3.069
1918	0.003	0.019	0.171	0.046	0.334	1.239	0.561	0.814	0.972	0.878	0.697	0.378	41.538
1919	1.160	0.616	0.019	0.052	0.000	0.129	0.794	0.193	0.398	0.004	0.055	0.047	7.980
1920	0.005	0.063	0.111	0.411	1.279	0.653	2.045	0.002	0.470	0.195	0.479	0.182	7.284
1921	0.285	0.041	0.078	0.402	0.288	0.041	0.043	0.365	0.092	0.275	0.537	0.488	0.601
1922	0.002	0.027	0.007	0.100	0.008	0.136	0.240	0.087	0.270	1.042	0.073	0.054	0.525
1923	0.236	0.175	0.057	0.539	0.312	0.010	0.046	0.000	3.564	0.276	0.574	0.362	36.639
1924	0.103	0.175	0.187	0.848	0.469	0.060	0.141	0.236	0.553	0.006	0.160	0.384	19.483
1925	0.016	0.061	0.107	0.000	0.230	0.381	0.019	0.131	0.019	4.076	0.006	1.261	1.040

Month	1916-1920:-			1921-1925:-		
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
January:	1.229	1.045	47.4	0.642	0.677	52.9
February:	1.009	0.649	69.2	0.479	0.331	93.5
March:	0.418	0.576	50.2	0.436	0.624	47.3
April:	0.566	0.728	46.2	1.889	1.177	52.2
May:	1.848	1.127	53.9	1.307	1.364	37.5
June:	3.286	1.723	47.0	0.628	0.761	46.6
July:	3.436	1.635	50.7	0.489	1.088	28.7

TABLE 58: Continued

Month	1916-1920:-			1921-1925:-		
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
August:	1.236	1.882	26.4	0.819	1.541	26.2
September:	4.970	2.487	40.1	4.498	2.345	40.4
October:	1.291	2.425	20.9	5.675	2.268	47.0
November:	1.716	1.643	35.8	1.350	1.158	44.9
December:	0.608	1.099	31.7	2.549	1.048	68.1
Annual:	59.957	17.038	20.3	58.288	14.381	23.7

1916-1920:-

Mean monthly yield: 1.418 ins.
Monthly data var(x): 0.730
" " " Fm^2: 0.360
" " " R^2: 0.507
Annual data var(x): 12.050
" " "Fm^2: 11.991
" " "R^2: 0.005

1921-1925:-

Mean monthly yield: 1.198 ins.
Monthly data var(x): 0.839
" " " Fm^2: 0.346
" " " R^2: 0.587
Annual data var(x): 14.968
" " "Fm^2: 11.657
" " "R^2: 0.221

However, 63 percent of the sum of squared differences for the 1921-25 annual data are accounted for by the 1923 value. Further, September 1923 and October 1925 together contribute 37 percent of the monthly squared differences for 1921-25. It is thus evident that root mean square values, or efficiency indices, need not prove to be reliable goodness of fit indicators without further close inspection of the results. The previous data show that if the occurrence of occasional large errors is acceptable, the calculated predicted values may be considered a reasonable representation of the measured record.

Paerau Bridge record extension: Multiple rainfall-runoff correlation and regression models

A more useful relationship for flow prediction is one which treats runoff for a period as a function of current and antecedent precipitation. The method is particularly relevant for basins with substantial carry-over storage from one period to the next, and the relationship may be expressed by an equation of general form:

$$Y = a + b(x_1-c) + d(x_2-e) \text{ ———————————— } (35).$$

x_2 is precipitation for the current period; x_1 is precipitation from the period which precedes the current period; a, b, c, d and e are constants.

Basic data used in the analysis is that employed for the simple correlations and regressions. Prediction equations for total catchment monthly and annual mean yield are thus developed by standard methods of multiple correlation. The equations are given in Table 59 and are more fully defined in Appendix I(5).

Generally poor correlations are shown by the results. Multiple correlation coefficients vary from 0.37 to 0.86 with a January maximum,

TABLE 59: Multiple regression equations for Upper Taieri Catchment mean rainfall - Paerau Bridge monthly mean yield (inches)

(Note: General equation of form $Y = a + b(x_1-c) + d(x_2-e)$; Y = predicted monthly yield in inches; x_1 = rainfall during the previous month in inches; x_2 = rainfall during the current month in inches; a, b, c, d, e = constants).

(i) January: $Y = 0.691 + 0.066\ (x_1-4.281) + 0.184\ (x_2-4.018)$.
(ii) February: $Y = 0.452 + 0.088\ (x_1-4.018) + 0.023\ (x_2-2.876)$.
(iii) March: $Y = 0.552 + 0.007\ (x_1-2.876) + 0.100\ (x_2-3.415)$.
(iv) April: $Y = 0.869 + 0.172\ (x_1-3.415) + 0.225\ (x_2-3.658)$.
(v) May: $Y = 1.223 + 0.057\ (x_1-3.658) + 0.178\ (x_2-3.279)$.
(vi) June: $Y = 0.984 + 0.115\ (x_1-3.279) + 0.242\ (x_2-1.950)$.
(vii) July: $Y = 1.233 - 0.099\ (x_1-1.950) + 0.186\ (x_2-2.115)$.
(viii) August: $Y = 1.370 + 0.144\ (x_1-2.115) + 0.139\ (x_2-2.963)$.
(ix) September: $Y = 2.056 + 0.183\ (x_1-2.963) - 0.165\ (x_2-2.738)$.
(x) October: $Y = 2.182 + 0.308\ (x_1-2.738) + 0.154\ (x_2-3.478)$.
(xi) November: $Y = 1.298 - 0.002\ (x_1-3.478) + 0.137\ (x_2-3.700)$.
(xii) December: $Y = 0.936 + 0.129\ (x_1-3.700) + 0.198\ (x_2-4.229)$.
(xiii) Annual: (simple regression equation only).
$Y = 14.641 - 5.183\ (x-37.712) + 0.072\ (x^2-1447.3)$.

and in only four months are the correlations significant at greater than the 95 percent level. Inspection of the partial correlation coefficients suggests that some prediction improvement could be expected by use of the additional antecedent precipitation variables. The results show that in seven months a marked contribution is made to the degree of correlation from the rainfalls for the previous month. To determine the duration of this rainfall-runoff response lag in the Upper Taieri basin, November was chosen for further analysis.

Multiple correlation calculations are thus repeated, using from two to six independent variables to represent monthly precipitation from June to November inclusive (Table 60 and Appendix I(5)). The use of six independent variables for prediction of November yield improves the multiple correlation coefficient from 0.48 to 0.67. However, no change in the level of significance results from the additional calculations. Further, rainfall for July is the only appreciable antecedent contribution to the degree of correlation for the total period June-November. Winter storage is known to considerably affect the annual flow distribution, but the four month lag suggested by these results is not thought representative of field observations. Comprehensive use of up to six independent variables for flow prediction thus appears unjustified, and subsequent calculations are made from the two independent variable equations given in Table 59.

The correlations are again considered only marginally satisfactory for record extension purposes. However, results of combining the measured Paerau Bridge record with synthetic data from multiple regression analysis are shown in Table 61.

Estimated standard errors of $\hat{\mu}_y$ given x_1 and x_2 equal $\bar{x}_1$ and $\bar{x}_2$, again suggest that little information has been gained by the analysis. When

TABLE 60: Multiple regression equations for Upper Taieri Catchment mean rainfall - Paerau Bridge November mean yield (inches)

(Note: General equation of form:-

$$Y = a + b_1(x_1^1 - c_1) + b_2(x_2^1 - c_2) + b_3(x_3^1 - c_3) + b_4(x_4^1 - c_4)$$
$$+ b_5(x_5^1 - c_5) + b_6(x_6^1 - c_6),$$ where

Y = predicted November yield in inches; x_1^1 = rainfall during June in inches; x_2^1 = July rainfall; x_3^1 = August rainfall; x_4^1 = September rainfall; x_5^1 = October rainfall; x_6^1 = November rainfall; a, b_1, b_2, b_3, b_4, b_5, b_6, c_1, c_2, c_3, c_4, c_5, and c_6 = constants).

(i) *For x June-November:* $Y = 1.298 + 0.048\ (x_1^1 - 1.950) + 0.170\ (x_2^1 - 2.115)$
$- 0.003\ (x_3^1 - 2.963) + 0.044\ (x_4^1 - 2.738)$
$+ 0.018\ (x_5^1 - 3.478) + 0.139\ (x_6^1 - 3.700)$.

(ii) *For x July-November:* $Y = 1.298 + 0.180\ (x_2^1 - 2.115) + 0.001\ (x_3^1 - 2.963)$
$+ 0.044\ (x_4^1 - 2.738) + 0.006\ (x_5^1 - 3.478)$
$+ 0.115\ (x_6^1 - 3.700)$.

(iii) *For x August-November:* $Y = 1.298 + 0.033\ (x_3^1 - 2.963) + 0.063\ (x_4^1 - 2.738)$
$+ 0.018\ (x_5^1 - 3.478) + 0.123\ (x_6^1 - 3.700)$.

(iv) *For x September-November:*
$Y = 1.298 + 0.093\ (x_4^1 - 2.738) + 0.012\ (x_5^1 - 3.478)$
$+ 0.122\ (x_6^1 - 3.700)$.

(v) *For x October-November:* $Y = 1.298 - 0.002\ (x_5^1 - 3.478) + 0.137\ (x_6^1 - 3.700)$.

TABLE 61: Paerau Bridge mean monthly and annual runoff parameters for the 1908-69 blended record

Month	1908-69 Mean Yield (inches)	n_1 (yrs)	n_2 (yrs)	d.f.	$S\hat{\mu}_{y.\bar{x}}$ (inches)	Col. (6) as % of mean yield Col. (2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
January:	0.717	30	31	10	0.111	15.4
February:	0.513	30	31	10	0.105	20.5
March:	0.702	30	31	10	0.070	10.0
April:	0.911	30	31	10	0.115	12.6
May:	1.297	30	31	10	0.190	14.6
June:	1.272	30	32	10	0.164	12.9
July:	1.183	30	32	10	0.205	17.4
August:	1.362	30	33	10	0.119	8.72
September:	2.170	30	33	10	0.223	10.3
October:	2.180	30	33	10	0.253	11.6
November:	1.429	30	33	10	0.149	10.4
December:	0.983	30	33	10	0.140	14.3
Year:	14.737	30	32	21	1.102	7.48

Notes: (1) Column (2) - values derived from the measured records (Table 55) and the synthetic record from multiple regression analysis. The annual value is the sum of monthly values shown.

(ii) Columns (3), (4), (5), (7) - as for Table 57.

(iii) Columns (6) - estimated standard error of $\hat{\mu}y$ given x is error free and equal to $\bar{x}$ for the blended record; determined from the weighted values of SE$\bar{y}$ (Table 28, 29) and $S\hat{\mu}_{y.\bar{x}_1}$, $\bar{x}_2$ from equation (27). Values correspond to SE$\bar{x}$ of Tables 28A, 29A.

column (6) data of Table 61 are compared with SEX̄ of Tables 28A and 29A, standard errors are shown to be reduced in half the months. However, on the basis of standard error as a percentage of the mean, only March shows any improvement over that given by the measured record alone. Nevertheless, standard errors as a percentage of the 1908-69 means are shown to be reduced overall compared with the simple regression analysis results of Table 57. The high values previously calculated for October and November have now been reduced to less than 12 percent.

The second study objective is again not satisfied by the analysis. Extension of the Paerau Bridge streamflow record by multiple regression does not allow parameter estimation at precision levels which are markedly greater than for the measured series alone. The standard errors shown in Table 61 must also be considered as minimum values, since the rainfall data used in the regressions are not error free. Synthetic monthly and annual streamflow data are thus not tabulated here for the period of missing record.

However, model efficiency is now evaluated in the same manner as shown for the simple regression models. Results of these efficiency calculations for the rainfall-runoff multiple regression models are summarised in Table 62. Monthly and annual values of var(x), F^2, Fm^2 and R^2 for 1916-20 and 1921-25 are again calculated from equations (30) to (32).

Mean square error for 1921-25 is calculated as 0.334, and overall simulation efficiency is 60.2 percent for the monthly yield data. Improved efficiency is shown over that derived for the simple rainfall-runoff models. However, Table 62 shows that when the multiple regression models are used for prediction purposes, the efficiency index falls from 0.602 to 0.567 for monthly data, and from 0.324 to zero for annual values.

Average monthly root mean square error for 1921-25 is calculated as 48 percent of the mean monthly yield, and ranges from 22 to 76 percent.

TABLE 62: *Paerau Bridge residual variance and index of efficiency calculations for the rainfall-runoff multiple regression models*

squared differences between computed and observed runoff for:-

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1916	0.003	0.000	0.036	0.021	0.054	0.004	0.022	0.175	0.421	0.119	0.023	0.000	0.001
1917	0.047	0.719	0.078	0.001	0.021	0.753	0.002	0.011	0.030	0.125	0.144	0.781	4.161
1918	0.005	0.074	0.298	0.042	0.462	1.440	0.327	0.727	0.514	0.771	1.508	0.576	39.980
1919	0.988	0.347	0.000	0.389	0.007	0.131	1.179	0.537	0.034	0.013	0.008	0.129	23.338
1920	0.001	0.094	0.040	0.008	0.764	0.601	2.053	0.022	0.315	0.094	0.527	0.333	2.647
1921	0.162	0.020	0.023	0.157	0.368	0.038	0.001	0.297	0.196	0.031	0.112	0.104	0.007
1922	0.006	0.110	0.049	0.107	0.000	0.014	0.354	0.033	0.210	0.587	0.081	0.002	4.919
1923	0.194	0.107	0.126	0.105	0.672	0.157	0.016	0.154	5.636	1.071	0.148	0.083	26.276
1924	0.006	0.069	0.109	0.528	0.373	0.061	0.115	0.246	0.257	0.658	0.031	0.069	14.861
1925	0.010	0.012	0.042	0.030	0.185	0.124	0.008	0.046	0.001	4.141	0.037	1.369	4.511

Month	F^2	1916-20:- Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	1921-25:- Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
January:	1.044	1.045	43.7	0.378	0.677	40.6
February:	1.234	0.649	76.5	0.318	0.331	76.2
March:	0.452	0.576	52.2	0.349	0.624	42.3
April:	0.461	0.728	41.7	0.927	1.177	36.6
May:	1.308	1.127	45.4	1.598	1.364	41.4
June:	2.929	1.723	44.4	0.394	0.761	36.9
July:	3.583	1.635	51.8	0.494	1.088	28.9
August:	1.472	1.882	28.8	0.776	1.541	25.5
September:	1.314	2.487	20.6	6.300	2.345	47.9

TABLE 62: *Continued*

Month	1916-20:-			1921-1925:-		
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
October:	1.122	2.425	19.5	6.488	2.268	50.2
November:	2.210	1.643	40.5	0.409	1.158	24.7
December:	1.819	1.099	54.9	1.627	1.048	54.4
Annual:	70.127	17.038	22.0	50.574	14.381	22.1

1916-20:-

Mean monthly yield: 1.418 ins.
Monthly data var(x): 0.730
" " " Fm^2: 0.316
" " " R^2: 0.567
Annual data var(x): 12.050
" " " Fm^2: 14.025
" " " R^2: 0.000

1921-1925:-

Mean monthly yield: 1.198 ins.
Monthly data var(x): 0.839
" " " Fm^2: 0.334
" " " R^2: 0.602
Annual data var(x): 14.968
" " "Fm^2: 10.115
" " "R^2: 0.324

Although the average value is similar to the 49 percent given for the simple regression models, nearly 50 percent of the sum of squared differences are accounted for by the combined September 1923 and October 1925 values.

Root mean square error for the 1921-25 mean annual data is 22 percent of the mean, though 52 percent of the sum of squared differences are accounted for by the 1923 value.

Results therefore again show that if occasional large errors are acceptable, the calculated predicted values may be considered a reasonable representation of the measured record. It is also concluded that in this study the multiple regression models are generally superior in simulation and prediction ability, compared with the previous simple regression models.

ALTERNATIVE DETERMINISTIC MODELS FOR TOTAL CATCHMENT STREAMFLOW TIME SERIES EXTENSION

Paerau Bridge record extension: water balance model

The basic water balance approach to system synthesis is described by Edwards & Rodda (1970) as a simplified version of a conceptual model. However, the information provided by the determination of a water balance is of utmost utility in many different fields of research. For example, knowledge of the moisture deficit, changes in soil moisture storage and the temporal relationships between these factors and moisture surplus, is fundamental to the economic or practical feasibility and scheduling of irrigation.

In this study, the term water balance refers to the climatic balance between the income of water from precipitation and the outflow of water by evapotranspiration. The magnitude of other related moisture parameters such as the water surplus, deficit, soil storage and runoff are determined by comparison of the seasonal march of precipitation and evapotranspiration.

The method of water balance determination proposed by Thornthwaite & Mather (1955, 1957) is used throughout this project. Modifications such as described by McDonald (1963), or Edwards & Rodda (op.cit) are not pursued in the interests of simplicity and generality. If these objectives are abandoned, there is little left to recommend the water balance method for runoff simulation in favour of the more sophisticated conceptual model techniques of say Boughton (1965, etc.) or Crawford & Linsley (1966).

Basic data used in the analysis comprise monthly values of catchment mean precipitation and potential evapotranspiration, and an average soil water holding capacity for the area of four inches, calculated from Table 63 and the percentage area represented by each soil (Figure 5).

TABLE 63: Average moistures of soils indicated (water holding capacity)

Soil	Available moisture in inches	
	Soil depth 0-12 inches	Soil depth 0-16 inches
Middlemarch	2.2	3.1
Blackstone	2.5	3.2
Matarae	2.3	N.A. Generally <16 inches deep
Arrow	2.5	3.2
Pukerangi	2.3	2.8
Teviot	3.1	4.3
Dunstan	3.1	4.3
Fraser Sand (sandy loam)	2.2	3.1
Clutha	2.9	3.8
Gladbrook	2.9	3.8

The available moisture values listed in Table 63 were derived by Cossens (1969), and cover the major soil sets found in the Upper Taieri basin. Since the effective root depth of most plants in the study area is 12-16 inches, the data used here are those given for the 0-16 inches soil depth. An exception is the Matarae soil, where the 0-12 inch available moisture figure applies.

Potential evapotranspiration is computed from the Elliot/Naseby State Forest mean monthly temperature record by a modified version of the method proposed by Thornthwaite (1948). The present technique contains an option of built-in altitudinal corrections dependent on variable seasonal lapse-rates (Coulter, 1967). It is thus possible to calculate values of potential evapotranspiration for any specified altitude, from one set of basic data at a known height above sea level.

Appendix II lists the computer programme used, and Table 64 gives the results for the mean annual data. Long-term mean annual potential evapotranspiration is hence determined for the total Upper Taieri catchment and for each of the previously designated sub-catchments. The values are 21.84 inches for area 1, 19.66 inches for area 2a, 20.93 inches for area 2b and the total catchment, and 20.49 inches for area 3.

Long-term total catchment monthly and annual mean yield data sets are thus computed, assuming initially a 50 percent carryover of water available for runoff (see Appendix II). Unlike the previous regression analyses, precision limits of parameter estimates derived by water balance or conceptual models are not readily quantifiable (Clarke, 1973). Standard errors of prediction cannot be calculated directly as shown for the simple and multiple regression models, and hence it is not possible to test the new blended records for the second study objective. Whether or not additional information is gained by inclusion of the new synthetic records is not directly known.

Parameter precision limits may be qualitatively deduced, however, by comparing calculated model efficiency with the values derived for

TABLE 64: Upper Taieri Catchment mean annual potential evapotranspiration (inches)

Year	2000'	2500'	3000'	3500'	4000'
1909	23.92	22.80	21.63	20.46	19.56
1910	24.17	23.07	22.03	20.93	19.86
1911	22.98	21.89	20.80	19.67	18.86
1912	22.69	21.60	20.43	19.44	18.65
1913	22.73	21.63	20.31	19.35	18.56
1914	22.69	21.52	20.30	19.24	18.37
1915	22.78	21.68	20.53	19.54	18.72
1916	23.10	21.99	20.89	19.80	19.00
1917	23.13	22.04	20.76	19.82	19.11
1918	22.43	21.25	20.01	19.22	18.42
1919	22.36	21.30	20.08	19.03	18.34
1920	22.54	21.44	20.12	19.15	18.33
1921	22.84	21.81	20.68	19.53	18.85
1922	22.50	21.30	20.25	19.30	18.54
1923	22.11	21.04	19.92	19.21	18.43
1924	23.46	22.40	21.11	20.14	19.44
1925	21.86	20.64	19.50	18.67	17.56
1926	22.31	21.26	19.96	18.82	17.94
1927	21.78	20.67	19.53	18.78	17.92
1928	22.88	21.83	20.57	19.35	18.50
1929	22.74	21.68	20.60	19.36	18.44
1930	21.55	20.42	19.36	18.65	17.86
1931	22.31	21.11	19.95	19.20	18.31
1932	22.56	21.55	20.31	19.34	18.54
1933	22.59	21.39	20.27	19.17	18.22
1934	23.06	21.95	20.84	19.68	18.83
1935	22.89	21.67	20.53	19.38	18.09
1936	22.92	21.97	20.93	19.94	18.81
1937	23.06	21.95	20.97	20.12	19.10
1938	23.38	22.36	21.24	20.21	19.37
1939	22.78	21.72	20.81	19.95	19.02
1940	23.07	22.10	20.97	19.77	18.69
1941	22.38	21.27	20.27	19.56	18.86
1942	23.08	22.13	21.07	20.03	19.06
1943	22.28	21.21	20.16	19.23	18.36
1944	22.56	21.55	20.28	19.10	18.21
1945	22.07	20.94	20.09	19.18	17.83
1946	22.57	21.62	20.52	19.30	18.20
1947	23.16	22.05	21.02	20.14	19.09
1948	23.06	21.98	20.77	19.61	18.64
1949	22.57	21.45	20.24	19.16	18.34
1950	22.82	21.68	20.49	19.77	19.16
1951	21.75	20.65	19.56	18.80	18.01
1952	22.33	21.26	20.36	19.39	18.54
1953	22.33	21.16	20.26	19.27	18.56
1954	22.95	21.83	20.73	19.81	18.88
1955	22.93	21.93	20.99	20.03	19.30
1956	22.94	21.79	20.64	19.52	18.65
1957	22.64	21.56	20.51	19.27	18.48
1958	22.72	21.78	20.74	19.49	18.68

TABLE 64: Continued

Year	2000'	2500'	3000'	3500'	4000'
1959	22.88	21.70	20.25	19.14	18.46
1960	22.78	21.72	20.45	19.32	18.57
1961	22.99	21.75	20.56	19.62	18.73
1962	23.47	22.49	21.37	20.14	19.19
1963	22.09	20.98	20.00	19.27	18.52
1964	22.68	21.61	20.30	19.14	18.24
1965	22.28	21.24	20.06	19.20	18.43
1966	22.67	21.50	20.28	19.26	18.33
1967	22.89	21.88	20.74	19.74	18.73
1968	22.43	21.45	20.38	19.39	18.44
1969	22.42	21.27	20.34	19.26	18.23
Mean: (1909-69)	22.70	21.61	20.49	19.49	18.61

the simple and multiple regression models of known minimum error. Model efficiency is evaluated in the same manner as before, and results of the calculations are summarised in Table 65. Monthly and annual values of var(x), F^2, Fm^2 and R^2 for 1916-20 and 1921-25 are again calculated from equations (30) to (32).

The predicted record is not a good reproduction of the measured series. An overall determination of prediction ability is shown when the Table 65 values are compared with the simple and multiple regression model results in Tables 58 and 62. Both five year intervals may be considered for "goodness of reconstruction" in this instance, since neither period contributed data for initial model development. Further, a two year pre-test interval warm-up period was allowed for the model.

Mean square error for the 1921-25 monthly data is calculated as 1.138, and for 1916-20 the value is 0.372. Overall model efficiency is zero for the 1921-25 monthly and annual yield data, but has a value of 49 percent for the 1916-20 monthly yields. The 1916-20 figure for annual values is 0.330.

Average monthly root mean square errors are 89 percent of the mean monthly yield for 1921-25 and 43 percent for 1916-20, with a variation of from 25 to 188 percent for the ten year interval. However, 49 percent of the sum of squared differences in 1921-25 are accounted for by the combined May, June and September 1923 and August 1925 values. Annual data for 1916-20 are a good reproduction of the measured values, particularly since 78 percent of the sum of squared differences occur in 1919.

The results suggest that the second study objective is unlikely to be satisfied by the record extension, and that the method as presented is generally unsatisfactory for Upper Taieri runoff prediction purposes.

TABLE 65: Paerau Bridge residual variance and index of efficiency calculations for the water balance model (50% carryover factor and 4 inches water holding capacity assumed)

squared differences between computed and observed runoff for:-

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1916	0.045	0.044	0.228	0.000	0.106	0.149	0.528	0.230	0.910	0.270	0.196	0.187	1.937
1917	0.042	0.692	0.426	0.203	0.015	0.518	0.000	0.024	0.000	0.068	0.384	0.025	2.155
1918	0.004	0.252	0.449	0.117	0.513	0.167	0.003	0.159	0.005	0.012	0.201	0.044	0.593
1919	1.423	0.253	0.446	0.120	0.004	0.497	0.008	3.024	2.859	0.080	0.044	0.038	31.595
1920	0.002	0.063	0.007	0.009	1.478	0.156	0.334	1.113	0.902	1.404	0.051	0.799	4.064
1921	0.360	0.024	0.430	0.063	0.223	1.537	2.208	0.033	0.044	0.019	0.250	0.541	12.138
1922	1.597	0.904	0.001	0.020	0.060	0.346	0.667	0.249	0.305	0.037	0.291	0.828	23.892
1923	0.138	0.475	0.591	3.294	6.200	6.661	0.797	0.384	11.567	3.826	0.228	0.008	18.524
1924	0.039	0.181	0.023	1.724	1.755	1.562	1.459	0.210	0.328	1.498	0.281	0.141	43.204
1925	0.002	0.003	0.000	0.027	0.515	0.146	0.118	8.750	1.435	1.397	1.243	0.210	28.729

Month	1916-20:-			1921-25:-		
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
January:	1.516	1.045	52.7	2.136	0.677	96.5
February:	1.304	0.649	78.7	1.587	0.331	170.2
March:	1.556	0.576	96.8	1.045	0.624	73.2
April:	0.449	0.728	41.1	5.128	1.177	86.0
May:	2.116	1.127	57.7	8.753	1.364	97.0
June:	1.487	1.723	31.6	10.252	0.761	188.2
July:	0.873	1.635	25.5	5.249	1.088	94.1
August:	4.550	1.882	50.7	9.626	1.541	90.0
September:	4.676	2.487	38.9	13.679	2.345	70.5

TABLE 65: Continued

Month	1916-20:-			1921-25:-		
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
October:	1.834	2.425	25.0	6.777	2.268	51.3
November:	0.876	1.643	25.5	2.293	1.158	58.5
December:	1.093	1.099	42.5	1.728	1.048	56.1
Annual:	40.344	17.038	16.7	126.489	14.381	35.0

Mean monthly yield: 1.418 inches
Monthly data var(x): 0.730
" " " Fm^2: 0.372
" " " R^2: 0.490
Annual data var(x): 12.050
" " " Fm^2: 8.069
" " " R^2: 0.330

Mean monthly yield: 1.198 inches
Monthly data var(x): 0.839
" " " Fm^2: 1.138
" " " R^2: 0.000
Annual data var(x): 14.968
" " " Fm^2: 25.298
" " " R^2: 0.000

However, inspection of the larger squared differences shows that a considerable proportion of the listed errors may be ascribed to incorrect determination of within year runoff distributions. Further study into the effects on the runoff distributions by a change of the percentage carryover factor is considered appropriate at this stage. Changes of this type only modify the monthly flow distribution and do not materially affect the annual total. To reduce the calculated annual totals requires either a change in the average waterholding capacity value, or reduction in mean precipitation, or an increase in actual evapotranspiration.

Table 65 shows that the method tends to grossly over estimate peak winter and spring runoffs, with only slight over estimation of summer values. Runoff prediction calculations are thus repeated, with the same water holding capacity value and an increased carryover factor of 70 percent. The results are summarised in Table 66.

Comparisons of Tables 66 and 65 show that model efficiency has increased from 0.490 to 0.605 for the 1916-20 monthly yield data and from 0.330 to 0.397 for the annual data. Model efficiency is still zero for the 1921-25 annual data, and the monthly data value has increased to only 0.160.

Average monthly root mean square error has reduced to 38 percent of the mean for 1916-20 and to 70 percent for 1921-25.

Some improvement in runoff prediction has been achieved by increasing the lag in runoff response from a constant 50 to 70 percent. However, the end result has been to proportionally sacrifice prediction accuracy over the summer months. Normally low yields in summer and early autumn are increased to unacceptable levels by the predictions. These trends are confirmed by additional calculations for 1966-69 with constant

TABLE 66: Paerau Bridge residual variance and index of efficiency calculations for the water balance model. (70% carryover factor and 4 inches water holding capacity assumed)

squared differences between computed and observed runoff for:-

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1916	0.008	0.004	0.060	0.000	0.024	0.023	0.116	0.001	1.164	0.068	0.083	0.473	0.173
1917	0.318	0.239	0.135	0.052	0.412	0.815	0.000	0.026	0.100	0.100	0.561	0.061	2.752
1918	0.187	0.632	0.133	0.024	0.484	0.632	0.026	0.061	0.045	0.007	0.066	0.035	1.136
1919	0.165	0.470	1.352	0.002	0.078	0.101	0.011	0.523	1.048	0.010	0.205	0.074	27.794
1920	0.273	0.546	0.252	0.056	0.630	0.284	1.250	0.461	0.162	0.882	0.068	1.184	4.460
1921	1.090	0.383	0.391	0.052	0.165	0.584	0.980	0.009	0.000	0.004	0.017	0.504	16.241
1922	0.607	1.318	0.098	0.001	0.071	0.433	0.480	0.175	0.177	0.002	0.061	0.132	20.711
1923	0.174	0.607	0.484	0.716	1.488	5.934	2.350	1.059	7.684	1.682	0.008	0.134	28.580
1924	0.022	0.217	0.086	0.872	0.722	0.797	0.891	0.051	0.064	0.335	0.416	0.547	36.156
1925	0.198	0.161	0.015	0.000	0.282	0.258	0.003	2.409	0.373	2.056	1.461	0.000	15.202

Month		1916-20:-			1921-25:-	
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
January:	0.951	1.045	41.7	2.091	0.677	95.5
February:	1.891	0.649	94.7	2.686	0.331	221.4
March:	1.932	0.576	107.9	1.074	0.624	74.2
April:	0.134	0.728	22.5	1.641	1.177	48.7
May:	1.628	1.127	50.6	2.728	1.364	54.1
June:	1.855	1.723	35.3	8.006	0.761	166.2
July:	1.403	1.635	32.4	4.704	1.088	89.1
August:	1.072	1.882	24.6	3.703	1.541	55.8
September:	2.519	2.487	28.5	8.298	2.345	54.9

TABLE 66: *Continued*

Month	1916-20:- F^2	1916-20:- Measured Mean Yield (inches)	1916-20:- Monthly Fm as % Column (3)	1921-25:- F^2	1921-25:- Measured Mean Yield (inches)	1921-25:- Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
October:	1.067	2.425	19.0	4.079	2.268	39.8
November:	0.983	1.643	27.0	1.963	1.158	54.1
December:	1.827	1.099	55.0	1.317	1.048	48.9
Annual:	36.315	17.038	15.8	116.890	14.381	33.6

	1916-20	1921-25
Mean monthly yield:	1.418 inches	1.198 inches
Monthly data var(x):	0.730	0.839
" " " Fm^2:	0.288	0.705
" " " R^2:	0.605	0.160
Annual data var(x):	12.050	14.968
" " " Fm^2:	7.263	23.378
" " " R^2:	0.397	0.000

carryover factors of 50, 60 and 70 percent. For some aspects of irrigation design in the study area it is important to be able to accurately determine monthly or seasonal runoff data for periods when soil moisture deficiency is either imminent or being experienced. Over-estimation of water surplus lost as winter or early spring runoff is thus not critical and need not be corrected for.

The results show that the water balance model is unreliable overall as a runoff prediction method for the Upper Taieri basin. The second study objective is again unlikely to be satisfied by the record extension. Although the version with a 70 percent carryover factor is found to be the most efficient of models considered thus far for the prediction of 1916-20 yields, this performance is not maintained for the 1921-25 predictions. More consistent performance is demonstrated by the multiple regression models, though with slightly lower efficiency values.

Paerau Bridge record extension: modified water balance model

The general water balance technique proposed by Thornthwaite & Mather (op. cit) is not satisfactory for Paerau Bridge runoff predictions. When a constant percentage carryover factor of water surplus is used in the yield calculations, the result is an inaccurate within year distribution of an otherwise reasonably predicted annual moisture excess.

Determination of a more realistic within year runoff distribution is considered desirable at this stage. The benefits of the original method are largely lost when changes are introduced, but a useful simple model may thus be developed specifically for the Upper Taieri basin.

The approach considered here is to use a constant 60 percent carryover factor and a variable direct response dependent on season. Winter surface runoff is delayed in storage and in this way the natural catchment conditions are more closely simulated. An annual input-output balance is also retained for the system.

Data used are monthly values of catchment mean precipitation and evapotranspiration for the period of measured yield, and an assumed four inches water holding capacity. New values of predicted runoff are given by the relationships:-

(i) $MPRO_x$ (Jan.-May, July, Aug., Nov., Dec.) = $0.60\ MPRO_{x-1} + 0.40S_x$.

(ii) MPRO (June) = 0.60 MPRO (May) + 0.10 S (June).

(iii) MPRO (Sept.)= 0.60 MPRO (Aug.)+ 0.40 S (Sept.) + 0.24 S (June).

(iv) MPRO (Oct.) = 0.60 MPRO (Sept.)+0.40 S (Oct.) + 0.06 S (June).

MPRO is modified predicted runoff and S is moisture surplus. The original predicted runoff (PRO) values used for comparison are derived from an equation of form:

PRO_x (Jan.-Dec.) = $0.50\ (PRO_{x-1} + Sx)$.

Results of the analysis are summarised in Table 67. Although the values shown are not directly comparable with previous results for the ten year test interval, marked improvements in prediction are evident when the modified model is used. Mean square error for the monthly data is reduced from 0.433 to 0.092 with the new version. Average monthly root mean square error is thus reduced from 47 to 21 percent of the mean monthly yield. However, these values and the results for each month suggest that the use of a modified water balance model for record extension is again unlikely to satisfy the second study objective.

Paerau Bridge record extension: conceptual model

Most digital simulation models reported in the literature have been applied to situations where sufficient data has been available. It is thus of interest to consider whether these models can be successfully applied to conditions which are not ideal and where the

TABLE 67: Monthly and annual mean yield for Paerau Bridge predicted from a modified water balance model. (4 inches water holding capacity assumed).

Abbreviations used (all units in inches):- PE = potential evapotranspiration; P = precipitation; S = moisture surplus; RO = measured runoff from available discharge records; PRO = predicted runoff using a standard water balance model with 50% carryover factor (i.e. PRO_x (Jan.-Dec.) = 0.50 (PRO_{x-1} + Sx); MPRO = modified PRO assuming:-

(i) MPRO_x (Jan-May, Nov., Dec.) = 0.60 MPRO_{x-1} + 0.40Sx.
(ii) MPRO (June) = 0.60 MPRO (May) + 0.10S (June).
(iii) MPRO_x (July,Aug.) = 0.60 MPRO_{x-1} + 0.40 Sx.
(iv) MPRO (Sept.) = 0.60 MPRO (Aug.) + 0.40S (Sept.) + 0.24S (June)
(v) MPRO (Oct.) = 0.60 MPRO (Sept.) + 0.40S (Oct.) + 0.06S (June).

Month	P	PE	S	RO	PRO	MPRO	squared differences between computed and observed runoff for:-	
							PRO	MPRO
January:	4.02	3.57	0.45	0.792	0.53	0.73	0.068	0.004
February:	3.56	2.96	0.60	0.559	0.56	0.68	0.000	0.014
March:	3.94	2.51	1.43	0.801	1.00	0.98	0.039	0.032
April:	2.72	1.58	1.14	1.097	1.07	1.04	0.001	0.003
May:	3.06	0.81	2.25	1.469	1.66	1.53	0.036	0.004
June:	3.20	0.17	3.03	1.283	2.34	1.22	1.117	0.004
July:	1.47	0.07	1.40	1.390	1.87	1.29	0.230	0.010
August:	1.77	0.35	1.42	1.638	1.65	1.34	0.000	0.089
September:	2.17	0.95	1.22	2.432	1.43	2.02	1.004	0.170
October:	2.81	2.04	0.77	2.484	1.10	1.70	1.915	0.614
November:	3.42	2.59	0.83	1.614	0.96	1.35	0.428	0.069
December:	3.58	3.31	0.27	1.217	0.62	0.92	0.356	0.088
Annual:	35.74	20.93	14.81	16.778	14.79	14.80	3.952	3.912
						Monthly data Fm^2:	0.433	0.092
						Annual data Fm^2:	3.952	3.912

available data is limited. Such conditions are found in the Upper Taieri basin.

(i) 'Boughton' version - the model used in this study is a modified version of that developed by Boughton (1965, 1966, 1968(a), (b)). Boughton's original model was designed particularly for 'small' catchments, with application to the problems of agricultural hydrology and in particular for the design of farm dams.

The structure of the original model is shown in Figure 39 and consists of an interception store (CEPMX) and two soil moisture stores (USMAX, SSMAX). Each soil moisture store has two divisions (DRMAX plus USMAX, and SDRMX within SSMAX); one division is depleted by drainage and the other by evapotranspiration loss. CEPMX is depleted only by evapotranspiration loss (when CEP is less than CEPMX), independent of soil moisture level.

The time unit in model operation is one day, and each adjustment of current moisture levels is made in three stages - wetting, drainage and drying cycles. If the amount of rainfall added to the interception store exceeds CEPMX, the excess (EX) is added to the upper soil and drainage stores. If these stores also overflow, surface runoff occurs in accordance with the equation RUN = EX-F tanh (EX/F), as does infiltration into the sub-soil store (SSMAX) in accordance with the equation F = FC + (FO-FC)/EXP(AAK.SS) - see Boughton (1968(b)).

Evapotranspiration losses occur from the interception, upper soil and sub-soil stores, with that from the interception store at potential rates. Losses from the remainder are determined in accordance with the relationships defined by Denmead & Shaw (1962), and Slatyer & Denmead (1963).

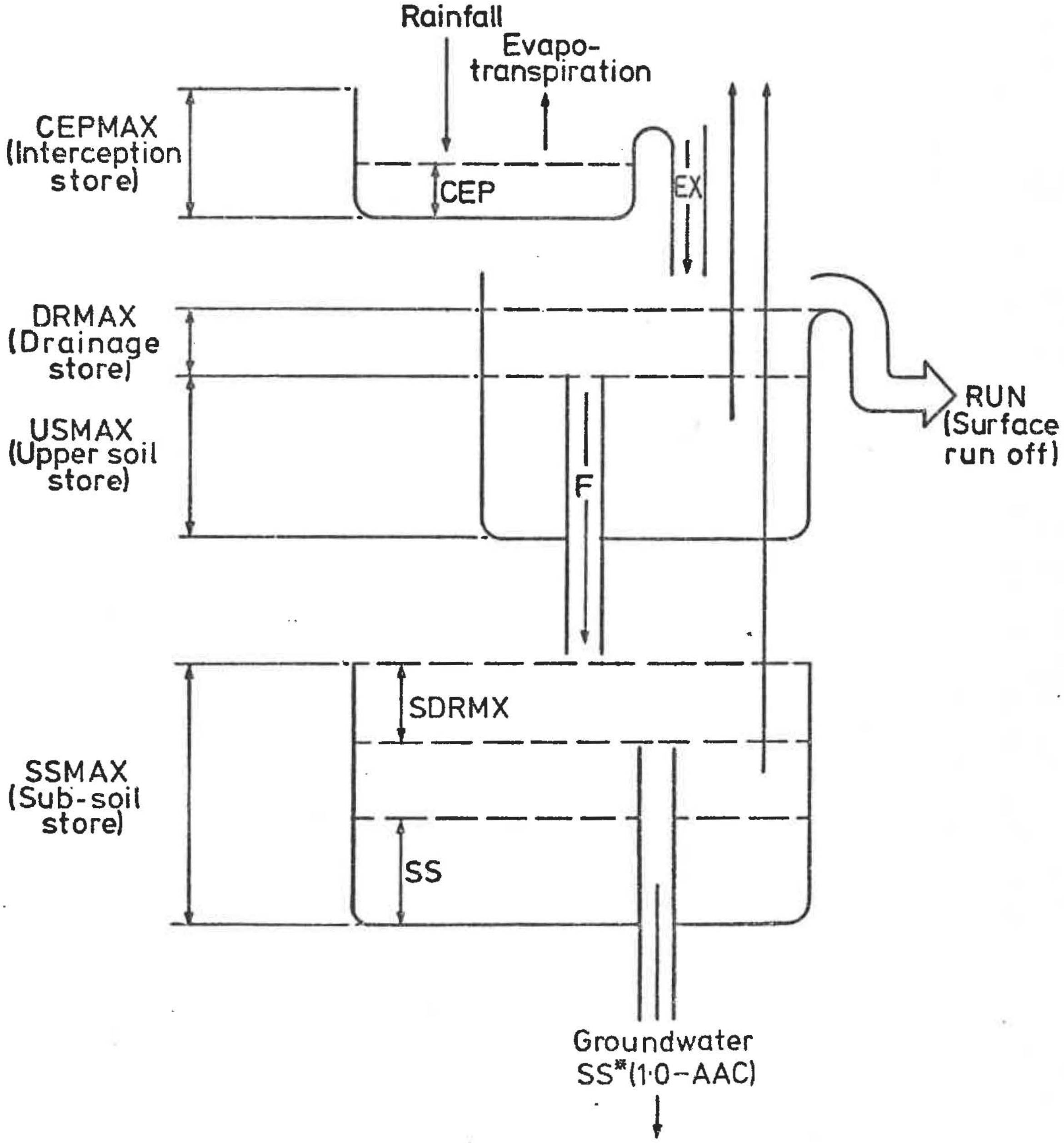


FIGURE 39: Structure of the original model

Finally, water is lost to groundwater from the sub-soil store by way of the expression SS (1.0-AAC), but only if the sub-soil moisture level (SS) is above a minimum value.

In the original model no attempt is made to separate interflow from surface runoff and the groundwater contribution to runoff is ignored. As a result, the major modifications introduced are the addition of a groundwater store and the provision for interflow and groundwater components in the total runoff (Hutchinson & Simmers, 1971).

(ii) Modified 'Boughton' version - the structure of the modified model is shown in Figure 40. The upper soil store represents that part of the soil moisture capacity which can immediately accept precipitation excess (EX). When US exceeds USMAX, surface depression storage occurs, as does flow into the subsoil store. The latter store represents that part of the soil moisture capacity which governs the flow to groundwater.

In the original model there is no direct flow between the upper and subsoil stores, nor is there any flow out of the subsoil store when SS falls below a level SSMAX-SDRMX. Interflow occurs in the modified model, so that after a dry spell SS can be greatly reduced while the water in the upper soil store is only slowly reduced by evapotranspiration. An impossible situation is thus developed, and necessitates the direct transfer of water from the upper to sub-soil stores to maintain a balance.

There is no theoretical relationship to apply to this water transfer since the two stores are not separate physical entities. However, it is argued that since interflow occurs at a greater than proportional rate to the moisture in the soil as the moisture increases, movement from upper to sub-soil stores should also be at greater than a proportional rate. Although the relationship should be exponential, it is simpler to assume that between store movement is proportional to the square of

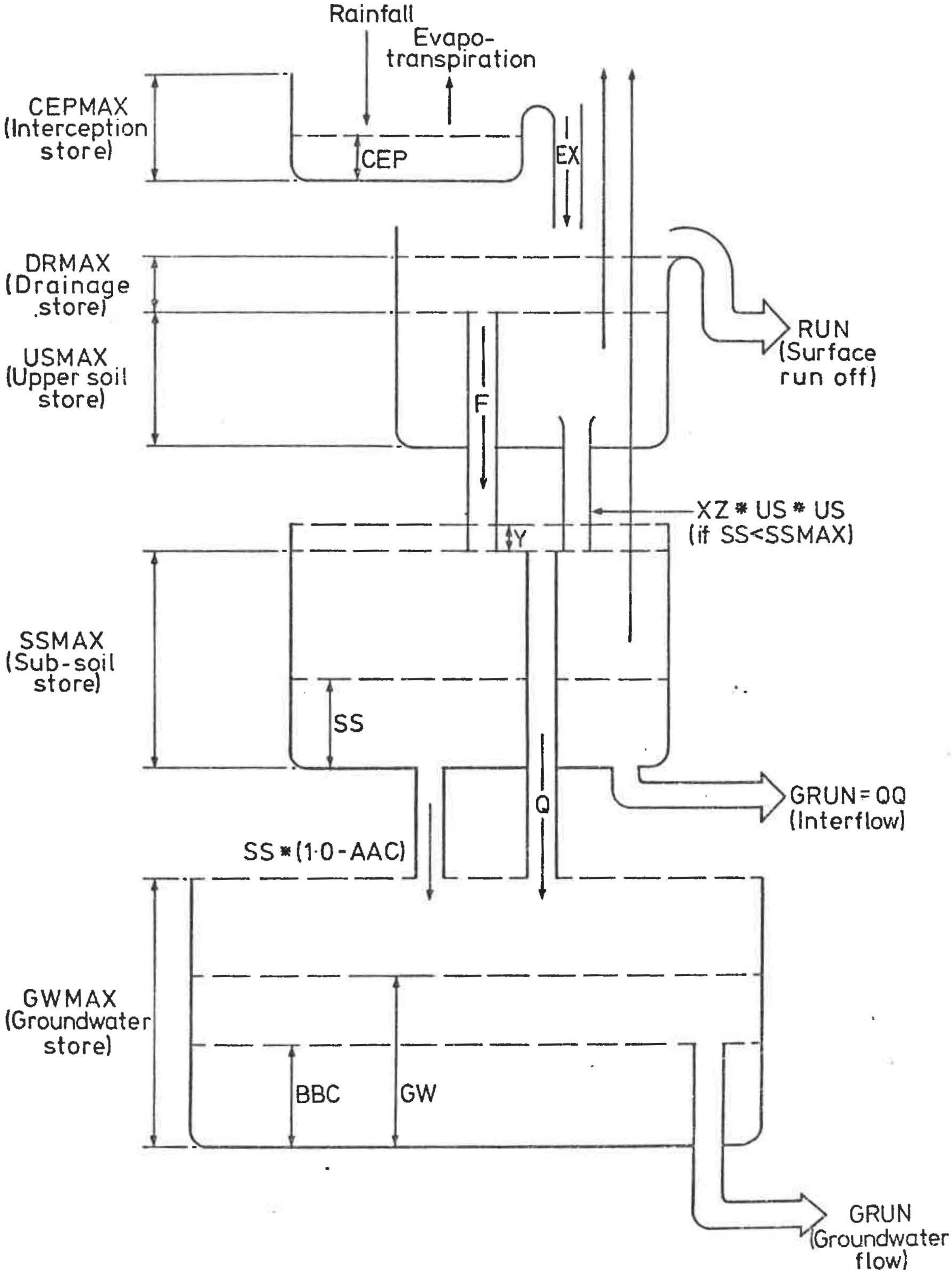


FIGURE 40: Structure of the revised model

the water in the upper soil store. However, the relationship is subject to available space in the sub-soil store, otherwise the excess water is held in the upper soil store.

It is assumed that interflow occurs from the sub-soil store. When total runoff is calculated, it is necessary to ensure that the shape as well as the volume of the derived hydrograph matches the measured records. Inspection of the basic precipitation and flow data shows that hydrograph peaks occur between two and four days after each rainstorm, and suggests a time of travel through the soil of up to four days. This time of travel is accommodated in the model by delay mechanisms which are depicted as dummy variables. The procedure is a variation from most models, which normally account for this delay by use of a further storage, usually called 'channel storage'.

A further complication occurs when daily rainfall exceeds 1.5 inches. Figure 40 shows that this could result in an overfull sub-soil store, with the excess depicted as Y. The sub-soil store thus contains more than the specified maximum, can be considered supersaturated, and would provide the conditions for rapid slips and slumps on steep ground. Y is also subject to a delay mechanism and is depleted to both interflow and groundwater.

A continuous flow to groundwater is retained from the original model, with the sub-soil depleted by a constant factor SS(1.0-AAC).

The groundwater store is an addition to the original model, and provides a reservoir and regulator for the groundwater component of runoff. Water flows into the store from Y and the sub-soil store, and is lost by groundwater runoff provided there is more than a minimum in the store. The minimum value BBC corresponds in physical terms to the condition where the water table level is below the bottom of the stream bed. Since the groundwater contribution to runoff will not be linearly dependent on water table level, a squared relationship is again chosen to represent this depletion.

(iii) Paerau Bridge predicted yields - precision limits of parameter estimates are again not readily quantifiable. Whether the second study objective is satisfied by record extension from digital simulation must therefore be qualitatively deduced. Model performance is evaluated on a daily and monthly basis, by way of the same split record technique shown for the simple and multiple regression analyses and the 1916-25 test interval.

The choice of an error function depends on the purpose of the study. Model efficiency is evaluated in the same manner as before for the monthly data to allow between model comparison. However, efficiency indices from equation (32) were not calculated for the computed daily data, and performance is assessed from the sum of squared differences between estimated and measured runoff (Chapman, 1970).

Optimised values of the catchment parameters and variables required for model operation were derived for 1921-25 using the computer programme listed in Appendix II. The results are shown in Table 68 and were initially determined by steepest-ascent methods (Boughton, 1968(b)). Input data were the mean catchment daily precipitation, and daily evapotranspiration calculated as the fraction of previously derived monthly potential evapotranspiration.

The optimised values from Table 68 were thus used to compute daily runoff for the full ten year period, and the results compared with the measured records (Table 69).

Sum of squared differences between estimated and measured daily runoff for 1921-25 total 1.903. Average root mean square simulation

TABLE 68: Modified conceptual model catchment parameters, variables and values given (see also Boughton, 1965, 1968(b) and Hutchinson & Simmers, 1971)

(Note: (i) op = value optimised before simulation;
(ii) all selected values are in inches)

Symbol	Selected value	Meaning
CEPMAX	0.100 (op)	Capacity of the Interception Store
DRMAX	0.400 (op)	Capacity of the Drainage Store
USMAX	1.000 (op)	Capacity of the Upper Soil Store
SSMAX	0.900 (op)	Capacity of the Subsoil Store
GWMAX	9.000 (op)	Capacity of the Groundwater Store
PCUS	60.000 (op)	% of evapotranspiration loss from the Upper Soil Store
FO	1.800 (op)	Daily infiltration rate at subsoil moisture level zero
FC	0.700 (op)	Minimum daily infiltration rate
AAK	0.600 (op)	Exponent K in infiltration equation
XX	0.500 (op)	Maximum limit of evapotranspiration rate
XZ	0.250 (op)	Coefficient of transfer from Upper Soil to Subsoil Store
AAC	0.800 (op)	Factor for depleting Subsoil moisture by drainage
ABC	0.002 (op)	Factor for depleting groundwater into runoff
BBC	1.000 (op)	Level of the groundwater store at which no contribution is made to runoff
C	0.70-2.10	Monthly adjustment to the Upper Soil Store
CEP		Moisture level of the Interception Store
DR		Moisture level of the Drainage Store
US		Moisture level of the Upper Soil Store
SS		Moisture level of the Subsoil Store
GW		Moisture level of the Groundwater Store
QQ, RR, ST, TT		Dummy variables of Interflow delay mechanism
Q, R, S		Dummy variables of depletion to Groundwater delay mechanism

TABLE 69: Sum of squared differences between estimated and measured mean daily runoff (inches) for Paerau Bridge

Month:	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925
January:	0.0038	0.0059	0.0177	0.0381	0.0272	0.0250	0.0996	0.0089	0.0040	0.0059
February:	0.0012	0.0368	0.0154	0.0568	0.0217	0.0133	0.0395	0.0061	0.0313	0.0094
March:	0.0025	0.0090	0.0744	0.0317	0.0161	0.0128	0.0160	0.0083	0.0189	0.0115
April:	0.0063	0.0011	0.0157	0.0321	0.0081	0.0155	0.0077	0.0689	0.0165	0.0070
May:	0.0063	0.2953	0.0392	0.0070	0.0104	0.0140	0.0037	0.0284	0.0208	0.0124
June:	0.0115	0.0439	0.1046	0.0423	0.0233	0.0078	0.0066	0.0459	0.0093	0.0116
July:	0.0060	0.0046	0.0435	0.0598	0.1429	0.0222	0.0166	0.0267	0.0189	0.0538
August:	0.0217	0.0113	0.0922	0.1767	0.0355	0.0302	0.0096	0.0331	0.0256	0.0669
September:	0.0508	0.1251	0.1174	0.4221	0.0291	0.0138	0.0208	0.4804	0.0100	0.0646
October:	0.0048	0.0269	0.0767	0.0085	0.0753	0.0270	0.0048	0.1322	0.0199	0.1176
November:	0.0180	0.0155	0.0543	0.0034	0.0518	0.0185	0.0068	0.0082	0.0128	0.0087
December:	0.0101	0.0161	0.0295	0.0065	0.0207	0.0041	0.0131	0.0074	0.0123	0.0298
F^2:	0.1430	0.5915	0.6806	0.8850	0.4621	0.2042	0.2448	0.8545	0.2003	0.3992

1916-20 Total F^2: 2.7622

1921-25 Total F^2: 1.9030

error is thus 0.032 inches, or 82 percent of the average 1921-25 mean daily flow. However, the results for 1916-20 show that when the model is used for prediction purposes, F^2 increases to 2.762 and Fm is calculated as 83 percent of the average daily mean values.

The results do not appear promising. Closer inspection shows, however, that much of the error is contributed by a very few days. For example, 25 percent of the 1921-25 total sum of squared differences is given by the September 1923 value, and 15 percent of the 1916-20 total is contributed by the September 1919 value. Since most of the larger errors occur between late autumn and early spring, it is concluded that a lack of knowledge as regards snowmelt is the major cause of apparent failure of this model to simulate daily runoff. There are also occasions when a hydrograph peak occurs in the observed record without rainfall being collected by the Paerau gauge. This demonstrates the random errors which may occur when a single gauge is considered to be representative of the total area for daily rainfalls.

A characteristic of this type of catchment model is that pairs or groups of parameters may be interdependent, and result in minor maxima or minima on the response surface. The steepest-ascent optimisation used by Boughton (1968(a)) need not result in truly optimum parameter values. To test the results obtained, therefore, a rotating coordinate automatic parameter optimiser developed by Rosenbrock (1960) was fitted to the computer programme. The final reduction in sum of squared differences amounted to only 0.12 for 1921-25 and 0.18 for the 1916-20 prediction interval.

It is thus concluded that the model is relatively insensitive to changes in value of variables near the optimum point. Marked differences between the previous and new optimised upper soil, sub-soil and infiltration values were evident, but differences between the two 1921-25 runoff patterns produced by simulation were barely distinguishable. A more detailed search to determine the absolute optimum set of values is considered unnecessary.

Efficiency of the model to generate monthly data is evaluated in the same manner as for the simple and multiple regression and water balance models. Results of the calculations are shown in Table 70.

Simulation and prediction ability of the model appear to be no better than previously demonstrated by the alternative simpler methods. Mean square error for 1921-25 is calculated as 0.529 and the simulation efficiency is 36.9 percent for monthly yield data. The results for 1916-20 indicate that when the model is used for prediction purposes, the efficiency index remains the same for monthly data but falls from 0.434 to 0.038 for annual values.

Further, the average monthly root mean square error for 1921-25 is 61 percent of the mean monthly yield, and ranges from 19 to 205 percent. Results for the mean annual data are lower, though the root mean square error is shown to be 20 percent for both intervals. However, 51 percent of the sum of squared differences for the 1921-25 annual data are accounted for by the 1924 value. For 1916-20, the 1919 squared difference is 70 percent of the total. Also, nearly 36 percent of the monthly sum of squared differences for 1921-25 is given by the September 1923 figure.

Although the second study objective is unlikely to be realised by use of the modified conceptual model for Paerau Bridge record extension, the computed monthly data are a reasonable representation of the measured record. Occasional large errors are evident, but the results appear superior to those derived by Wood & Sutherland (1970) from the same data and the Stanford Watershed Model IV of Crawford & Linsley (1966). However,

TABLE 70: *Paerau Bridge residual variance and index of efficiency calculations for the modified conceptual model*

squared differences between computed and observed runoff (inches) for:-

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1916	0.024	0.012	0.018	0.175	0.008	0.016	0.000	0.000	1.048	0.058	0.071	0.320	0.248
1917	0.181	0.371	0.133	0.001	1.141	0.150	0.064	0.032	0.531	0.453	0.464	0.011	5.354
1918	0.054	0.419	0.015	0.007	0.515	1.395	0.841	0.193	0.479	1.605	1.153	0.383	9.666
1919	0.356	0.954	0.954	0.045	0.132	0.025	1.100	0.119	5.116	0.278	0.066	0.081	40.870
1920	0.760	0.626	0.501	0.228	0.240	0.069	0.711	0.518	0.348	1.214	0.365	0.490	1.844
1921	0.752	0.325	0.142	0.096	0.243	0.021	0.438	0.051	0.052	0.343	0.186	0.047	1.030
1922	1.638	1.094	0.071	0.013	0.038	0,206	0.199	0.051	0.422	0.026	0.027	0.000	8.071
1923	0.054	0.048	0.200	0.135	0.186	1.478	0.637	0.022	11.330	2.842	0.003	0.201	1.958
1924	0.099	0.597	0.586	0.443	0.610	0.268	0.559	0.016	0.145	0.140	0.157	0.333	21.697
1925	0.154	0.249	0.356	0.089	0.397	0.356	0.069	0.299	0.799	1.395	0.003	0.019	8.585

Month	1916-20:-			1921-25:-		
	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)	F^2	Measured Mean Yield (inches)	Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
January:	1.375	1.045	50.2	2.697	0.677	108.5
February:	2.382	0.649	106.3	2.313	0.331	205.4
March:	1.621	0.576	98.8	1.355	0.624	83.4
April:	0.456	0.728	41.4	0.776	1.177	33.4
May:	2.036	1.127	56.6	1.474	1.364	39.8
June:	1.655	1.723	33.4	2.329	0.761	89.7
July:	2.716	1.635	45.1	1.902	1.088	56.7
August:	0.862	1.882	22.1	0.439	1.541	19.2
September:	7.522	2.487	49.3	12.748	2.345	68.1

TABLE 70: Continued

Month	1916-20:- F^2	1916-20:- Measured Mean Yield (inches)	1916-20:- Monthly Fm as % Column (3)	1921-25:- F^2	1921-25:- Measured Mean Yield (inches)	1921-25:- Monthly Fm as % Column (3)
(1)	(2)	(3)	(4)	(2)	(3)	(4)
October:	3.608	2.425	35.0	4.746	2.268	42.9
November:	2.119	1.643	39.6	0.376	1.158	23.7
December:	1.285	1.099	46.1	0.600	1.048	33.0
Annual:	57.982	17.038	20.0	42.341	14.381	20.2

Mean monthly yield: 1.418 inches
Monthly data var(x): 0.730
" " " Fm^2: 0.460
" " " R^2: 0.370
Annual data var(x): 12.050
" " " Fm^2: 11.596
" " " R^2: 0.038

Mean monthly yield: 1.198 inches
Monthly data var(x): 0.839
" " " Fm^2: 0.529
" " " R^2: 0.369
Annual data var(x): 14.968
" " " Fm^2: 8.468
" " " R^2: 0.434

it is acknowledged that the results presented by Wood & Sutherland (op. cit) were obtained by matching peak flows rather than flow volumes. Optimum prediction thus resulted in computed flow volumes which were too high in all cases.

The final results of the present study fall short of what is desired for water resource assessment purposes. Principal limiting factors are considered to be the random errors of daily rainfall measurement which result from the use of only one gauge to represent the total area, and a lack of knowledge as regards snowmelt. The model developed should be capable of much improved performance, given basic data which are more suited to the general method, and addition of the automatic parameter optimisation technique (Rosenbrock, op. cit).

The method has only limited value if used to compute the balance of missing flow records for Paerau Bridge, since daily data are required for model input. Runoff determination beyond 1940 is precluded by a lack of precipitation data for the area. This problem could be overcome by the use of Monte Carlo generated daily rainfall sequences as model input, but such an approach is considered beyond the scope of the present water resource study and is not attempted.

COMPARISON OF DETERMINISTIC MODELS USED FOR EXTENSION OF THE TOTAL CATCHMENT STREAMFLOW RECORD

The available yield measurements for Paerau Bridge allow estimates of the annual and at least some of the monthly and seasonal population parameters to within 20 percent of actual at the 95 percent confidence level. The measured record is not of adequate length to satisfy the stated error criterion for all months or seasons. It was thus necessary to synthesise data in an attempt to increase at this stage the amount of information contained in the data series as compared with the measured series alone. Because of a lack of nearby long-term streamflow data, techniques which involve measured climatic data were used to extend the record.

Little information was gained by the analyses. The addition of synthesised data to the measured Paerau Bridge record still does not allow population parameters to be determined for all months with the required degree of precision. It is further concluded that none of the models chosen for Paerau Bridge streamflow record extension allow parameter estimation to markedly greater precision levels than for the measured series alone.

Precision limits of parameter estimates derived by water balance or conceptual models are not readily quantifiable; whether additional information is gained when the new synthetic records are included in a blended series is thus not directly known. However, parameter precision limits are qualitatively deduced by comparing the calculated model efficiency with similar values derived for simple and multiple regression models of known error. In this way, although estimates of the population parameters may not be derived here at the required precision level, all the models used can be evaluated for simulation and prediction ability, and missing flow records computed with minimised errors of prediction. Table 71 gives a summary of residual variance and index of efficiency calculations for the yield models discussed. The values are taken from Tables 58, 62, 65, 66 and 70, and do not require lengthy discussion. Conclusions reached above are hence determined by comparison of the Table 71 data with that already presented in Tables 28A, 29A, 57 and 61.

The simple regression models do not accommodate the appreciable observed lag between rainfall and runoff. However, in common with all the models used, total error is composed of occasional large values.

TABLE 71: Comparison of residual variance and index of efficiency calculations for Paerau Bridge yield models (see Tables 58, 62, 65, 66 and 70)

	simple rainfall/ runoff models		multiple regression models		water balance model (50% carryover factor)		water balance model (70% carryover factor)		conceptual model	
Month	Fm as a percentage of measured mean yield for:-									
	1916-20	1921-25	1916-20	1921-25	1916-20	1921-25	1916-20	1921-25	1916-20	1921-25
January	47.4	52.9	43.7	40.6	52.7	96.5	41.7	95.5	50.2	108
February	69.2	93.5	76.5	76.2	78.7	170	94.7	221	106	205
March	50.2	47.3	52.2	42.3	96.8	73.2	108	74.2	98.8	83.4
April	46.2	52.2	41.7	36.6	41.1	86.0	22.5	48.7	41.4	33.4
May	53.9	37.5	45.4	41.4	57.7	97.0	50.6	54.1	56.6	39.8
June	47.0	46.6	44.4	36.9	31.6	188	35.3	166	33.4	89.7
July	50.7	28.7	51.8	28.9	25.5	94.1	32.4	89.1	45.1	56.7
August	26.4	26.2	28.8	25.5	50.7	90.0	24.6	55.8	22.1	19.2
September	40.1	40.4	20.6	47.9	38.9	70.5	28.5	54.9	49.3	68.1
October	20.9	47.0	19.5	50.2	25.0	51.3	19.0	39.8	35.0	42.9
November	35.8	44.9	40.5	24.7	25.5	58.5	27.0	54.1	39.6	23.7
December	31.7	68.1	54.9	54.4	42.5	56.1	55.0	48.9	46.1	33.0
Annual	20.3	23.7	22.0	22.1	16.7	35.0	15.8	33.6	20.0	20.2
Monthly data Fm^2	0.360	0.346	0.316	0.334	0.372	1.138	0.288	0.705	0.460	0.529
" " " R^2	0.507	0.587	0.567	0.602	0.490	0.000	0.605	0.160	0.370	0.369
Annual data Fm^2	11.991	11.657	14.025	10.115	8.069	25.298	7.263	23.378	11.596	8.468
" " " R^2	0.005	0.221	0.000	0.324	0.330	0.000	0.397	0.000	0.038	0.434

If the occurrence of these large errors is acceptable, the predicted record may be considered a reasonable representation of the measured data.

The addition of an antecedent rainfall component is relevant when there is substantial carryover from one period to the next. Paerau Bridge multiple regression models show improved flow prediction results compared with the simple methods, though occasional large errors are still produced. Of interest is that prediction ability is not greatly improved by the use of up to six precipitation variables.

The modified conceptual model is generally unsatisfactory for Upper Taieri runoff prediction purposes. Although Table 71 shows improved simulation and prediction ability for the annual data, the monthly results are no better than those derived by the simpler alternative methods. Further, operation beyond 1940 is precluded by a lack of daily rainfall data for the area.

The general water balance method proposed by Thornthwaite & Mather (1955) is a convenient and simple way to study the fundamental processes within the hydrological cycles. However, when used as a runoff prediction method for Paerau Bridge, the water balance model presented here is found to be unreliable overall. Although the version with a 70 percent carryover factor is the most efficient of all the models considered for the prediction of 1916-20 yields, this performance is not maintained for the 1921-25 predictions. More consistent performance is demonstrated by the multiple regression models, though with slightly lower efficiency values. A large proportion of the water balance runoff prediction errors can be ascribed to incorrect determination of within-year runoff distributions. Principal value of the method in the Upper Taieri area is thus to determine the spatial and temporal variations in moisture deficit - critical for irrigation scheme design and operation schedules.

It is concluded that the multiple regression models are the most suitable for prediction of the missing Paerau Bridge streamflow records. Mean monthly, seasonal and annual values for the periods 1909-11, 1914-15, 1929-35, 1940, 1945-46 and 1951-66 are thus calculated by the equations listed in Table 59, and the results given in Tables 72 and 73. The values may be used in conjunction with the measured data from Table 19 or 55, and the long-term means calculated from the blended record are already listed in Table 61.

However, use of the data must be in full awareness of the likely errors involved. Estimated minimum standard errors of $\hat{\mu}y$ given x_1 and x_2 equal $\bar{x}_1$ and $\bar{x}_2$ are shown in Table 61 for the combined record. The data are derived from the weighted values of $SE\bar{y}$ from Table 28 and $S\hat{\mu}y.\bar{x}_1,\bar{x}_2$ as given by equation (27).

If the values listed in Table 72 are considered as estimates of mean y for a particular x, then their minimum standard errors of prediction are given by $S\hat{\mu}y.x_1,x_2$ from equation (27), and the statistics shown in Appendix I(5). However, if the Table 72 data are considered to be the predictions of individual y, given x, then the minimum standard errors are computed by the equation:-

$$\hat{S}y.x_1,x_2 = t0.05\ Sy.x_1,x_2 \left[(x_1-\bar{x}_1,x_2-\bar{x}_2) \begin{bmatrix} C_{11}C_{12} \\ C_{21}C_{22} \end{bmatrix} \begin{bmatrix} x_1-\bar{x}_1 \\ x_2-\bar{x}_2 \end{bmatrix} + 1 + \frac{1}{n} \right]^{\frac{1}{2}} \quad (36).$$

For example, the new 1909-69 blended record minimum mean monthly discharge for April is shown to be 16.9 cusecs, but equation (36) gives a prediction standard error of plus or minus 98 cusecs. Similarly, the new July minimum of 57.4 cusecs given in Table 72 has a prediction standard error of 330 cusecs. These are extreme examples and not typical of all the presented results. Equation (36) shows that the new maximum mean monthly discharge for June has a prediction standard error of plus or

TABLE 72: Paerau Bridge predicted mean discharge record (cusecs): 1909-1911; 1914-1915; 1929-1935; 1940; 1945-1946; 1951-31.5.66

Year	J	F	M	A	M	J	J	A	S	O	N	D	Year
1909	264	157	173	264	185	262	230	279	549	460	296	97.6	268
1910	61.8	81.3	96.2	47.2	194	221	275	260	455	553	261	89.5	217
1911	96.4	83.5	89.2	47.8	172	224	270	273	495	367	400	243	231
1914	202	131	111	127	313	552	123	225	469	396	298	182	261
1915	102	106	120	78.4	228	322	195	199	483	425	342	189	233
1929	111	94.2	155	98.3	153	358	328	339	569	310	365	223	259
1930	114	89.8	52.2	142	201	197	282	272	499	556	337	164	243
1931	305	235	76.6	136	191	223	255	316	556	509	269	108	265
1932	174	127	103	147	291	337	195	259	539	443	232	74.2	244
1933	77.4	82.1	97.6	395	420	305	275	294	563	455	353	408	311
1934	214	130	157	280	362	362	287	311	459	540	282	127	293
1935	199	158	256	359	372	720	57.4	255	576	305	422	261	328
1940	122	137	170	147	311	236	295	241	454	412	328	121	248
1945	205	186	170	380	420	268	289	273	462	534	310	311	318
1946	265	152	75.9	16.9	252	288	275	296	306	827	269	119	263
1951	190	134	148	191	229	249	258	273	499	486	372	218	271
1952	98.9	94.3	110	102	259	264	261	243	398	662	340	234	256
1953	177	127	203	396	256	210	244	259	528	384	347	194	277
1954	87.0	86.8	210	231	241	291	269	291	516	403	306	144	257
1955	187	137	221	254	309	424	331	356	504	442	364	129	305
1956	118	103	60.8	120	457	380	237	246	504	438	350	298	276
1957	138	100	211	312	424	408	221	194	405	554	358	294	302
1958	291	209	205	363	363	293	241	233	476	452	288	253	306
1959	165	107	143	164	332	297	237	202	450	403	342	259	259
1960	127	105	229	266	237	312	233	278	431	574	369	170	278
1961	124	141	189	224	184	349	296	355	491	476	355	70.2	271
1962	113	130	183	306	255	407	233	336	558	491	296	143	288
1963	108	112	150	170	287	307	233	391	636	559	310	205	290
1964	89.7	70.6	179	166	237	212	256	282	552	413	319	313	258
1965	251	161	153	212	341	416	220	291	518	476	314	83.8	287
1966	234	179	172	178	194	-	-	-	-	-	-	-	229
Mean:	162	127	151	204	280	323	247	277	497	477	326	191	272
Mean: (inches)	0.655	0.464	0.611	0.799	1.133	1.265	0.999	1.121	1.946	1.930	1.276	0.773	12.97

TABLE 73: Paerau Bridge predicted mean seasonal discharge record (cusecs): 1909-1911; 1914-1915; 1929-1935; 1940; 1945-1946; 1951-1966

Year	Summer	Autumn	Winter	Spring	Jan.-Mar.	Oct.-Mar.
; 1909	-	207	257	435	198	-
1909-10; 1910	80.2	112	252	423	79.8	182
1910-11; 1911	89.8	103	256	421	89.7	195
1911-12;	189	-	-	-	-	274
1913-14; 1914	296	184	300	388	148	312
1914-15; 1915	130	142	239	417	109	201
1915-16;	128	-	-	-	-	211
1928-29; 1929	108	135	342	415	120	286
1929-30; 1930	142	132	250	464	85.3	192
1930-31; 1931	235	134	265	445	206	279
1931-32; 1932	136	180	264	405	135	215
1932-33; 1933	77.9	304	291	457	85.7	168
1933-34; 1934	251	266	320	427	167	286
1934-35; 1935	161	329	344	434	204	260
1935-36;	146	-	-	-	-	241
1939-40; 1940	206	209	257	398	143	488
1940-41;	116	-	-	-	-	209
1944-45; 1945	284	323	277	435	187	312
1945-46; 1946	243	115	286	467	164	275
1946-47;	192	-	-	-	-	292
1950-51; 1951	161	189	260	452	157	150
1951-52; 1952	137	157	256	467	101	230
1952-53; 1953	179	285	238	420	169	291
1953-54; 1954	123	227	284	408	128	218
1954-55; 1955	156	261	370	437	182	233
1955-56; 1956	117	213	288	431	93.9	203
1956-57; 1957	179	316	274	439	150	256
1957-58; 1958	265	310	256	405	235	319
1958-59; 1959	175	213	245	398	138	235
1959-60; 1960	164	244	274	458	154	244
1960-61; 1961	145	199	333	441	151	261
1961-62; 1962	104	248	325	448	142	221
1962-63; 1963	121	202	310	502	123	217
1963-64; 1964	122	194	250	428	113	236
1964-65; 1965	242	235	309	436	188	268
1965-66; 1966	166	181	233	277	195	243
Mean:	165	211	281	428	146	239
Mean (inches/ month:	0.631	0.848	1.128	1.717	0.577	0.952

(Annual: 1.081 ins./month)

minus 263 cusecs. However, this value is only 36 percent of the 720 cusecs computed for 1923 in Table 72.

Finally, since the multiple regression equations listed in Table 59 can only be used to predict mean monthly yields, it is not possible to improve estimate precision of the Paerau Bridge extreme values. The standard errors of X_T for maximum and minimum daily discharges given in Tables 39 and 41 remain unchanged.

SUBCATCHMENT STREAMFLOW RECORD EXTENSION

Simple correlation and regression models:

It has been concluded that the measured data available for the principal sub-catchments do not allow direct estimation of monthly, seasonal, or annual yield parameters to within the stated error criterion.

Only the Loganburn station has sufficient measured data to make any estimates of sub-catchment yield possible. However, Tables 28 and 29 show that the records are of insufficient length - standard errors of up to 42 percent are calculated for the mean seasonal discharges, and up to 60 percent for the monthly values. The other stations on the major tributaries (Styx and Serpentine Creeks) and on the upper reaches of the main river (Upper Styx Valley Bridge), have insufficient measured data available to make any direct parameter estimates possible. It is thus necessary to extend these other records in order to determine parameter estimates at the required precision level.

The first method of record extension attempted is simple linear regression analysis. Basic data used are stream gauging records and rating tables for all stations over the period 1965-70, and the continuous water level records from Paerau Bridge (1966-69), Patearoa-Paerau Bridge (1966-70), and Loganburn (1966-70).

Discharge prediction equations are thus developed for all flow measurement stations in the Upper Taieri basin, using the graphical technique outlined by Searcy (1960). The equations are given in Table 74 and are more fully defined in Appendix I(6). Discontinuities are shown for the three Taieri River relationships and these are allowed for in all subsequent analyses.

With the exception of Styx Creek, correlation coefficients vary between 0.894 and 0.995, and are generally significant at greater than the 99 percent level. The value of 0.742 for Styx Creek probably reflects the difficulty in obtaining a stable stage-discharge relationship at this gauging site, and the problems of runoff correlation from areas of different size (Searcy, op. cit).

The correlations are all considered satisfactory for record extension purposes. Although equations (18) and (22) cannot be used to test for increased estimate precision of population means and variances, equation (20) shows that effective record extensions vary from nine to 21 years. Mean monthly discharge records equivalent in length to the measured Paerau Bridge series are thus calculated for the major tributaries, Upper Styx Valley and the Patearoa-Paerau Bridge stations. Results of the analyses are summarised in Table 75. The data for Serpentine Creek, Styx Creek, Loganburn and Upper Styx Valley Bridge are assumed to be representative of sub-catchment areas 1, 2a, 2b and 3 respectively.

Estimated standard errors of the Patearoa-Paerau Bridge and Loganburn mean discharges are calculated from the blended predicted and measured data. The results are given by the weighted average of measured standard error of the mean from Tables 28 and 29, and $S\hat{\mu}y.\bar{x}$ from equation (24). Values of x in equation (24) are initially assumed to be error free, and are the $\bar{x}$ data for Paerau Bridge given in Tables 28A and 29A.

TABLE 74: *Discharge regression equations for synthetic record determination (cusecs)*

(Note: Q_p = Taieri discharge at Paerau; Q_{pp} = Taieri discharge at Patearoa-Paerau; Qus = Taieri discharge at Upper Styx Valley; Q_L = Loganburn discharge at Paerau; Q_{SE} = Serpentine discharge at McDonald's Br.; Q_{ST} = Styx Creek discharge at Paerau).

A. *Taieri River at Paerau Bridge:*

(i) $Q_p = 6.56\ Q_L - 23.22$

(ii) $Q_p = 1.04\ Q_{pp} - 6.00$ (For $Q_{pp} < 200$ cusecs).

(iii) $Q_p = 0.90\ Q_{pp} + 28.00$ (For $Q_{pp} \geqslant 200$ cusecs).

B. *Taieri River at Patearoa-Paerau Bridge:*

(i) $Q_{pp} = 0.90\ Q_p + 14.00$ (For $Q_p < 200$ cusecs).

(ii) $Q_{pp} = 1.07\ Q_p - 19.70$ (For $Q_p \geqslant 200$ cusecs).

C. *Taieri River at Upper Styx Valley Bridge:*

(i) $Qus = 0.61\ Q_p - 6.00$ (For $Q_p < 120$ cusecs).

(ii) $Qus = 0.44\ Q_p + 15.00$ (For $Q_p \geqslant 120$ cusecs).

D. *Loganburn at Paerau:*

(i) $Q_L = 0.15\ Q_p + 3.92$

E. *Serpentine Creek at McDonald's Bridge:*

(i) $Q_{SE} = 0.111\ Q_p - 1.38$

F: *Styx Creek at Paerau:*

(i) $Q_{ST} = 0.05\ Q_p + 3.28$

TABLE 75: Mean discharge parameters for stations Patearoa-Paerau Bridge, Upper Styx Valley Bridge, Loganburn, Serpentine Creek and Styx Creek (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1.6.66-31.5.69)

A. *Taieri River at Patearoa-Paerau Bridge:*
(Catchment area above station - 285 square miles)

	J	F	M	A	M	J	J	A	S	O	N	D
Mean discharge (cusecs):	168	133	171	241	311	281	294	346	530	524	353	257
Mean yield (inches):	0.680	0.486	0.692	0.943	1.258	1.100	1.189	1.400	2.075	2.120	1.382	1.040
$S\hat{\mu}y.\bar{x}$ (cfs):	4.53	5.48	20.8	45.0	22.5	26.8	12.8	22.8	22.1	48.4	17.3	17.7
$S\mu y.\bar{x}$ as % mean discharge:	2.70	4.12	12.2	18.6	7.24	9.55	4.35	6.58	4.17	9.23	4.89	6.88
Maximum mean monthly discharge:	556	668	699	575	910	652	636	629	1377	1146	991	554
Minimum mean monthly discharge:	28.9	25.4	24.3	38.8	44.3	58.0	131	122	159	162	108	49.2

	Summer	Autumn	Winter	Spring	Oct.-Mar.	Jan.-Mar.	Annual
Mean Q (cfs):	184	241	307	469	260	158	301
Mean yield (ins/mth):	0.735	0.964	1.230	1.859	1.067	0.619	14.34 (ins)
$S\hat{\mu}y.\bar{x}$ (cfs):	8.55	18.1	15.6	26.1	11.8	6.87	11.8
$S\mu y.\bar{x}$ as % mean Q:	4.65	7.49	5.07	5.56	4.53	4.35	3.93
Max. mean seasonal/ annual discharge:	520	701	512	1171	525	577	499
Min. mean seasonal/ annual discharge:	47.7	58.9	136	189	133	41.2	133

(n_1 = 3 years; n_2 = 27 years)

TABLE 75: Continued

B. *Taieri River at Upper Styx Valley Bridge:*
(catchment area above station - 101 square miles)

	J	F	M	A	M	J	J	A	S	O	N	D
Mean Q (cfs):	80.0	62.6	81.1	114	146	133	139	161	240	237	163	120
Mean yield (ins.):	0.913	0.645	0.926	1.259	1.667	1.496	1.587	1.838	2.651	2.705	1.801	1.370
$S\hat{\mu}y.\bar{x}$ (cfs):	3.89	4.07	3.90	5.70	8.70	7.36	7.95	10.4	19.4	19.1	10.6	6.39
$S\mu y.\bar{x}$ as % mean Q:	4.86	6.50	4.81	5.00	5.96	5.53	5.72	6.43	8.08	8.05	6.53	5.32
Max. mean monthly Q:	250	296	310	290	399	290	283	280	597	499	433	249
Min. mean monthly Q:	9.80	7.00	6.80	15.2	18.5	26.5	68.5	63.9	79.8	81.0	53.4	21.4

	Summer	Autumn	Winter	Spring	Oct.-Mar.	Jan.-Mar.	Annual
Mean Q (cfs):	86.8	114	144	214	121	75.0	140
Mean yield (ins/mth):	0.976	1.284	1.631	2.386	1.393	0.828	18.81 (ins)
$S\mu y.\bar{x}$ (cfs):	4.07	5.70	8.51	16.4	6.47	3.85	8.28
$S\hat{\mu}y.\bar{x}$ as % mean Q:	4.69	5.00	5.91	7.66	5.35	5.14	5.91
Max. mean seasonal/ annual Q:	234	311	231	510	236	258	224
Min. mean seasonal/ annual Q:	20.6	26.3	68.8	91.6	62.2	16.9	64.2

(n_2 = 30 years)

TABLE 75: Continued

C. Loganburn at Paerau:

(catchment area above station - 58 square miles)

	J	F	M	A	M	J	J	A	S	O	N	D
Mean Q (cfs):	28.1	22.2	28.8	38.6	48.6	46.6	46.7	54.8	80.5	79.8	54.6	40.3
Mean yield (ins):	0.558	0.399	0.572	0.742	0.966	0.896	0.928	1.089	1.548	1.586	1.050	0.801
$S\hat{y}.\bar{x}$ (cfs):	1.71	1.03	7.85	10.4	1.88	9.20	2.89	7.51	3.88	7.62	3.78	2.12
$S\hat{y}.\bar{x}$ as % mean Q:	6.10	4.66	27.3	27.1	3.86	19.7	6.19	13.7	4.83	9.54	6.92	5.26
Max. mean monthly Q:	83.9	101	105	120	135	125	95.4	102	202	169	147	83.5
Min. mean monthly Q:	7.20	2.60	1.50	9.20	9.70	12.0	22.5	21.2	26.8	26.8	19.3	10.7

	Summer	Autumn	Winter	Spring	Oct.-Mar.	Jan.-Mar.	Annual
Mean Q (cfs):	29.8	38.7	49.4	71.7	41.2	26.4	47.5
Mean yield (ins/mth):	0.586	0.760	0.971	1.395	0.828	0.510	11.12 (ins)
$S\hat{y}.\bar{x}$ (cfs):	1.14	5.78	6.17	3.75	1.63	2.39	2.31
$S\hat{y}.\bar{x}$ as % mean Q:	3.84	14.9	12.5	5.24	3.96	9.04	4.87
Max. mean seasonal/ annual Q:	78.7	105	94.7	173	79.3	86.9	75.6
Min. mean seasonal/ annual Q:	10.5	12.1	23.2	30.9	22.2	9.2	22.8

(n_1 = 3 years; n_2 = 27 years)

TABLE 75: Continued:

D. *Serpentine Creek at McDonald's Bridge:*
(catchment area above station - 41 square miles)

	J	F	M	A	M	J	J	A	S	O	N	D
Mean Q (cfs):	15.4	11.8	15.7	22.6	29.6	26.6	27.9	33.4	52.1	50.1	33.8	24.3
Mean yield (ins):	0.433	0.300	0.441	0.615	0.832	0.724	0.784	0.939	1.418	1.409	0.920	0.683
$S\mu y.\bar{x}$ (cfs):	2.76	3.01	2.75	2.59	2.87	2.70	2.77	3.16	5.37	5.28	3.21	2.62
$S\mu y.\bar{x}$ as % mean Q:	17.9	25.5	17.5	11.4	9.71	10.1	9.93	9.45	10.3	10.5	9.51	10.8
Max. mean monthly Q:	54.3	65.4	68.4	56.0	89.5	63.6	62.0	61.4	136	113	97.7	54.0
Min. mean monthly Q:	1.50	1.20	1.10	2.50	3.20	4.40	11.6	10.8	14.5	14.9	9.30	3.40

	Summer	Autumn	Winter	Spring	Oct.-Mar.	Jan.Mar.	Annual
Mean Q (cfs):	16.3	21.8	28.3	43.7	23.5	13.7	27.6
Mean yield (ins/mth):	0.472	0.629	0.816	1.249	0.698	0.391	9.14 (ins)
$S\mu y.\bar{x}$ (cfs):	2.69	2.59	2.85	4.56	2.62	2.83	2.81
$S\mu y.\bar{x}$ as % mean Q:	16.5	11.9	10.0	10.4	11.2	20.6	10.2
Max. mean seasonal/ annual Q:	48.6	66.0	47.8	111	49.0	54.1	46.5
Min. mean seasonal/ annual Q:	3.10	4.20	11.6	16.8	11.3	2.50	11.4

(n_2 = 30 years)

TABLE 75: Comtinued

E. Styx Creek at Paerau:
(catchment area above station - 16 square miles) :

	J	F	M	A	M	J	J	A	S	O	N	D
Mean Q (cfs):	11.3	9.60	11.3	14.3	17.6	16.4	17.2	19.6	28.3	28.0	19.9	15.5
Mean yield (ins):	0.814	0.625	0.814	0.997	1.268	1.144	1.239	1.412	1.973	2.018	1.388	1.117
$S\hat{\mu}y.\bar{x}$ (cfs):	2.74	2.99	2.72	2.34	2.15	2.20	2.17	2.14	2.98	2.94	2.15	2.27
$S\hat{\mu}y.\bar{x}$ as % mean Q:	24.2	31.1	24.1	16.4	12.2	13.4	12.6	10.9	10.5	10.5	10.8	14.7
Max. mean monthly Q:	29.8	35.3	36.7	27.0	46.9	34.5	33.7	33.5	69.5	58.3	50.8	29.8
Min. mean monthly Q:	4.50	4.30	4.20	4.90	5.30	5.90	9.40	9.10	10.9	10.9	8.40	5.70

	Summer	Autumn	Winter	Spring	Oct.-Mar.	Jan.-Mar.	Annual
Mean Q (cfs):	12.1	14.4	17.7	25.5	15.6	10.8	17.5
Mean yield (ins/mth):	0.825	1.026	1.265	1.793	1.129	0.751	14.85 (ins)
$S\hat{\mu}y.\bar{x}$ (cfs):	2.64	2.34	2.15	2.58	2.26	2.80	2.16
$S\hat{\mu}y.\bar{x}$ as % mean Q:	21.8	16.3	12.1	10.1	14.5	26.0	12.3
Max. mean seasonal/ annual Q:	28.2	36.9	27.8	59.5	28.4	31.0	27.2
Min. mean seasonal/ annual Q:	5.50	6.00	9.70	12.3	9.60	5.20	9.60

(n_2 = 30 years)

For the other stations listed in Table 75, the values of $S\hat{\mu}y.\bar{x}$ are the prediction standard errors as determined from equation (24) - x is again $\bar{x}$ for the long-term Paerau Bridge record.

Marked improvements in mean discharge estimate precision are shown by the extended Patearoa-Paerau Bridge and Loganburn records when compared with the results in Tables 28 and 29. Standard errors as a percentage of the mean are reduced for all time intervals at both sites. Long-term mean monthly discharges for Patearoa-Paerau Bridge may be estimated by regression from the stated Paerau Bridge values, with standard errors of less than 10 percent in all but two months (March, April). The mean annual discharge is estimated to within four percent, and seasonal values to within eight percent.

Loganburn long-term mean annual discharge is now estimated to within 10 percent at the 95 percent confidence level. Results for the mean monthly data show that only March, April, June and August now have standard errors in excess of 10 percent.

Prediction standard errors for mean discharge estimates at Upper Styx Valley Bridge are shown by Table 75 to be all less than eight percent. The values for Styx and Serpentine Creeks are higher, and all figures except for four months at Serpentine Creek are in excess of 10 percent.

The Table 75 results suggest that the second study objective is satisfied in part for the principal sub-catchments. Addition of regression estimates to the measured Loganburn record now appears to allow determination of mean discharge at the required precision level for most time intervals of a month or more. Similar conclusions may be drawn for the Upper Styx Valley Bridge predictions, though not for the Styx and Serpentine Creek sub-catchments.

However, the Paerau Bridge values used in the regressions are not error free, since the $\bar{x}$ data listed in Tables 28A and 29A represent $\hat{\mu}_x$ with errors as indicated by the listed SE$\bar{x}$ values. As such, if the mean discharges listed in Table 75 are to be considered as estimates of $\hat{\mu}y$ rather than $\bar{y}$ with $\bar{x}$ assumed to be error free, then the standard errors will exceed the values given. The $\bar{x}$ data may be maximised and minimised in accordance with the errors shown in Tables 28A and 29A, a range of new discharges calculated for Table 75, and the standard error recomputed. Results of this analysis are summarised in Table 76.

The data show that only the long-term mean annual discharges for the Patearoa-Paerau Bridge and Loganburn stations may now be estimated with a standard error of less than 10 percent. However, comparison of Tables 76, 28 and 29 shows that for Patearoa-Paerau Bridge and Loganburn stations, more precise estimates of mean discharge may still be made from the combined record than from the measured series alone. Although the second study objective is not realised, increased information is obtained from the blended records.

Full summaries of the synthesised sub-catchment mean discharges for the period of record covered by the Paerau Bridge series are not listed here. However, use of the data should be in awareness of the likely errors involved, with reference made to equations (24) or (28) and the statistics given in Appendix I(6).

Subcatchment extreme discharge estimates from regression analysis:

Available measurements of daily mean or instantaneous discharge do not allow estimation of total or sub-catchment annual flood or minimum flows to within 10 percent of actual discharge for any return period. Standard errors of about 11 percent are calculated for both the flood and minimum flows at T equals two years, and values of up to 21 percent are evident for the higher recurrence intervals.

TABLE 76: Standard errors of long-term Patearoa-Paerau Bridge, Upper Styx Valley Bridge, Loganburn, Serpentine Creek, and Styx Creek mean discharges, where x is not error free

values of $S\hat{\mu}y.\bar{x}$ as a % of Table 75 mean discharges for:-

	Patearoa-Paerau Bridge (1)	Upper Styx Valley Br. (2)	Loganburn (3)	Serpentine Creek (4)	Styx Creek (5)
January:	15.5	17.6	18.9	34.4	35.0
February:	19.5	22.4	19.8	46.6	43.6
March:	24.0	17.5	38.9	33.4	34.0
April:	30.3	14.9	37.0	24.3	25.5
May:	17.7	15.7	14.4	22.3	21.6
June:	19.2	13.5	27.7	20.3	20.7
July:	12.2	12.9	13.3	18.6	19.2
August:	14.1	13.0	20.4	17.4	16.8
September:	12.6	15.4	12.7	19.4	18.0
October:	17.6	15.6	17.0	19.5	17.7
November:	14.2	14.4	15.4	19.5	18.1
December:	19.1	15.8	15.9	23.8	23.8
Summer:	15.8	17.3	16.1	33.1	31.8
Autumn:	17.4	14.0	24.0	23.8	24.6
Winter:	11.1	11.1	17.8	17.1	16.9
Spring:	13.0	14.0	11.6	18.6	16.5
Oct-Mar:	12.7	12.4	11.1	20.4	20.5
Jan-Mar:	15.2	16.5	19.7	35.7	34.2
Annual:	9.63	10.7	9.68	16.3	16.6

Results from Tables 75 and 76 further suggest that regression analysis is of no help in the estimation of sub-catchment extreme values at the required degree of precision. Sub-catchment annual flood and minimum flows are computed by regression from the collated long-term Paerau Bridge maximum and minimum mean daily flow series, subjected to frequency analysis, and the results listed in Tables 77 and 78. Minimum standard errors of x_T comparable with Tables 39 and 41 are not calculated, but may be readily determined from the listed control curve data if required.

If the sub-catchment extreme events are initially assumed to equate with measured data, and hence not subject to standard errors of prediction, some features of interest arise from the results.

Flood discharges per unit area decrease from the Upper Styx Valley Bridge through Paerau to the Patearoa-Paerau Bridge, and are greater for the main river than for each of the principal sub-catchments. The tributaries show a maximum for Styx Creek and a minimum for Serpentine Creek. Calculated differences would reflect the integrating effects of different precipitation regimes and catchment storage characteristics. Also, values of zero baseflow are calculated for only Loganburn and Serpentine Creek. These features are generally in accordance with field observation and expected trends.

However, although Tables 77 and 78 show marked differences in discharge per unit area between sub-catchments, any conclusions can only be of a tentative nature. Differences may be more apparent than real, since the data are subject to both standard errors of x_T for the measured Paerau Bridge records and the prediction errors given by equation (28). The errors are likely to be greater than those listed in Tables 39 and 41 for Paerau Bridge, and probably excessive. Highest percentage

TABLE 77: Annual flood frequency analysis summaries for the Taieri River at Patearoa-Paerau and Upper Styx Valley Bridges, Loganburn, Serpentine and Styx Creeks (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1967-69)

A. Taieri River at Patearoa-Paerau Bridge:

Return Period (years)	Flow (cusecs)	Flow - (cusecs/ square mile)	Control curves :- Lower Limit	Upper Limit
1.01	320	1.12	138	502
1.03	438	1.53	301	576
1.10	611	2.14	500	722
1.20	741	2.59	636	846
1.30	830	2.91	725	934
1.50	958	3.35	850	1066
2.00	1163	4.07	1042	1284
5.00	1667	5.83	1479	1855
10	2000	7.00	1725	2276
15	2189	7.66	1856	2522
20	2321	8.12	1947	2694
25	2422	8.48	2018	2826
50	2735	9.57	2235	3234
100	3045	10.66	2538	3552

B. Taieri River at Upper Styx Valley Bridge:

Return Period (years)	Flow (cusecs)	Flow - (cusecs/ square mile)	Control curves:- Lower Limit	Upper Limit
1.01	150	1.49	72.5	227
1.03	200	1.98	142	258
1.10	273	2.70	226	320
1.20	328	3.25	283	372
1.30	365	3.61	321	409
1.50	420	4.16	374	465
2.00	506	5.01	455	557
5.00	719	7.12	640	799
10	861	8.52	744	977
15	940	9.31	799	1081
20	996	9.86	838	1154
25	1039	10.29	868	1210
50	1171	11.59	960	1382
100	1303	12.90	1088	1517

C. Loganburn at Paerau:

Return Period (years)	Flow (cusecs)	Flow - (cusecs/ square mile)	Control curves:- Lower Limit	Upper Limit
1.01	49.8	0.86	23.5	76.1
1.03	66.9	1.15	47.1	86.7
1.10	91.8	1.58	75.8	108
1.20	110	1.90	95.3	126

TABLE 77: Continued

C. Loganburn at Paerau (continued)

Return Period (years)	Flow (cusecs)	Flow - (cusecs/ square mile)	Control curves:- Lower Limit	Upper Limit
1.30	123	2.12	108	138
1.50	142	2.45	126	157
2.00	171	2.95	154	189
5.00	244	4.21	217	271
10	292	5.03	252	332
15	319	5.50	271	367
20	338	5.83	284	392
25	353	6.09	295	411
50	398	6.86	326	460
100	443	7.64	370	516

D. Serpentine Creek at McDonald's Bridge:

Return Period (years)	Flow (cusecs)	Flow - (cusecs/ square mile)	Control curves:- Lower Limit	Upper Limit
1.01	30.6	0.75	12.4	48.8
1.03	42.4	1.03	28.7	56.1
1.10	59.7	1.46	48.6	70.7
1.20	72.6	1.77	62.1	83.1
1.30	81.5	1.99	71.1	92.0
1.50	94.4	2.30	83.6	105
2.00	115	2.80	103	127
5.00	165	4.02	146	184
10	199	4.85	171	226
15	217	5.29	184	251
20	231	5.63	193	268
25	241	5.88	200	281
50	272	6.63	222	322
100	303	7.39	252	354

E. Styx Creek at Paerau:

Return Period (years)	Flow (cusecs)	Flow - (cusecs/ square mile)	Control curves:- Lower Limit	Upper Limit
1.01	18.6	1.16	9.82	27.3
1.03	24.3	1.52	17.7	30.9
1.10	32.6	2.04	27.2	37.9
1.20	38.8	2.43	33.8	43.8
1.30	43.1	2.69	38.1	48.1
1.50	49.3	3.08	44.1	54.5
2.00	59.1	3.69	53.3	64.9
5.00	83.3	5.21	74.3	92.4
10	99.4	6.21	86.1	113
15	108	6.75	92.4	124
20	115	7.19	96.8	133
25	120	7.50	100	139
50	135	8.44	111	159
100	150	9.38	125	174

TABLE 78: Annual minimum flow frequency analysis summaries for the Taieri River at Patearoa-Paerau and Upper Styx Valley Bridges, Loganburn, Serpentine and Styx Creeks (1912-13; 1916-28; 1936-39; 1941-44; 1947-50; 1967-69)

A. *Taieri River at Patearoa-Paerau Bridge:* (ε = 13.65 cusecs)

Return Period (years)	Flow (cusecs)	Flow (cusecs/ square mile)	Log flow (=log$_e$(Q−ε))	Control curves:- Lower Limit (log)	Upper Limit (log)
1.01	205	0.718	5.2555	4.8321	5.6789
1.03	151	0.527	4.9204	4.5345	5.3064
1.10	97.7	0.342	4.4317	4.1004	4.7630
1.20	71.9	0.252	4.0651	3.7683	4.3618
1.30	58.9	0.206	3.8129	3.5168	4.1089
1.50	45.1	0.158	3.4496	3.1435	3.7557
2.00	31.3	0.110	2.8701	2.5271	3.2131
5.00	17.9	0.063	1.4440	0.9112	1.9768
10	15.3	0.054	0.4998	-0.9356	1.9351
15	14.6	0.052	-0.0329	-1.4683	1.4024
20	14.3	0.050	-0.4059	-1.8413	1.0294
25	14.15	0.050	-0.6932	-2.1286	0.7421
50	13.86	0.049	-1.5783	-3.0136	-0.1429
100	13.74	0.048	-2.4568	-3.8921	-1.0214

B. *Taieri River at Upper Styx Valley Bridge:* (ε = 0.57 cusecs)

Return Period (years)	Flow (cusecs)	Flow (cusecs/ square mile)	Log flow (=log$_e$(Q−ε))	Control curves:- Lower Limit (log)	Upper Limit (log)
1.01	101	1.005	4.6142	4.2219	5.0065
1.03	74.6	0.739	4,3047	3,9474	4.6621
1.10	47.7	0.472	3.8533	3.5470	4.1597
1.20	34.2	0.338	3.5147	3.2407	3.7888
1.30	27.2	0.269	3.2818	3.0084	3.5553
1.50	19.6	0.194	2.9463	2.6636	3.2290
2.00	11.7	0.116	2.4111	2.0943	2.7280
5.00	3.56	0.035	1.0940	0.6020	1.5861
10	1.82	0.018	0.2220	-1.1036	1.5476
15	1.34	0.013	-0.2700	-1.5956	1.0557
20	1.11	0.011	-0.6145	-1.9401	0.7112
25	0.99	0.010	-0.8798	-2.2054	0.4458
50	0.76	0.008	-1.6972	-3.0228	-0.3716
100	0.65	0.006	-2.5085	-3.8342	-1.1829

TABLE 78: Continued

C. *Loganburn at Paerau:* (ε = 0.00 cusecs)

Return Period (years)	Flow (cusecs)	Flow (cusecs/ square mile)	Log flow (=$\log_e(Q-\varepsilon)$)	Control curves:-	
				Lower Limit (log)	Upper Limit (log)
1.01	27.80	0.479	3.3251	3.1310	3.5191
1.03	24.32	0.404	3.1535	2.9742	3.3329
1.10	18.24	0.314	2.9034	2.7453	3.0614
1.20	15.12	0.261	2.7157	2.5713	2.8601
1.30	13.28	0.229	2.5866	2.4426	2.7306
1.50	11.03	0.190	2.4006	2.2517	2.5496
2.00	8.20	0.141	2.1040	1.9371	2.2709
5.00	3.95	0.068	1.3740	1.1148	1.6332
10	2.44	0.042	0.8907	0.4877	1.2937
15	1.86	0.032	0.6180	0.1135	1.1226
20	1.53	0.026	0.4271	-0.1486	1.0027
25	1.32	0.023	0.2800	-0.3504	0.9104
50	0.84	0.014	-0.1730	-0.9078	0.5617
100	0.54	0.009	-0.6227	-1.3575	0.1120

D. *Serpentine at McDonald's Bridge:* (ε = 0.00 cusecs)

Return Period (years)	Flow (cusecs)	Flow (cusecs/ square mile)	Log flow (=$\log_e(Q-\varepsilon)$)	Control curves:-	
				Lower Limit (log)	Upper Limit (log)
1.01	18.55	0.452	2.9206	2.5001	3.3411
1.03	13.27	0.324	2.5855	2.2016	2.9694
1.10	8.14	0.199	2.0968	1.7662	2.4273
1.20	5.64	0.138	1.7301	1.4334	2.0269
1.30	4.38	0.107	1.4779	1.1819	1.7740
1.50	3.05	0.074	1.1147	0.8086	1.4208
2.00	1.71	0.042	0.5352	0.1921	0.8782
5.00	0.41	0.010	-0.8909	-1.4237	-0.3581
10	0.16	0.004	-1.8351	-2.8830	-0.7872
15	0.09	0.002	-2.3678	-3.8032	-0.9325
20	0.06	0.001	-2.7408	-4.1762	-1.3055
25	0.05	0.001	-3.0281	-4.4635	-1.5928
50	0.02	0.000	-3.9132	-5.3485	-2.4778
100	0.01	0.000	-4.7917	-6.2271	-3.3563

TABLE 78: Continued

E. Styx Creek at Paerau: (ε = 3.84 cusecs)

Return Period (years)	Flow (cusecs)	Flow (cusecs/ square mile)	Low Flow (=$\log_e(Q-\varepsilon)$)	Control curves:-	
				Lower Limit (log)	Upper Limit (log)
1.01	13.05	0.816	2.2206	1.7972	2.6439
1.03	10.43	0.652	1.8858	1.4995	2.2714
1.10	7.88	0.493	1.3967	1.0654	1.7280
1.20	6.64	0.415	1.0301	0.7334	1.3268
1.30	6.02	0.376	0.7779	0.4818	1.0740
1.50	5.35	0.334	0.4146	0.1085	0.7207
2.00	4.69	0.293	-0.1649	-0.5079	0.1782
5.00	4.04	0.253	-1.5910	-2.1238	-1.0582
10	3.92	0.245	-2.5352	-3.9705	-1.0998
15	3.89	0.243	-3.0679	-4.5032	-1.6325
20	3.87	0.242	-3.4409	-4.8762	-2.0055
25	3.86	0.241	-3.7282	-5.1635	-2.2928
50	3.85	0.241	-4.6132	-6.0486	-3.1779
100	3.84	0.240	-5.4917	-6.9271	-4.0564

errors are likely to be produced for the series of annual minima. In any event, sub-catchment population parameters are unlikely to be determined for any month or season to the required degree of precision.

Water balance model:

Precision limits of parameter estimates derived by water balance models are not readily quantifiable. However, the general water balance model proposed by Thornthwaite & Mather (1955) is shown to be unreliable for runoff prediction in the Upper Taieri area. The second study objective is thus unlikely to be satisfied by water balance derived sub-catchment yield records. Nevertheless, a large proportion of the prediction errors can be ascribed to incorrect determination of within year runoff distributions. Principal value of the method in the Upper Taieri area, therefore, is to determine the spatial and temporal variations in soil moisture deficit. It is hence of interest to now consider the relative areal effectiveness of precipitation input, as shown by these average spatial variations of moisture deficit or surplus throughout the year. Total and sub-catchment average water balances are computed from the previously derived 1908-69 mean monthly precipitation and potential evapotranspiration values. The literature shows that this method is standard practice as a means of presenting such average water balance data. A four inch water holding capacity is assumed as before, and the results are summarised in Table 79.

The seasonal changes of moisture surplus or deficit are clearly defined. Of interest is that although the average annual rainfall exceeds average annual water need in all areas, seasonal moisture deficits are shown for each of the sub-catchments except Area 3. Average annual rainfall exceeds need by about 16 inches for the total catchment, and the sub-catchment values vary from four to 23 inches. However, summer

TABLE 79: Upper Taieri River average catchment mean and sub-areas 1, 2a, 2b and 3 mean monthly water balance calculations (Thornthwaite & Mather, 1957) for 1908-69

(Notes: (i) Four inches water holding capacity is assumed
(ii) Calculations are made using the 1908-69 mean precipitation and potential evapotranspiration data
(iii) Abbreviations used (all units in inches):
D = moisture deficit; S = moisture surplus)

	Catchment Mean (Paerau Br.)		Sub-Area 1 (Serpentine Ck.)		Sub-Area 2a (Styx Ck.)		Sub-Area 2b (Loganburn)		Sub-Area 3 (U.Styx Valley Br.)	
	D	S	D	S	D	S	D	S	D	S
January:	0	0.21	0.03	0	0.01	0	0.02	0	0	0.90
February:	0	0.47	0.29	0	0.01	0	0.01	0	0	1.13
March:	0	1.28	0	0	0	0.10	0	0.09	0	2.00
April:	0	1.53	0	0	0	1.02	0	1.01	0	2.12
May:	0	2.15	0	0	0	1.73	0	1.66	0	2.73
June:	0	2.69	0	1.50	0	2.29	0	2.22	0	3.27
July:	0	1.68	0	1.03	0	1.42	0	1.39	0	2.04
August:	0	1.80	0	0.97	0	1.63	0	1.43	0	2.27
September:	0	1.39	0	0.62	0	1.05	0	1.00	0	1.85
October:	0	1.00	0	0.01	0	0.53	0	0.49	0	1.56
November:	0	0.85	0	0	0	0.28	0	0.26	0	1.50
December:	0	0.59	0.09	0	0	0	0	0	0	1.35
Summer:	0	1.27	0.68	0	0.02	0	0.03	0	0	3.38
Autumn:	0	4.96	0	0	0	2.85	0	2.76	0	6.85
Winter:	0	6.17	0	3.50	0	5.34	0	5.04	0	7.58
Spring:	0	3.24	0	0.63	0	1.86	0	1.75	0	4.91
Oct-Mar.:	0	4.40	0.68	0.01	0.02	0.91	0.03	0.84	0	8.44
Jan-Mar.:	0	1.96	0.59	0	0.02	0	0.03	0.09	0	4.03
Annual:	0	15.71	0.68	4.13	0.02	10.05	0.03	9.55	0	22.82

moisture deficits which range from 0.68 to 0.02 inches are calculated by these average data for areas 1, 2a and 2b. Effective rainfall thus occurs in other than the summer months on average.

Although average water balances give a useful indication of likely seasonal trends in the climatic and related moisture parameters, derivation from long-term average data as commonly found in the literature may lead to an over-generalised and incorrect picture. In an area where more than a minor seasonal moisture deficit is suspected, use of the average monthly data, as in Table 79, results in an under-estimation of water surplus and deficiency. Mean annual yields may be under-estimated, and moisture deficits may in fact occur in an area where the use of average data suggests no such condition.

The above conclusion is demonstrated by Table 80. Mean monthly, seasonal and annual moisture deficits and surpluses have been recalculated for each sub-area, by taking the average of each variable month by month over the full 62 year record. Comparison of Tables 79 and 80 shows marked differences in the results.

New values for the total catchment give a mean annual surplus of 16.35 inches, and a mean deficit of 0.69 inches which extends from October to April. No deficit was calculated previously. Such trends are also shown by the sub-catchment results. For Area 1, average annual moisture surplus has increased from 4.13 to 5.56 inches, and the deficit from 0.68 to 2.22 inches. Area 2a has a surplus of 11.22 inches compared with 10.05 inches, and a deficit of 1.15 inches. Comparable values for Area 2b are 10.74 inches surplus and 1.22 inches deficit. Changes for Area 3 are less marked, as expected.

These results and general conclusions are important when estimates of mean monthly and annual runoff are made from the basic water balance

TABLE 80: *Upper Taieri average catchment mean and sub-areas 1, 2a, 2b and 3 moisture surplus and deficiency calculations (Thornthwaite & Mather, 1957) for 1908-69*

Notes: (i) Four inches water holding capacity is assumed
(ii) D = moisture deficit (inches); S = moisture surplus (inches)
(iii) Listed values are the averages of individual D and S calculations from the full 62 year year record

	Catchment Mean (Paerau Br.)		Sub-Areal (Serpentine Ck.)		Sub-Area 2a (Styx Ck.)		Sub-Area 2b (Loganburn)		Sub-Area 3 (U.Styx Valley Br.)	
	D	S	D	S	D	S	D	S	D	S
January:	0.15	0.56	0.61	0.12	0.29	0.29	0.30	0.30	0.08	1.07
February:	0.21	0.91	0.67	0.23	0.31	0.45	0.33	0.47	0.16	1.42
March:	0.14	1.16	0.34	0.09	0.25	0.47	0.26	0.49	0.13	1.93
April:	0.01	1.15	0.07	0.27	0.03	0.59	0.04	0.59	0.01	1.82
May:	0	1.99	0.01	0.55	0	1.36	0	1.30	0	2.71
June:	0	2.54	0	1.14	0	2.13	0	2.00	0	3.36
July:	0	1.68	0	0.87	0	1.43	0	1.35	0	2.19
August:	0	1.81	0	0.98	0	1.64	0	1.46	0	2.43
September:	0	1.39	0	0.60	0	1.07	0	1.00	0	1.94
October:	0.02	1.21	0.05	0.38	0.03	0.77	0.03	0.76	0.02	1.75
November:	0.04	0.98	0.13	0.16	0.06	0.53	0.07	0.52	0.02	1.55
December:	0.11	0.97	0.34	0.17	0.18	0.49	0.20	0.50	0.08	1.56
Summer:	0.47	2.44	1.63	0.52	0.78	1.23	0.83	1.27	0.32	4.05
Autumn:	0.15	4.30	0.42	0.91	0.28	2.42	0.30	2.38	0.14	6.46
Winter:	0	6.03	0	2.99	0	5.20	0	4.81	0	7.98
Spring:	0.06	3.58	0.18	1.14	0.09	2.37	0.10	2.28	0.04	5.24
Oct-Mar.:	0.67	5.79	2.14	1.15	1.13	3.00	1.19	3.04	0.49	9.28
Jan-Mar.:	0.50	2.63	1.61	0.44	0.85	1.21	0.89	1.26	0.37	4.42
Annual:	0.69	16.35	2.22	5.56	1.15	11.22	1.22	10.74	0.50	23.75

equation given as Q = P-PE. The method has been demonstrated by Penman (1956), Kohler (1964), Clark & Bruce (1966) and Scarf (1972), and is recommended for regions where there are no streamflow records. These authors suggest that the method is most appropriate for long time intervals where changes in storage can be considered small or zero, and is further conditional on the absence of leaks in the hydrological system.

Figure 41 is presented to test the assumption that the amount and areal distribution of surface water resources in the Upper Taieri basin may be adequately defined by a basic water balance equation. The map shows isolines of 'potential' mean annual runoff for the period 1908-69, derived from the previously calculated long-term precipitation and potential evapotranspiration data. Maps of this type do not give values of runoff at a point directly, but first require isohyetal integration above the point. In this lies their value, since runoff data can be obtained from the map at any point on any stream by simple planimetering of between isohyetal areas.

For comparative purposes, total and sub-catchment mean annual runoff values are calculated firstly from Figure 41 by the standard isohyetal method, and secondly, from the basic equation. The results are given in Table 81. Also listed are mean annual yield summaries from Tables 55, 75, 79 and 80. Individual values do not require further discussion at this stage, though marked differences are shown between both methods and sub-areas.

The data are subject to the previously calculated standard errors of mean annual precipitation, temperature and yield determination. However, it is concluded that except for initial estimates, general application of the basic water balance equation cannot be recommended for yield calculations.

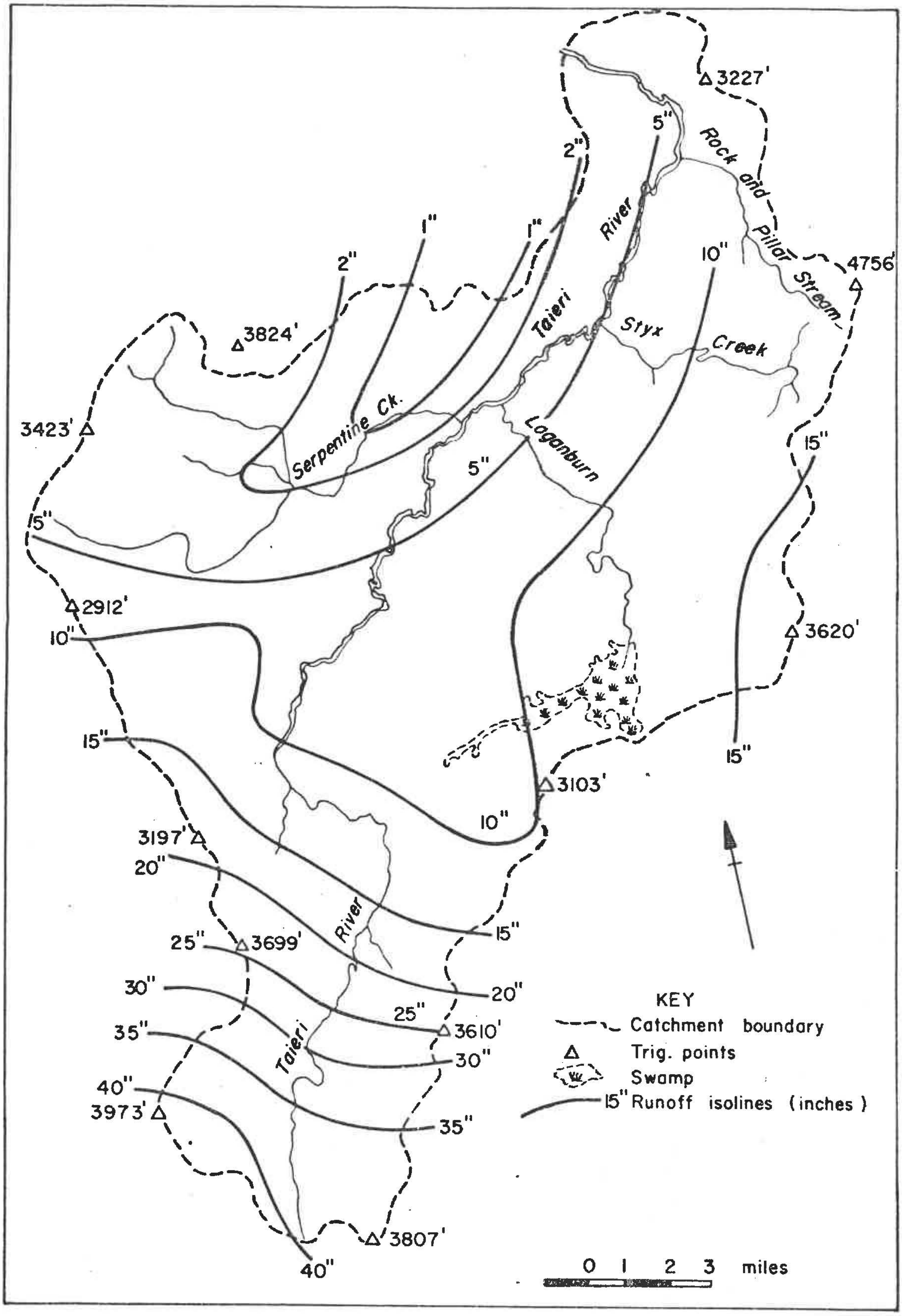


FIGURE 41: Upper Taieri catchment isolines of potential mean annual runoff (1908-1969)

TABLE 81: *Upper Taieri River total and sub-catchment mean annual potential evapotranspiration (PE), precipitation (P), and yield (Q) summaries for 1908-69*

(Note: see Tables 50, 51, 55, 64, 75, 79, 80 and Figure 41)

	Area 1	Area 2a	Area 2b	Area 3	Total Catchment
'Representative' station:	Serpentine Ck.	Styx Ck.	Loganburn	U.Styx Valley Br.	Paerau Br.
Area (sq.miles):	77.2	29.8	81.1	97.0	285
Mean altitude (ft):	2400	3400	2800	3000	2800
1908-69 mean annual PE (inches):	21.84	19.66	20.93	20.49	20.93
1908-69 mean annual P (inches):	25.33	29.73	30.52	43.35	36.64
1908-69 mean annual 'potential' yield (Q = P-PE):	3.49	10.07	9.59	22.86	15.71
1908-69 isohyetal mean annual potential yield (inches):	3.54	10.66	9.64	18.76	11.20
1908-69 mean annual yield (inches) - ex Table 79:	4.13	10.05	9.55	22.82	15.71
1908-69 mean annual yield (inches) - ex Table 80:	5.56	11.22	10.74	23.75	16.35
Mean annual yield ex Tables 55, 75 (inches):	9.14	14.85	11.12	18.81	16.78

Between method yield differences tend to increase with greater values of computed mean moisture deficit. The total catchment mean annual yield calculated by the basic water balance equation is considered acceptable as a first estimate. However, percentage errors can be expected to rapidly increase when data are required for shorter time intervals, for non-watertight catchments, or when seasonal moisture deficits can be expected. The present results again suggest that precipitation amounts may be under estimated in the headwaters of Serpentine and Styx Creeks (Figure 38).

STOCHASTIC MODEL FOR EXTENSION OF THE TOTAL-CATCHMENT STREAMFLOW RECORD

Thomas & Fiering sequential generation model: general

Stochastic flow simulation is a useful technique for generating hypothetical sequences of events from a shorter historical data series. The sequences have the same probability characteristics of the past, and include patterns of expected high and low flows not included in the measured record.

A major limitation is that the quality of the new information is no better than the data from which generated. However, subsequent analyses are more reliable than when based on a single recorded sequence. The method has direct application to the design of multi-structure, multi-purpose systems of water resource development and management.

A stochastic model can thus be considered as an alternative means to synthesise missing flow sequences within the 1909-70 Upper Taieri record. Since historic monthly and annual flows are not reproduced by the simulation, it is not possible to directly compare the results with those produced by parametric methods of streamflow generation. However, the computed data are equally valuable for engineering design purposes, and a flow series of any predetermined length can be generated.

The technique developed by Thomas & Fiering (1962) is used in this study to generate long-term flow series for the Taieri River at Paerau Bridge. The model is formulated as a recursion equation for unit time intervals of months, and takes the form:

$$Q_{(i+1)} = \bar{Q}_{(j+1)} + b_j \, (Q_i - \bar{Q}_j) + t_i \sigma_{(j+1)} (1 - r_j^2)^{\frac{1}{2}} \qquad \text{———————} \quad (37).$$

Q_i and $Q_{(i+1)}$ are discharges for the ith and (i+1)st month respectively, reckoned from the start of the synthesised sequence; $\bar{Q}_j$ and $\bar{Q}_{(j+1)}$ are the mean monthly discharges for the jth and (j+1)st month respectively, within a repetitive annual cycle of 12 months; b_j is the regression coefficient to estimate flow in the (j+1)st month from the jth month; t_i is a random, normal deviate with zero mean and unit variance; $\sigma_{(j+1)}$ is the standard deviation of flows in the (j+1)st month; r_j is the correlation coefficient between the flows of the jth and (j+1)st month.

Equation (37) characterises a circular random walk, with discharge in the (i+1)st month comprising a component which is linearly related to that in the ith month, and a random additive element. Derivation of $Q_{(i+1)}$ produces a continuous, unbounded, and serially correlated flow sequence for simulation studies.

Thomas & Fiering sequential generation model: Paerau Bridge streamflow record generation

Generation of streamflow records for the Taieri River at Paerau is achieved by way of the DASTAT and GENSYN computer programmes developed by Pearson (1968), and listed here in Appendix II. DASTAT is a programme for the statistical analysis of measured streamflow records, and GENSYN is a sequential generation programme to derive a synthetic long-term flow series. Basic data used in the analysis are the 1916-28 mean monthly flows recorded at the Paerau Bridge station.

Table 82 summarises results from the DASTAT analysis, and lists the flow parameters required for input to GENSYN. The serial correlation coefficients for seven of the 12 months are significant at the 90 percent level. Probable reasons for the weak May to September correlations are the variable nature of catchment storage in winter and the spring thaw.

Several series of 70 year monthly flow sequences could hence be generated. A variety of predetermined random sequence initialising values and skew conditions were assumed for the GENSYN programme operation, and are given in Table 83. The random sequence initialising values are nine digit odd integers which specify the random number sequence, and hence determine the random component of the synthetic record. A large number of possible values may be chosen for this variable. In this simulation the values 999999999 and 100000001 are used.

The variable 'skewmin' describes the conditions which limit the synthetic flow distribution. It takes a value of 1.00 if skew values for the original data are to be maintained in the synthetic flow record, though negative flows may appear in the results. These are automatically set to zero, and the method is shown by the literature to have general application to storage studies and problems other than when low-flows are critical.

Skewmin takes a value of zero for low flow studies if skew values are chosen such that minimum values in the synthetic record are not less than the absolute minimum flows for each month. The absolute minimum flows used in the Upper Taieri analysis are given in Table 83(B), and are arbitrarily chosen to be one cusec less than the long-term recorded minima. When skewmin is set to zero, the skew values used for flow synthesis are not those derived from DASTAT in Table 82. In general, skewmin is set to zero for record generation where low flows are important, and 1.00 when the synthetic record is required to approach as closely as possible the

TABLE 82: (DASTAT) Statistical analysis of river flow: analysis of mean monthly flow (cusecs) for Taieri River at Paerau Rd. Bridge

(Notes: (1) D = dimensional; N = non-dimensional; (2) Length of record = 13 years; (3) SE = standard error; Std. Dev. = standard deviation; Reg. Co. = regression coefficient; Cor. Co. = correlation coefficient).

	Statistic	J	F	M	A	M	J	J	A	S	O	N	D
(1)	Mean (D):	162	117	129	212	250	270	291	324	503	517	317	220
	SE of Mean:	38	28	22	36	36	38	39	33	51	58	33	38
	Mean + SE:	201	145	151	248	286	308	330	357	554	574	350	258
	Mean - SE:	124	89	107	175	214	232	253	291	452	459	284	183
(2)	STD.DEV.(D):	127	101	78.3	131	146	141	135	131	185	209	137	130
	SE of Std.Dev:	25	20	15.4	26	29	28	27	26	36	41	27	26
	Std.Dev.+SE:	151	121	93.7	156	174	169	162	157	222	249	164	156
	Std.Dev.-SE:	102	81	62.9	105	117	113	109	105	149	168	110	105
(3)	SKEW(N):	1.569	0.965	-0.047	0.496	0.687	0.700	0.755	0.680	0.555	0.420	0.186	0.316
	SE of Skew:	0.616	0.616	0.616	0.616	0.616	0.616	0.616	0.616	0.616	0.616	0.616	0.616
	Skew + SE:	2.186	1.582	0.569	1.112	1.303	1.316	1.371	1.296	1.171	1.036	0.802	0.932
	Skew - SE:	0.953	0.349	-0.664	-0.120	0.071	0.084	0.139	0.063	-0.061	-0.197	-0.430	-0.300
(4)	REG.CO.(N):	0.382	0.228	0.759	0.832	0.131	0.039	0.024	0.098	0.197	0.309	0.474	0.560
	SE of Reg.Co.:	0.189	0.224	0.449	0.305	0.223	0.326	0.258	0.275	0.286	0.300	0.312	0.256
	Reg.Co. + SE:	0.571	0.452	1.208	1.136	0.353	0.365	0.282	0.373	0.483	0.609	0.786	0.815
	Reg.Co. - SE:	0.194	0.005	0.310	0.527	-0.092	-0.288	-0.234	-0.177	-0.089	0.009	0.162	0.304
(5)	COR. CO. (N):	0.521	0.492	0.454	0.413	0.174	0.036	0.028	0.166	0.298	0.404	0.490	0.551

(6) MEAN ANNUAL FLOW (D): - 276 cusecs.

TABLE 83: (GENSYN) synthetic record of river flow: input statistics of monthly flows for Taieri River at Paerau Rd. Bridge (70 year synthetic record)

A. SKEWMIN = 1.00; RANDOM SEQUENCE INITIALISING VALUE = 999999999 (NINE DIGIT ODD INTEGER)

Month	Mean	Std. Dev.	Skew	Reg. Co.	Cor. Co.
1	162	127	1.569	0.382	0.521
2	117	101	0.965	0.228	0.492
3	129	78.3	-0.047	0.759	0.454
4	212	131	0.496	0.832	0.413
5	250	146	0.687	0.131	0.174
6	270	141	0.700	0.039	0.036
7	291	135	0.755	0.024	0.028
8	324	131	0.680	0.098	0.166
9	503	185	0.555	0.197	0.298
10	517	209	0.420	0.309	0.404
11	317	137	0.186	0.474	0.490
12	220	130	0.316	0.560	0.551

B. SKEWMIN = 0.00; RANDOM SEQUENCE INITIALISING VALUE = 999999999 (NINE DIGIT ODD INTEGER)

Month	Mean	Abs. Min.	Std. Dev.	Skew	Reg. Co.	Cor. Co.
1	162	25.0	127	5.464	0.382	0.521
2	117	21.0	101	4.001	0.228	0.492
3	129	20.0	78.3	1.560	0.759	0.454
4	212	34.0	131	2.462	0.832	0.413
5	250	40.0	146	4.255	0.131	0.174
6	270	53.0	141	1.466	0.039	0.036
7	291	123	135	1.689	0.024	0.028
8	324	115	131	1.279	0.098	0.166
9	503	150	185	1.099	0.197	0.298
10	517	152	209	1.349	0.309	0.404
11	317	101	137	2.427	0.474	0.490
12	220	44.0	130	3.058	0.560	0.551

(Abs. Min. = Absolute Minimum Q (cusecs)).

C. SKEWMIN = 0.00; RANDOM SEQUENCE INITIALISING VALUE = 100000001 (NINE DIGIT ODD INTEGER) - Input statistics as for B.

historic record from which the flow statistics were derived.

The closeness of fit between the historic and synthetic series flow parameters is adopted here as the criterion of model acceptance. Generated sequences from GENSYN for different combinations of skewmin and random generator are thus further analysed by DASTAT, and the results summarised in Tables 84 to 86. The recorded maximum and minimum flows given in Table 86 are extracted from Table 19. The various model versions are hence evaluated by comparison of Tables 84 to 86 with Table 82.

Good agreement is shown between the historic and synthesised flow statistics, except for expected deviations of the skew coefficients when skewmin is set to zero. Values from the generated series generally lie within the error limits given for the measured data. Reproduction of mean monthly flows is acceptable by all synthesis runs, though there is a tendency to over estimate this parameter when the all nines random generator is used, irrespective of whether skewmin is set at zero or unity.

The maximum flows generated approximate those recorded for the long-term Paerau Bridge series, but the minimum flow series is less well simulated. Zero or negative flows are produced in half the months for the sequence calculated from observed skew coefficients and the 999999999 random generator. Such a result is improbable for the Paerau Bridge station. Hence, if emphasis on low flows is required, results from this generated sequence cannot be recommended for further analysis. Measured minimum flow conditions are more closely simulated by the model which uses zero skewmin and a random generator of 100000001. Values are slightly over estimated, but correction would require a better assessment of the absolute minima. This last version is concluded to be the most generally suited to streamflow simulation for multipurpose engineering design.

TABLE 84: (DASTAT) statistical analysis of river flow: analysis of synthetic mean monthly flow (cusecs) from Gensyn for Taieri River at Paerau Rd. Bridge. (Length of record = 70 years; Skewmin = 1.00; Random generator = 999999999)

Statistic	J	F	M	A	M	J	J	A	S	O	N	D
(1) Mean (D):	185	141	122	222	260	269	303	327	502	538	350	239
SE of Mean:	14	10	7.8	14	20	17	16	16	21	25	17	15
Mean + SE:	198	151	130	236	279	286	319	342	524	563	367	254
Mean - SE:	171	131	115	208	240	252	287	311	481	514	333	225
(2) STD. DEV.(D):	115	85.4	64.9	119	165	142	136	130	180	208	143	122
SE of Std.Dev.:	9.7	7.2	5.5	10	14	12	12	11	15	18	12	10
Std.Dev. + SE:	125	92.6	70.4	129	179	154	148	141	195	226	155	132
Std.Dev. - SE:	105	78.2	59.4	109	151	130	125	119	165	191	131	112
(3) SKEW (N):	0.711	0.796	0.298	0.444	0.537	0.565	0.259	0.808	-0.262	0.303	-0.243	0.145
SE of Skew:	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287
Skew + SE:	0.997	1.082	0.585	0.731	0.823	0.851	0.056	1.094	0.024	0.590	0.044	0.432
Skew - SE:	0.424	0.509	0.011	0.157	0.250	0.278	-0.028	0.521	-0.549	0.016	-0.529	-0.141
(4) REG.CO.(N):	0.323	0.160	0.599	0.903	0.149	0.092	-0.102	0.049	0.221	0.342	0.425	0.384
SE of Reg.Co.:	0.081	0.090	0.209	0.129	0.103	0.116	0.115	0.168	0.138	0.072	0.089	0.103
Reg.Co. + SE:	0.404	0.250	0.808	1.032	0.252	0.208	0.013	0.217	0.359	0.414	0.514	0.487
Reg.Co. - SE:	0.241	0.070	0.390	0.775	0.046	-0.024	-0.216	-0.119	0.083	0.270	0.335	0.281
(5) COR.CO.(N):	0.434	0.210	0.328	0.648	0.173	0.096	-0.107	0.035	0.191	0.497	0.499	0.413
(6) Max. Value (D):	513	409	289	515	656	664	684	717	879	1181	685	510
(7) Min. Value (D):	0.0	0.0	6.0	0.0	0.0	0.0	29.0	87.0	79.0	66.0	13.0	0.0

(8) MEAN ANNUAL FLOW (D): 288 cusecs.

TABLE 85: (DASTAT) statistical analysis of river flow: analysis of synthetic mean monthly flow (cusecs) for Taieri River at Paerau Rd. Bridge. (Length of record = 70 years; Skewmin = 0.00; Random generator = 999999999)

	Statistic	J	F	M	A	M	J	J	A	S	O	N	D
(1)	Mean (D):	173	119	126	208	234	271	289	337	553	526	333	231
	SE of Mean:	9.4	7.8	7.9	14	14	14	15	15	22	22	17	15
	Mean + SE:	182	127	134	222	248	285	304	351	575	548	349	246
	Mean - SE:	163	111	118	194	219	256	274	322	530	505	316	216
(2)	STD. DEV.(D):	78.3	65.2	66.0	116	119	118	126	122	187	181	138	126
	SE of Std.Dev.:	6.6	5.5	5.6	9.8	10	10	11	10	16	15	12	11
	Std.Dev. + SE:	85.0	70.7	71.6	125	129	128	136	132	203	197	150	136
	Std.Dev. - SE:	71.7	59.6	60.4	106	109	108	115	112	171	166	127	115
(3)	SKEW (N):	0.965	1.209	1.248	2.028	1.233	0.562	1.333	0.896	0.828	1.364	1.611	1.627
	SE of Skew:	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287
	Skew + SE:	1.252	1.496	1.534	2.315	1.520	0.849	1.620	1.183	1.115	1.650	1.897	1.914
	Skew - SE:	0.678	0.922	0.961	1.741	0.947	0.275	1.047	0.610	0.541	1.077	1.324	1.340
(4)	REG.CO.(N):	0.455	0.134	0.767	0.806	0.321	0.127	-0.054	0.301	0.104	0.356	0.443	0.492
	SE of Reg.Co.:	0.084	0.122	0.191	0.078	0.114	0.128	0.118	0.182	0.117	0.082	0.096	0.048
	Reg.Co. + SE:	0.540	0.256	0.958	0.884	0.434	0.255	0.063	0.483	0.220	0.438	0.539	0.540
	Reg.Co. - SE:	0.371	0.012	0.576	0.728	0.207	-0.001	-0.172	0.119	-0.013	0.274	0.347	0.444
(5)	COR. CO. (N):	0.547	0.132	0.438	0.780	0.324	0.119	-0.056	0.196	0.107	0.467	0.487	0.779
(6)	Max. value (D)	442	316	375	746	644	616	684	675	1204	1233	925	735
(7)	Min. value (D):	54.0	34.0	38.0	58.0	87.0	83.0	133	166	232	221	154	78.0

(8) MEAN ANNUAL FLOW (D): 283 cusecs.

TABLE 86: (DASTAT) statistical analysis of river flow: analysis of synthetic mean monthly flow (cusecs) from Gensyn for Taieri River at Paerau Rd. Bridge. (Length of record = 70 years; Skewmin = 0.00; Random generator = 100000001).

Statistic	J	F	M	A	M	J	J	A	S	O	N	D
(1) Mean (D):	156	107	129	196	235	272	283	330	511	542	308	208
SE of Mean:	8.7	7.0	9.0	13	14	15	15	15	20	23	13	12
Mean + SE:	165	114	138	209	249	287	298	345	531	565	321	220
Mean - SE:	147	100	120	183	221	257	268	314	490	519	296	196
(2) STD. DEV.(D):	72.7	58.2	75.1	110	118	125	127	129	171	194	106	103
SE of Std.Dev.:	6.1	4.9	6.3	9.3	10	11	11	11	14	16	9.0	8.7
Std.Dev. + SE:	78.9	63.2	81.4	119	128	136	138	139	186	210	115	112
Std.Dev. - SE:	66.6	53.3	68.7	101	108	114	116	118	157	177	97.1	94.2
(3) SKEW (N):	0.960	2.000	1.486	1.844	1.028	0.747	1.342	1.113	0.542	0.750	0.923	1.340
SE of Skew:	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287	0.287
Skew + SE:	1.247	2.286	1.773	2.131	1.315	1.033	1.629	1.400	0.829	1.037	1.210	1.627
Skew - SE:	0.674	1.713	1.200	1.557	0.742	0.460	1.055	0.827	0.255	0.463	0.636	1.054
(4) REG.CO.(N):	0.295	0.254	0.848	0.772	0.236	-0.130	-0.040	-0.063	0.246	0.333	0.395	0.510
SE of Reg.Co.:	0.090	0.153	0.145	0.090	0.125	0.122	0.123	0.161	0.134	0.053	0.108	0.059
Reg.Co. + SE:	0.385	0.407	0.993	0.863	0.362	-0.008	0.083	0.098	0.380	0.385	0.502	0.569
Reg.Co. - SE:	0.205	0.100	0.704	0.682	0.111	-0.252	-0.163	-0.225	0.112	0.280	0.287	0.451
(5) COR.CO.(N):	0.368	0.197	0.580	0.719	0.223	-0.128	-0.039	-0.047	0.218	0.608	0.407	0.722
(6) Max. value (D):	349	359	411	654	621	602	739	811	951	1144	649	543
(7) Min. value (D):	54.0	32.0	34.0	59.0	66.0	99.0	141	157	208	211	144	75.0
(8) MEAN ANNUAL FLOW (D):	273 cusecs.											
(9) Recorded Max.:	533	641	670	550	873	625	610	603	1322	1100	951	531
(10) Recorded Min.:	25.9	22.1	21.3	35.1	40.9	53.8	124	116	151	153	102	45.4

The method is shown to be successful overall as a generation model of mean monthly flow sequences for the Taieri River at Paerau Bridge. Tables 86 and 82 show excellent agreement between the measured and synthesised mean monthly flows, with an average monthly error of less than four percent. The average annual flow differs by only one percent for the simulation.

However, the measured record used as model input does not allow estimates of flow parameters at the level of precision required by the first study objective. Therefore, although the model is shown to be of value, it cannot be used in this instance to satisfy the requirements of the second study objective. Long-term flow sequences generated from the available continuous measured data will not give population parameter estimates with standard errors of less than 10 percent. A long-term synthetic flow series is thus not tabulated here.

CONCLUSIONS

The available measured precipitation and streamflow data do not allow estimation of all the needed population parameters at the required precision level. Methods for data synthesis are thus necessary in order to increase the amount of information contained at this stage in the data series, as compared with the measured records alone.

In an attempt to satisfy the stated objectives of the study, long-term records of precipitation, temperature and streamflow are developed from the available measured data to cover a common period of historic record. Techniques chosen for time series extension and spatial extrapolation are linear, curvilinear and multiple regression analyses, water balance, conceptual and stochastic models. The operation of each model is described, and the limitations or advantages are outlined.

The statistical theory needed to test the second study objective is defined. Also considered in detail are the theoretical aspects which concern precision of population parameter estimates from blended data, standard errors of prediction for synthetic records, and the relative simulation and prediction abilities of the models chosen. Split record techniques are used throughout to evaluate the within and between model efficiencies. The period 1916-25 is taken as a test interval for each model - the first five years to evaluate the "goodness of reconstruction", and the interval 1921-25 to test the "goodness of fit". It is also shown that extension of a short record may not always be desirable. Under certain circumstances, estimates of population parameters based on a blended record will be less reliable than those based on the measured record alone. In these instances, a decrease in statistical information is experienced by record extension.

The results show that the second study objective has not been realised in full. Addition of synthesised records to the precipitation and streamflow data series still does not permit estimates of all required population parameters at the levels of precision stated as needed. A summary of the principal conclusions reached is given as follows.

Estimates of mean seasonal and annual station precipitation are now available to greater precision than for the measured series alone. Mean annual rainfall is estimated to within seven percent at the 95 percent confidence level. Results for the monthly data show that only August now has a standard error in excess of 10 percent, and effective record lengths have increased by up to 20 years. However, conditions favourable for improved estimates of the station variance are found for only three months.

Average catchment mean annual precipitation for the period 1908-69 is calculated as 36 inches, and varies from 23 to 63 inches. Highest values occur to the south, intermediate values on the eastern hill country, and the lowest totals to the north and west of the Taieri River and on the floor of the Styx Basin. Listed standard errors suggest that for the given monthly Paerau data, mean values of average basin rainfall may be estimated by regression to within six percent. However, these errors may increase to almost 40 percent if the independent variables are not considered error free. It is concluded that standard errors of total or sub-catchment mean precipitation determination are unlikely to be less than those shown for network design by way of the structural function. It does not appear possible to estimate areal population parameters to the required precision with the precipitation data available.

The basin is divided into four sub-areas on the basis of displayed precipitation and vegetation patterns, with the principal stream in each considered as the 'representative' sub-catchment. Sub-catchments thus chosen form the basis of subsequent analyses.

Measured temperature data already allow parameter estimates at the required precision level. However, extension of the existing record is shown to be necessary in order to complete streamflow synthesis by water balance and conceptual models. Temperature record extension is achieved without loss of information.

Extension of the total catchment streamflow record is achieved by way of techniques which use measured climatic data. Little information was gained by the analyses. The addition of synthesised data to the measured Paerau Bridge record still does not allow population parameters to be determined for all months with the required degree of precision. In fact, none of the four deterministic models chosen for Paerau Bridge record extension allow parameter estimation to markedly greater precision levels than for the measured series alone.

Results for the simple rainfall-runoff regression models show that in only three months does the blended record give estimates of the long-term mean which are any more precise than those calculated from the 30 year measured record. Standard errors of up to 31 percent are shown for October and November, and only in the winter months is the value less than 10 percent. The maximum gain in effective record length is shown to be 11 years.

However, in common with all the models tested, total error is principally composed of occasional large values. If these occasional large errors are acceptable, the predicted records may be considered a reasonable representation of the measured data.

Paerau Bridge multiple rainfall-runoff regression models show improved flow prediction results compared with the simple regression method, though the second study objective is not satisfied by the analysis. Further, prediction ability is not greatly improved by the use of up to six precipitation variables.

Precision limits of parameter estimates derived by water balance and conceptual models are not readily quantifiable. However, these limits may be qualitatively deduced by comparing the calculated model efficiency with similar values derived for simple and multiple regression models of known error. In this way, although population parameters may not be derived here at the required precision level, all the models can be evaluated for simulation and prediction ability, and missing flow records computed with minimised errors of prediction.

The water balance model proposed by Thornthwaite & Mather (1955) is used here. However, a modification to the original model is that potential evapotranspiration is now computed by a method which contains built-in altitudinal corrections dependent on variable seasonal lapse rates. It is thus possible to calculate values of potential evapotranspiration for any specified altitude, from one set of basic temperature data at a known height above sea level. The presented model is found to be unreliable overall when used as a runoff prediction method for the Paerau Bridge station. Versions with 50 and 70 percent carryover factors of water available for runoff are tested. Although the version with a 70 percent carryover factor is the most efficient of all the models considered for the prediction of 1916-20 yields, this performance is not maintained for the 1921-25 predictions. More consistent performance is shown by the multiple regression models, though with slightly lower efficiency values.

A modified water balance model is also developed for the Upper Taieri. Natural catchment conditions are thus more closely simulated by use of a constant 60 percent carryover factor and variable direct response dependent on season. However, the benefits of model generality are lost by the changes.

A large proportion of the general water balance runoff prediction errors can be ascribed to incorrect determination of within year runoff distributions. Principal value of the method in the Upper Taieri area is thus to determine the spatial and temporal variations in moisture deficit - critical for irrigation scheme design and operation schedules.

The results show seasonal moisture deficits which extend for all areas from October to April. Total catchment mean annual deficit is calculated as 0.69 inches and varies from 2.22 inches for area 1 to 0.50 inches for area 3. Comparable values for area 2a and 2b are 1.15 inches and 1.22 inches respectively.

It is also shown, *inter alia*, from these results that except for initial estimates, general application of the basic water balance equation cannot be recommended for yield calculations. Catchment mean annual yield may be given to within acceptable error limits. However, percentage errors can be expected to increase rapidly when data are required for shorter time intervals, for non-watertight catchments, or when seasonal moisture deficits can be expected.

The conceptual model used in this study is a modified version of that developed by Boughton (1965, 1966, 1968(a), (b)). Since the original model was designed particularly for small catchments, the chief modifications introduced are the addition of a groundwater store, and provision for interflow and groundwater components in the total runoff. An automatic parameter optimisation technique was also tested.

The results for Paerau Bridge fall short of what is required by the study objectives, and the modified model is generally unsatisfactory for Upper Taieri runoff prediction. Monthly results are no better than those derived by the simpler alternative methods.

The stochastic sequential generation model developed by Thomas & Fiering (1962) is shown to be successful overall for simulation of total catchment mean monthly flow sequences. However, the model cannot be used in this instance to satisfy the second study objective. The measured record used as model input does not allow all flow parameter estimates to be made at the required precision level. Long-term sequences generated from these data will thus give population parameter estimates with standard errors greater than the 10 percent allowed.

It is concluded that the multiple regression models are the most suitable for prediction of the missing Paerau Bridge streamflow records. However, use of the predicted values must be in full awareness of the likely errors involved. Since the multiple regression equations are only used to predict mean monthly yields, it is not possible to improve estimate precision of the Paerau Bridge extreme values. The standard errors of X_T for maximum and minimum daily discharges thus remain unchanged.

Measured streamflow data available for the principal sub-catchments do not allow direct estimation of discharge parameters at the required precision level. The continuous measured record for Loganburn is of insufficient length, and the other stations do not have recorded data of a type suitable for any direct form of parameter estimation. Sub-catchment record extension is achieved by way of simple linear regression analysis.

Effective record extensions are shown to vary from nine to 21 years. The results suggest that the second study objective is partly satisfied. Addition of regression estimates to the measured Loganburn record now appears to allow determination of mean discharge at the required precision level for most time intervals of a month or more. Mean annual discharge is estimated to within five percent from the blended record, and only four months have standard errors which exceed 10 percent. Prediction standard errors for Upper Styx Valley Bridge mean discharge estimates are also shown to be less than eight percent. Styx and Serpentine Creek values are higher and are generally in excess of 10 percent.

However, the Paerau Bridge data used as independent variables in the regressions are not error free. If the sub-catchment mean discharges are to be considered as population estimates, then the standard errors increase and require recalculation as shown. Only the long-term mean annual discharge for Loganburn may now be estimated with a standard error of less than 10 percent.

Full summaries of the synthesised sub-catchment data are not listed, but use of any of the predicted values should again be in awareness of the likely errors. Finally, regression analysis is shown to be no help in the estimation of sub-catchment extreme values at the required precision level. Any conclusions from the results given can only be tentative, since the computed data are subject to both standard errors of prediction and the tabulated errors of X_T for the measured Paerau Bridge records. Total errors are likely to be greater than those already given for the Paerau Bridge extreme values, and probably excessive.

The overall results show that compared with the measured data alone, many more population parameters may now be estimated at the required precision levels from the extended records of each variable. However, the second study objective has not been fully realised. It is thus evident that for engineering design of any proposed irrigation scheme to proceed now, the chosen error criteria must be judged too stringent for the Upper Taieri data, and the calculated standard errors accepted. If the presented standard errors are unacceptably high, all the precipitation and streamflow records from the post-1966 network will require extension by additional observations.

CHAPTER VI: REPRESENTATIVE BASINS AND REGIONAL HOMOGENEITY

DESCRIPTION OF THE PROBLEM

An essential feature in the hydrology of any country is the establishment of hydrological networks. In the past, observation stations have been established at points either where an immediate problem occurred, or in the near vicinity. Investigations have been generally restricted to larger catchments, and the number of stations necessarily curtailed for economic reasons.

Continued network establishment by the above principles has become untenable because of population and development pressures. Problems develop faster than observation stations can be established and may occur in the smallest catchment. The cost of ad hoc hydrological observations becomes so great that the quantity and quality of information suffer as a consequence.

The logical development is to establish primary and secondary observation stations in order to sample the time and space variability of hydrological variables. It is necessary to introduce a sampling technique for the long-term primary stations, and from this need has developed the concepts of regional hydrology and representative basins (Toebes & Ouryvaev, 1970). Representative basins, by definition, are selected as representative of a hydrological region within which hydrological similarity is assumed. A complete network of representative basins in any one country would thus sample the hydrology of the entire country.

The purposes of representative basins have been stated by Toebes & Ouryvaev (op. cit). Since they represent hydrological regions, representative basins give an indication of regional hydrological features and

and can thus be used for data extrapolation within the regions. Further, since they represent an area or entire country, they are useful as a source of data for development of general prediction techniques.

Regional classification is complex, since hydrological classification of an area with regard to one purpose or phase of the hydrological cycle may be quite different from the classification for another purpose or aspect. Every hydrological division is thus only approximate, and based on the most important factors. Several regional networks are equally likely, each based on the hydrological parameters considered most important.

However, since the establishment of hydrological regions may be initially considered as an exercise in stratified hydrological sampling, some classification is essential, to enable representative basins to be selected. Initial regional selection may be on the basis of natural physiographic regions. Where detailed hydrological data are not available, the literature suggests that regional selection must be on climatic, vegetational, geomorphological, pedological and geological characteristics.

New Zealand was first classified into hydrological regions by Toebes & Neef (1962). In this initial classification, lithology and rainfall were considered to be the most important factors, since lithology appeared to be reasonably correlated with soil type and topography. Toebes & Palmer (1969) have consolidated the earlier work with a quantitative classification into 90 regions. The variables used in the 1969 classification were precipitation, rock type and slope.

Regional classification in New Zealand is thus based on the uniformity of basin characteristics alone - these are in turn assumed to produce hydrological similarity within each region. The relative success of this division must await the establishment of representative basins in each hydrological region, the subsequent testing of basin representativity, and comparison between them. The Upper Taieri area lies within the East Otago Region, and accords with the general regional classification given by Toebes & Palmer (op. cit). A further function of this study is thus the opportunity to test the within-catchment variations of yield and flow characteristics from a single basin which is assumed to be 'representative' of a hydrologically homogeneous region. From this, it is theoretically possible to check the validity of commonly accepted concepts of 'regional hydrology', at least within the East Otago Region.

DEFINITION OF REGIONAL HOMOGENEITY

Several New Zealand studies have been reported which attempt to demonstrate either the uniformity of basin characteristics within present hydrological regions (Blake, *et al.*, 1979), or the similarity of hydrological parameters from areas with like basin characteristics.

For example, Waugh (1970(a), (b)) concluded that in Northland the rock type is the only major influence on low flow. He showed that for each major hydrological region the base-flow recessions form a distinct group recognisable by the slope of the recession curves, and the minimum flows. However, it is not possible to say that the present regional classification meets the requirements of other hydrological characteristics. Grant (1971) has also shown the influence of rock type on low flow characteristics. He concluded that on the East Coast, North Island, differences in mean recession rates from limestone, siltstone and argillite are significant, and that within a climatic regime there is a need to recognise rock type rather than broad hydrological region.

However, closer study of the above results suggests that the data do not entirely confirm the conclusions made. Inter-region differences of mean recession rate are quoted as significant, though no attempt is made to demonstrate this conclusion with standard tests of significance for between sample means. It is further suspected that the within region recession rate differences are equally as significant as those which supposedly demonstrate between region differences. Martin (1973) has recently reached the same conclusion with respect to the Northland results.

Hydrological similarity thus cannot be assumed to equate with uniformity of basin characteristics, at least for low flows. A stratified hydrological sampling programme has been initiated, with 'representative' basins chosen by physiographic criteria. However, these catchments need not be representative of regions which are hydrologically homogeneous. If, as stated, the purpose of representative basins is to extrapolate data within a region, then concern must be with regional homogeneity of hydrological parameters.

Hydrological regions are thus better defined in terms of allowable spatial variation for any stated hydrological parameters. The parameters chosen, their permissable limits of spatial variation, and the size of hydrological region, will be related to the purpose for which the data are to be used. A numerical statement as to allowable variation may be different for each parameter and must be chosen with care. For example, a homogeneous region for river control purposes may be smaller than one for irrigation purposes. In this way, a hierarchy of nested regions for a given parameter or set of parameters is developed. The larger areas are those with the less stringent variation criteria (Hutchinson, 1973).

Such an approach is attempted here. Unless otherwise stated, plus or minus 20 percent from the 'representative' value is chosen as the permissable limit of areal variation for each parameter. Streamflow parameters selected to test the hydrological homogeneity of the Upper Taieri basin by this criterion are mean annual yield, variability index (Lane & Lei, 1949), base-flow recession constant, and unit area base-flow.

TESTS OF REGIONAL HOMOGENEITY

Mean Annual Yield:

Tables 28 and 75 show that mean annual yield to Paerau Bridge is 16.78 inches, and that the sub-catchment values range from 9.14 inches for area 1 to 18.81 inches for area 3.

Measured mean yield for the total catchment is considered as a representative base for within-catchment comparison. If 20 percent is accepted as the allowable difference criterion, limits of spatial variation in mean annual yield become 13.42 and 20.14 inches. In terms of unit area discharge, the comparable range is 0.99-1.48 cusecs per square mile (csm).

The results suggest that the study area is not hydrologically homogeneous by the stated criterion. Serpentine Creek and Loganburn cannot be included in the same area as the other sub-catchments. Although each of the values used are subject to the standard errors shown by Tables 28 and 76, appropriate corrections to the mean annual yields do not affect the above conclusion.

The spatial variations in mean annual yield appear to reflect the sub-catchment mean annual precipitation. Further, with the exception of the Loganburn and Serpentine Creek data, the sub-catchments show markedly similar rainfall-runoff relationships when allowance is made for differences in mean altitude.

Reasons for the apparently anomalous rainfall-runoff-altitude relationship for Serpentine Creek can only be tentative. Variation from that expected may be due to inadequate estimation of precipitation or yield, or because of a different hydrological regime. Departure of the Loganburn relationship from the expected regional pattern can be explained by the dominant influence on the runoff characteristics of variations in Great Moss Swamp moisture storage. It is concluded that runoff opportunity is reduced by storage of water in the upper catchment, and that the area which contributes to the Loganburn runoff varies with season. In this respect, area 2b is hydrologically dissimilar from the surrounding region, and yield characteristics defined for the Loganburn cannot be generally translated elsewhere.

Flow-duration curve variability indices:

A flow-duration curve is a cumulative frequency curve that shows the percentage of time for which specified discharges are equalled or exceeded. The shape of the curve is determined by the hydrological and geological characteristics of the drainage basin, and may be used to compare the characteristics of one basin with those of another (McMahon, 1969).

Average annual flow-duration curves have been computed from the total and sub-catchment daily mean discharge data sets, in accordance with the method described by Searcy (1959). The results are summarised in Table 87, and show discharges for given percentage exceedences. In this way the data are better suited to hydrological comparisons than is the currently accepted format in New Zealand, which shows percentage exceedence for a given discharge.

TABLE 87: *Upper Taieri catchment average flow duration tables, percentile yields, and variability indices for 1912-13; 1916-28; 1936-44; 1947-50; 1966-69*

(Note: Column (1) is daily mean discharge in cusecs; column (2) is daily mean discharge in cusecs per square mile (csm); column (3) is percentile yield in inches)

% Time discharge equalled or exceeded	Taieri R. at Paerau Br.			Taieri R. at U.Styx Valley Br.			Loganburn at Paerau		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
0.1	1690	7.25	98.4	730	7.23	98.1	298	5.14	69.8
0.5	1270	5.45	74.0	600	5.94	80.6	215	3.71	50.4
2	980	4.21	57.1	450	4.46	60.5	161	2.78	37.7
5	790	3.39	46.0	350	3.47	47.1	128	2.21	30.0
10	630	2.70	36.6	279	2.76	37.5	100	1.72	23.3
15	525	2.25	30.5	236	2.34	31.8	83.0	1.43	19.4
20	450	1.93	26.2	207	2.05	27.8	72.2	1.24	16.8
25	390	1.67	22.7	184	1.82	24.7	63.5	1.09	14.8
35	300	1.29	17.5	149	1.48	20.1	50.0	0.86	11.7
45	235	1.01	13.7	123	1.22	16.6	41.0	0.71	9.64
50	220	0.94	12.8	110	1.09	14.8	38.0	0.66	8.96
55	190	0.82	11.1	102	1.01	13.7	33.2	0.57	7.74
65	146	0.63	8.55	83	0.82	11.1	26.9	0.46	6.24
75	107	0.46	6.24	63	0.62	8.42	20.6	0.36	4.89
80	89.0	0.38	5.16	53	0.52	7.06	17.8	0.31	4.21
85	72.2	0.31	4.21	43	0.43	5.84	15.0	0.26	3.53
90	54.1	0.23	3.12	30	0.30	4.07	12.1	0.21	2.85
95	35.5	0.15	2.04	15	0.15	2.04	8.80	0.15	2.04
99	20.8	0.09	1.22	6.0	0.06	0.81	4.25	0.07	0.95
99.9	15.0	0.06	0.81	3.9	0.04	0.54	-	-	-
variability index (Lane & Lei, 1949):		0.409			0.395			0.352	

TABLE 87: Continued

% Time discharge equalled or exceeded	Styx Creek at Paerau			Serpentine Creek at McDonald's Br.		
	(1)	(2)	(3)	(1)	(2)	(3)
0.1	85.2	5.33	72.4	170	4.15	56.3
0.5	67.2	4.20	57.0	133	3.24	44.0
2	51.5	3.22	43.7	100	2.44	33.1
5	41.0	2.56	34.8	79.0	1.93	26.2
10	33.0	2.06	28.0	62.0	1.51	20.5
15	28.6	1.79	24.3	51.8	1.26	17.1
20	25.6	1.60	21.7	45.5	1.11	15.1
25	23.0	1.44	19.6	40.0	0.98	13.3
35	19.0	1.19	16.1	31.2	0.76	10.3
45	15.8	0.99	13.4	24.7	0.60	8.14
50	15.0	0.94	12.8	21.0	0.51	6.92
55	13.4	0.84	11.4	19.5	0.48	6.52
65	11.0	0.69	9.37	15.0	0.37	5.02
75	9.00	0.56	7.60	10.6	0.26	3.53
80	8.30	0.52	7.06	8.55	0.21	2.85
85	7.50	0.47	6.38	6.80	0.17	2.31
90	6.68	0.42	5.70	4.90	0.12	1.63
95	5.70	0.36	4.89	2.85	0.07	0.95
99	4.42	0.28	3.80	-	-	-
99.9	-	-	-	-	-	-
variability index (Lane & Lei, 1949):			0.269		0.433	

The results cannot be used to conclusively demonstrate or refute hydrological homogeneity in the Upper Taieri area by the stated criterion. Likely standard errors of prediction given by equation (24) and Appendix I(6) for sub-catchment streamflow estimates, preclude reliable determination of within catchment discharge differences. However, the results suggest some possible sub-catchment variations which are of interest.

Low flow portions of the frequency curve may be considered as indices of groundwater contribution to streamflow. Sustained low flows are evident for Styx Creek and the Upper Styx Valley Bridge. However, the Loganburn ceases to show the effect of storage in the Great Moss Swamp beyond the 98 percent exceedence value, and suggests that zero flows are likely in drought periods. Similarly, Serpentine Creek results indicate poor base-flow contribution, and probable zero flows early in a drought.

The above differences in sub-catchment flow-duration curves may also be quantified from the individual variability indices (Lane & Lei, 1949). The calculated values are shown in Table 87, and vary from 0.433 for Serpentine Creek to 0.169 for Styx Creek. Again, the magnitude of between catchment differences cannot be readily determined unless the sub-catchment discharge data are considered to be error free. Hydrological inhomogeneity can only be suspected.

However, the presented data do demonstrate the skewed nature of the runoff distributions, and confirm that for flow studies the median discharge is a more meaningful parameter than the mean. The results from the measured Paerau Bridge data series show that the mean annual discharge is 1.3 times the median value, and is equalled or exceeded only 36 percent of the time. This demonstrates the danger of attaching too much importance to the average flow.

Base-flow recession curve indices:

Base-flow recession curves represent withdrawals from groundwater storage, and are shown by the literature to have many practical uses. Amongst these, Waugh (1970) has suggested that recession curves for each major hydrological region form distinct groups, recognisable by their slope and minimum flow. The 'representative' basin recession rate is thus a useful index of regional groundwater condition, and is of value for water resource determination over an extended area.

Although the ideal base-flow does not plot as a straight line on semi-logarithmic paper (Singh, 1968), a non-linear recession curve can be adequately obtained from combinations of linear curves (Hall, 1968). The simple exponential expression is thus used in this study, and has the general form

$$Q_t = Q_o e^{-at} \qquad \text{------------} \quad (38).$$

Q_o is the initial discharge, Q_t the discharge at time t, and K (equals e^{-a}) is the recession constant.

Master recession curves are determined for each of the flow measurement stations, using the methods described by Toebes *et al.* (1969). The basic data comprise all hydrograph recession current meter gaugings, and the measured daily mean discharges in the period 1913-69 for each subcatchment, Paerau Bridge and Patearoa-Paerau Bridge stations. Table 88 gives a summary of the results.

Spatial variability of low flow characteristics is assessed from the differences in presented K values and unit area base-flows. Breaks in slope are found for all the recession curves, but separate equations for each section are only derived if the break is significant. From the work of Cross (1949), Hall (1968) and Schneider (1965), it is

TABLE 88: *Upper Taieri basin master discharge recession curve equations and parameters*

(<u>Note</u>: $K = e^{-a}$ = recession constant; $t_{0.5}$ = time taken for baseflow of stream to halve (Martin, 1973);

$*Q^1_0$ (csm) = discharge in cusecs per sq.mile at t = 0 days;

$*Q^1_{10}$ (csm) = discharge in cusecs per sq.mile at t = 10 days.
(*see text for location on recession curve)

A. *Taieri River at Patearoa-Paerau Bridge:*

(a) June 1966-August 1969: For $t > 0$ days; $Q < 380$ cusecs;
$Q = 380e^{-0.096t}$ (<u>or</u> $Q = 380(0.908)^t$).
$Q^1_0 = 0.35$ csm; $Q^1_{10} = 0.14$ csm;
$K = 0.908$; $t_{0.5} = 7.2$ days.

B. *Taieri River at Paerau Bridge:*

(a) April 1913-August 1969: For $t \leqslant 14$ days; $Q \geqslant 103$ cusecs;
$Q = 490e^{-0.111t}$ (<u>or</u> $Q = 490(0.895)^t$).
$K = 0.895$

(b) April 1913-August 1969: For $t > 14$ days; $Q < 103$ cusecs;
$Q = 103e^{-0.108t}$ (<u>or</u> $Q = 103(0.898)^t$);
$Q^1_0 = 0.44$ csm; $Q^1_{10} = 0.15$ csm;
$K = 0.898$; $t_{0.5} = 6.4$ days.

C. *Taieri River at Upper Styx Valley Bridge:*

(a) June 1966-August 1969: For $t \leqslant 14$ days; $Q \geqslant 56$ cusecs;
$Q = 178e^{-0.083t}$ (<u>or</u> $Q = 178(0.917)^t$);
$K = 0.917$

(b) June 1966-August 1969: For $t > 14$ days; $Q < 56$ cusecs;
$Q = 56e^{-0.137t}$ (<u>or</u>$Q = 56(0.871)^t$);
$Q^1_0 = 0.55$ csm; $Q^1_{10} = 0.14$ csm;
$K = 0.871$; $t_{0.5} = 5.0$ days.

D. *Styx Creek at Paerau:*

(a) June 1966-August 1969: For $t \leqslant 15$ days; $Q \geqslant 7.4$ cusecs;
$Q = 21.8e^{-0.072t}$ (<u>or</u> $Q = 21.8(0.935)^t$);
$K = 0.935$

(b) June 1966-August 1969: For $t > 15$ days; $Q < 7.4$ cusecs;
$Q = 7.4e^{-0.042t}$ (<u>or</u> $Q = 7.4(0.962)^t$);
$Q^1_0 = 0.46$ csm; $Q^1_{10} = 0.32$ csm;
$K = 0.962$; $t_{0.5} = 18$ days.

TABLE 88: Continued

E. *Loganburn at Paerau:*

(a) March 1966–August 1969: For $t > 0$ days; $Q < 63$ cusecs;
$Q = 63e^{-0.082t}$ (<u>or</u> $Q = 63(0.926)^{t}$);
$Q^{1}_{0} = 0.31$ csm; $Q^{1}_{10} = 0.14$ csm;
$K = 0.926$; $t_{0.5} = 9.0$ days.

F. *Serpentine Creek at McDonald's Bridge:*

(a) March 1966–August 1969: For $t \leqslant 12$ days; $Q \geqslant 12.5$ cusecs;
$Q = 39e^{-0.095t}$ (<u>or</u> $Q = 39(0.909)^{t}$);
$K = 0.909$

(b) March 1966–August 1969: For $t > 12$ days; $Q < 12.5$ cusecs;
$Q = 12.5e^{-0.128t}$ (<u>or</u> $Q = 12.5(0.881)^{t}$);
$Q^{1}_{0} = 0.31$ csm; $Q^{1}_{10} = 0.09$ csm;
$K = 0.881$; $t_{0.5} = 5.5$ days.

assumed that base-flow conditions are represented by the portions of each recession curve below the breaks in slope. The discontinuity in each curve is thus assumed to be the initial reference point for groundwater discharge.

Unit area values of Q^1_0 at these points are seen to vary between 0.55 csm for the Upper Styx Bridge and 0.31 csm for Serpentine Creek. The main river shows a downstream reduction in Q^1_0 from 0.55 csm through 0.44 csm to 0.35 csm at the Patearoa-Paerau Bridge. If 20 percent is again accepted as the allowable difference criterion, the Serpentine Creek Q^1_0 value is the only exception to hydrological homogeneity.

Similar conclusions are made from the unit area base-flow discharge values ten days later (Q^1_{10}). In this instance, both Serpentine and Styx Creek results are calculated to be outside the allowable variation limits of 0.12 to 0.18 csm.

The Q^1_0 and Q^1_{10} data in Table 88 show the variations of available groundwater quantities in the Upper Taieri area, and also give an indication of storage depletion rate. However, a more direct index of natural groundwater withdrawal is the base-flow recession constant.

Sub-catchment K values are shown to vary from 0.962 for the Styx Creek to 0.871 for the Upper Styx Valley Bridge (Table 88). The 20 percent difference criterion is obviously inappropriate when used to define allowable limits for K value homogeneity. Grant (1971) implies that an areal variation of up to plus or minus seven percent is acceptable for within region hydrological uniformity. A value of three percent is thus considered here as an initial test, though this may still be unacceptably high. Styx Creek is found to have the only K value outside the limit of this criterion.

However, Martin (op. cit) suggests that the time taken for the base-flow of a stream to halve ($t_{0.5}$) is a more satisfactory parameter than the K value to determine recession rate differences. $t_{0.5}$ values are given for each station in Table 88. If plus or minus 25 percent is accepted as the $t_{0.5}$ limits of within catchment variation, Styx Creek is again found to be hydrologically dissimilar from the surrounding region. $t_{0.5}$ has an allowable range of from five to nine days by the stated criterion.

Overall results from the total and sub-catchment recession curve analyses suggest that the Upper Taieri catchment is not hydrologically homogeneous by the stated criteria. However, the regional boundaries vary dependent on the parameter considered. If interest is in the rate of groundwater storage depletion irrespective of the amount available, then Styx Creek should be excluded from the adjacent hydrological region. From the basis of available groundwater quantities per unit area, Serpentine Creek is shown to be atypical of the remaining area. Q_0^1 discharge for Styx Creek accords with the regional pattern, but a lower rate of recession is shown. The Serpentine Creek recession rate is within the limits allowed for hydrological homogeneity, but the low Q_0^1 again suggests a poor base-flow contribution and zero flows early in a drought period.

CONCLUSIONS

The concept of regional hydrology is outlined and the principal uses of representative basins are discussed. Regional classification is complex, but is concluded to be necessary so that a stratified hydrological sampling programme may be established on a national basis.

Variables used in the New Zealand regional classification are precipitation, rock type, and slope (Toebes & Palmer, 1969). Only the uniformity of basin characteristics has thus been considered in the definition of present regions. These uniform catchment characteristics are in turn assumed to produce hydrological similarity within each region.

Several New Zealand studies have been reported which attempt to demonstrate the similarity of hydrological parameters from areas with like basin characteristics (Grant, 1971; Waugh, 1970(a), (b)). However, the results do not appear to entirely verify the conclusions reached. Although between region differences of low flow parameters are stated to be significant, no attempt is made to statistically verify this conclusion. Further, the demonstrated parameter differences within regions seem to be equally as significant as those which supposedly illustrate the between region differences.

It thus appears that hydrological homogeneity cannot be assumed to equate with uniformity of basin characteristics, at least for low flows. Hydrological regions are better defined in terms of allowable areal variation for stated hydrological parameters. A numerical value for allowable variation may be different for each parameter. Further, the parameters chosen, their permissable limits of spatial variation, and size of hydrological region, will be related to the purpose for which the data are to be used.

The permissable limit of hydrological homogeneity for Upper Taieri streamflow parameters is generally chosen as a variation of plus or minus 20 percent from the 'representative' value. Different criteria are found to be necessary, however, when differences in the sub-catchment recession constant and half-flow period values are considered.

The results are disappointing overall. Standard errors of prediction for some of the sub-catchment streamflow parameter values preclude reliable determination of within catchment differences. Nevertheless, the sub-catchment mean annual yields and base-flow recession parameters are sufficiently error free to suggest that the study area is not hydrologically homogeneous by the stated criteria.

Furthermore, the boundaries of hydrologically similar regions are shown to vary dependent on the streamflow parameter considered. Serpentine Creek and Loganburn have mean annual yields which are atypical of the remaining area. However, comparison of sub-catchment recession curve parameters suggests that the Loganburn accords with the homogeneity criteria, but that Styx Creek and again Serpentine Creek are excluded from the region. Styx Creek recession rate is lower than the regional pattern, though unit area groundwater quantities are within the allowed limits of areal variation. Conversely, the Serpentine Creek recession rate is within the limits required for hydrological homogeneity, but the low unit area base-flow quantities are not typical and suggest zero flows early in a drought period.

Differences in hydrological characteristics are thus again evident for an area with basin characteristics classified as uniform by the present regional divisions. The variations in streamflow parameters tested are concluded to be largely due to spatial differences of catchment precipitation and storage.

CHAPTER VII: UPPER TAIERI AGRICULTURAL HYDROLOGY

CLIMATIC LIMITATIONS TO PLANT GROWTH

Much has been written on the general climatic character of Central Otago and for a detailed description reference should be made to Kidson (1950), Maunder (1965), Mark (1965) and Leslie (1966). The area is one of climatic extremes. Summers are warm and winters very cold, with clear dry weather and high radiation levels common at any time. Sunshine hours are high; the average annual duration exceeds 2,000 hours, or 46 percent of possible hours. Humidities below 50 percent are very common at 9 a.m. in spring and summer. The overall effect of this climatic regime is to produce a wide range of annual and diurnal temperatures, a high likelihood of frost, and high potential evapotranspiration rates in the warmer months.

The most significant features of climate in relation to plant growth and production are those which affect the length and characteristics of the growing period (Slatyer, 1960). In the Upper Taieri basin where pastoral farming predominates, the availability of soil water for plant growth and the influence of temperature conditions are of primary importance.

Previous discussion and the data in Table 80, show that the summer concentration of a modest annual rainfall produces significant moisture deficits in the lowland area. However, the periods in which plant growth can be expected are:-

(a) in spring, using stored soil moisture and spring rainfall;

(b) in summer and autumn, using the sporadic rains for flushes of growth which may continue into winter.

The earlier such autumn rains occur the greater is the pasture output for the year.

Leslie (op. cit) has shown that continuous autumn growth can be expected to commence in late March for about three years out of five. This change from sporadic summer growth to a period of growth unimpeded by soil water, appears to be mainly attributable to the sharp drop in mean temperature.

A lack of soil water does not appear to limit plant growth in October and November more often than one year in 2.3 for the Styx Basin. However, for only one year in three does uninterrupted growth occur until the end of December. For January and February, these recurrence values become one year in seven and four respectively. The gradual cessation of spring growth is due to an increase in evapotranspiration rather than diminished rainfall.

Frost incidence in the area also has considerable influence on agricultural diversity and production. The primary influence of frost is to limit the period of active growth. To determine the effect of this factor, Table 89 shows the incidence of screen and ground frosts, and the probability of ground frost in the growing season. The data are extracted from N.Z. Meteorological Service summaries for Naseby State Forest over the period 1923-60, and are considered to be representative of the lower valley floor areas of the Upper Taieri basin.

TABLE 89: Frosts

A. *Number of days with ground frost:*
(Naseby State Forest: 1923-60; 2,000 feet)

J	F	M	A	M	J	J	A	S	O	N	D	Year
2.9	3.2	7.3	14.0	21.8	25.0	27.2	24.8	19.5	13.8	7.1	3.7	170.3 (46.7%)

B. *Number of days with screen frost:*
(Naseby State Forest: 1923-60; 2,000 feet)

J	F	M	A	M	J	J	A	S	O	N	D	Year
1.1	1.2	3.6	8.2	17.8	22.7	25.4	22.5	16.0	9.0	4.5	1.6	133.6 (36.6%)

TABLE 89: Continued

C. *Probability of ground frost in the growing season:*

Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April
1:1.54	1:2.25	1:4.26	1:8.38	1:10.69	1:8.75	1:4.25	1:2.14

(Note: 78.4% of ground frost days have screen frost)

Ground frost is common in winter, with an average of 27 days recorded in July. About 170 days of ground frost are experienced annually, and no month is entirely frost free. January and February are the least frosty months with only about three days each. Approximately 78 percent of the days with ground frost also have screen frost. Only isolated frosts which affect horticultural species or pasture can be expected after the end of October. Similarly, such events are likely to occur with increased frequency after the end of March. Frost incidence in the Upper Taieri basin effectively reduces the eight month active growing season common to most other agricultural areas in New Zealand, to the period November-March. Only limited growth can generally be expected in September and April.

Periods of high temperature can also limit plant growth, particularly when accompanied by strong dry winds. Although the mean monthly temperatures in summer are not excessive (Table 14), a wide diurnal range is evident. The effects are marked, however, since the highest temperatures tend to occur when there is low relative humidity, no appreciable cloud cover, and thus high insolation.

The above climatic factors in combination give an air of uncertainty to pastoral farming in the area. In summary, plant growth in summer and autumn is largely limited by a lack of effective rainfall. Frost is the principal limitation to growth later in autumn. In spring, accumulated soil moisture storage and rainfall are generally adequate to maintain uninterrupted growth until November. Although sporadic frosts can occur after the end of October, a decrease in available soil moisture is the general limitation to continued growth in late spring. Frost incidence may limit plant growth in September, even though the available soil moisture is sufficient to meet evapotranspiration demands.

MOISTURE DEFICIT DISTRIBUTION AND FREQUENCY

It has been shown that there is a need for irrigation in the Upper Taieri area if potential crop production is to be attained. Thornthwaite (1953) has concluded that water requirements for irrigation are best determined from soil moisture deficits calculated by a water balance approach. The total and sub-catchment monthly moisture deficits for 1908-69 which were used to calculate Table 80, are thus analysed further. In this way, Upper Taieri basin water needs, in both space and time, may be derived for practical application. The results are summarised in Table 90. Only the growing season data are presented, since deficits which may occur in the period April to September for this area are not considered sufficiently important to warrant specific attention.

The results presented are largely self explanatory, some have already been discussed, and further detailed comment is not required. However, a few aspects of interest are only shown by the full data sets. The areal average data for the total basin show that zero deficits are quite common for all months or seasons. However, such a minimum value has occurred only twice on an annual basis in the 62 year record. Further, 1956 is shown to be the only year since 1939 with an appreciable annual deficit.

The Styx Basin lowlands are shown to be the area which is most critically in need of irrigation in the Upper Taieri catchment. Subsequent

TABLE 90: Upper Taieri total and sub-catchment mean monthly, seasonal and annual moisture deficits in inches for the period 1908-69 (4 inches water holding capacity assumed)

1. *Total Catchment:*

	J	F	M	O	N	D	Annual	Spring	Summer	Autumn	Oct-Mar.	Jan-Mar.
Mean:	0.147	0.214	0.145	0.025	0.036	0.113	0.693	0.061	0.479	0.156	0.682	0.506
Max:	1.259	1.633	1.373	0.591	0.528	1.056	2.911	0.723	3.195	1.674	3.220	2.799
Year:	1917	1911	1956	1929	1937	1961	1911	1937	1917	1930	1956	1911
Min:	0	0	0	0	0	0	0	0	0	0	0	0

2. *Sub-area 1 (Serpentine Creek):*

	J	F	M	O	N	D	Annual	Spring	Summer	Autumn	Oct-Mar.	Jan-Mar.
Mean	0.607	0.666	0.335	0.052	0.130	0.340	2.221	0.184	1.632	0.423	2.144	1.608
Max:	1.939	2.930	1.763	0.716	0.913	1.526	6.179	1.186	4.382	1.949	6.087	5.017
Year:	1930	1938	1956	1929	1937	1939	1929	1937	1917	1929	1911	1930
Min:	0	0	0	0	0	0	0.217	0	0	0	0	0

3. *Sub-area 2a (Styx Creek):*

	J	F	M	O	N	D	Annual	Spring	Summer	Autumn	Oct-Mar.	Jan-Mar.
Mean:	0.285	0.311	0.249	0.029	0.062	0.183	1.154	0.091	0.787	0.284	1.125	0.845
Max:	1.434	1.891	1.477	0.567	0.666	1.043	4.110	0.868	3.561	1.961	4.341	3.675
Year:	1917	1911	1956	1929	1937	1961	1911	1937	1917	1930	1911	1911
Min:	0	0	0	0	0	0	0.027	0	0	0	0	0

TABLE 90: Continued

4. *Sub-area 2b (Loganburn):*

	J	F	M	O	N	D	Annual	Spring	Summer	Autumn	Oct-Mar.	Jan-Mar.
Mean:	0.300	0.325	0.259	0.033	0.067	0.195	1.219	0.109	0.828	0.298	1.184	0.883
Max:	1.499	1.993	1.563	0.601	0.688	1.106	4.386	0.923	3.753	2.074	4.559	3.849
Year:	1917	1911	1956	1929	1937	1961	1911	1937	1917	1930	1911	1911
Min:	0	0	0	0	0	0	0.021	0	0	0	0	0

5. *Sub-area 3 (U. Styx Valley Bridge):*

	J	F	M	O	N	D	Annual	Spring	Summer	Autumn	Oct-Mar.	Jan-Mar.
Mean:	0.083	0.158	0.125	0.020	0.024	0.077	0.495	0.044	0.321	0.133	0.486	0.366
Max:	1.073	1.455	2.380	0.579	0.372	0.997	2.741	0.579	2.744	2.380	3.087	2.741
Year:	1917	1933	1956	1929	1937	1961	1956	1929	1917	1956	1956	1956
Min:	0	0	0	0	0	0	0	0	0	0	0	0

discussion is thus of the results derived for Area 1. 72 percent of the average annual deficit occurs between January and March. The maximum annual deficit was 6.18 inches (1929), and for summer, January-March, and October-March, the values were 4.38 inches, 5.02 inches, and 6.09 inches respectively. 1956 was the only year since 1940 with an annual deficit in excess of 4.50 inches. Other years over the 62 year period were 1910, 1911, 1929, 1930, 1937 and 1938. For October-March, a deficit of 5.50 inches was exceeded in 1909/10, 1910/11, 1929/30 and 1937/38. Zero deficits have occurred in all months, but the minimum annual value calculated over the total period was 0.22 inches.

The results from Areas 2a, 2b and 3 are not discussed. However, the trends are similar to those shown for Area 1, though the moisture deficit values are correspondingly lower.

Total and sub-catchment monthly, seasonal and annual moisture deficits may also be shown as frequency distributions, in the same manner as given by Figures 23 or 24. Such curves are a convenient means to indicate the variations in calculated deficits, and illustrate the deviation of these values from the mean. The frequency curves may also be used to give estimates of return periods for stated deficit amounts, though the results should be applied with caution.

Moisture deficit frequency curves are calculated by the procedure used previously for the rainfall, temperature and discharge considerations. The results for the total area and each sub-catchment are shown by Figures 42 to 46.

Discussion is limited here to the Area 1 data in Figure 43, but information for the total area or each of the other sub-catchments is readily obtained from the diagrams if required. For summer, January-

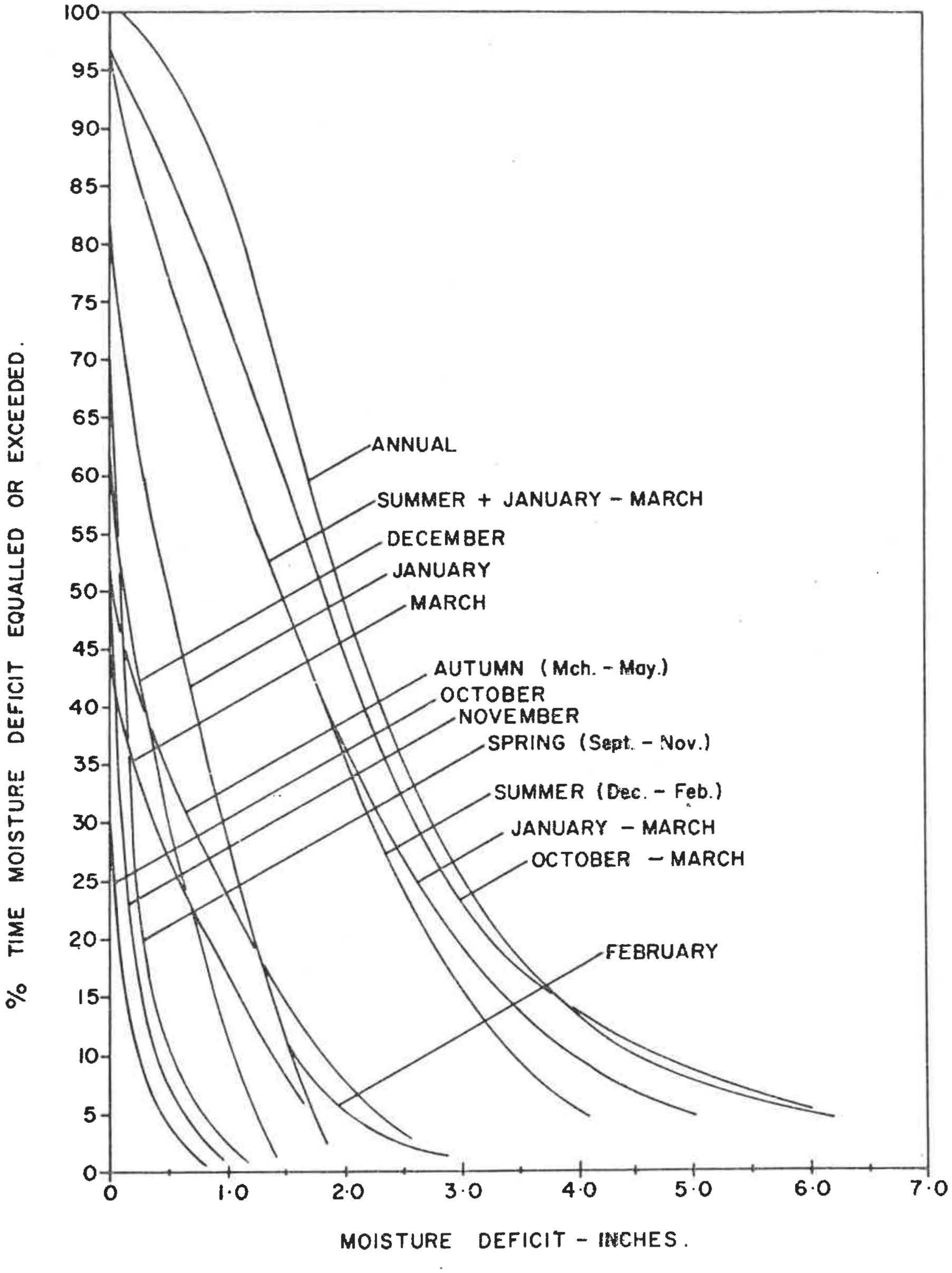


FIGURE 43: Percentage time Upper Taieri sub-Area 1 mean monthly, seasonal and annual moisture deficits are equalled or exceeded for the period 1908-1969

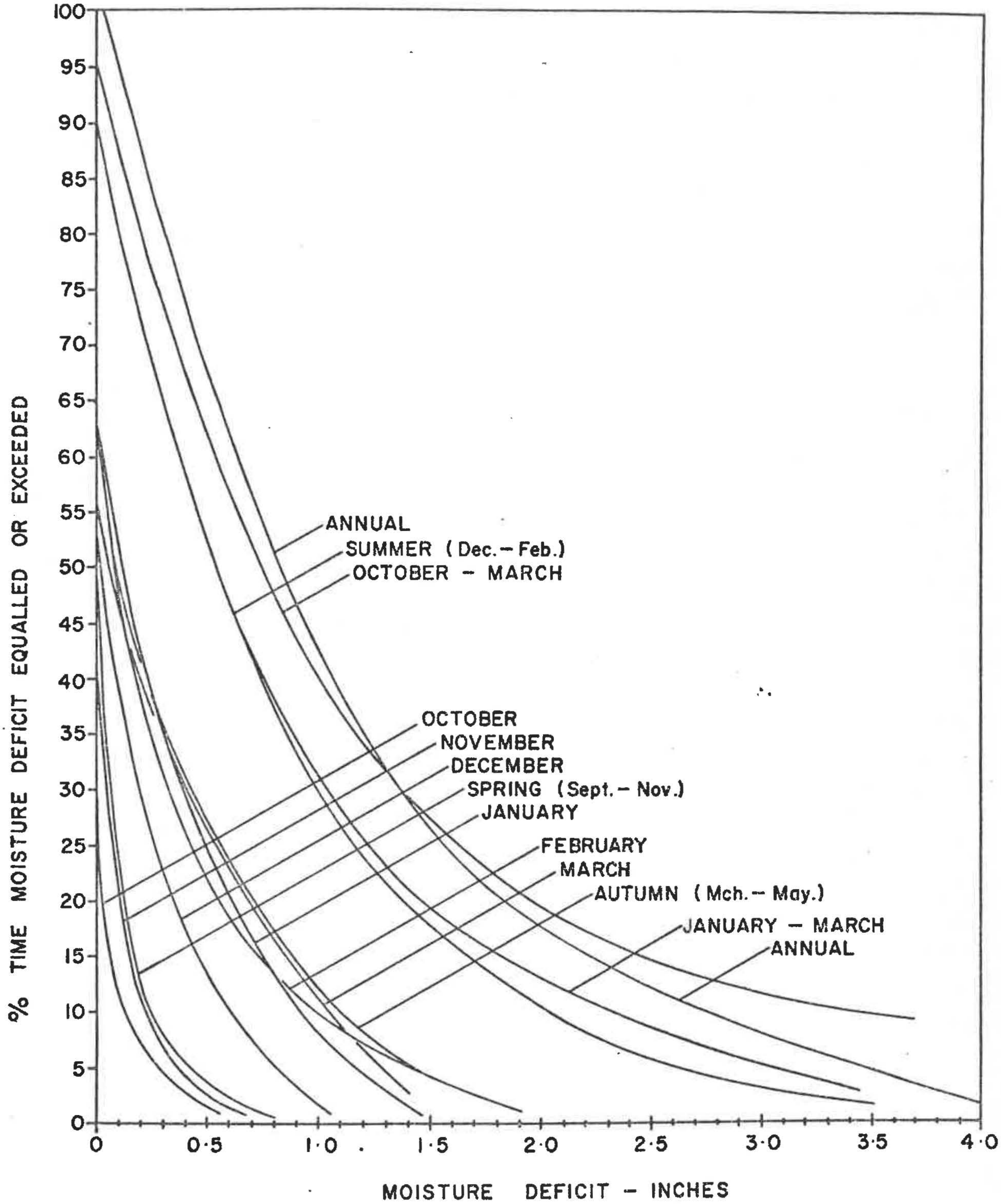


FIGURE 44: Percentage time Upper Taieri sub-Area 2a mean monthly, seasonal and annual moisture deficits are equalled or exceeded for the period 1908-1969

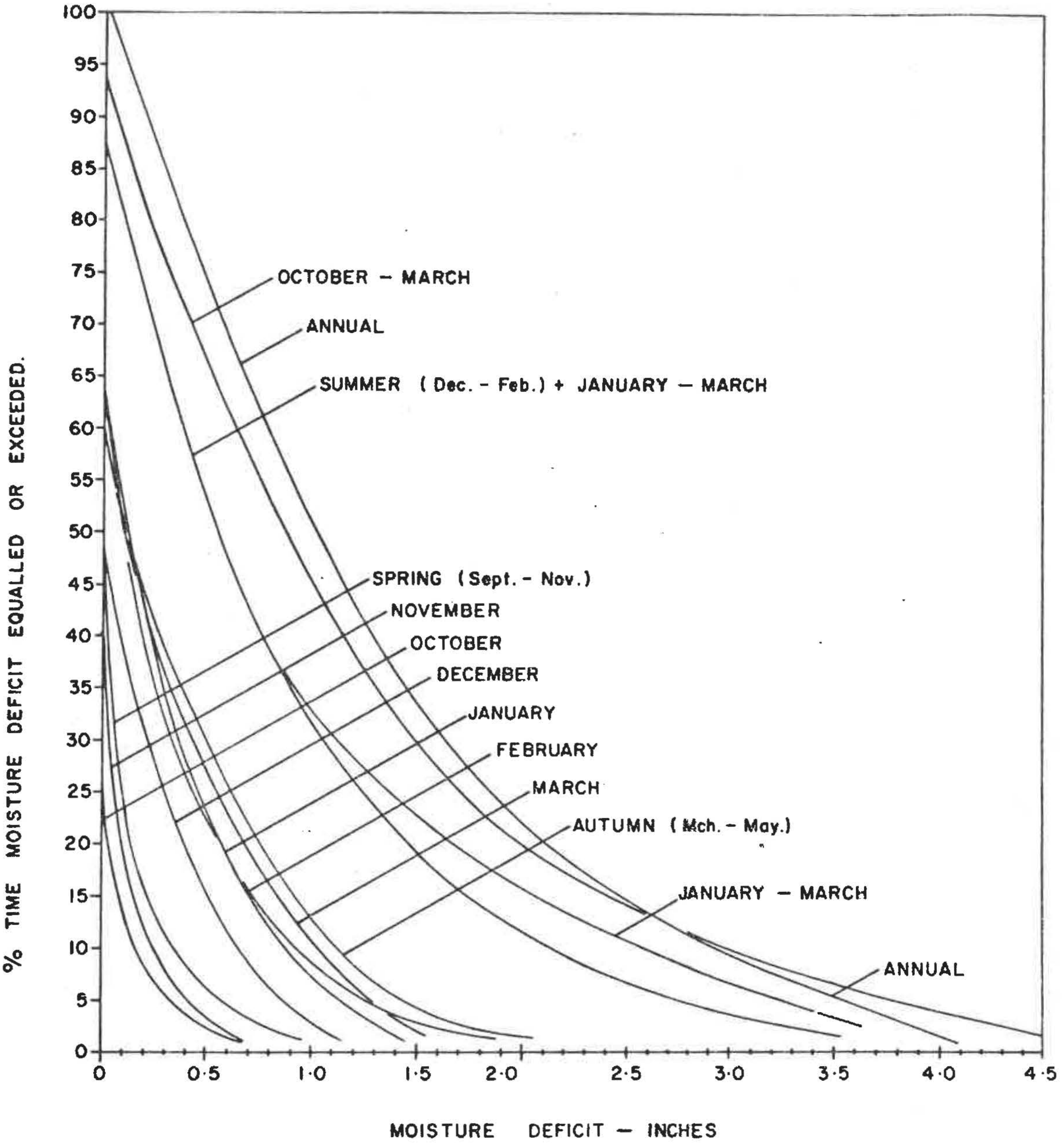


FIGURE 45: Percentage time Upper Taieri sub-Area 2b mean monthly, seasonal and annual moisture deficits are equalled or exceeded for the period 1908-1969

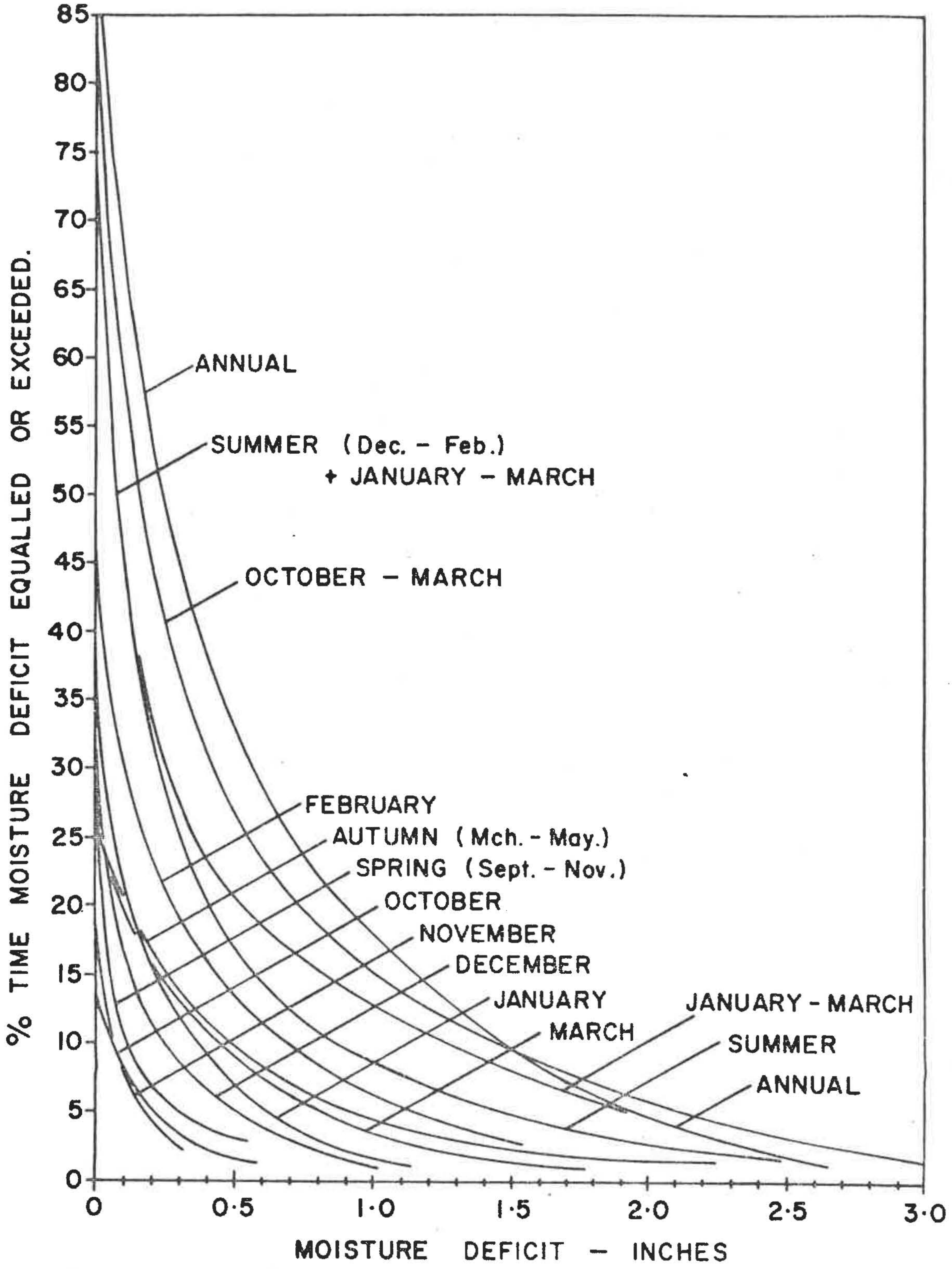


FIGURE 46: Percentage time Upper Taieri sub-Area 3 mean monthly, seasonal and annual moisture deficits are equalled or exceeded for the period 1908-1969

March and October-March, there is a 50 percent chance that the moisture deficit will exceed 1.50 inches. In about one year in ten however, values for the same periods are likely to exceed 3.50 inches, and for one year in 20 these deficits increase to about four inches. Monthly deficits which exceed 1.50 inches are uncommon - only January, February and March have such values more frequently than five percent of years. In about 30 of the 62 years of record, annual moisture deficits show a fluctuation range of 1.70 inches between lower and upper quartile limits.

STYX BASIN IRRIGATION REQUIREMENTS

It is apparent from the above results that irrigation of the Styx Basin is necessary in almost every year for the period December-March. October and November are also months in which some irrigation could be beneficial in order to maintain regular crop production. It is assumed that frost severity and/or available moisture storage preclude economic irrigation between April and September.

Provisional estimates of Styx Basin irrigation water needs are thus calculated from the Area 1 moisture deficit data, and the results summarised in Table 91. An irrigation efficiency of 60 percent is assumed. The data shown comprise monthly, seasonal, and annual moisture deficits, estimated gross irrigation requirements, and the percentage of years in which irrigation is not needed. The last aspect is computed with zero deficit in soil moisture storage as a reference point.

Table 91 shows that in 98 percent of years moisture shortage prevents uninterrupted plant growth between October and March in Area 1. The average gross irrigation requirement for the period October-March is 3.57 inches, and for January-March the value is 2.70 inches. Median requirement values are of course less.

TABLE 91: Estimated irrigation requirements in the Upper Taieri Styx Basin Area (Area 01): 1908-69 (62 years)

(Based on Thornthwaite & Mather, 1957; 4 inches water holding capacity and 60 percent irrigation efficiency assumed)

A.

	Moisture Deficit (Ins.)				Gross Irrigation Requirements (Ins.)			
Period	Mean	Median	Highest in 75% of years	Highest in 90% of years	Mean	Median	Highest in 75% of years	Highest in 90% of years
October:	0.05	0.00	0.04	0.25	0.08	0.00	0.07	0.42
November:	0.13	0.00	0.14	0.40	0.22	0.00	0.23	0.67
December:	0.34	0.14	0.63	1.07	0.57	0.23	1.05	1.78
January:	0.61	0.50	1.10	1.56	1.02	0.83	1.83	2.60
February:	0.67	0.50	1.10	1.59	1.12	0.83	1.83	2.65
March:	0.34	0.00	0.60	1.40	0.57	0.00	1.00	2.33
Annual:	2.22	1.97	3.02	4.50	3.70	3.28	5.03	7.50
Spring:*	0.18	0.10	0.24	0.53	0.30	0.17	0.40	0.88
Summer:*	1.62	1.14	2.83	4.22	2.70	1.90	4.72	7.03
Autumn:*	0.42	0.03	0.95	1.81	0.70	0.05	1.58	3.02
Oct-Mar.:*	2.14	1.14	3.61	6.27	3.57	1.90	6.02	10.45
Jan-Mar.:*	1.62	1.00	2.80	4.55	2.70	1.67	4.67	7.58

(*seasonal data summed from individual monthly values)

B. *PERCENTAGE OF YEARS IN WHICH IRRIGATION NOT REQUIRED:*

	O	N	D	J	F	M	Year	Spr.	Sum.	Aut.	Oct-Mar.	Jan-Mar.
Area 01:	43	43	34	15	26	56	0	15	2	33	2	2
Area 2a:	63	57	44	36	36	62	0	33	10	48	5	11
Area 2b:	61	59	44	33	36	64	0	31	7	48	5	8
Area 03:	79	72	66	64	56	74	7	52	25	69	17	26
Total Area:	75	70	56	49	51	70	3	49	17	64	12	21

However, although the average October-March requirement amount to only 3.57 inches, irrigation need varies from year to year. It is generally impracticable for economic reasons to aim at water supplies sufficient to satisfy the full requirements every year. Hence, dependent on the type of irrigation enterprise, it is usual to adjust the extent of irrigated area to ensure sufficient water supply in 75 percent or 90 percent of years (Basinski, 1960). The maximum seasonal water requirements in a corresponding percentage of years are thus important.

Table 91 suggests that in 75 percent of years the estimated highest requirement for October-March is about six inches, and increases to 10.5 inches for 90 percent of years. Similar values for January-March are about 4.7 inches and 7.6 inches respectively. Further, the highest monthly requirements govern the capacity of the water distribution and application system. The maximum need values are thus those shown for February - 1.83 inches in 75 percent of years, and 2.65 inches for 90 percent of years.

These presented water need data should only be used as a guide. The values are probably conservative estimates of actual need, and practical experience is needed to confirm their validity. Monthly moisture deficit data may not show the full extent of the need for irrigation, since the precipitation may also be poorly distributed within a month.

In terms of production, the uses to which irrigation could best be put in this area would appear to be for growing summer-active species such as lucerne or fodder crops. Irrigation of clover pasture in spring and autumn could also be beneficial and result in marked production increases. However, the economics of production must be considered in terms of irrigation water availability, and the cost of irrigation equipment installation. The former aspect has been discussed, but the latter question is beyond the scope of this study and is not considered further.

DROUGHTS

General:

Closely associated with the presented analyses of moisture deficits and irrigation water needs, is a study of the severity and occurrence frequency of "drought" in the Upper Taieri and nearby areas.

It is difficult to establish universal "drought" criteria, since conditions which constitute a "drought" vary in different parts of the world dependent on the amount and reliability of the rainfall. Although a number of "drought" definitions may be cited, distinction must be made between the short period dry spell as defined by Blumenstock (1942) and Coulter (1966, 1968), and long-term drought as defined and applied by Palmer (1965), Herbst *et al* (1966), and Grant (1968, 1969). Drought can be considered as prolonged and widespread, while dry spells are generally of shorter duration and more or less random in their occurrence at points. This drought study is confined to an examination of dry spells, as determined by the concepts of "absolute" and "partial drought" (Coulter op. cit), and to aspects of long-term drought.

Partial and absolute droughts:

Analysis of these aspects requires daily precipitation data, and thus for the study area is restricted to the 1909-37 Paerau record. However, daily rainfall records from Waipiata (1915-60), Patearoa (1924-60) and Ranfurly (1943-60) are also considered for comparative purposes, in order to demonstrate the areal variability of the two drought parameters. Partial and absolute drought periods are determined as defined in the literature, and the results are listed in Table 92.

TABLE 92: Partial and absolute drought summary

1. *Partial Droughts:*

A. *WAIPIATA (Sept. 1915-Sept. 1960) - 45 years*

	Total No. days partial drought	Av. No. days/yr partial drought	No. partial droughts/yr.	Av. length of partial drought period (days)
Summer	422	9.38	0.38	24.82
Autumn	967	21.49	0.73	29.30
Winter	1806	40.13	1.11	36.12
Spring	1143	25.40	0.87	29.31
Annual	4338	96.40	1.98	48.74

B. *PATEAROA (Jan. 1924-Sept. 1960) - 36.75 years*

Summer	441	12.00	0.46	25.94
Autumn	987	26.86	0.93	29.03
Winter	1924	52.35	1.36	38.48
Spring	1202	32.71	0.98	33.39
Annual	4554	123.90	2.34	52.95

C. *RANFURLY (Apr. 1943-Sept. 1960) - 17.5 years*

Summer	150	8.57	0.29	30.00
Autumn	323	18.46	0.63	29.36
Winter	841	48.06	1.09	44.26
Spring	357	20.40	0.74	27.46
Annual	1671	95.49	1.71	55.70

D. *PAERAU (Jan. 1909-Dec. 1937) - 29 years*

Summer	98	3.38	0.14	24.50
Autumn	166	5.72	0.21	27.67
Winter	245	8.45	0.24	35.00
Spring	149	5.14	0.17	29.80
Annual	658	22.69	0.55	41.13

E. *PAERAU (Jan. 1924-Dec. 1937) - 14 years*

Summer	12	0.86	0.07	12.00
Autumn	84	6.00	0.14	42.00
Winter	166	11.86	0.36	23.20
Spring	131	9.36	0.29	32.75
Annual	393	28.07	0.64	43.67

F. *WAIPIATA (Jan. 1924-Dec. 1937) - 14 years*

Summer	71	5.07	0.29	17.75
Autumn	389	27.79	0.86	32.42
Winter	419	29.93	1.07	27.93
Spring	374	26.71	0.71	37.40
Annual	1253	89.50	1.86	48.19

TABLE 92: Continued

G. PATEAROA (Jan. 1924-Dec. 1937) - 14 years

	Total No. days partial drought	Av. No. days/yr partial drought	No. partial droughts/yr	Av. length of partial drought period (days)
Summer	170	12.14	0.57	21.25
Autumn	419	29.93	1.14	26.19
Winter	714	51.00	1.57	32.45
Spring	506	36.14	1.00	36.14
Annual	1809	129.21	2.64	48.89

H. PAERAU (Sept. 1915-Dec. 1937) - 22.33 years

Summer	40	1.79	0.09	20.00
Autumn	102	4.57	0.18	25.50
Winter	245	10.97	0.31	35.00
Spring	131	5.87	0.18	32.75
Annual	518	23.20	0.54	43.17

I. WAIPIATA (Sept. 1915-Dec. 1937) - 22.33 years

Summer	191	8.55	0. 40	21.22
Autumn	481	21.54	0.76	28.29
Winter	655	29.33	1.03	28.48
Spring	615	27.54	0.90	30.75
Annual	1942	86.97	1.93	45.16

2. *Absolute Droughts:*

A. PAERAU (Jan. 1909-Dec. 1937) - 29 years

Summer	284	9.79	0.66	14.95
Autumn	155	5.34	0.34	15.50
Winter	241	8.31	0.52	16.07
Spring	152	5.24	0.38	13.82
Annual	847	29.21	1.55	18.82

3. *Longest Absolute Droughts:*

A. WAIPIATA (Sept. 1915-Sept. 1960) - 45 years

Summer	25.11.55 to 4.1.56	41 days
Autumn	17.2.30 to 7.4.30	50 days
Winter	27.7.57 to 31.8.57	36+ days (Sept. missing)
Spring	20.9.29 to 21.10.29	32 days

B. PATEAROA (Jan. 1924-Sept. 1960) - 36.75 years

Summer	15.2.47 to 9.3.47	23 days
Autumn	16.4.50 to 24.5.50	39 days
Winter	31.7.48 to 3.9.48	34 days
Spring	20.9.29 to 2.11.29	44 days

TABLE 92: Continued

C. *RANFURLY (Apr. 1943-Sept. 1960) - 17.5 years*

Summer	29.11.55 to 2.1.56	35 days
Autumn	17.4.50 to 4.5.50	18 days
	8.4.55 to 25.4.55	18 days
Winter	30.6.43 to 30.7.43	31 days
Spring	1.10.54 to 25.9.54	25 days

D. *PAERAU (Jan. 1909-Dec. 1937) - 29 years*

Summer	22.1.11 to 17.2.11	27 days
Autumn	23.2.30 to 27.4.30	32 days
Winter	26.6.23 to 4.8.23	40 days
Spring	12.11.23 to 7.12.23	26 days

4. *Longest partial droughts:*

A. *WAIPIATA (Sept. 1915-Sept. 1960) - 45 years*

Summer	29.11.16 to 21.1.17	54 days (0.51" Rainfall)
Autumn	1.2.30 to 15.5.30	104 days (0.95" Rainfall)
Winter	22.6.23 to 10.9.23	81 days (0.79" Rainfall)
Spring	14.9.41 to 6.11.41	54 days (0.43" Rainfall)
	10.5.58 to 21.10.58	165 days (1.63" Rainfall)
	13.6.59 to 12.10.59	122 days (1.16" Rainfall)
	1.7.35 to 18.10.35	110 days (1.07" Rainfall)

B. *PATEAROA (Jan. 1924-Sept. 1960) - 36.75 years*

Summer	25.1.29 to 17.3.29	52 days (0.43" Rainfall)
Autumn	30.1.30 to 27.4.30	88 days (0.85" Rainfall)
Winter	1.7.38 to 14.10.38	106 days (0.92" Rainfall)
Spring	3.9.29 to 2.11.29	61 days (0.50" Rainfall)
	15.4.50 to 14.10.50	183 days (1.82" Rainfall)
	9.5.58 to 24.10.58	169 days (1.63" Rainfall)
	21.5.35 to 18.10.35	151 days (1.50" Rainfall)

C. *RANFURLY (Apr. 1943-Sept. 1960) - 17.5 years*

Summer	24.11.55 to 21.1.56	59 days (0.59" Rainfall)
Autumn	16.4.50 to 12.7.50	88 days (0.83" Rainfall)
Winter	13.6.48 to 3.9.48	83 days (0.75" Rainfall)
Spring	24.8.54 to 22.10.54	61 days (0.57" Rainfall)
	9.5.58 to 22.10.58	168 days (1.63" Rainfall)
	13.6.59 to 30.9.59	109 days (1.08" Rainfall)
	30.4.53 to 10.8.53	103 days (0.95" Rainfall)

D. *PAERAU (Jan. 1909-Dec. 1937) - 29 years)*

Summer	7.2.18 to 15.3.18	37 days (0.22" Rainfall)
Autumn	17.2.30 to 27.4.30	70 days (0.36" Rainfall)
Winter	26.6.23 to 21.8.23	57 days (0.14" Rainfall)
	19.6.35 to 16.8.35	57 days (0.57" Rainfall)
Spring	10.9.29 to 2.11.29	54 days (0.49" Rainfall)

The data are initially tabulated for the complete records available, and then for comparative purposes on the basis of common record periods. The full records cannot be used for partial drought comparisons between stations, since the differences shown in sections (1)E and (1)H of Table 92 reflect the trends given by the precipitation cumulative departure curves in Figure 22.

Partial droughts decrease in frequency and severity away from Patearoa. Of the stations considered, the area represented by the Paerau gauge is the least susceptible to the phenomenon, and reflects the increase in precipitation from Patearoa outwards. At all stations, the incidence of partial drought is greatest in winter and least in summer.

Table 92 suggests that the number of partial droughts per year at Paerau is only about one-quarter of that at Patearoa. The calculations show that partial drought occurs once in every two years at Paerau, with an average duration of 41 days. Partial droughts in winter occur on average one year in every four, and in summer one year out of seven. The probability of drought in the Maniototo is shown to be high, but considerably less so in the Upper Taieri area.

The absolute drought data for Paerau have quite different characteristics from those derived for partial drought over the same 29 year period. Absolute drought occurs three times in every two years, and has an average length of 19 days. On a seasonal basis, the phenomenon is recorded seven years out of ten in summer, one year out of two in winter, and one year in three for spring and autumn.

Long-term droughts and trends: Grant (1968, 1969)

Partial and absolute drought studies are of only limited value to agriculture, since they do not allow for either the current water needs of plants, or the antecedent meteorological and soil moisture conditions. While small daily rains will sustain grass and benefit some crops, frequent larger rains are necessary to replenish deep soil moisture and groundwater.

This investigation of long-term droughts in the Upper Taieri Basin is initially based on a method proposed by Grant (op. cit). The technique involves a study of the relative periodic changes in "effective rainfall". A major disadvantage is that daily rainfall data are required, which again limits the Upper Taieri study to the period 1909-37.

Paerau daily rainfalls are classified into four size groups, the frequency of rainfalls in each group in each year determined for spring, summer, and autumn, and the results collated in periods of change for each season. The choice of periods is dictated by the cumulative departure curve trends given in Figure 22, and the record is separated into natural rather than arbitrary periods for analysis. Table 93 lists the Paerau rain size frequencies (F) and percentage number of years when the rains did not occur (N).

1926 is the major spring change point for the period 1909-37. The frequency of rains in the higher size groups decreased markedly from 1926, with a slight increase in frequency of rainfalls in the lower groups evident after this date. Four natural change periods are chosen for summer and autumn, and wide fluctuations in the values of F and N are evident.

The average seasonal rainfall in each size group, for each period, is next considered as a percentage of the periodic mean. Results of these calculations are given in Table 94. Also shown are the rainfall effectiveness index (RE index) values for each period - derived as described by Grant (1968). The higher the RE index the lower the drought severity. Average spring rainfall has decreased by 11 percent since 1926, with smaller contributions from rains which exceed one inch. The reduction in spring RE Index since 1926 suggests an increase in drought severity.

TABLE 93: Paerau rain size frequencies (F) and percentage number of years when rains did not occur (N)

A. *SPRING: (September-November)*

Rain Group (inches)	1909-1926 (18 years)		1927-1937 (11 years)	
	F	N	F	N
>1.50	0.33	72.2	0.09	90.9
1.01-1.50	0.67	33.3	0.36	63.6
0.51-1.00	3.00	0.0	3.27	9.1
0.01-0.50	25.94	0.0	25.36	0.0

B. *SUMMER: (December-February)*

Rain Group (inches)	1910-1916 (7 years)		1917-1926 (10 years)		1927-1929 (3 years)		1930-1937 (8 years)	
	F	N	F	N	F	N	F	N
>1.50	0.29	85.7	0.80	40.0	0.00	100.0	0.88	50.0
1.01-1.50	1.00	14.3	1.10	40.0	1.33	33.3	1.13	25.0
0.51-1.00	2.14	14.3	4.00	10.0	2.33	0.0	3.88	0.0
0.01-0.50	24.43	0.0	19.0	0.0	19.67	0.0	26.00	0.0

C. *AUTUMN: (March-May)*

Rain Group (inches)	1909-1921 (13 years)		1922-1926 (5 years)		1927-1931 (5 years)		1932-1937 (6 years)	
	F	N	F	N	F	N	F	N
>1.50	0.15	84.6	1.00	40.0	0.40	60.0	1.17	33.3
1.01-1.50	0.46	61.5	0.40	60.0	0.40	60.0	2.00	16.7
0.51-1.00	2.54	7.7	5.00	0.0	1.00	20.0	2.67	0.0
0.01-0.50	24.62	0.0	16.40	0.0	20.40	0.0	24.83	0.0

TABLE 94: Paerau rain size percentage contributions (Rainfall for each group as a percentage of period mean) and RE Indices

A. SPRING: (September-November)

Rain Group (inches)	1909-1926 (18 years)	1927-1937 (11 years)
>1.50	9.38	2.53
1.01-1.50	11.05	6.77
0.51-1.00	29.07	35.10
0.01-0.50	50.50	55.60
Period mean (in.):	7.44	6.65
R.E. Index:	1.91	0.68

B. SUMMER: (December-February)

Rain Group (inches)	1910-1916 (7 years)	1917-1926 (10 years)	1927-1929 (3 years)	1930-1937 (8 years)
>1.50	8.05	17.31	0.00	15.99
1.01-1.50	18.02	14.50	23.47	15.66
0.51-1.00	22.85	31.03	23.47	30.23
0.01-0.50	51.08	37.16	53.06	38.12
Period Mean (in.):	7.13	9.38	6.85	9.53
R.E. Index:	2.52	4.37	2.10	4.41

C. AUTUMN: (March-May)

Rain Group (inches)	1909-1921 (13 years)	1922-1926 (5 years)	1927-1931 (5 years)	1932-1937 (6 years)
>1.50	5.85	23.44	15.39	24.29
1.01-1.50	8.68	6.23	8.77	23.39
0.51-1.00	26.01	36.09	13.52	19.11
0.01-0.50	59.46	34.24	62.32	33.21
Period Mean (in.):	6.50	9.08	5.13	10.67
R.E. Index:	1.11	3.83	1.64	9.72

Similar calculations for summer show that when the periods are ranked to accord with increases in drought severity, the order is 1930-37, 1917-26, 1910-16, and 1927-29. For the autumn data, the intervals are ranked in order of increasing drought severity as 1932-37, 1922-26, 1927-31 and 1909-21.

The individual seasonal RE index curves, and those derived from a combination of the seasonal data, are shown in Figure 47. Grant (op. cit) has concluded that the important curves for pasture and crop growth are probably spring and summer, either alone or in combination, and that growth is related to curves (d) or (e). The data show that rainfall effectiveness was generally lowest for at least the interval 1927-30, and that this period thus recorded the greatest drought severity of the 29 year record. The next most stringent period was 1909-17.

Long-term droughts and trends: Herbst et (1966)

In order to check the previous results and to extend the Paerau analysis from 1937 to 1969, drought periods are recalculated by way of a technique which was developed by Herbst *et al.* (op. cit) for South African conditions. The present study is based on monthly records, though daily drought calculations are possible by the method.

It is assumed that farming practice is adapted to a prevailing climatic pattern, and that because of rainfall variability, seasonal droughts of moderate proportion should not be included in an assessment of severe conditions. As such, only deficits which exceed the average deficit for any month are included in the drought evaluation. Calculations are thus made of drought occurrence, duration, and severity at Paerau, from a modified version of a computer programme provided by the Division of Hydrology, Department of Water Affairs, Pretoria (see Appendix II). The analysis results are summarised in Table 95; column headings are as defined by Herbst.

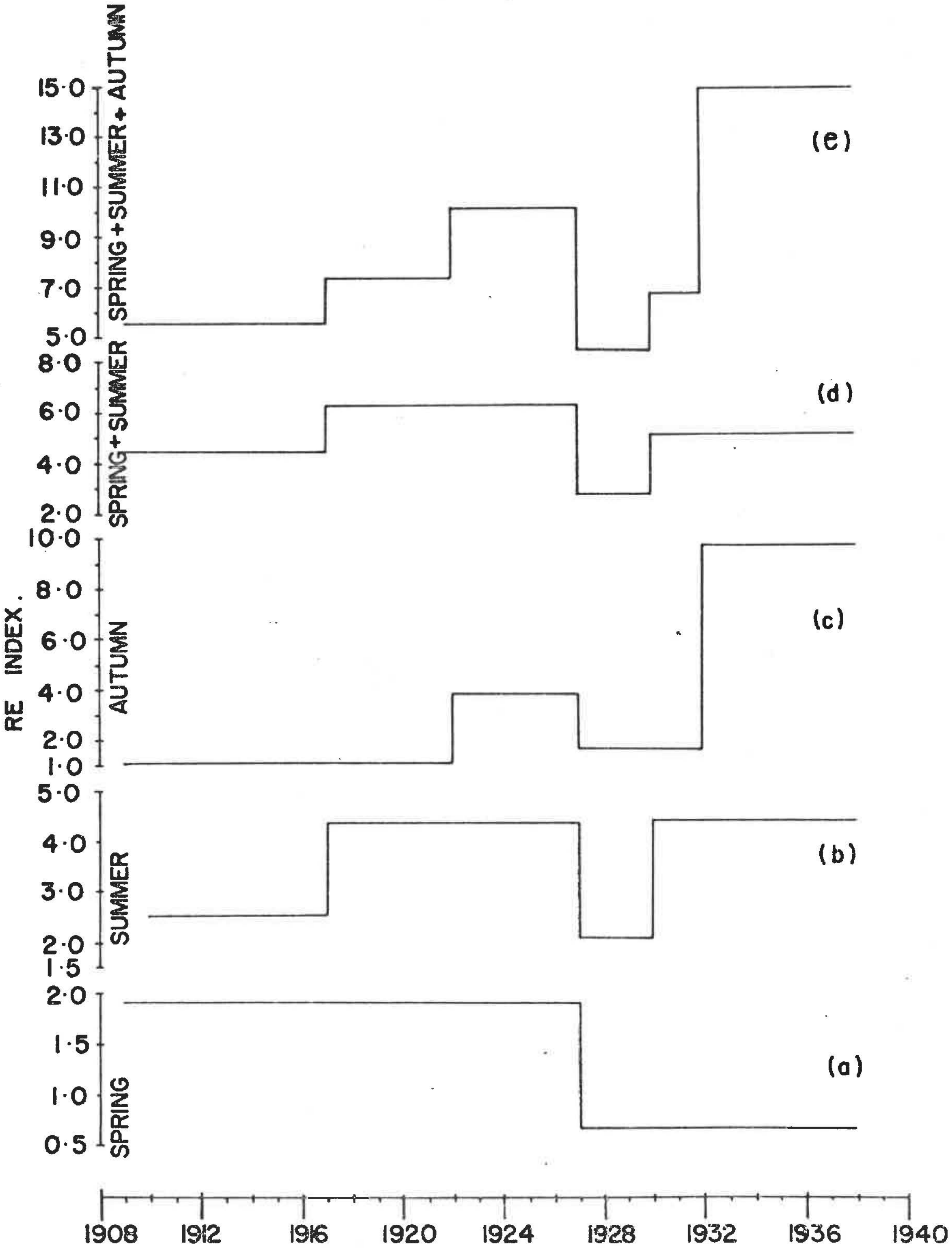


FIGURE 47: Mean rainfall effectiveness (RE) Indices for respective periods at Paerau for record 1909-1937

TABLE 95: Summary of data in periods identified as droughts at Paerau (1908-1969)

Onset of drought		End of drought		Duration of drought (months)	Drought intensity (x100)	Drought severity (x100)
mth.	year	mth.	year			
2	1909	7	1913	53	88.1	4671.0
7	1914	9	1917	38	78.3	2976.1
3	1920	7	1920	4	109.6	438.5
2	1922	11	1922	9	54.7	492.1
7	1923	2	1924	7	130.4	912.5
11	1924	7	1925	8	63.3	506.8
6	1927	10	1930	40	110.2	4406.3
3	1931	4	1933	25	94.5	2362.8
7	1935	3	1936	8	99.3	794.3
9	1937	4	1938	7	170.6	1194.5
2	1939	2	1940	12	110.8	1330.0
4	1940	11	1941	19	62.0	1177.6
5	1943	2	1944	9	77.5	697.9
3	1946	9	1946	6	88.1	528.7
11	1946	6	1947	7	74.0	517.8
12	1947	10	1948	10	49.1	490.7
9	1949	1	1950	4	71.6	286.3
4	1950	11	1950	7	68.7	481.2
1	1952	9	1952	8	45.4	363.3
6	1953	3	1955	21	47.2	991.3
12	1955	4	1956	4	196.7	786.7
9	1958	11	1959	14	50.8	711.4
1	1964	12	1964	11	76.0	836.1
4	1966	9	1967	17	85.2	1448.9
11	1968	12	1969	13	106.1	1379.5

The droughts are ranked in order (1-10) of increasing severity as 1953-55, 1940-41, 1937-38, 1939-40, 1968-69, 1966-67, 1931-33, 1914-17, 1927-30 and 1909-13. The results compare favourably with the cumulative departure rainfall trends in Figure 22, and the RE index curves for the period to 1937 (Figure 47).

Long-term droughts and trends: Conclusions

When the methods used in this study of long-term drought are compared, it is concluded that the technique proposed by Herbst *et al* (op. cit) is of better value overall than that developed by Grant (op. cit).

Grant's method depends on the availability of daily rainfall records, and its operation cannot strictly be considered to represent a model of drought determination. Comparisons of drought duration or severity can only be made on an average basis within the limits of pre-determined periods of natural change. As a result, the values of the RE Indices used as the basis for comparison can be amended at will, by a re-definition of the periods of change. Relative ranking may alter accordingly.

Herbst's method is preferred, since it is simple to operate by computer, and determines drought periods, trends, and indices of drought severity. Further, the model can be operated with only monthly rainfall data if required.

Overall results from this Upper Taieri study indicate that the drought of 1909-13 was the most severe for the 62 years to 1969. The period 1927-30 is ranked next in severity, and it is of interest to note that the four most severe drought periods all occurred before the mid-1930s. Further, the droughts defined for the late 1960s were more severe than any other since the early 1930s, though were closely followed by the general drought period of the late 1930s to early 1940s.

UPPER TAIERI OPEN WATER EVAPORATION

Irrigation of the Maniototo has been investigated periodically since the early 1900s, and has caused considerable controversy. Two major proposals have been considered in recent years. The first was presented in 1961, and proposed the irrigation of 41,000 acres solely by gravity feed. The second scheme, in 1964, involved a pumping extension to the earlier gravity proposal, with a consequent increase in the irrigated area to 64,500 acres.

Both these schemes rely on the construction of a storage dam below the Paerau Bridge, with inundation of about 9,500 acres of the Styx Basin lowlands. Details of the schemes have been summarised by Leslie (1966) and the Ministry of Works (1967). More recent alternative proposals appear to favour either a run-of-river approach to irrigation, or the use of upland reservoir storage.

However, should either the 1961 or 1964 proposals be adopted and the Styx Basin become a storage reservoir, then estimates of open water evaporation will be required.

Since the use of open water evaporation data has often been demonstrated as a viable method of potential evapotranspiration estimation, then the converse is also held to be true. That is, given a potential evapotranspiration/evaporation relationship, it should be possible to determine a long-term evaporation record from the previously calculated Upper Taieri potential evapotranspiration values.

In order to calculate such a relationship, and thus a long-term evaporation record for the Styx Basin, measured evaporation pan data for 1948-55 have been collated and listed in Table 96. The data do not form a complete time series, and have been derived from a non-standard pan set at an altitude of 1800 feet in approximately the centre of the

TABLE 96: Styx Basin monthly open water evaporation and potential evapotranspiration at 1800 feet for the period 1948 to 1955

(Note: Evaporation tank used was a 24 inches diameter galvanised iron tank, rim 12 inches above ground level, set in approximately the centre of the proposed storage reservoir area).

Year	Month	Pan Evaporation - inches (24 ins.diam. tank)	Equiv. open water evaporation-inches (= Pan evap.x0.81; after Young,1947)	Potential Evapotranspiration - inches (Thornthwaite)
1948	8	1.3	1.05	0.85
	9	3.1	2.51	1.00
	10	4.2	3.40	2.06
	11	5.1	4.13	2.46
	12	6.0	4.86	3.70
1949	1	6.6	5.35	3.40
	2	6.3	5.10	3.37
	3	4.0	3.24	2.47
	4	1.8	1.46	1.38
	5	0.7	0.57	0.82
	6	0.3	0.24	0.35
1950	4	2.0	1.62	1.52
	5	1.1	0.89	1.19
	6	0.8	0.65	0.35
	7	1.8	1.46	0.53
	8	2.9	2.35	0.48
	9	3.4	2.75	1.18
	10	4.6	3.73	2.39
	11	5.1	4.13	2.95
	12	5.3	4.29	3.42
1951	1	6.2	5.02	3.63
	2	5.3	4.29	2.99
	3	3.6	2.92	2.82
	4	2.5	2.03	1.63
	5	2.8	2.27	0.75
	6	1.4	1.13	0.06
	7	0.6	0.49	0.52
	8	0.6	0.49	0.47
	9	2.6	2.11	1.20
	10	3.9	3.16	2.14
	11	5.3	4.29	2.76
	12	3.5	2.84	3.10
1952	1	4.4	3.56	3.38
	2	4.6	3.73	3.15
	3	3.4	2.75	2.52
	4	2.3	1.86	1.73
	5	1.1	0.89	0.87
	6	0.3	0.24	0.33
	7	0.5	0.41	0.17
	8	0.7	0.57	0.89
	9	2.8	2.27	1.22
	10	4.7	3.81	2.36
	11	4.5	3.65	2.46

TABLE 96: Continued

Year	Month	Pan Evaporation - inches (24 ins.diam. tank)	Equiv. open water evaporation-inches (= Pan evap.x0.81; after Young,1947)	Potential Evapo-transpiration - inches (Thornthwaite)
1952	12	4.1	3.32	3.55
1953	1	6.1	4.94	3.47
	2	3.6	2.92	2.82
	3	3.3	2.67	2.52
	4	1.9	1.54	1.68
	5	1.2	0.97	0.93
	6	0.6	0.49	0.30
	7	0.2	0.16	0.28
	8	1.4	1.13	0.82
	9	2.8	2.27	1.09
	10	3.7	3.00	2.13
	11	4.9	3.97	2.99
	12	6.2	5.02	3.62
1954	1	5.0	4.05	3.66
	2	5.0	4.05	3.34
	3	3.2	2.59	2.59
	4	1.8	1.46	1.31
	5	1.6	1.30	1.05
	6	1.5	1.22	0.69
	7	0.1	0.08	0.22
	8	1.2	0.97	0.52
	9	1.7	1.38	0.98
	10	4.8	3.89	2.15
	11	4.5	3.65	3.25
	12	7.0	5.67	3.49
1955	1	5.2	4.21	3.78

proposed irrigation storage reservoir area. Also shown in Table 96 are the equivalent values of open water evaporation using a pan-open water coefficient of 0.81 (Young, 1947), and the 1948-55 monthly potential evapotranspiration data calculated for 1800 feet.

An open water evaporation prediction equation is thus developed by way of simple linear correlation and regression and the data from Table 96. The equation and other statistical information are given in Table 97:

TABLE 97: *Styx Basin open water evaporation-potential evapotranspiration (Thornthwaite) relationship for the period 1948-54*

(<u>Notes</u>: (i) All data are for an altitude of 1800 feet;
(ii) Y = open water evaporation in inches;
x = potential evapotranspiration in inches;
(iii) Pan-open water coefficient is 0.81 (Young, 1947)).

<u>STYX BASIN EVAPORATION:</u> $Y = 1.20x + 0.28$
$n = 69$; $(n-2)$d.f.; $S_{y.x} = 0.634$ inches; $C_{11} = 0.0106$;
$\bar{x} = 1.89$ inches; $S_x = 1.18$ inches; $r = 0.91$;
s.l. <0.01

The correlation coefficient of 0.91 is significant at greater than the 99 percent level, and the relationship is considered to be satisfactory for record extension purposes. Monthly, seasonal, and annual open water evaporation records are thus derived for the period 1909-69, and the results summarised in Table 98. Also shown are the standard errors of prediction for mean open water evaporation, as determined from equation (24). The values of x are the 1909-69 mean monthly, seasonal and annual Styx Basin potential evapotranspiration data calculated for 1800 feet, and are assumed to be error free.

TABLE 98: Styx Basin mean monthly, seasonal and annual open water evaporation parameters for the period 1909-69 and an altitude of 1800 feet

Month/ season	1909-69 mean open water evaporation (inches)	$S\hat{\mu}y.\bar{x}$ (inches)	Column (3) as percentage of Column (2)	Maximum mean monthly/ seasonal open water evap'n. (inches)	Minimum mean monthly/ seasonal open water evap'n. (inches)
(1)	(2)	(3)	(4)	(5)	(6)
January:	4.43	0.127	2.88	5.68	4.11
February:	3.68	0.098	2.65	4.67	3.41
March:	3.23	0.085	2.62	4.02	2.62
April:	2.09	0.080	3.83	2.92	1.85
May:	1.29	0.102	7.93	1.77	0.71
June:	0.76	0.123	16.2	1.16	0.28
July:	0.66	0.127	19.3	1.23	0.28
August:	1.05	0.111	10.6	1.59	0.72
September:	1.35	0.100	7.44	1.90	1.08
October:	2.68	0.076	2.85	3.58	2.32
November:	3.37	0.088	2.62	4.62	2.54
December:	4.14	0.115	2.79	5.52	2.48
Summer:	12.25	0.533	4.35	15.87	10.00
Autumn:	6.61	0.233	3.53	8.71	5.18
Winter:	2.47	0.076	3.09	3.98	1.28
Spring:	7.40	0.274	3.71	10.10	5.94
Jan-March:	11.34	0.484	4.27	14.37	10.14
Oct-March:	21.53	1.035	4.81	28.09	17.48
Annual:	27.86	1.379	4.95	29.60	26.57

Notes:

(i) Columns (2), (5) and (6) - values derived from the 1909-69 synthetic record calculated by the potential evapotranspiration/evaporation relationship in Table 97.

(ii) Column (3) - estimated standard error of $\hat{\mu}y$, given x is error free and equal to $\bar{x}$; determined from equation (24).

(iii) Column (4) - $S\hat{\mu}y.\bar{x}$ values in Column (3) as a percentage of the 1909-69 means listed in Column (2).

The results show that mean monthly open water evaporation between October and March is estimated by regression with standard errors of less than three percent. Standard errors approach 20 percent in the winter months, though the evaporation is of course low. Mean seasonal and annual open water evaporation is also estimated by regression to within 10 percent at the 95 percent probability level. However, the standard errors given by Table 98 must be considered as minimum values, since the potential evapotranspiration data used in the regressions are not error free. Nevertheless, although the errors of evapotranspiration estimation are not readily quantifiable, they are considered to be small.

Table 98 shows that the maximum monthly evaporation occurs in January, and the lowest in July. Mean annual open water evaporation is 27.86 inches, and on average 77 percent of this occurs in the period October to March. Mean summer evaporation is 12.25 inches, equivalent to 1.6 times the average summer rainfall for low-lying areas of the Styx Basin. The average annual open water evaporation is calculated to be 110 percent of the average annual rainfall for Area 1. Although full summaries of the evaporation data derived for 1909-69 are not given here, use of the values should be in awareness of the errors involved - reference should be made to equations (24) or (28), and the statistics given in Table 97.

Of further interest from the results is the calculation of mean reduction factors used to derive potential evapotranspiration from open water evaporation. Factors computed for the presented Styx Basin data are compared in Table 99 with the values proposed by Penman (1948) and Finkelstein (1961).

The two sets of factors are in close agreement overall, and suggest that the use of a 0.81 pan-open water coefficient was realistic for the measured pan data. The results also accord with the findings of Rickard

(1957) for the Canterbury Plains, in that the reduction factor for the combined months March, April, September and October is approximately as high as that given for November-February.

TABLE 99: Styx Basin potential evapotranspiration/open water evaporation reduction factors

(Notes: (i) Styx Basin reduction factor values for 1909-69 are derived from the long-term evaporation data given in Table 98, and the 1909-69 mean monthly potential evapotranspiration data calculated for 1800 feet.
(ii) The presented Penman reduction factors have been converted to Southern Hemisphere climatic conditions (Finkelstein, 1961).

	Styx Basin Reduction factors for 1909-69	Penman (1948) reduction factors
May-August:	0.57	0.6
March, April, September, October:	0.79	0.7
November-February:	0.83	0.8
Year:	0.74	0.75

CHAPTER VIII: CONCLUSIONS

The objective of water resources planning is to make the most effective use of the available water supply to meet all the foreseeable short and long-term needs of a region. To this end, a survey of the water resources of a region is intended to provide an estimate of the sources, extent, characteristics, magnitude and dependability of this supply. From such a survey one can realise the advantages of multiple use, reconcile conflicting interests, and achieve optimum coordination between all interests concerned.

To plan a data collection programme it is vital to first establish the purposes for which the gathered data are to be used, and the degree of precision of the information at a particular confidence level that will be adequate. The purpose will determine the required data precision. Precision requirements will in turn dictate the minimum record lengths of each variable necessary to estimate population parameters at a point, and the network density needed for parameter estimation over an area. A numerical statement as to what data precision is required may be different for each parameter and may refer to any number of variables over whatever time period.

This study is concerned with the data requirements and analyses for the planning of an irrigation scheme in the Maniototo Plains and Styx Basin, Central Otago. Simple standard or appropriately modified techniques are used to provide useful information with least cost in time and money.

The 95 percent confidence level is adopted for required data precision. Specified values of parameter precision for each variable are determined from the limiting factors of:

(i) the minimum acceptable precision as deduced from logical consideration of the design criteria; and

(ii) the maximum degree of precision likely to be achieved irrespective of either record length or network density, because of random and systematic errors inherent in the basic data measurement and processing.

Allowable standard errors of population parameter estimates are stated to be plus or minus 10 percent for streamflow and precipitation, and plus or minus five percent for temperature.

Upper Taieri basin data analyses and result presentation are oriented towards three study objectives. The first two may be stated in the form of hypotheses:-

(i) That the measurements of precipitation, temperature and streamflow in the catchment permit estimates of the station, total, and subcatchment monthly, seasonal and annual mean, variability, and extremes of the variables at the required precision levels.

Should this objective not be realised, then:-

(ii) That deterministic and stochastic models of data synthesis increase the information contained in the data series for each variable, as compared with the measured series alone, and enable estimates of the population parameters to be determined at the required precision levels. The deterministic techniques chosen are simple and multiple regression analyses, water balance, and conceptual models.

A further function of this study is the opportunity to test the within-catchment variations of yield and flow characteristics from a single basin, which is assumed to be 'representative' of a hydrologically homogeneous region. From this, it is theoretically possible to check the validity of commonly accepted concepts of 'regional hydrology', at least within the East Otago Region. The third study objective is thus stated as:-

(iii) To define regional homogeneity, by stating permissable limits of areal variation in annual yield and low flow characteristics. Hence, to determine whether the Upper Taieri area is hydrologically homogeneous by the stated criteria, using the parameters annual yield, variability index, base-flow recession constant and unit area base-flow.

The principal conclusions reached in this study are summarised as follows:-

1. Records of precipitation and streamflow in the Upper Taieri basin to 1966 were sparse, and insufficient for a water resources appraisal of the area. The data collection network was thus extended as shown in Figure 2.
2. It is essential to be able to determine the network density required to assess rainfall and/or temperature over an area to a given precision. Earlier techniques used to estimate the errors, and thus optimum network density, are rejected for this study, in favour of those described by Hutchinson (1969(a)) and Gandin (1970) - inter-station correlation and the structural function.
3. Use of the inter-station correlation approach to precipitation network design shows that the present station separation of 5.3 miles is quite adequate to satisfy the 0.9 correlation coefficient criterion for annual data and for 75 percent of months. However, the results suggest that for practical purposes it may not be feasible to establish a network of sufficient density to give estimates of mean areal rainfall to the required precision for every month.
4. Network design by structural function analysis supersedes the above inter-station correlation coefficient-distance relationships to determine mean or minimum grid distances, since the correlation-distance technique cannot give an absolute value of the standard error. However, assessment of the present network by way of structural function analysis confirms the results found for the

previous inter-station correlation approach. The present network is quite adequate for annual data; distances between gauges of up to 30 miles would satisfy the design criterion. Results for the monthly data are less promising. In no month does the present network allow mean areal rainfall estimation to within 20 percent of actual rainfall at the 95 percent confidence level. Further, in only five months is it possible to estimate values with standard errors of interpolation which are less than 10 percent, no matter how dense the network. The chosen allowable error thus appears too stringent a criterion for the study area, though a higher value may be unacceptable for engineering and water resources purposes.

5. To lower the calculated values of $\sqrt{E}$ from equation (3) for the Upper Taieri measured monthly precipitation data, requires either a decrease in the values of sample variance through an increase in record length, or increases in the values of μ with corresponding decreases in η. However, it is suspected that the general Otago correlation-distance relationship under-estimates μ for small distances in the Upper Taieri Basin. This increases ϵ_{opt} and thus the value of $\sqrt{E}$.

6. Structural function analysis also shows that the present Meteorological Service temperature recording network is adequate for areal estimates of monthly and annual mean temperatures to within the required design criterion. Values of $\sqrt{E}$ are less than 10 percent at the 95 percent confidence level. For a station separation of up to 80 miles, monthly $\sqrt{E}$ is less than four percent of the mean and the equivalent annual value is less than one percent. Naseby State Forest records may thus be used to represent monthly and annual mean temperature data in the Upper Taieri area with only minor errors introduced.

7. Measured streamflow and temperature records in the Upper Taieri area are necessarily assumed to be consistent and homogeneous. The

precipitation data are shown to be consistent, though earlier data from the extended Upper Taieri network required correction for evaporation losses. Kerosene is found to be unacceptable as an anti-evaporant for storage gauge catch, and has been replaced by a light oil. The oil is also found to be a useful additive in winter if frost damage of storage gauges is expected.

8. The presented summaries of measured monthly, seasonal and annual precipitation, temperature and streamflow data provide basic information of value for engineering design, and give an insight into the general hydrological characteristics of the Upper Taieri area. However, if records are short, the parameters may be poor estimates of the population parameters. Ultimate value for engineering design can only be achieved when the available measured data are considered in terms of the degree of precision to which the parameters are estimated, and comparison of these values with the required precision levels. The statistical parameters considered in this study for each variable are the mean, variability and extremes for time intervals which vary from daily to average annual values.
9. Although recognised as an approximation of actual conditions, all the measured data are considered to be stationary time series of either normal or log-normal distribution, and without serial correlation.
10. Mean seasonal and annual station precipitation may be estimated from the measured Paerau data with standard errors of less than 10 percent. The error criterion could be satisfied by five year's data for an annual mean, and by 17 year's records for a seasonal mean. However, half the months from the 35 year measured record have standard errors greater than 10 percent, and calculations show that up to 60 years of data may be needed to achieve the stated criterion for all months.
11. Estimation of total and sub-catchment long-term areal mean precipitation to within 10 percent of actual precipitation is unlikely from the

measured data. All station records from the post-1966 network need considerable extension in order to allow direct estimation of areal population parameters with less than the allowable total error.

12. For maximum one, two and three-day rainfalls, standard errors of less than 10 percent only occur for estimates of the annual extreme values at T less than about five years. Higher return period values of annual X_T show possible standard errors well in excess of the 10 percent stated as acceptable.

13. Available measured temperature data allow estimates of station monthly, seasonal and annual mean and variability at the required precision level. Standard errors of the mean are all less than one percent for the 45 year record, and for the stated time intervals the error criterion could have been satisfied by only two years of record.

14. Total catchment mean annual, winter, spring, and October-March discharges may be estimated from the 25 to 30 year measured Paerau Bridge record, with standard errors of less than 10 percent. For these time intervals the error criterion could have been satisfied by 17 years of record. However, for the seasons which remain, and half the months, standard errors in estimating the mean exceed 10 percent. Streamflow population estimates with standard errors less than 10 percent could theoretically be achieved by an increase in record length, though this is an impractical solution for the months December to March. Alternatively, a less stringent error criterion must be accepted for the summer and early autumn months.

15. Available measured data for the principal sub-catchments do not allow direct estimation of monthly, seasonal, or annual discharge parameters to within the allowable total error. Upper Taieri flow measurement stations other than Loganburn have insufficient data of a type suitable for any direct form of parameter estimation. The continuous measured

record for Loganburn is of insufficient length - standard errors of up to 42 percent are calculated for the mean seasonal discharges, and up to 60 percent for monthly values.

16. Measurements of daily mean or instantaneous discharge do not allow estimation of total or sub-catchment annual flood or minimum flows at the required precision level for any return period. Standard errors of about 11 percent are given for both the flood and minimum flows at T equals two years, and values of up to 21 percent are evident for the higher recurrence intervals.

17. When items 10-16 are considered together, it is evident that the first study objective has not been fully realised. Although the data collection network is theoretically acceptable for most purposes, the measured values do not allow estimation of all the needed population parameters at the required precision level. Record collection from all precipitation and streamflow measurement stations in the post-1966 network needs to be continued, unless indirect ways are used to obtain parameter estimates to within the stated precision level.

18. Record synthesis is thus necessary in order to increase the amount of information contained at this stage in the precipitation and streamflow data series. The results show that the second study objective has also not been realised in full. Addition of synthesised records to the precipitation and streamflow data series still does not permit estimates of all the required population parameters at the required precision levels. In fact, under some circumstances, estimates of population parameters based on the blended records are shown to be less reliable than those based on the measured record alone. In these instances, a decrease in statistical information is experienced by record extension. Additional conclusions which are related to assessment of the second study objective are given as

follows (Items 19-34).

19. Estimates of mean seasonal and annual precipitation at Paerau are now available to greater precision than for the measured series alone. The additional data are derived from simple linear and curvilinear correlation and regression analyses. Mean annual rainfall is estimated to within seven percent at the 95 percent confidence level. Results for the monthly data show that only August now has a standard error which exceeds 10 percent, and that effective record lengths have increased by up to 20 years. However, conditions for improved estimates of the station variance are found for only three months.

20. It does not appear possible to estimate areal precipitation parameters to the required degree of precision with the data available. Standard errors from regression estimates of long-term average catchment precipitation suggest that, for the given monthly Paerau data, mean values of average basin rainfall may be estimated to within six percent. However, these errors increase to almost 40 percent if the independent variables are not considered to be error free. Standard errors of total or sub-catchment mean precipitation estimation are unlikely to be less than those shown for the network assessment by structural function analysis.

21. Extension of the total catchment streamflow record is achieved by way of techniques which use measured climatic data. Little information was gained by the analyses. None of the four deterministic models chosen for Paerau Bridge record extension allow parameter estimation to markedly greater precision levels than for the measured series alone. Precision limits of parameter estimates derived by water balance and conceptual models are not readily quantifiable. However, these limits may be qualitatively deduced by comparing the calculated model efficiency with similar values derived for simple and multiple regression models of known error.

22. Results for the simple rainfall-runoff regression models show that in only three months does the blended record give estimates of the long-term mean which are any more precise than those calculated from the measured record. Standard errors of up to 31 percent are found for October and November estimates, and only in winter is the value less than 10 percent. The maximum gain in effective record length is 11 years.

23. Paerau Bridge multiple rainfall-runoff regression models give improved flow prediction results compared with those derived from the other deterministic models tested. The second study objective is not satisfied by the analysis, but these multiple regression models are shown to be the most suitable for prediction of the missing Paerau Bridge streamflow records. Since the equations are only used here to predict mean monthly yields, it is not possible to improve precision estimates of the Paerau Bridge extreme values.

24. The water balance model used in this study is a modified version of that proposed by Thornthwaite & Mather (1955). The major change from the original model is that potential evapotranspiration is now computed by a method which contains built-in altitudinal corrections dependent on variable seasonal lapse rates. It is thus possible to calculate values of potential evapotranspiration for any specified altitude, from one set of basic temperature data at a known height above sea level. Versions of the model with 50 and 70 percent carryover factors of water available for runoff are tested, but both are found to be unreliable for Paerau Bridge runoff prediction. A model is developed which uses a 60 percent carryover factor, and variable direct response dependent on season. Although natural catchment conditions are more closely simulated, the benefits of model generality are lost by the changes.

25. A large proportion of the general water balance yield prediction

errors can be ascribed to incorrect determination of within year runoff distributions. Principal value of the method in the Upper Taieri area is thus to determine the space and time variations in soil moisture deficits.

26. Except for initial estimates, general application of the basic water balance equation cannot be recommended for yield calculations. Catchment mean annual yield may be given to within acceptable error limits. However, percentage errors can be expected to increase rapidly when data are required for shorter time intervals, for non-watertight catchments, or when seasonal moisture deficits can be expected.

27. The conceptual model used in this study is a modified version of that developed by Boughton (1965, 1966, 1968). Principal changes introduced are the addition of a groundwater store, and provision for interflow and groundwater components in the total runoff. The model is generally unsatisfactory for Upper Taieri runoff prediction. Mean monthly yields at Paerau Bridge are no more precise than those synthesised by the simpler alternative methods.

28. However, total error from each of the deterministic models used for Paerau Bridge runoff generation is composed mainly of occasional large values. If these occasional large errors are acceptable, the predicted records may be considered a reasonable representation of the measured data.

29. The stochastic sequential generation model developed by Thomas & Fiering (1962) is successful overall when used to simulate total catchment mean monthly flow sequences. However, the model cannot be used here to satisfy the second study objective, since the measured model input data will not allow flow series to be generated with population parameter estimate standard errors of less than the 10 percent allowed.

30. Sub-catchment streamflow records are extended by simple linear regression analysis, with the Paerau Bridge data as the independent variables. Effective record extensions vary from nine to 21 years.

31. If the independent variables are assumed to be error free, addition of regression estimates to the Loganburn streamflow record allows determination of mean discharge at the required precision level for most time intervals of a month or more. Mean annual discharge is estimated to within five percent from the blended record, and only four months have standard errors which exceed 10 percent. Prediction standard errors for Upper Styx Valley Bridge mean discharge estimates are less than eight percent, but the Styx and Serpentine Creek values generally exceed 10 percent.

32. However, the independent variables in the regressions are not error free. When the sub-catchment mean discharges are considered as population estimates, then only the long-term mean annual discharge for Loganburn is determined with a standard error of less than 10 percent.

33. Regression analysis is no help in the estimation of sub-catchment extreme values at the required precision level. The computed data are subject to both standard errors of prediction and the calculated errors of X_T for the measured Paerau Bridge records - total errors are thus likely to be excessive.

34. For engineering design of any proposed irrigation scheme to proceed now, the chosen error criteria must be judged too stringent for the Upper Taieri data. If the calculated standard errors cannot be accepted, all the precipitation and streamflow records from the post-1966 network will require extension by additional observations.

35. The establishment of a stratified hydrological sampling programme on a national basis, requires the use of representative basins and an acceptance of the concepts of regional hydrology. Regional classifi-

cation is complex, but in New Zealand only the uniformity of basin characteristics has been considered in the definition of present regions. These uniform catchment characteristics are assumed to produce hydrological similarity within each region.

36. Several New Zealand studies have attempted to demonstrate the similarity of hydrological parameters from areas with like basin characteristics (Grant, 1971; Waugh, 1970). However, the results do not seem consistent with the conclusions reached. Between-region differences of low flow parameters are stated as significant, but no attempt is made to statistically verify this conclusion. Further, parameter differences within regions seem to be equally as significant as those which supposedly illustrate the between-region differences.

37. Hydrological homogeneity cannot be assumed to equate with uniformity of basin characteristics, at least for low flows. Hydrological regions are better defined in terms of allowable areal variation for stated hydrological parameters. A numerical value for allowable variation may be different for each parameter. The parameters chosen, their permissable limits of spatial variation, and size of hydrological region, will be related to the purpose for which the data are to be used.

38. The permissable limit of hydrological homogeneity for Upper Taieri streamflow parameters is generally chosen as a variation of plus or minus 20 percent from the 'representative' value. Different criteria are necessary, however, when differences in the sub-catchment recession constant and half-flow period values are considered.

39. The Upper Taieri results are disappointing overall. Standard errors of prediction for some of the sub-catchment streamflow parameter values preclude reliable determination of within catchment differences. Nevertheless, the sub-catchment mean annual yields and base-flow

recession parameters are sufficiently error free to conclude that the study area is not hydrologically homogeneous by the stated criteria. Further, the boundaries of hydrologically similar regions are shown to vary dependent on the streamflow parameter considered.

40. Differences in hydrological characteristics are thus again evident for an area with basin characteristics classified as uniform by the present regional divisions.

41. The general climatic character of the Upper Taieri basin gives an air of uncertainty to pastoral farming in the area. Plant growth in summer and autumn is largely limited by a lack of effective rainfall, with frost the principal limitation to growth later in autumn. In spring, accumulated soil moisture storage and rainfall are generally adequate to maintain uninterrupted growth until November. A decrease in available soil moisture is the general limitation to growth in late spring.

42. There is a need for irrigation in the Upper Taieri area if potential crop production is to be attained. Calculated soil moisture deficit values show that irrigation of the Styx Basin lowland area is necessary in almost every year for the period December to March. If an irrigation efficiency of 60 percent is assumed, the estimated highest water requirement in 75 percent of years for October-March is about six inches. The value increases to 10.5 inches in 90 percent of years. Further, the highest monthly requirements govern the capacity of the water distribution and application system. In this study, the maximum need values are calculated as 1.83 inches in 75 percent of years and 2.65 inches for 90 percent of years.

43. Should either the 1961 or 1964 irrigation scheme proposals be implemented and the Styx Basin become a storage reservoir, then

estimates of open water evaporation will be required. Mean monthly evaporation between October and March is estimated by regression with standard errors which approximate three percent. Average annual evaporation in the proposed storage area is calculated as 28 inches. The mean summer value is 12.25 inches, equivalent to 1.6 times the average summer rainfall for low-lying areas of the Styx Basin.

44. Closely associated with the analyses of moisture deficits and irrigation water needs, is a study of the severity and occurrence frequency of drought in the Upper Taieri and nearby areas. The probability of drought in the Maniototo is high, but considerably less so in the Upper Taieri Basin. Long-term droughts in the study area, for the period 1909-69, are ranked in order of increasing severity as 1953-55, 1940-41, 1937-38, 1939-40, 1968-69, 1966-67, 1931-33, 1914-17, 1927-30 and 1909-13.

45. For this study of long-term drought, the drought severity index approach developed by Herbst *et al.* (1966) is concluded to be of better value overall than the rainfall effectiveness index method proposed by Grant (1968, 1969). Grant's method depends on daily rainfall records for operation, and cannot strictly be considered to represent a model of drought determination. Comparisons of drought duration or severity can only be made on an average basis within limits of predetermined periods of natural change. The RE Index values can thus be changed at will, by a re-definition of these periods of change. Herbst's method is preferred, since it is simple to operate, and determines drought periods, trends, and indices of drought severity from either monthly or daily precipitation data.

46. The principal study objectives have been only partially realised.

However, the region's usable surface water resources are determined and analysed for their areal distribution and time variation. The information provided is of both local and national importance. The study is most timely, since too much engineering design has already been done in New Zealand without the types of consideration encompassed by this project. Similarly, the techniques used here have too frequently been applied elsewhere without question.

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APPENDIX I: UPPER TAIERI CATCHMENT MONTHLY AND ANNUAL PRECIPITATION, TEMPERATURE AND RUNOFF PREDICTION EQUATIONS.

APPENDIX I(1): Monthly and annual rainfall regression equation statistics for Paerau synthetic record determination (see Table 42).

A. *Paerau-Manorburn Dam:* *(Data 1914-40).*

(i) January: $n = 27$; $(n-2)$d.f.; $Sb_1 = 0.1933$; $Sy.x = 1.176$ ins.; $C_{11} = 0.0270$; $\bar{x} = 2.40$ ins.; $F = 32.94$; significance level (s.l.) <0.001.

(ii) February: $n = 27$; $(n-3)$d.f.; $Sb_1 = 0.7528$; $Sy.x,x^2 = 1.020$ ins.; $C_{11} = 0.5444$; $C_{12} = -0.1294$; $C_{22} = 0.0330$; $\bar{x} = 1.71$ ins.; $\bar{x}^2 = 3.91$ ins.; $F = 27.05$; s.l.<0.001.

(iii) March: $n = 27$; $(n-3)$d.f.; $Sb_1 = 0.7660$; $Sy.x,x^2 = 1.268$ ins.; $C_{11} = 0.3649$; $C_{12} = -0.0750$; $C_{22} = 0.0167$; $\bar{x} = 1.81$ ins.; $\bar{x}^2 = 4.64$ ins.; $F = 14.55$; s.l. <0.001.

(iv) April: $n = 27$; $(n-2)$d.f.; $Sb_1 = 0.1974$; $Sy.x = 0.909$ ins.; $C_{11} = 0.0472$; $\bar{x} = 2.01$ ins., $F = 49.23$; s.l. <0.001.

(v) May: $n = 27$; $(n-3)$d.f.; $Sb_1 = 0.3216$; $Sy.x,x^2 = 0.729$ ins.; $C_{11} = 0.1944$; $C_{12} = -0.0250$; $C_{22} = 0.0036$; $\bar{x} = 1.87$ ins.; $\bar{x}^2 = 5.32$ ins.; $F = 32.38$; s.l. <0.001.

(vi) June: $n = 27$; $(n-4)$d.f.; $Sb_1 = 4.897$; $Sy.x,x^2,x^3 = 1.079$ ins.; $C_{11} = 20.610$; $C_{12} = -12.503$; $C_{13} = 2.233$; $C_{22} = 7.768$; $C_{23} = -1.414$; $C_{33} = 0.262$; $\bar{x} = 1.40$ ins.; $\bar{x}^2 = 2.50$ ins.; $\bar{x}^3 = 5.31$ ins.; $F = 9.36$; s.l. <0.001.

(vii) July: $n = 27$; $(n-2)$d.f.; $Sb_1 = 0.2813$; $Sy.x = 0.696$ ins.; $C_{11} = 0.1634$; $\bar{x} = 0.99$ ins.; $F = 18.29$; s.l. <0.001.

(viii) August: $n = 27$; $(n-4)$d.f.; $Sb_1 = 2.8072$; $Sy.x,x^2,x^3 = 0.985$ ins; $C_{11} = 8.125$; $C_{12} = -6.518$; $C_{13} = 1.408$; $C_{22} = 5.474$; $C_{23} = -1.215$; $C_{33} = 0.276$; $\bar{x} = 1.08$ ins.; $\bar{x}^2 = 1.50$ ins.; $\bar{x}^3 = 2.51$ ins.; $F = 13.12$; s.l. <0.001.

(ix) September: $n = 27$; $(n-2)$d.f.; $Sb_1 = 0.2013$; $Sy.x = 0.162$ ins.; $C_{11} = 1.549$; $\bar{x} = 1.29$ ins.; $F = 15.84$; s.l.<0.001.

(x) October: $n = 27$; $(n-2)$d.f.; $Sb_1 = 0.1074$; $Sy.x = 0.623$ ins.; $C_{11} = 0.0298$; $\bar{x} = 1.76$ ins.; $F = 101.68$; s.l. <0.001.

(xi) November: $n = 27$; $(n-2)$d.f.; $Sb_1 = 0.1648$; $Sy.x = 0.762$ ins.; $C_{11} = 0.0468$; $\bar{x} = 2.03$ ins.; $F = 42.22$; s.l. <0.001.

(xii) December: $n = 27$; $(n-3)$d.f.; $Sb_1 = 0.9833$; $Sy.x,x^2 = 1.244$ ins.; $C_{11} = 0.5957$; $C_{12} = -0.1117$; $C_{22} = 0.0228$; $\bar{x} = 2.01$ ins.; $\bar{x}^2 = 4.80$ ins., $F = 10.24$; s.l. <0.001.

(xiii) Annual: $n = 27$; $(n-3)$d.f.; $Sb_1 = 1.4811$; $Sy.x,x^2 = 4.761$ ins.; $C_{11} = 0.0968$; $C_{12} = -0.0019$; $C_{22} = 0.00004$; $\bar{x} = 20.37$ ins.; $\bar{x}^2 = 430.79$ ins.; $F = 9.80$; s.l. <0.001.

B. *Paerau-Patearoa:* *(Data 1916-40)*

(i) January: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.1203$; $Sy.x = 0.737$ ins.; $C_{11} = 0.0267$; $\bar{x} = 2.04$ ins.; $r = 0.912$; $F = 117.38$; s.l. <0.001.

(ii) February: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.3149$; $Sy.x = 1.251$ ins.; $C_{11} = 0.0635$; $\bar{x} = 1.39$ ins.; $r = 0.732$; $F = 27.06$; s.l. <0.001.

(iii) March: $n = 25$; $(n-4)$d.f.; $Sb_1 = 3.694$; $Sy.x,x^2,x^3 = 1.324$ ins.; $C_{11} = 7.784$; $C_{12} = -6.378$; $C_{13} = 1.483$; $C_{22} = 5.578$; $C_{23} = -1.358$; $C_{33} = 0.343$; $\bar{x} = 1.27$ ins.; $\bar{x}^2 = 2.06$ ins.; $\bar{x}^3 = 3.77$ ins.; $r = 0.636$; $F = 9.02$; s.l. <0.001.

(iv) April: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.3023$; $Sy.x = 1.221$ ins.; $C_{11} = 0.0614$; $\bar{x} = 1.41$ ins.; $r = 0.644$; $F = 16.88$; s.l. <0.001.

(v) May: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.2648$; $Sy.x = 0.847$; $C_{11} = 0.0979$; $\bar{x} = 1.06$ ins.; $r = 0.811$; $F = 41.72$; s.l.<0.001.

(vi) June: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.6000$; $Sy.x = 1.363$ ins.; $C_{11} = 0.1938$; $\bar{x} = 0.82$ ins.; $r = 0.444$; $F = 3.51$; s.l. >0.05.

(vii) July: $n = 25$; $(n-3)$d.f.; $Sb_1 = 0.5645$; $Sy.x,x^2 = 0.695$ ins.; $C_{11} = 0.6600$; $C_{12} = -0.1884$; $C_{22} = 0.0619$; $\bar{x} = 0.86$ ins.; $\bar{x}^2 = 1.20$ ins.; $r = 0.486$; $F = 8.66$; s.l. <0.01.

(viii) August: $n = 25$; $(n-4)$d.f.; $Sb_1 = 3.554$; $Sy.x,x^2,x^3 = 1.168$ ins.; $C_{11} = 9.265$; $C_{12} = -8.646$; $C_{13} = 2.268$; $C_{22} = 8.682$; $C_{23} = -2.405$; $C_{33} = 0.696$; $\bar{x} = 0.86$ ins.; $\bar{x}^2 = 1.08$ ins.; $\bar{x}^3 = 1.67$ ins.; $r = 0.641$; $F = 6.97$; s.l. <0.01.

(ix) September: $n = 25$; $(n-4)$d.f.; $Sb_1 = 2.876$; $Sy.x,x^2,x^3 = 0.920$ ins.; $C_{11} = 9.783$; $C_{12} = -8.583$; $C_{13} = 2.112$; $C_{22} = 8.044$; $C_{23} = -2.068$; $C_{33} = 0.549$; $\bar{x} = 0.96$ ins.; $\bar{x}^2 = 1.24$ ins.; $\bar{x}^3 = 1.99$ ins.; $r = 0.440$; $F = 3.43$; s.l.<0.05.

(x) October: $n = 25$; $(n-3)$d.f.; $Sb_1 = 0.3550$; $Sy.x,x^2 = 0.553$ ins.; $C_{11} = 0.413$; $C_{12} = -0.0970$; $C_{22} = 0.0245$; $\bar{x} = 1.35$ ins.; $\bar{x}^2 = 2.80$ ins.; $r = 0.891$; $F = 55.78$; s.l. <0.001.

(xi) November: $n = 25$; $(n-3)$d.f.; $Sb_1 = 1.0014$; $Sy.x,x^2 = 0.920$ ins.; $C_{11} = 1.185$; $C_{12} = -0.3590$; $C_{22} = 0.1160$; $\bar{x} = 1.35$ ins.; $\bar{x}^2 = 2.33$ ins.; $r = 0.674$; $F = 11.72$; s.l. <0.001.

(xii) December: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.3772$; $Sy.x = 1.351$ ins.; $C_{11} = 0.0780$; $\bar{x} = 1.83$ ins.; $r = 0.698$; $F = 16.08$; s.l. <0.001.

(xiii) Annual: $n = 25$; $(n-4)$d.f.; $Sb_1 = 87.231$; $Sy.x,x^2,x^3 = 5.671$ ins.; $C_{11} = 236.626$; $C_{12} = -14.625$; $C_{13} = 0.297$; $C_{22} = 0.906$; $C_{23} = -0.0184$; $C_{33} = 0.00038$; $\bar{x} = 15.15$ ins.; $\bar{x}^2 = 233.39$ ins.; $\bar{x}^3 = 3657.17$ ins.; $r = 0.227$; $F = 2.99$ s.l. >0.05.

C. *Paerau-Waipiata Sanatorium* *(Data 1916-40).*

(i) January: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.1566$; $Sy.x = 1.015$ ins.; $C_{11} = 0.0238$; $\bar{x} = 2.07$ ins.; $r = 0.837$; $F = 53.95$; s.l. <0.001.

(ii) February: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.3033$; $Sy.x = 1.246$ ins.; $C_{11} = 0.0593$; $\bar{x} = 1.50$ ins.; $r = 0.738$; $F = 27.46$; s.l. <0.001.

(iii) March: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.3260$; $Sy.x = 1.221$ ins.; $C_{11} = 0.0713$; $\bar{x} = 1.29$ ins.; $r = 0.770$; $F = 33.54$; s.l. <0.001.

(iv) April: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.2582$; $Sy.x = 1.201$ ins.; $C_{11} = 0.0463$; $\bar{x} = 1.61$ ins.; $r = 0.664$; $F = 18.18$; s.l. <0.001.

(v) May: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.2599$; $Sy.x = 1.008$ ins.; $C_{11} = 0.0664$; $\bar{x} = 1.30$ ins.; $r = 0.704$; $F = 22.61$; s.l. <0.001.

(vi) June: $n = 25$; $(n-4)$d.f.; $Sb_1 = 6.754$; $Sy.x,x^2,x^3 = 1.085$ ins.; $C_{11} = 38.757$; $C_{12} = -32.126$; $C_{13} = 7.835$; $C_{22} = 27.428$; $C_{23} = -6.836$; $C_{33} = 1.733$; $\bar{x} = 1.12$ ins.; $\bar{x}^2 = 1.31$ ins.; $\bar{x}^3 = 2.05$ ins.; $r = 0.479$; $F = 6.95$; s.l. <0.01.

(vii) July: $n = 25$; $(n-2)$d.f.; $Sb_1 = 0.2270$; $Sy.x = 0.575$ ins.; $C_{11} = 0.1560$; $\bar{x} = 0.97$ ins.; $r = 0.775$; $F = 34.48$; s.l. <0.001.

(viii) August: $n = 25$; $(n-4)$d.f.; $Sb_1 = 1.859$; $Sy.x,x^2,x^3 = 0.710$ ins.; $C_{11} = 6.863$; $C_{12} = -5.820$; $C_{13} = 1.391$; $C_{22} = 5.387$; $\bar{x} = 1.04$ ins.; $\bar{x}^2 = 1.52$ ins.; $\bar{x}^3 = 2.72$ ins.; $r = 0.768$; $F = 30.80$; s.l. <0.001; $C_{23} = -1.364$; $C_{33} = 0.359$.

(ix) September: $n = 25$; $(n-4)$d.f., $Sb_1 = 2.426$; $Sy.x,x^2,x^3 = 0.893$ ins.; $C_{11} = 7.382$; $C_{12} = -5.597$; $C_{13} = 1.226$; $C_{22} = 4.660$; $C_{23} = -1.087$; $C_{33} = 0.256$; $\bar{x} = 1.12$ ins.; $\bar{x}^2 = 1.64$ ins.; $\bar{x}^3 = 2.89$ ins.; $r = 0.418$; $F = 4.07$; s.l. <0.025.

(x) October: n = 25; (n-2)d.f.; Sb_1 = 0.1598; Sy.x = 0.687 ins.;
C_{11} = 0.0514; $\bar{x}$ = 1.36 ins.; r = 0.875; F = 74.94;
s.l. <0.001.

(xi) November: n = 25; (n-3)d.f.; Sb_1 = 0.9513; $Sy.x,x^2$ = 0.933 ins.;
C_{11} = 1.041; C_{12} = -0.2880; C_{22} = 0.0848; $\bar{x}$ = 1.57 ins.;
$\bar{x}^2$ = 3.12 ins.; r = 0.671; F = 11.12; s.l. <0.001.

(xii) December: n = 25; (n-2)d.f.; Sb_1 = 0.3009; Sy.x = 1.413 ins.;
C_{11} = 0.0454; $\bar{x}$ = 1.99 ins.; r = 0.597; F = 12.71;
s.l. <0.001.

(xiii) Annual: n = 25; (n-3)d.f.; Sb_1 = 4.562; $Sy.x,x^2$ = 5.721 ins.;
C_{11} = 0.6360; C_{12} = -0.0172; C_{22} = 0.00047;
$\bar{x}$ = 16.84 ins.; $\bar{x}^2$ = 289.34 ins.; r = 0.450; F = 3.71;
s.l. <0.05.

APPENDIX I(2): Raingauge network regression equation statistics. (see Table 46). (Base station Elliot (≡Paerau) is x).

(i) *Mulholland:* n = 30; (n-2)d.f.; Sx = 0.822 ins.; Syx = 0.403 ins.;
C_{11} = 0.051; $\bar{x}$ = 1.08 ins.; r = 0.858; s.l. <0.01.

(ii) *Aitken:* n = 33; (n-2)d.f.; Sx = 0.707 ins.; Syx = 0.352 ins.;
C_{11} = 0.0645; $\bar{x}$ = 0.952 ins.; r = 0.882; s.l. <0.01.

(iii) *Onslow Road:* n = 22; (n-2)d.f.; Sx = 1.633 ins.; Syx = 0.347 ins.;
C_{11} = 0.0179; $\bar{x}$ = 1.31 ins.; r = 0.974; s.l. <0.01 .

(iv) *Smith:* n = 27; (n-2)d.f.; Sx = 1.366 ins.; Syx = 0.573 ins.;
C_{11} = 0.0206; $\bar{x}$ = 1.15 ins.; r = 0.911; s.l. <0.01.

(v) *Bottle Rock North:* n = 24; (n-2)d.f.; Sx = 1.815 ins.; Syx = 0.526 ins.;
C_{11} = 0.0132; $\bar{x}$ = 1.29 ins.; r = 0.977; s.l. <0.001.

(vi) *Great Moss Swamp:* n = 26; (n-2)d.f.; Sx = 1.689 ins.; Syx = 0.352 ins.;
C_{11} = 0.0140; $\bar{x}$ = 1.10 ins.; r = 0.987; s.l. <0.01.

(vii) *Bottle Rock:* n = 17; (n-2)d.f.; Sx = 2.244 ins.; Syx = 0.574 ins.;
C_{11} = 0.0124; $\bar{x}$ = 1.54 ins.; r = 0.983; s.l. <0.01.

(viii) *Longstone:* n = 20; (n-2)d.f.; Sx = 2.010 ins.; Syx = 0.313 ins.;
C_{11} = 0.0130; $\bar{x}$ = 1.56 ins.; r = 0.991; s.l. <0.01.

(ix) *Round Hill:* n = 29; (n-2)d.f.; Sx = 1.638 ins.; Syx = 0.381 ins.;
C_{11} = 0.0133; $\bar{x}$ = 1.13 ins.; r = 0.981; s.l. <0.01.

(x) *Musterer's Huts:* n = 20; (n-2)d.f.; Sx = 2.012 ins.; Syx = 0.949 ins.;
C_{11} = 0.0130; $\bar{x}$ = 1.56 ins.; r = 0.971; s.l.<0.01.

(xi) *Trig 'H':* n = 25; (n-2)d.f.; Sx = 1.712 ins.; Syx = 1.244 ins.;
C_{11} = 0.0142; $\bar{x}$ = 1.11 ins.; r = 0.943; s.l. <0.01.

(xii) *Lammerlaw Top:* n = 18; (n-2)d.f.; Sx = 2.373 ins.; Syx = 1.056 ins.;
C_{11} = 0.0104; $\bar{x}$ = 1.41 ins.; r = 0.979; s.l. <0.01.

APPENDIX I(3): Monthly mean temperature regression equation statistics for Naseby State Forest synthetic record determination (see Table 51).

Tapanui-Naseby State Forest: *(Data 1923-65).*

(i) January: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.0928$; $Sy.x = 1.61^{\circ}F$;
$C_{11} = 0.0033$; $\bar{x} = 57.55^{\circ}F$; $r = 0.783$; $F = 50.18$;
s.l. <0.001.

(ii) February: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.0757$; $Sy.x = 1.39^{\circ}F$
$C_{11} = 0.00299$; $\bar{x} = 56.69^{\circ}F$; $r = 0.768$; $F = 53.30$;
s.l. <0.001.

(iii) March: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.0882$; $Sy.x = 1.37^{\circ}F$;
$C_{11} = 0.00415$; $\bar{x} = 54.10^{\circ}F$; $r = 0.758$; $F = 47.24$;
s.l. <0.001.

(iv) April: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.0935$; $Sy.x = 1.62^{\circ}F$;
$C_{11} = 0.0033$; $\bar{x} = 49.86^{\circ}F$; $r = 0.682$; $F = 37.41$;
s.l. <0.001.

(v) May: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.1140$; $Sy.x = 1.52^{\circ}F$;
$C_{11} = 0.0056$; $\bar{x} = 44.58^{\circ}F$; $r = 0.677$; $F = 21.63$;
s.l. <0.001.

(vi) June: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.1289$; $Sy.x = 1.76^{\circ}F$;
$C_{11} = 0.0053$; $\bar{x} = 40.10^{\circ}F$; $r = 0.716$; $F = 23.15$;
s.l. <0.001.

(vii) July: $n = 43$; $(n-4)$d.f.; $Sb_1 = 23.21$; $Sy.x,x^2,x^3 = 1.74^{\circ}F$;
$C_{11} = 178.054$; $C_{12} = -4.756$; $C_{13} = 0.0420$;
$C_{22} = 0.1272$; $C_{23} = -0.0011$; $C_{33} = 0.00001$;
$\bar{x} = 39.54^{\circ}F$; $\bar{x}^2 = 1570.11^{\circ}F$; $\bar{x}^3 = 62618.74^{\circ}F$; $r = 0.664$;
$F = 10.84$; s.l. <0.001.

(viii) August: $n = 43$; $(n-3)$d.f.; $Sb_1 = 3.0560$; $Sy.x,x^2 = 1.49^{\circ}F$;
$C_{11} = 4.2112$; $C_{12} = -0.0505$; $C_{22} = 0.00061$;
$\bar{x} = 42.17^{\circ}F$; $\bar{x}^2 = 1783.28^{\circ}F$; $r = 0.657$; $F = 13.44$;
s.l. <0.001.

(ix) September: $n = 43$; $(n-2)$d.f.; $Sb_1 = 0.0972$; $Sy.x = 1.38^{\circ}F$;
$C_{11} = 0.0050$; $\bar{x} = 46.03^{\circ}F$; $r = 0.562$; $F = 15.30$;
s.l. <0.001.

(x) October: $n = 43$; $(n-3)$d.f.; $Sb_1 = 3.185$; $Sy.x,x^2 = 1.43^{\circ}F$;
$C_{11} = 4.9543$; $C_{12} = -0.0498$; $C_{22} = 0.00050$;
$\bar{x} = 49.80^{\circ}F$; $\bar{x}^2 = 2485.71^{\circ}F$; $r = 0.613$; $F = 17.45$;
s.l. <0.001.

(xi) November: $n = 43$; $(n-3)$d.f.; $Sb_1 = 3.239$; $Sy.x,x^2 = 1.76^{\circ}F$;
$C_{11} = 3.378$; $C_{12} = -0.0325$; $C_{22} = 0.00031$;
$\bar{x} = 52.53^{\circ}F$; $\bar{x}^2 = 2767.29^{\circ}F$; $r = 0.700$; $F = 21.48$;
s.l.<0.001.

(xii) December: $n = 43$; $(n-3)$d.f.; $Sb_1 = 0.9313$; $Sy.x,x^2 = 1.62^{\circ}F$;
$C_{11} = 0.3289$; $C_{12} = -0.0031$; $C_{22} = 0.00003$;
$\bar{x} = 55.13^{\circ}F$; $\bar{x}^2 = 3052.21$; $r = 0.540$; $F = 31.26$;
s.l. <0.001.

APPENDIX I(4): *Monthly and annual yield regression equation statistics for Paerau Bridge synthetic record determination (see Table 56).*

(i) January: $n = 24$; $(n-2)$d.f.; $Sb_1 = 0.0545$; $Sy.x = 0.498$ ins.; $C_{11} = 0.0120$; $\bar{x} = 3.51$ ins.; $r = 0.705$; $F = 8.22$; s.l. <0.01.

(ii) February: $n = 24$; $(n-3)$d.f.; $Sb_1 = 0.1080$; $Sy.x,x^2 = 0.381$ ins.; $C_{11} = 0.0803$; $C_{12} = -0.0071$; $C_{22} = 0.0007$; $\bar{x} = 3.54$ ins.; $\bar{x}^2 = 18.33$; $r = 0.756$; $F = 8.77$; s.l. <0.01.

(iii) March: $n = 24$; $(n-2)$d.f.; $Sb_1 = 0.0494$; $Sy.x = 0.511$ ins.; $C_{11} = 0.0093$; $\bar{x} = 3.72$ ins.; $r = 0.608$; $F = 3.94$; s.l. >0.05.

(iv) April: $n = 24$; $(n-2)$d.f; $Sb_1 = 0.0605$; $Sy.x = 0.479$ ins.; $C_{11} = 0.0160$; $\bar{x} = 3.36$ ins.; $r = 0.668$; $F = 6.21$; s.l. <0.025.

(v) May: $n = 24$; $(n-2)$d.f.; $Sb_1 = 0.0936$; $Sy.x = 0.706$ ins.; $C_{11} = 0.0176$; $\bar{x} = 2.78$ ins.; $r = 0.694$; $F = 7.57$; s.l. <0.025.

(vi) June: $n = 24$; $(n-2)$d.f., $Sb_1 = 0.0707$; $Sy.x = 0.531$ ins.; $C_{11} = 0.0177$; $\bar{x} = 2.48$ ins.; $r = 0.617$; $F = 4.24$; s.l. $= 0.05$.

(vii) July: $n = 24$; $(n-2)$d.f.; $Sb_1 = 0.1151$; $Sy.x = 0.502$ ins.; $C_{11} = 0.0526$; $\bar{x} = 2.10$ ins.; $r = 0.615$; $F = 4.02$; s.l. >0.05.

(viii) August: $n = 24$; $(n-2)$d.f.; $Sb_1 = 0.0544$; $Sy.x = 0.484$ ins.; $C_{11} = 0.0126$; $\bar{x} = 2,74$ ins.; $r = 0.742$; $F = 10.44$; s.l. <0.01.

(ix) September: $n = 24$; $(n-4)$d.f.; $Sb_1 = 5.0861$; $Sy.x,x^2,x^3 = 0.875$; $C_{11} = 33.784$; $C_{12} = -11.531$; $C_{13} = 1.202$; $C_{22} = 3.985$; $C_{23} = -0.419$; $C_{33} = 0.0445$; $\bar{x} = 2.54$ ins.; $\bar{x}^2 = 7.53$; $\bar{x}^3 = 25.99$; $r = 0.496$; $F = 2.74$; s.l. >0.05.

(x) October: $n = 24$; $(n-4)$d.f.; $Sb_1 = 1.140$; $Sy.x,x^2,x^3 = 0.901$; $C_{11} = 1.602$; $C_{12} = -0.446$; $C_{13} = 0.0362$; $C_{23} = -0.0111$; $C_{33} = 0.00096$; $\bar{x} = 3.30$ ins.; $\bar{x}^2 = 13.82$; $\bar{x}^3 = 67.31$; $r = 0.300$; $F = 1.15$; s.l. >0.05; $C_{22} = 0.131$.

(xi) November: $n = 24$; $(n-4)$d.f.; $Sb_1 = 2.597$; $Sy.x,x^2,x^3 = 0.708$ ins.; $C_{11} = 13.469$; $C_{12} = -3.971$; $C_{13} = 0.361$; $C_{22} = 1.196$; $C_{23} = -0.110$; $C_{33} = 0.0103$; $\bar{x} = 3.45$ ins.; $\bar{x}^2 = 13.76$; $\bar{x}^3 = 60.89$; $r = 0.353$; $F = 0.91$; s.l. >0.05.

(xii) December: $n = 24$; $(n-2)$d.f.; $Sb_1 = 0.0526$; $Sy.x = 0.571$ ins.; $C_{11} = 0.00848$; $\bar{x} = 4.37$ ins.; $r = 0.741$; $F = 10.80$; s.l. <0.01.

(xiii) Annual: $n = 24$; $(n-3)$d.f.; $Sb_1 = 1.7376$; $Sy.x,x^2 = 3.677$ ins.; $C_{11} = 0.2233$; $C_{12} = -0.0029$; $C_{22} = 0.00004$; $\bar{x} = 37.71$ ins.; $\bar{x}^2 = 1447.3$; $r = 0.584$; $F = 6.61$; s.l. <0.01.

APPENDIX I(5): *Monthly yield multiple regression equation statistics for Paerau Bridge synthetic record determination (see Table 59).*

(i) January: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.326$ ins.; $\bar{x}_1 = 4.28$ ins.; $\bar{x}_2 = 4.02$ ins.; $C_{11} = 0.0479$; $C_{12} = -0,0211$; $C_{22} = 0.0251$; Multiple correlation coefficient $(r^1) = 0.857$; Partial correlation coefficients $r^{11}(x_1) = 0.279$ and $r^{11}(x_2) = 0.747$; $F = 13.85$; s.l. <0.01.

(ii) February: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.362$ ins.; $\bar{x}_1 = 4.02$ ins.; $\bar{x}_2 = 2.88$ ins.; $C_{11} = 0.0179$; $C_{12} = 0.0078$; $C_{22} = 0.0292$; $r^1 = 0.503$; $r^{11}(x_1) = 0.499$; $r^{11}(x_2) = 0.117$; $F = 1.69$; s.l. >0.05.

(iii) March: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.0898$; $\bar{x}_1 = 2.88$ ins.; $\bar{x}_2 = 3.42$ ins.; $C_{11} = 0.0262$; $C_{12} = 0.0034$; $C_{22} = 0.0249$; $r^1 = 0.558$; $r^{11}(x_1) = 0.045$; $r^{11}(x_2) = 0.557$; $F = 2.259$; s.l. >0.05.

(iv) April: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.330$; $\bar{x}_1 = 3.42$ ins.; $\bar{x}_2 = 3.66$ ins.; $C_{11} = 0.0258$; $C_{12} = 0.0064$; $C_{22} = 0.0302$; $r^1 = 0.824$; $r^{11}(x_1) = 0.717$; $r^{11}(x_2) = 0.778$; $F = 10.59$; s.l. <0.01.

(v) May: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.665$; $\bar{x}_1 = 3.66$ ins.; $\bar{x}_2 = 3.28$; $C_{11} = 0.0325$; $C_{12} = -0.0099$; $C_{22} = 0.0254$; $r^1 = 0.539$; $r^{11}(x_1) = 0.147$; $r^{11}(x_2) = 0.470$; $F = 2.04$; s.l. >0.05.

(vi) June: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.470$ ins.; $\bar{x}_1 = 3.28$ ins.; $\bar{x}_2 = 1.95$ ins.; $C_{11} = 0.0239$; $C_{12} = 0.0110$; $C_{22} = 0.0758$; $r^1 = 0.569$; $r^{11}(x_1) = 0.448$; $r^{11}(x_2) = 0.509$; $F = 2.40$; s.l. >0.05.

(vii) July: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.595$; $\bar{x}_1 = 1.95$ ins.; $\bar{x}_2 = 2.12$ ins.; $C_{11} = 0.0749$; $C_{12} = -0.0165$; $C_{22} = 0.0663$; $r^1 = 0.370$; $r^{11}(x_1) = -0.188$; $r^{11}(x_2) = 0.359$; $F = 0.79$; s.l. $>0,05$.

(viii) August: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.339$; $\bar{x}_1 = 2.12$ ins.; $\bar{x}_2 = 2.96$ ins.; $C_{11} = 0.0725$; $C_{12} = -0.0143$; $C_{22} = 0.0208$; $r^1 = 0.785$; $r^{11}(x_1) = 0.446$; $r^{11}(x_2) = 0.668$; $F = 8.01$; s.l. <0.01.

(ix) September: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.744$ ins.; $\bar{x}_1 = 2.96$ ins.; $\bar{x}_2 = 2.74$ ins.; $C_{11} = 0.0259$; $C_{12} = -0.0256$; $C_{22} = 0.0823$; $r^1 = 0.435$; $r^{11}(x_1) = 0.435$; $r^{11}(x_2) = -0.237$; $F = 1.17$; s.l. >0.05.

(x) October: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.863$ ins.; $\bar{x}_1 = 2.74$ ins.; $\bar{x}_2 = 3.48$ ins.; $C_{11} = 0.0649$; $C_{12} = 0.0143$; $C_{22} = 0.0260$; $r^1 = 0.440$; $r^{11}(x_1) = 0.405$; $r^{11}(x_2) = 0.331$; $F = 1.20$; s.l. >0.05.

(xi) November: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.466$ ins.; $\bar{x}_1 = 3.478$; $\bar{x}_2 = 3.70$ ins.; $C_{11} = 0.0311$; $C_{12} = 0.0183$; $C_{22} = 0.0408$; $r^1 = 0.475$; $r^{11}\ (x_1) = -0.007$; $r^{11}\ (x_2) = 0.418$; $F = 1.46$; s.l. >0.05.

From Table 60:-

(a) June-November: $r^1 = 0.670$; $r^{11}\ (x_1^1) = 0.099$; $r^{11}\ (x_2^1) = 0.434$; $r^{11}\ (x_3^1) = -0.016$; $r^{11}\ (x_4^1) = 0.118$; $r^{11}\ (x_5^1) = 0.071$; $r^{11}\ (x_6^1) = 0.366$; $F = 0.814$; s.l. >0.05.

(b) July-November: $r^1 = 0.666$; $r^{11}\ (x_2^1) = 0.470$; $r^{11}\ (x_3^1) = 0.006$; $r^{11}\ (x_4^1) = 0.115$; $r^{11}\ (x_5^1) = 0.026$; $r^{11}\ (x_6^1) = 0.408$; $F = 1.12$; s.l. >0.05.

(c) August-November: $r^1 = 0.535$; $r^{11}\ (x_3^1) = 0.140$; $r^{11}(x_4^1) = 0.148$; $r^{11}\ (x_5^1) = 0.068$; $r^{11}\ (x_6^1) = 0.389$; $F = 0.80$; s.l. >0.05.

(d) September-November: $r^1 = 0.521$; $r^{11}\ (x_4^1) = 0.243$; $r^{11}(x_5^1) = 0.047$; $r^{11}(x_6^1) = 0.383$; $F = 1.12$; s.l. >0.05.

(e) October-November: As for November above.

(xii) December: $n = 13$; $(n-3)$d.f.; $Sy.x_1,x_2 = 0.458$ ins.; $\bar{x}_1 = 3.70$ ins.; $\bar{x}_2 = 4.23$ ins.; $C_{11} = 0.0303$; $C_{12} = 0.0024$; $C_{22} = 0.0288$; $r^1 = 0.678$; $r^{11}\ (x_1) = 0.456$; $r^{11}\ (x_2) = 0.628$; $F = 4.26$; s.l. <0.05.

(xiii) Annual: As for Appendix I(4).

APPENDIX I(6): *Discharge regression equation statistics for synthetic record determination (cusecs). (see Table 74).*

A. *Taieri River at Paerau Bridge:*

(i) (ex Loganburn): n = 9; (n-2)d.f.; C_{11} = 0.00031; Sx = 20.2 cfs.;
$\bar{x}$ = 27.2 cfs.; Sy.x = 20.9 cfs.; r = 0.995; s.l. <0.01.

(ii) (ex Patearoa-Paerau Br. for Qpp <200 cfs.): n = 16; (n-2)d.f.;
Sx = 62.2 cfs.; $\bar{x}$ = 141 cfs.; Sy.x = 16.8 cfs.;
C_{11} = 0.00002; r = 0.970; s.l. <0.01.

(iii) (ex Patearoa-Paerau Br. for Qpp ⩾200 cfs.): n = 29; (n-2)d.f.;
Sx = 248 cfs.; $\bar{x}$ = 289 cfs.; Sy.x = 61.4 cfs.;
C_{11} = 0.000001; r = 0.985; s.l. <0.01.

B. *Taieri River at Patearoa-Paerau Bridge:*

(i) (ex Paerau Br. for Qp <200 cfs.): n = 16; (n-2)d.f.; Sx = 67.0 cfs.;
$\bar{x}$ = 141 cfs.; Sy.x = 15.8 cfs.; C_{11} = 0.00001; r = 0.970;
s.l. <0.01.

(ii) (ex Paerau Br. for Qp ⩾200 cfs.): n = 29; (n-2)d.f.; Sx = 227 cfs.;
$\bar{x}$ = 288 cfs.; Sy.x = 46.3 cfs.; C_{11} = 0.000001; r = 0.985;
s.l. <0.01.

C. *Taieri River at Upper Styx Valley Bridge:*

(i) (ex Paerau Br. for Qp <120 cfs.); n = 20; (n-2)d.f.; Sx = 98.9 cfs.;
$\bar{x}$ = 163 cfs.; Sy.x = 31.0 cfs.; C_{11} = 0.00001; r = 0.894;
s.l. <0.01.

(ii) (ex Paerau Br. for Qp ⩾120 cfs.): n = 19; (n-2)d.f.; Sx = 84.5 cfs.;
$\bar{x}$ = 150 cfs.; Sy.x = 16.8 cfs.; C_{11} = 0.00001; r = 0.922;
s.l. <0.01.

D. *Loganburn at Paerau Bridge:*

(i) n = 9; (n-2)d.f.; Sx = 134 cfs.; $\bar{x}$ = 155 cfs.; Sy.x = 3.00 cfs.;
C_{11} = 0.00001; r = 0.995; s.l. <0.01.

E. *Serpentine Creek at McDonald's Bridge:*

(i) n = 4; (n-2)d.f.; Sx = 178 cfs.; $\bar{x}$ = 220 cfs.; Sy.x = 5.17 cfs.;
C_{11} = 0.00001; r = 0.956; s.l. <0.025.

F. *Styx Creek at Paerau:*

(i) n = 26; (n-2)d.f.; Sx = 246 cfs.; $\bar{x}$ = 317 cfs.; Sy.x = 10.9 cfs.;
C_{11} = 0.000001; r = 0.742; s.l. <0.01.

APPENDIX II: NON-STANDARD COMPUTER PROGRAMMES

APPENDIX II(1): Drought analysis (see Herbst et al, 1966). (Written in Fortran IV for the IBM 360 computer at Otago University)

```
      DIMENSION OPS(18),GEM(12),WR(12),REEN(1000),VER(1000),W(12),PAR(12),
      VV(12),MIR(12)
  93  REWIND 4
      N = O
      READ(5,25) RK,RM,NBG,KX
  25  FORMAT(2F3.2,13,12)
      IF(RM) 200,200,201
 201  READ(5,26) (OPS(I),I=1,18)
  26  FORMAT(18A4)
      WRITE(6,27) (OPS(I),I=1,18)
  27  FORMAT(1H1,5X,18A4/// 62H ONSET      END      DURATION     SUM     SUM O
     IF   SUM OF NUMBER OF ,20X,42HACTUAL RAIN ACTUAL RAIN DURATION OF
     2   WET /4X,122HOF      OF       OF          OF        MEAN       TOTAL  MO
     3NTHS OF  DROUGHT  DROUGHT AS PERCENT  IN WET TIME WET PERIOD  SEV
     4ERITY/125H DROUGHT DROUGHT DROUGHT DEFICITS DEFICITS DEFICITS EXC
     5ESS D. INTENSITY SEVERITY  OF MEAN   . AS PERCENT    MONTHS       IN
     1DEX)
      DO 28 I = 1,12
  28 GEM(I) = O.
   5 READ(5,1)JAAR,(MIR(I),I=1,12)
   1 FORMAT(3X,12,12I4)
     LS=O
     LX=O
     MXR=O
     IF(JAAR) 3,3,4
   4 N = N + 1
     IF(MXR) 400,400,401
 400 DO 402 I = 1,12
     WR(I) = MIR(I)
 402 WR(I) = WR(I)/100.
     GO TO 403
 401 DO 404 I = 1,12
     WR(I) = MIR(I)
 404 WR(I) = WR(I)/254.
 403 IF(LS) 500,500,501
 501 SS = N - 1
     DO 502 I = KX,12
 502 WR(I) = GEM(I)/SS + 0.2*GEM(I)/SS
     GO TO 503
 500 IF(LX) 503,503,504
 504 SS = N - 1
     DO 505 I = 1,12
 505 WR(I) = GEM(I)/SS + 0.2*GEM(I)/SS
 503 DO 29 I = 1,12
  29 GEM(I) = GEM(I) + WR(I)
     WRITE(4) (WR(I),I=1,12)
     GO TO 5
   3 REWIND 4
     S = N
     TOT = O.
     DO 10 I = 1,12
     GEM(I) = GEM(I)/S
  10 TOT = TOT + GEM(I)
     NN = O
  31 READ(4) (WR(I),I=1,12)
    DO 30 I = 1,12
    K = NN*12 + I
    REEN(K) = WR(I)
```

```
 30 VER(K) = REEN(K) - GEM(I)
    NN = NN + 1
    IF(NN-N) 31,32,32
 32 REWIND 4
    DO 33 I = 1,12
 33 W(I) = 0.1*(1.+GEM(I)/(TOT/12.))
    NN = N*12
    DO 34 I = 2,NN
    J = I - (I/12)*12
    IF(J) 35,35,36
 35 J = 12
 36 VER(I) = VER(I) + VER(I-1)*W(J)
 34 CONTINUE
    DO 39 I = 1,12
 39 PAR(I) = GEM(I)
    DO 40 J = 1,11
    JJ = J + 1
    DO 40 I = JJ,12
    IF(PAR(J)-PAR(I)) 43,43,40
 43 TYD = PAR(I)
    K = I - J
    DO 44 IR = 1,K
    KK = I - IR + 1
 44 PAR(KK) = PAR(KK-1)
    PAR(J) = TYD
 40 CONTINUE
    DO 45 I = 1,12
    K = 13 - I
    TOP = 0.
    DO 46 J = 1,K
 46 TOP = TOP + PAR(J)
    PAR(K) = TOP
 45 CONTINUE
    DO 48 I = 1,12
    VV(I) = 0.
    DO 48 J = I,NN,12
    IF(VER(J)) 49,48,48
 49 VV(I) = VV(I) + VER(J)
 48 CONTINUE
    TVV = 0.
    DO 50 I = 1,12
    VV(I) = VV(I)/S
 50 TVV = TVV + VV(I)
    X = (RK*TVV + RM*PAR(1))/11.
    LM = 1
188 DO 56 I = LM,NN
    IF(VER(I)) 57,56,56
 57 IL = I - I/12*12
    IF(IL) 222,222,223
222 IL = 12
223 IF(VER(I)-VV(IL)) 224,224,56
224 IF(ABS(VER(I))-RM*PAR(1)) 58,60,60
 58 BTP = VER(I)
    BTNP = VER(I)
    DO 59 J = 1,11
    K = I + J
    IF(K-NN) 100,56,56
100 IF(VER(K)) 61,62,62
 61 BTP = BTP + VER(K)
 62 BTNP = BTNP + VER(K)
    IF(BTNP) 63,56,56
 63 FJ = J
    IF(ABS(BTP) - PAR(1) + FJ*X) 59,60,60
```

```
 59  CONTINUE
     GO TO 56
 60  BTP = 0.
     RNN = 0.
     WMP = 0.
     BOP = 0.
     MA = 0.
     RNT = 0.
     IME = I - 1
     IF(IME-LM) 161,162,162
162  DO 160 IQ = LM,IME
160  RNT = RNT + REEN(IQ)
     LL = LM
     LDD = I - LL
     SSR = LDD/12
     RNN = SSR * TOT
     WMP = SSR * TVV
     IA = LL + (LDD/12)*12
     IF(IA - IME) 410,410,430
410  IF((IA/12)-(IME/12)) 412,411,411
411  IA = IA - (IA/12)*12
     IME = IME - (IME/12)*12
     IF(IA) 413,413,414
413  IA = 12
     GO TO 422
414  IF(IME) 415,415,416
415  IME = 12
416  DO 417 M = IA,IME
     WMP = WMP + VV(M)
417  RNN = RNN + GEM(M)
     GO TO 430
412  IA = IA - (IA/12)*12
     IME = IME - (IME/12)*12
     IF(IA) 419,419,420
419  IA = 12
420  IF(IME) 421,421,422
421  IME = 12
     GO TO 416
422  DO 423 M = IA,12
     WMP = WMP + VV(M)
423  RNN = RNN + GEM(M)
     DO 424 M = 1,IME
     WMP = WMP + VV(M)
424  RNN = RNN + GEM(M)
430  PER = RNT/RNN * 100.
     XYZ = LDD
     PPP = ((RNT-RNN+WMP)/ABS(WMP))*100.*XYZ
161  DO 64 J = I,NN
     IF(VER(J)) 65,66,66
 65  BTP = BTP + VER(J)
     JN = J-(J/12)*12
     IF(JN) 405,405,406
405  JN = 12
406  IF(VER(J)-VV(JN)) 407,407,66
407  BOP = BOP + VER(J) - VV(JN)
     MA = MA + 1
 66  IF(J-NN) 101,68,68
101  IF(VER(J)) 64,102,102
102  IF(VER(J+1)) 67,67,68
 67  IF(VER(J+2)) 64,64,68
 68  BTNP = 0.
     WPF = 0.
     KK = J + 11
     DO 69 K = J,KK
     BTNP = BTNP + VER(K)
```

```
      WRF = WRF + REEN(K)
      KI = 1 + K - J
   72 IF(K - NN) 73,70,70
   73 IF(BTNP) 64,64,74
   74 IF(KI-3) 69,75,75
   75 IF(WRF - PAR(KI)) 69,70,70
   69 CONTINUE
      GO TO 64
   70 RNW = 0.
      LTD = J - I
      IB = I
      IE = J - 1
      DO 408 K = IB,IE
  408 RNW = RNW + REEN(K)
      SJR = LTD/12
      ZR = SJR * TVV
      RNG = SJR * TOT
      IB = I + (LTD/12) * 12
      IE = J - 1
      IF(IB-IE) 92,92,87
   92 IF((IB/12)-(IE/12)) 82,81,81
   81 IB = IB - (IB/12)*12
      IE = IE - (IE/12)*12
      IF(IB) 83,83,84
   83 IB = 12
      GO TO 308
   84 IF(IE) 85,85,86
   85 IE = 12
   86 DO 88 K = IB,IE
      RNG = RNG + GEM(K)
   88 ZR = ZR + VV(K)
      GO TO 87
   82 IB = IB - (IB/12)*12
      IE = IE - (IE/12)*12
      IF(IB) 305,305,306
  305 IB = 12
  306 IF(IE) 307,307,308
  307 IE = 12
      GO TO 86
  308 DO 89 K = IB,12
      RNG = RNG + GEM(K)
   89 ZR = ZR + VV(K)
      DO 90 K = 1,IE
      RNG = RNG + GEM(K)
   90 ZR = ZR + VV(K)
   87 Y = BOP/ZR * 100.
      RNP = RNW/RNG*100.
      XXX = LTD
      XX = Y*XXX
      IIB = I/12 + NBG
      IB = I - (I/12)*12
      IF(IB) 300,300,301
  300 IB = 12
      IIB = IIB - 1
  301 JJB = J/12 + NBG
      IE = J - (J/12) * 12
      IF(IE) 302,302,303
  302 IE = 12
      JJB = JJB - 1
  303 WRITE(6,76) IB,IIB,IE,JJB,LTD,BTP,ZR,BOP,MA,Y,XX,RNP,PER,LDD,PPP
   76 FORMAT(1HO,I2,2H 1,213,2H 1,13,16,2X,F8.1,F9.1,3X,F6.1,3X,I6,3X,F
     18.1,F10.1,F9.1,3X,F10.1,F11.1,F11.1)
      LM = J
      GO TO 91
   64 CONTINUE
   56 CONTINUE
      GO TO 166
```

```
   91 IF(LM-NN-3) 188,166,166
  166 WRITE(6,163) (GEM(I),I=1,12),TOT
  163 FORMAT(24HOMONTHLY MEAN RAINFALLS ,12F9.2/23HOANNUAL MEAN RAINFALL
     1 =,F9.2)
      WRITE(6,164) (W(I),I=1,12)
  164 FORMAT(16HOTHE WEIGHTS ARE/1X,12F8.3)
      WRITE(6,165) (VV(I),I=1,12),TVV
  165 FORMAT(31HOTHE MONTHLY MEAN DEFICITS ARE /1X,12F8.2/32HOAND THE AN
     1NUAL MEAN DEFICIT IS ,F8.2)
      WRITE(6,777) (PAR(I),I=1,12)
  777 FORMAT(43HOSUMS OF 1 - 12 MONTHS OF MAXIMUM RAINFALL /1X,12F8.2)
      GO TO 93
  200 STOP
      END
```

APPENDIX II(2): Potential evapotranspiration and water balance (see Thornthwaite, 1948; Thornthwaite & Mather, 1955, 1957). (Written in Fortran IV for the IBM 360 computer at Otago University)

```
C  PETHORN CALCULATES THORNTHWAITE POTENTIAL EVAPROTRANSPIRATION
C  TEMP IS MEAN MONTHLY TEMP DEGREES FAHRENHEIT TO ONE DECIMAL PLACE
C  H IS ALTITUDE IN HUNDREDS OF FEET A.S.L.
C  TABLE IS LATITUDE AND POSSIBLE DURATION OF SUNLIGHT CORRECTOR
C  1 IS LAT 35S 2 IS LAT 40S 3 IS LAT 42S 4 IS LAT44S 5 IS LAT 46S
C  IF YOU WISH THE PROGRAM ONLY TO DO THE CALCULATION OF THE POTENTIAL
C  EVAPOTRANSPIRATION, THEN REMOVE THE TWO SUBROUTINES AND ALL THE
C  YELLOW CARDS APPEARING IN THE MAIN SOURCE DECK - OTHERWISE THE PROGRAM
C  WILL PUNCH AS OUTPUT THE LAPSED TEMPERATURES AND THE POTENTIAL
C  EVAPOTRANSPIRATION
       DIMENSION TEMP(12),PE(12),P(12),TABLE(5,12),ATEMP(12), PE(12)
C  PE - POTENTIAL EVAPOTRANSPIRATION IN CMS.
C  APE - POTENTIAL EVAPOTRANSPIRATION IN INCHES
C  P - UNADJUSTED PE
       INTEGER ALT,UL,ALI
       DOUBLE PRECISION LATIT,LATI(5)
       DEFINE FILE 7(10000,20,U,IND)
       COMMON K,IND
       K = 0
       READ (1,607)(LATI(I), I = 1,5)
   607 FORMAT(A8,72X)
       READ(1,2)(TABLE(I,J),J=1,12),I=1,5)
     2 FORMAT(4X,12F5.2)
       READ (1,99) LAT,HH
    99 FORMAT (15,F5.2)
       LATIT = LATI(LAT)
       ALI = IFIX(HH*100.0 + 0.1)
C  A POTENTIAL EVAPORATION TABLE ISPRODUCED FOR EACH ALTITUDE L, (SEE
C  BELOW) STARTING AT LL AND GOING TO UL, INCREMENTING BY INC.
C  LL - LOWER LIMIT OF ALTITUDE RANGE IN FEET
C  UL - UPPER LIMIT OF ALTITUDE RANGE IN FEET
C  INC - INCREMENT OF ALTITUDE RANGE IN FEET
       READ (1,1) LL,KO
     1 FORMAT (215)
   100 READ (1,57) NNN,IYR,TEMP
    57 FORMAT (1X,15,12,T11,12F4.2)
       H = HH
       IF (NNN) 98,98,97
    97 IF (KO) 702,701,702
   701 WRITE(3,608) LATIT,ALI
   608 FORMAT('1',10X,'INPUT INFORMATION',//10X,'LATITUDE IS ',A8,' & ALT
      1ITUDE IS',15//,10X,'MONTH',5X,'TEMPERATURE',/)
       DO 301 I=1,12
   301 WRITE(3,300) I,TEMP(I)
   300 FORMAT(10X,14,9X,F6.2)
C  THIS CONVERTS TO CENTIGRADE
   702 DO 305 I=1,12
  1300 TEMP(I)=(TEMP(I)-32)*5.0/9.0
C  THIS LAPSES TEMPERATURES TO SEA LEVEL, DEPENDING UPON THE SEASON OF
C  THE YEAR
       IF(H-20.)40,40,42
    40 GO TO (400,400,401,401,401,402,402,402,403,403.403.400),I
   400 TEMP(I)=TEMP(I)+(0.056*H)
       GO TO 450
   401 TEMP (I)=TEMP(I)+(0.133*H)
       GO TO 450
   402 TEMP(I)=TEMP(I)+(0.239*H)
       GO TO 450
   403 TEMP(I)=TEMP(I)+(0.123*H)
       GO TO 450
    42 GO TO (410,410,411,411,411,412,412,412,413,413,413,410),I
   410 TEMP(I)=TEMP(I)+(0.206*(H-20.0)+1.12
       GO TO 450
   411 TEMP(I)=TEMP(I)+(0.195*(H-20.0))+2.66
       GO TO 450
   412 TEMP(I)=TEMP(I)+(0.240*(H-20.0))+4.78
       GO TO 450
```

```
   413 TEMP(I)=TEMP(I)+(0.195*(H-20.0))+2.46
       GO TO 450
   450 CONTINUE
   305 CONTINUE
C  THIS TAKES THE SEA LEVEL TEMPERATURES AND LAPSES THEM BACK TO THOSE
C  OF THE REQUIRED ALTITUDES AS INDICATED BY THE VALUE OF H
       H = FLOAT(LL)
       ALT =IFIX(H + 0.1)
       H = H/100.0
       DO 204 I=1,12
       IF(H-20.0)50,50,52
    50 GO TO (500,500,501,501,501,502,502,502,503,503,503,500),I
   500 ATEMP(I)=TEMP(I)-(0.056*H)
       GO TO 550
   501 ATEMP(I)=TEMP(I)-(0.133*H)
       GO TO 550
   502 ATEMP(I)=TEMP(I)-(0.239*H)
       GO TO 550
   503 ATEMP(I)=TEMP(I)-(0.123*H)
       GO TO 550
    52 GO TO (510,510,511,511,511,512,512,512,513,513,513,510),I
   510 ATEMP(I)=TEMP(I)-(0.206*(H-20.0))-1.12
       GO TO 550
   511 ATEMP(I)=TEMP(I)-(0.195*(H-20.0))-2.66
       GO TO 550
   512 ATEMP(I)=TEMP(I)-(0.240*(H-20.0))-4.78
       GO TO 550
   513 ATEMP(I)=TEMP(I)-(0.195*(H-20.0))-2.46
   550 CONTINUE
   204 CONTINUE
C  THIS CALCULATES THE HEAT INDEX
       SUMPE=0.0
       SUMI=0.0
       DO 10 I=1,12
       AATEMP = ATEMP(I)
       IF (AATEMP) 10,10,600
   600 SUMI = SUMI + (AATEMP   /5.0)**1.514
    10 CONTINUE
C  SUM1 EQUALS THORNTHWAITE I
C  A EQUALS THORNTHWAITE SMALL A P EQUALS THORNTHWAITE SMALL E
       A = 0.675E-6*SUMI**3 -0.771E-4*SUMI*SUMI +0.017921*SUMI +0.49239
       DO 11 I=1,12
       AATEMP  = ATEMP(I)
       IF (AATEMP) 605,605,606
   605 P(I) = 0.
       GO TO 11
   606 P(I) = 1.6*(10.*AATEMP   /SUMI)**A
    11 CONTINUE
       IF(LAT-5)34,34,32
    32 WRITE (3,33) LAT
    33 FORMAT (' INVALID LATITUDE',15)
       GO TO 100
    34 DO 41 I=1,12
       PE(I) = P(I)*TABLE(LAT,I)
       APE(I) = PE(I)/2.54
    41 SUMPE = SUMPE + PE(I)
       IF (KO) 704,703,704
   703 WRITE (3,205) LATIT,ALT,NNN,IYR
       SUMAPE = SUMPE/2.54
   205 FORMAT ('-',//9X,'LATITUDE IS ',A8,2X,'ALTITUDE IS', I5,'  SITE NO
      1. IS',I6,'       YEAR IS 19',12,///)
       WRITE (3,202)
   202 FORMAT(26X,'JAN      FEB    MARCH    APRIL     MAY      JUNE     J
      1ULY   AUGUST     SEPT      OCT     NOV      DEC',/)
       WRITE(3,203)(ATEMP(I),I=1,12)
   203 FORMAT (10X,'TEMP C',4X,12F9.3)
C  CONVERTS THE ABOVE TEMPERATURES TO FAHRENHEIT
   704 DO 604 I = 1,12
   604 ATEMP(I) = ATEMP(I)*9.0/5.0 + 32.0
       IF (KO) 706,705,706
   705 WRITE(3,603)(ATEMP (I),I= 1,12)
   603 FORMAT(10X,'TEMP F',4X,12F9.3)
```

```
      WRITE(3,303)(P(I),I=1,12)
  303 FORMAT(10X,'PE UNADJ. ',12F 9.3)
      WRITE(3,304)(TABLE(LAT,I),I=1,12)
  304 FORMAT(10X,'CORRECTOR ',12F9.3)
      WRITE(3,308)(PE(I),I=1,12)
  308 FORMAT(10X,'P.E. CMS. ',12F9.3)
      WRITE(3,306)(APE(I),I=1,12)
  306 FORMAT (10X,'P.E. INS  ',12F9.3,//)
      WRITE(3,201)SUMPE,SUMAPE
  201 FORMAT (10X,'TOTAL PE EQUALS',F9.2,' CMS',F9.2,' INS',///)
  706 K = K +1
      WRITE(7'K) IYR,ATEMP
      K = K + 1
      WRITE(7'K) IYR,APE
  206 CONTINUE
      GO TO 100
   98 CONTINUE
      CALL MATHER
      CALL SKIP
      END
      SUBROUTINE MATHER
      COMMON L,IND
C        WATER BALANCE BY THE METHOD OF THORNTHWAITE AND MATHER, (1957).
C        REFERENCE..
C        'INSTRUCTIONS AND TABLES FOR COMPUTING POTENTIAL EVAPOTRANSPIR-
C        AND WATER BALANCE'                                        ATION
C        DREXEL INSTITUTE OF TECHNOLOGY LABORATORY OF CLIMATOLOGY PUBLI-
C      IN CLIMATOLOGY, VOLUME 10, NUMBER 3, 1957.                CATIONS
      DIMENSION T(12),P(12),PE(12),WR(1800)
C        T - TEMPERATURE (TEMP)
C        P - PRECIPITATION (PREC)
C        PE - POTENTIAL EVAPOTRANSPIRATION
C        WR - SOIL MOISTURE RETENTION TABLE
      INTEGER TABL
C        TABL - THE NUMBER OF ENTRIES IN THE SOIL MOISTURE RETENTION
C        TABLE.        4'' ... 1100,       3'' ... 900
      READ (1,4) TABL
    4 FORMAT (I5)
      READ (1,8) (WR(J), J = 1,TABL)
    8 FORMAT(6X,10F6.2,14X)
C       THIS SETS INITIAL CONDITIONS
C        AC - ACCUMULATED POTENTIAL WATER LOSS
C        ST - SOIL MOISTURE STORAGE
C        RO - RUNOFF
C        SMRET - THE PARTICULAR SOIL MOISTURE RETENTION TABLE BEING USED
C        ALT - MEAN CATCHMENT ALTITUDE                           EG 4"
      READ(1,80)AC,ST,RO,SMRET,ALT
   80 FORMAT(5F10.2)
      WRITE(3,99)
   99 FORMAT('1')
      WRITE(3,1)
    1 FORMAT(20X,'WATER BALANCE FOR THE UPPER TAIERI BY THORNTHWAITE'//)
C        SNST - SNOW STORAGE AVAILABLE FOR RUNOFF WHEN THE TEMPERATURE
C        GREATER THAN 30.2 DEG F.
C        I - COUNTER FOR CHECKING THE PROPORTION OF SNST THAT BECOMES
C        SMRO IN SUCCEEDING MONTHS  (SEE BELOW)
      SNST =0
      I = 0
      DO 111 M = 1,L
      READ(7'M) IY,T
      M = M + 1
      READ(7'M) IY,PE
      READ(1,3)(P(J),J = 1,12)
    3 FORMAT(5X,12F4.2)
      WRITE(3,13)IY
   13 FORMAT(//20X,'WATER BALANCE FOR YEAR 19',I2,'   (IN INCHES)'/)
      WRITE(3,46)
   46 FORMAT(///'   MONTH  TEMP F     PE        P   P-PE   A P WL     ST
     1     DST       AE        D         S        RO   SMRO  TOT RO      DT'/)
C        A P WL - AC .. ACCUMULATED SUM OF NEGATIVE P - PE VALUES
C        ST - STORAGE
C        DST - CHANGE IN STORAGE
C        AE - ACTUAL EVAPOTRANSPIRATION
```

```
C          D - MOISTURE DEFICIT
C          S - MOISTURE SURPLUS (AMOUNT AVAILABLE FOR RUNOFF)
C          SMRO - SNOW MELT RUN OFF
C          PPE - P - PE
C          TOTRO = RO + SMRO
C          TOT... - VARIOUS ANNUAL TOTALS OF THE ABOVE VARIABLES.
C            TOTRRO - TOTAL RO
C            TOTSMR - TOTAL SMRO
C            TTOTRO - TOTAL TOTRO
C            TOTSNO - TOTAL PPE (= P) THAT FELL AS SNOW
      TOTPE = 0.
      TOTPPE = 0.
      TOTP = 0.
      TOTAE = 0.
      TOTD = 0.
      TOTS = 0.
      TOTRRO = 0.
      TOTRRO = 0.
      TOTSMR = 0.
      TTOTRO = 0.
      TOTSNO = 0.
      DO 30 J = 1,12
      PREC = P(J)
      POTEV = PE(J)
      TEMP = T(J)
      PPE = PREC - POTEV
      TOTPE = TOTPE + POTEV
      TOTPPE = TOTPPE + PPE
      TOTP = TOTP + PREC
      ACC = AC
      IF (PPE  )6,7,7
C        ACCUMULATES  P - PE LT 0 AND FINDS THE APPROPRIATE WR(I) FOR THE
                                                                       AC
    6 AC = AC + PPE
      INTERM = IFIX(-AC*100.0 + 0.5) + 1
      IF (INTERM - TABL) 16,16,5
    5 INTERM = TABL
   16 THISST = WR(INTERM)
      IF (ABS(ACC) - 0.001) 101,101,106
  101 IF (ST - 3.999) 105,105,106
  105 THISST = ST - (SMRET - THISST)
C        IF PPE LT 0, AND SNOW IS STILL STORED IN ST FROM THE PREVIOUS
C        MONTH THEN THE SNOW IS IGNORED AS FAR AS THIS PART OF ST IS
C        CONCERNED AND ST = SMRET TO OBTAIN A MEANINGFUL DST
  106 IF (ST - SMRET) 90,90,95
   95 ST = SMRET
      GO TO 90
    7 AC = 0.
C        TEST FOR SNOW
      IF (TEMP - 30.2) 89,82,82
C        IF PPE GT 0 AND SNOW STILL STORED IN ST FROM PREVIOUS MONTH
C        THEN THE SNOW IS IGNORED AS FAR AS THIS PART OF ST IS
C        CONCERNED AND ST = SMRET TO OBTAIN A MEANINGFUL DST
   82 IF (ST - SMRET) 60,60,61
   61 ST = SMRET
C        ENSURES THAT THIS MONTH'S ST (THISST) IS LE SMRET.  IF IT IS THEN
C        THISST = SMRET
   60 IF (ST + PPE    - SMRET - .001) 91,91,92
   92 THISST = SMRET
      GO TO 90
C        IF THISST LT SMRET, THEN THISST = LAST MONTH'S STORAGE (ST) +
C        EXCESS OF P OVER PE (PPE).
   91 THISST = ST + PPE
      GO TO 90
C        SNOW ACCUMULATION WHEN THE MONTHLY TEMPERATURE LT 30.2 DEG F.
   89 THISST = ST + PPE
      SNST = THISST - SMRET
      TOTSNO = TOTSNO + PPE
      DST = 0.
C        SNST GT 0 - ASSUMPTION THAT THIS PART OF THISST IS LYING AS SNOW
C        ON GROUND SURFACE
      IF (SNST) 90,90,81
```

```
   90 DST = THISST - ST
   81 ST = THISST
C         CALCULATIONS OF AE .. IF PPE GT 0 ASSUME AE = PE OTHERWISE STMT
      IF (PPE    )9,10,10                                                 9
   10 AE = POTEV
      GO TO 11
    9 AE = PREC - DST
   11 D = POTEV - AE
      TOTAE = TOTAE + AE
      TOTD = TOTD + D
C         CALCULATION OF MOISTURE SURPLUS
      IF (TEMP - 30.2) 12,14,14
   12 S = 0.
      GO TO 17
   14 IF (PPE    ) 12,15,15
   15 S =  PPE    - DST
      IF (S) 12,17,17
C         CALCULATION OF RO
C         50% RO AND S CARRY OVER FROM MONTH TO MONTH.
   17 RO = RO/2. + S/2.
C         THIS FIGURE OF 2 COULD BE VARIED SEE PAGE 194 OF ABOVE ARTICLE
      TOTS = TOTS + S
      TOTRRO = TOTRRO + RO
C         SNOWMELT SECTION.   ONLY SMRO WHEN TEMP GT 30.2 DEG F.
      IF (TEMP - 30.2) 25,26,26
   25 SMRO = 0.
      GO TO 27
   26 IF (SNST) 28,28,29
          THIS FIGURE MAY NEED ALTERING
   28 SMRO = 0.
      SNST = 0.
      GO TO 27
   29 X = SNST
      I=I+1
      IF (I-1)31,31,33
C         10% OF SNST BECOMES SMRO IN FIRST MONTH OF SMRO
   31 SMRO = X/10
      GO TO 27
C         IF ALTITUDE GT 500 FEET, 25% OF REMAINING SNST BECOMES SMRO
C         IN THE SECOND MONTH OF SMRO, OTHERWISE 50%
   33 IF (ALT - 500.0) 43,53,53
   53 IF (I - 2) 41,41,43
   41 SMRO = X/4.0
      GO TO 27
C         SUCCEEDING MONTHS ALWAYS 50%
   43 SMRO = X/2.
   27 SNST = SNST - SMRO
      IF (SNST - 0.001) 71,72,72
   71 SNST = 0.
      I = 0
   72 TOTRO = RO + SMRO
      TOTSMR = TOTSMR + SMRO
      TTOTRO = TTOTRO + TOTRO
      DT = ST + RO
      IF (SMRO - 0.001) 34,77,77
   77 DT = DT + SNST
   34 CONTINUE
      K = J
      WRITE(3,35)TEMP,POTEV,PREC,PPE    ,AC,ST,DST,AE,D,S,RO,SMRO,TOTRO,D
     1T,K
   35 FORMAT(8X,14F8,3,16)
   30 CONTINUE
  111 WRITE(3,100)  TOTPE,TOTP,TOTPPE,TOTAE,TOTD,TOTS,TOTRRO,TOTSMR
     1TTOTRO,TOTSNO
  100 FORMAT('O ANNUAL',8X,3F8.3,24X,6F8.3,///,20X'SNOW',F8.3,' INCHES'
     1/'1')
  110 RETURN
      END
```

APPENDIX II(3): Maximum daily rainfall and flood probability analysis (see Gumbel, 1958(a), 1958(b); Robertson, 1963) (Written in PL/I for the IBM 360 computer at Otago University)

```
RF..
  PROC OPTIONS(MAIN,ONSYSLOG),.
     DCL IN FILE RECORD INPUT ENV(MEDIUM(SYSIPT,1442) F(80) BUFFERS(2))
        , OUT FILE RECORD OUTPUT ENV(MEDIUM(SYSLST,1443) F(121)
               BUFFERS(2) CTLASA),.
     DCL PLSYS8 RECORD INPUT ENV(MEDIUM(SYS008,2311) F(800,80)),.
     DCL HIG CHAR(3),.
     DCL EXTREM ENTRY,.
     DCL (TEST,A,B,AA,BB,XX) FLOAT (16),.
     DCL (C,CARD) CHAR(80), LINE CHAR(121),.
     DCL 1 RFL,
            2 EXT (50) FLOAT(16),
            2 UTYPE CHAR(8),
            2 YRS BIN FIXED (31),
            2 UNIT CHAR (6),.
     DCL  (I,CARDNO,LIMIT) BIN FIXED (31),
          (START,MAX) PIC 'ZZZZZZ',
          VAR(12) PIC 'ZZZZZZ' DEF CARD,.
     DCL J BIN FIXED (31),.
     DCL ($P,$PP) PTR,
          P BIN FIXED (31) DEFINED $P,
          V PIC 'ZZZZZZ' BASED ($P),.
     OPEN FILE (IN),.
     OPEN FILE (PLSYS8),.
     ON ENDFILE (IN) GO TO NEXT,.
     HIG = HIGH(3),.
     READ FILE (IN) INTO (C),.
     UNIT = SUBSTR(C,75,6),.
     LINE = '1'CAT SUBSTR(C,1,74),.
     WRITE FILE (OUT) FROM (LINE),.
     LINE = '-',.
     WRITE FILE (OUT) FROM (LINE),.
     UTYPE = 'FLOW',.
     READ FILE (IN) INTO (C),.
     GET STRING (C) EDIT (TEST,A,B,AA,BB) (5 F(10,5)),.
     $PP = ADDR(VAR),.
     START = 0,.
     YRS = 0,.
  NEXTYEAR..
     MAX = START,.
     READ FILE (PLSYS8) INTO (C),.
     IF HIG = SUBSTR(C,1,3) THEN GOTO NEXT,.
     DO I = 1 TO 31,.
       READ FILE (PLSYS8) INTO (CARD),.
        $P = $PP,.
        DO P = P BY 110B TO P + 1000010B,.
           IF MAX LT V THEN  MAX = V,.
        END,.
     END,.
     YRS = YRS + 1,.
     XX = FLOAT(MAX,16),.
     IF XX LT TEST THEN EXT(YRS) = A*XX + B,.
        ELSE EXT(YRS) = AA*XX + BB,.
     GO TO NEXTYEAR,.
NEXT..
     CALL EXTREM (RLF),.
     CLOSE FILE (OUT),.
     CLOSE FILE (IN),.
  END RF,.
EXTREM..
 PROCEDURE(XS),.
    DCL 1 XS, 2 X(50) FLOAT(16),
              2 MAP CHAR(8),
              2 N BIN FIXED (31), 2 NAME CHAR(6),.
    DCL OUT FILE RECORD OUTPUT ENV(MEDIUM(SYSLST,1443) F(121) CTLASA),.
/*
    THIS PROCEDURE CALCULATES THE EXTREME VALUE PREDICTIONS FROM GIVEN
    EXTREME VALUES OF LARGE SAMPLES - IN THIS CASE EACH SAMPLE IS A
    YEAR.
```

```
  *****REFERENCES*****
  GUMBEL, E.J. 1958  'STATISTICS OF EXTREMES' (COLUMBIA U. P., N.Y.)
  GUMBEL, E.J. 1958 'STATISTICAL THEORY OF FLOODS AND DROUGHTS'
    (JNL INST. WATER ENGS VOL 12(3) PP 157 - 184)
  ROBERTSON, N.G. 1963 'THE FREQUENCY OF HIGH INTENSITY RAINFALLS
    IN NEW ZEALAND' (N.Z. MET. SERVICE MISC. PUB. 118)
*/
  DCL (NPM,K,J,I) BIN FIXED (31),.
  DCL SIGMAX FLOAT(16) INIT(0),.
  DCL SIGMAY FLOAT(16) INIT(0.),
      SIGMAXSQ FLOAT(16) INIT(0.),
      SIGMAYSQ FLOAT(16) INIT(0.),.
  DCL (TEMP,XX,NN,T,AINV,XT,EQ,U,EQ1,XN,TN,EQ2,T85,ALP) FLOAT (16),.
  DCL (EQ0,EQ3,X1,T15,T1,ZLP) FLOAT(16),.
  DCL (Y1,Y15,Y85,YN) FLOAT(16),.
  DCL LINE CHAR(121),.
  NPM = N + 1,.
  DO I = 1 TO N,.
     TEMP =  -LOG(-LOG(FLOAT(I)/FLOAT(NPM))),.
/*
  TEMP IS THE VARIABLE DERIVED FROM  (M/(N + 1)) ....  SEE GUMBEL
*/
      SIGMAY = SIGMAY + TEMP,.
      SIGMAYSQ = SIGMAYSQ + TEMP*TEMP,.
      XX = X(I),.
      SIGMAX = SIGMAX + XX,.
      SIGMAXSQ = SIGMAXSQ + XX*XX,.
  END,.
  LINE = '0',.
  SUBSTR(LINE,5,8) = HAP,.
  SUBSTR(LINE,21,13) = 'RETURN PERIOD',.
  SUBSTR(LINE,42,11) = 'LOWER LIMIT',.
  SUBSTR(LINE,61,11) = 'UPPER LIMIT',.
  WRITE FILE (OUT) FROM (LINE),.
  LINE = ' ',.
  SUBSTR)LINE,3,9) = 'IN' CAT NAME,.
  SUBSTR(LINE,23,8) = 'IN YEARS',.
  WRITE FILE (OUT) FROM (LINE),.
  LINE = ' ',.
  WRITE FILE (OUT) FROM (LINE),.
  NN = FLOAT(N),.
  AINV = SQRT((SIGMAXSQ - SIGMAX*SIGMAX/NN)/(NN - 1.0))/
         SQRT((SIGMAYSQ - SIGMAY*SIGMAY/NN)/(NN - 1.0),.
/*
  AINV IS 1/ALPHA
*/
  U = SIGMAX/NN - SIGMAY/NN*AINV,.  /* AS IN GUMBEL */
  DO I = 1 TO N - 1,.       /*  ORDERING X LOWEST TO HIGHEST   */
     DO J = 1 TO N - I,.
        IF X(J) GT X(J+1)  THEN DO,.
           XX = X(J+1),.
           X(J+1) = X(J),.
           X(J) = XX,.
       END,.
    END,.
 END,.
/*
  THE NEXT GROUP OF STATEMENTS ARE TO DO WITH SETTING UP THE TWO
  CONTROL BANDS WHICH ARE DIVIDED INTO FIVE SECTIONS.
*/
  EQ0 = AINV/(-LOG(0.15)*SQRT(NN*3.0/17.0)),.
  EQ1 = AINV/(-LOG(0.85)*SQRT(NN*17.0/3.0)),.
  EQ2 = 1.14078*AINV,.
  EQ3 = 1.14078*AINV/LOG(NN),.
  X1 = X(1),.
  XN = X(N),.
  Y1 = 1./ANIV*(X1-U),.
  YN = 1./AINV*(XN-U),.
  T1 = 1.0/(1.0 - EXP(-EXP(-Y1))),.
  T15 = 20.0/17.0,.
  T85 = 20.0/3.0,.
  TN = 1.0/(1.0 - EXP(-EXP(-YN))),.
  Y15 = -LOG(-LOG(1.-1./T15)),.
```

```
  Y85 = -LOG(-LOG(1.-1./T85)),.
  ZLP = (EQ3 - EQ0)/(Y1 - Y15),.
  ALP = (EQ2 - EQ1)/(YN - Y85),.
  DO I = 101,103,110,120,130,150,200,500 BY 500 TO 2500,5000,10000,.
    T = FLOAT(I)/100.0,.
    TEMP = -LOG(1.0 - 1.0/T),.
    XT = U +(-LOG(TEMP))*AINV,.
/*
    THIS GROUP OF IF.THEN..ELSES IS TO SELECT WHICH SECTION OF
    THE CONTROL BAND THE PARTICULAR VALUE OF T - THE RETURN
    PERIOD - LIES IN AND TO CALCULATE THE APPROPRIATE VALUE OF EQ.
    EQ IS ADDED TO & SUBTRACTED FROM EACH XT - THE FLOW FOR A
    PARTICULAR T - TO GIVE THE CONTROL BAND POINTS.
*/
    IF T LT T1 THEN EQ = EQ3,.  ELSE
      IF T LT T15 THEN EQ = (-LOG(TEMP)-Y15)*ZLP+EQ0,.   ELSE,.
        IF T LT T85 THEN EQ = AINV/(TEMP*SQRT(NN*(T - 1.0))),.
          ELSE IF T LT TN THEN EQ = (-LOG(TEMP)-Y85)*ALP+EQ1,.
            ELSE EQ = EQ2,.
    LINE = ' ',.
    PUT STRING (LINE) EDIT (XT,T,XT - EQ,XT + EQ)(X(1),F(9,2),X(12),
      F(7,2),X(12),F(9,2),X(10),F(9,2)),.
    WRITE FILE (OUT) FROM (LINE),.
  END,.
  LINE = ' ',.
  PUT STRING (LINE) EDIT ('0',U+AINV*0.5772156649,'2.33','MEAN ANNU',
    'AL EXTREME')(A,F(9,2),X(15),A,X(6),2 A),.
  WRITE FILE (OUT) FROM (LINE),.
  PUT STRING (LINE) EDIT (U,'MOST PROBABLE ANNUAL EXTREME')
    (X(1),F(9,2),X(25),A),.
  WRITE FILE (OUT) FROM (LINE),.
  LINE = '1',.
  WRITE FILE (OUT) FROM (LINE),.
  LINE = (6)' ' CAT 'X' CAT (11)' ' CAT 'RANK' CAT (11)' ' CAT
    'PLOT POSN',.
  WRITE FILE (OUT) FROM (LINE),.
  LINE = ' ',.
  WRITE FILE (OUT) FROM (LINE),.
  TEMP = FLOAT (NPM),.
  DO I = 1 TO N,.
    PUT STRING (LINE) EDIT (X(I),I,TEMP/(TEMP - FLOAT(I)))
      (X(1),F(9,2),X(9),F(3),X(9),F(9,2)),.
    WRITE FILE (OUT) FROM (LINE),.
  END
END EXTREM,.
```

APPENDIX II(4): Minimum flow probability analysis (See Gumbel, 1958(a), 1958(b)). (Written in PL/I for the IBM 360 computer at Otago University)

```
RF..
  PROC OPTIONS(MAIN,ONSYSLOG),.
    DCL PLSYS8 RECORD INPUT ENV(MEDIUM(SYS008,2311) F(800,80)),.
     DCL IN FILE RECORD INPUT ENV(MEDIUM(SYSIPT,1442) F(80) BUFFERS(2))
       , OUT FILE RECORD OUTPUT ENV(MEDIUM(SYSLST,1443) F(131)
             BUFFERS(2) CTLASA),.
    DCL HIG CHAR(3),.
     DCL EXTREM ENTRY,.
     DCL (TEST,A,B,AA,BB,XX) FLOAT (16),.
     DCL (C,CARD) CHAR(80), LINE CHAR(131),.
     DCL 1 RFL,
          2 EXT (50) FLOAT(16),
          2 UTYPE CHAR(8),
          2 YRS BIN FIXED (31),
          2 UNIT CHAR (6),.
     DCL  (I,CARDNO,LIMIT) BIN FIXED (31),
         (START INIT (999999),MAX,DELETE INIT(0)) PIC 'ZZZZZZ',
         VAR(12) PIC 'ZZZZZZ' DEF CARD,.
     DCL J BIN FIXED (31),.
     DCL ($P,$PP) PTR,
         P BIN FIXED (31) DEFINED $P,
         V PIC 'ZZZZZZ' BASED ($P),.
     OPEN FILE (IN),.
     OPEN FILE (OUT),.
    OPEN FILE (PLSYS8),.
    HIG = HIGH(3),.
     READ FILE (IN) INTO (C),.
     UNIT = SUBSTR(C,75,6),.
     LINE = '1'CAT SUBSTR(C,1,74),.
     WRITE FILE (OUT) FROM (LINE),.
     LINE = '-',.
     WRITE FILE (OUT) FROM (LINE),.
     UTYPE = 'FLOW',.
     READ FILE (IN) INTO (C),.
     GET STRING (C) EDIT (TEST,A,B,AA,BB) (5 F(10,5)),.
     $PP = ADDR(VAR),.
     YRS = O,.
  NEXTYEAR..
     MAX = START,.
    READ FILE (PLSYS8) INTO (C),.
    IF HIG = SUBSTR(C,1,3) THEN GOTO NEXT,.
     DO I = 1 TO 31,.
       READ FILE (PLSYS8) INTO (CARD),.
        $P = $PP,.
        DO P = P BY 110B TO P + 1000010B,.
               IF V GT DELETE THEN IF MAX GT V THEN MAX = V,.
        END,.
     END,.
     YRS = YRS + 1,.
     XX = FLOAT(MAX,16),.
     IF XX LT TEST THEN EXT(YRS) = A*XX + B,.
        ELSE EXT(YRS) = AA*XX + BB,.
     TO TO NEXTYEAR,.
NEXT..
     CALL EXTREM (RFL),.
     CLOSE FILE (OUT),.
     CLOSE FILE (IN),.
  END RF,.
/*
EXTREM..
 PROCEDURE(XS),.
    DCL 1 XS, 2 X(50) FLOAT(16),
              2 HAP CHAR(8),
              2 N BIN FIXED(31), 2 NAME CHAR(6),.
    DCL OUT FILE RECORD OUTPUT ENV(MEDIUM(SYSLST,1443) F(131) CTLASA),.
/*
    THIS PROCEDURE CALCULATES THE EXTREME VALUE PREDICTIONS FROM
    GIVEN EXTREME VALUES OF LARGE SAMPLES - IN THIS CASE EACH
    SAMPLE IS A YEAR
```

```
    ***** REFERENCES*****
    GUMBEL, E.J. 1958 'STATISTICS OF EXTREMES' (COLUMBIA U. P.,  N.Y.)
    GUMBEL, E.J. 1958 'STATISTICAL THEORY OF FLOODS AND DROUGHTS'
       (JNL INST. WATER ENGS VOL 12(3) PP 157 - 184)
*/
    DCL (NPM,K,J,I) BIN FIXED (31),.
    DCL SIGMAX FLOAT(16) INIT(0.),.
    DCL SIGMAXSQ FLOAT(16) INIT(0.),.
    DCL SIGMAX3 FLOAT(16) INIT(0.),.
    DCL (TEMP,XX,NN,T,AINV,XT,EQ,U,EQ1,XN,TN,EQ2,T85,ALP) FLOAT (16),.
    DCL (EQO,EQ3,X1,T15,T1,ZLP) FLOAT(16),.
    DCL LINE CHAR(131),.
    DCL (KK,KKINV,RM,LNXM) FLOAT(16),.
    DCL SQRTB1 FLOAT(16),.
    DCL GAMMA INTERNAL RETURNS (FLOAT(16)),.
    DCL F INTERNAL RETURNS (FLOAT(16)),.
    DCL FN INTERNAL RETURNS (FLOAT(16)),.
    DCL FCT INTERNAL RETURNS (FLOAT(16)),.
    DCL BINCHOP INTERNAL RETURNS (FLOAT(16)),.
    DCL IM BIN FIXED(31),.
    DCL (Y1,Y15,Y85,YN,XPLOT,XU,XL) FLOAT (16),.
    DCL (V,EPS,G1) FLOAT(16),.
    NPM = N + 1,.
    DO I = 1 TO N - 1,.    /*  ORDERING X LOWEST TO HIGHEST  */
       DO J = 1 TO N - I,.
          IF X(J) LT X(J+1) THEN DO,.
             XX = X(J+1),.
             X(J+1) = X(J),.
             X(J) = XX,.
         END,.
       END,.
    END,.
    DO I = 1 TO N,.
       XX = X(I),.
       SIGMAX = SIGMAX + XX,.
       SIGMAXSQ = SIGMAXSQ + XX*XX,.
       SIGMAX3 = SIGMAX3 + XX*XX*XX,.
    END,.
    NN = FLOAT(N),.
    XN = SIGMAX/NN,.        /*  MU1 OR MEAN  */
                /* MU2 OR VARIANCE */
    AINV =     ((SIGMAXSQ - SIGMAX*SIGMAX/NN)/(NN - 1.0)),.
              /* SKEW = MU3/(MU2**(3/2))     */
    SQRTB1 = (SIGMAX3 - 3.*SIGMAX*SIGMAXSQ/NN + 2.*SIGMAX*SIGMAX*SIGMAX
        /(NN*NN))/NN/SQRT(AINV*AINV*AINV),.
    DISPLAY('START METHOD 1'),.
    KK = BINCHOP(F),.
    IF KK = 0.0 THEN DO,.
       DISPLAY('START METHOD 2'),.
       GOTO METHOD TWO,.
    END,.
    KKINV = 1./KK,.
    G1 = GAMMA(1.+KKINV),.
          /* CHARACTERISTIC DROUGHT  */
    V = XN + SQRT(AINV)*(1.-G1)/SQRT(GAMMA(1.+2.*KKINV) - G1*G1),.
         /* VALUE WHICH DISTRIBUTION IS ASYMPTOTIC TI    */
    EPS = (XN - V*G1)/(1. - G1),.
    IF EPS GE X(N) THEN DO,.
METHODTWO..
      RM = 0.63212*(NN + 1.),.
      IM = BINARY(RM,31,0),.
      LNXM = LOG(X(IM)),.
      V = EXP((RM - FLOAT(IM,16))*(LOG(X(IM + 1)) - LNXM) - LNXM),.
      KK = BINCHOP(FN),.
      IF KK = 0.0 THEN DO,.
         DISPLAY('START METHOD 3'),.
         EPS = 0.0,.
         KK = BINCHOP(FCT),.
         IF KK = 0.0 THEN DO,.
            LINE = '-METHODS 1, 2 & 3 ALL FAILED',.
            WRITE FILE (OUT) FROM (LINE),.
            GOTO FINS,.
         END,.
         KKINV = 1./KK,.
         V = XN/GAMMA(1. + KKINV),.
      END,.
```

```
         ELSE DO,.
            KKINV = 1./KK,.
            G1 = GAMMA(1. + KKINV),.
            EPS = (XN - V*G1)/(1. -G1),.
         END,.
      END,.
      IF EPS LE 0.0 THEN
         IF NAME = 'CUSECS' THEN EPS = 0.0
      PUT STRING (LINE) EDIT ('OKK =',KK,' V =',V,' EPS =',EPS,
         ' X(N) =',X(N))(4 (A,E(20,10,11))),.
      WRITE FILE (OUT) FROM (LINE),.
      LINE = '1',.
      WRITE FILE (OUT) FROM (LINE),.
      LINE = '0',.
      SUBSTR(LINE,5,8) = HAP,.
      SUBSTR(LINE,21,13) = 'RETURN PERIOD',.
      SUBSTR(LINE,42,11) = 'LOWER LIMIT',.
      SUBSTR(LINE,61,11) = 'UPPER LIMIT',.
      SUBSTR(LINE,81,8) = 'LOG FLOW',.
      SUBSTR(LINE,104,3) = 'LOG',.
      SUBSTR(LINE,124,3) = 'LOG',.
      WRITE FILE (OUT) FROM (LINE),.
      LINE = ' ',.
      SUBSTR(LINE,3,9) = 'IN ' CAT NAME,.
      SUBSTR(LINE,23,8) = 'IN YEARS',.
      SUBSTR(LINE,100,11) = 'LOWER LIMIT',.
      SUBSTR(LINE,120,11) = 'UPPER LIMIT',.
      WRITE FILE (OUT) FROM (LINE),.
      LINE = ' ',.
      WRITE FILE (OUT) FROM (LINE),.
      NN = FLOAT(N),.
/*
      THE NEXT GROUP OF STATEMENTS ARE TO DO WITH SETTING UP THE TWO
      CONTROL BANDS WHICH ARE DIVIDED INTO FIVE SECTIONS.
*/
      EQ0 =KKINV/(-LOG(0.15)*SQRT(NN*3.0/17.0)),.
      EQ1 =KKINV/(-LOG(0.85)*SQRT(NN*17.0/3.0)),.
      EQ2 = 1.14078*KKINV,.
      EQ3 = 1.14078*KKINV/LOG(NN),.
      X1 = LOG(X(1) - EPS),.
      XN = LOG(X(N) - EPS),.
      U = LOG(V - EPS),.
      YN = KK*(XN - U),.     /* FROM TN */
      Y1 = KK*(X1 - U),.        /* FROM T1 */
      T1 = 1.0/(1.0 - EXP(-EXP(Y1))),.
      T15 = 20.0/17.0,.
      T85 = 20.0/3.0,.
      TN = 1.0/(1.0 - EXP(-EXP(YN))),.
      Y15 = LOG(-LOG(1. - 1./T15)),.
      Y85 = LOG(-LOG(1. - 1./T85)),.
      ZLP = (EQ3 - EQ0)/(Y1 - Y15),.
      ALP = (EQ2 - EQ1)/(YN - Y85),.
      DO I =101,103,110,120,130,150,200,500 BY 500 TO 2500,5000,10000,.
         T = FLOAT(I)/100.0,.
         TEMP = -LOG(1.0 - 1.0/T),.
           /*  XT IS THE PREDICTED FLOW FOR THE PARTICULAR T.    */
         XT = EPS + (V - EPS)*(TEMP**KKINV),.
/*
         THIS GROUP OF IF..THEN..ELSES IS TO SELECT WHICH SECTION OF
         THE CONTROL BAND THE PARTICULAR VALUE OF T - THE RETURN
         PERIOD - LIES IN AND TO CALCULATE THE APPROPRIATE VALUE OF EQ.
         EQ IS HALF THE CONTROL BAND WIDTH OF THE LOG - TRANSFORMED
         VARIATE XT - EPS.
*/
         IF T LT T1 THEN EQ = EQ3,. ELSE
            IF T LT T15 THEN EQ = (LOG(TEMP) - Y15)*ZLP + EQ0,. ELSE
               IF T LT T85 THEN EQ =KKINV/(TEMP*SQRT(NN*(T - 1.0))),.
                  ELSE IF T LT TN THEN EQ = (LOG(TEMP) - Y85)*ALP + EQ1,.
                    ELSE EQ = EQ2,.
         LINE = ' ',.
         XPLOT = LOG(XT - EPS),.
         XU = XPLOT + EQ,.
```

```
         XL = XPLOT - EQ,.
         PUT STRING (LINE) EDIT (XT,T,EXP(XL)+EPS,EXP(XU)+EPS,XPLOT,XL,
         XU)(X(1),F(9,2),X(12),F(7,2),X(12),F(9,2),X(10),F(9,2),X(10),
         F(9,4),X(11),F(9,4),X(12),F(9,4)),.
      WRITE FILE (OUT) FROM (LINE),.
   END,.
   LINE = '1',.
   WRITE FILE (OUT ) FROM (LINE),.
   LINE = (6)' ' CAT 'X' CAT (11)' ' CAT 'LOG X' CAT (11) ' ' CAT
      'RANK' CAT (11)' ' CAT 'PLOT POSN',.
   WRITE FILE (OUT) FROM (LINE),.
   LINE = ' ',.
   WRITE FILE (OUT) FROM (LINE),.
   TEMP = FLOAT(NPM),.
   DO I = 1 TO N,.
    PUT STRING (LINE) EDIT (X(I),LOG(X(I)-EPS),I,TEMP/(TEMP-FLOAT(I)))
         (X(1),F(9,2),X(6),F(9,4),X(9),F(3),X(12),F(9,2)),.
      WRITE FILE (OUT) FROM (LINE),.
   END,.
             /* F - THE FUNCTION VALUE FOR BINCHOP   */
F..
PROC (K) FLOAT(16),.
   DCL (K,KINV,G,N,G2,FN) FLOAT(16),.
      KINV = 1.0/K,.
      G = GAMMA(1.0 + KINV),.
   G2 = GAMMA(1. + 2.*KINV),.
   N = G2 - G*G,.
   FN = (GAMMA(1. + 3.*KINV) - 3.*G2*G + 2.*G*G*G)/SQRT(N*N*N) -
      SQRTB1,.
   RETURN (FN),.
 END F,.
/*
      END F
      BEGIN GAMMA FUNCTION .. ALGORITHM
*/
 GAMMA..
    PROC (X) FLOAT(16),.
       DCL (H INIT(1.0),Y,X) FLOAT(16),.
       Y = X,.
    A1..
       IF Y = 0.0 THEN H = 1.0E50,.
       ELSE IF Y = 2.0 THEN GOTO A2,.
       ELSE IF Y LT 2.0 THEN DO,.
          H = H/Y,.
          Y = Y + 1.0,.
          GO TO A1,.
       END,.
       ELSE IF Y GE 3.0 THEN DO,.
          Y = Y - 1.0,.
          H = H*Y,.
          GOTO A1,.
       END,.
       ELSE DO,.
          Y = Y - 2.0,.
          H = (((((((.0016063118*Y + .0051589951)*Y
              + .0044511400)*Y + .0721101567)*Y
              + .0821117404)*Y + .4117741955)*Y
              + .4227874605)*Y + .9999999758)*H,.
       END,.
    A2..
       RETURN(H),.

    END GAMMA,.
          /*  BEGIN BINCHOP WHICH SOLVES SKEW FOR KK VALUE  */
BINCHOP..
PROC(Z) FLOAT (16),.
   DCL Z RETURNS (FLOAT(16)),.
   DCL (C,EPSILON INIT(1.E-10),A INIT(1.499),B INIT (1.50),TEST)
      FLOAT(16),.
   ON OVERFLOW GOTO OVERFLOWEXIT,.
TRYAGAIN..
```

```
   IF Z(A)*Z(B) LT 0. THEN DO,.
AGAIN..
      C = (A + B)/2.,.
      IF Z(A)*Z(C) LT 0. THEN B = C,.
      ELSE A = C,.
      TEST = ABS(A - B),.
         IF TEST GT EPSILON THEN GOTO AGAIN,.
      RETURN (C),.
   END,.
   ELSE DO,.
      PUT STRING (LINE) EDIT ('OSOLUTION OF Z(X) IS OUTSIDE RANGE..',
         '    X =',A,'  TO X =',B)(A,2 (A,E(20,10,11))),.
      WRITE FILE (OUT) FROM (LINE),.
      A = A/2.,.          B = B*2.,.
      GO TO TRYAGAIN,.
   END,.
OVERFLOWEXIT..
   RETURN(0.0),.
END BINCHOP,.
FN..
PROC(K) FLOAT(16),.
   DCL (G1,KINV,K) FLOAT(16),.
   KINV = 1./K,.
   G1 = GAMMA(1. + KINV),.
   RETURN((1. - G1)/SQRT(GAMMA(1. +2.*KINV) - G1*G1) - (V - XN)/
      SQRT(AINV)),.
END FN,.
FCT..
PROC(K) FLOAT(16),.
   DCL (G1,KINV,K) FLOAT(16),.
   KINV = 1./K,.
   G1 = GAMMA(1. + KINV),.
   RETURN(GAMMA(1. + 2.*KINV)/(G1*G1) - 1. - AINV/(XN*XN)),.
END FCT,.
FINS..
END EXTREM,.
```

APPENDIX II(5): Modified conceptual model of system synthesis (see Hutchinson & Simmers, 1971; Boughton, 1965, 1968(b)). (Written in Fortran IV for the IBM 360 computer at Otago University)

```
      DIMENSION RAIN(31,12),EVAP(12),FEBETC(12),ROF(31,12),C(12)
      READ (1,1)CEPMAX,USMAX,DRMAX,SSMAX
    1 FORMAT (4F5.2)
      READ(1,1) CEP,US,DR,SS
      READ(1,1)ABC,PCUS,GWMAX,GW
      READ(1,1)FO,FC,AAK,AAC
      READ(1,1)XZ,XY,XX,BBC
      READ(1,2)(FEBETC(J),J=1,12)
    2 FORMAT(12A4)
C CEPMAX IS MAX INTERCEPTION STORE. USMAX IS MAX UPPER SOIL STORE.
C DRMAX IS MAX DRAINAGE STORE. SSMAX IS MAX SUBSOIL STORE.
C H IS MAX LIMIT FOR EVAPOTRANSPIRATION RATE.
C PCUS IS PERCENT ET LOST FROM US STORE.
C FO  DAILY INFILTRATION AT ZERO SOIL MOISTURE
C FC  IS MIN INF. RATE. AAK IS K IN INF. EQN. AAC IS FACTOR FORDEPLETING
C SUBSOIL MOISTURE BY DRAINAGE.
      WRITE(3,500)CEPMAX,USMAX,DRMAX, SSMAX
      WRITE(3,500)CEP,US,DR,SS
      WRITE(3,500)ABC,PCUS,GWMAX,GW
      WRITE(3,500)FO,FC,AAK,AAC
      WRITE(3,500)XZ,XY,XX
  500 FORMAT(4F10.3)
      WRITE(3,3)
    3 FORMAT(12X,'DAY MONTH YEAR     EST      EXCESS    SUBSL  CEP      US
     1 DRAIN SUBSL SPILL   DEF   GRNDWTR')
      WRITE(3,4)
    4 FORMAT(29X, 'RUNOFF   RAIN    STORE  STORE  STORE  STORE')
      F = FO
      CEPMAX = 0.
      Q = 0.0
      R = 0.0
      S = 0.0
      DIFF = 0.0
      QQ = 0.0
      H = XX
      DDIFF = 0.0
      RR = 0.0
      ST = 0.0
  223 SPILL = 0.
      SUM = CEPMAX + USMAS + DRMAX
      DEF = 0.
      READ(1,1002)NM,NYEARS,INIT
 1002 FORMAT(3I5)
      READ(1,1003)(C(J),J=1,12)
 1003 FORMAT(12F5.2)
      WRITE(3,1003)(C(J),J=1,12)
      GRUN = 0.01
    5 READ(1,1008)(EVAP(J),J=1,12)
 1008 FORMAT(5X,12F4.2)
      DO 577 J=1,12
  577 EVAP(J) =EVAP(J)/25.0
      WRITE(3,1003)(EVAP(J),J=1,12)
      DO 400 J=1,12
      READ(1,1004)RAIN(K,J),K=1,31)
 1004 FORMAT(10X,16F4.2/10X,15F4.2)
      DO 401 K = 1,31
```

```
  401 RAIN(K,J) = 1.08*RAIN(K,J)
  400 CONTINUE
      READ(1,555)((ROF(K,J),K=1,31),J=1,12)
  555 FORMAT(12F6.2,8X)
      DO  102 M = NM,12
      USMAX = USMAX*C(M)
      ROFF = 0.0
      DEFMAX = 0.
      P   = 0.
      ROM = 0.
      DIFF = 0.
      DO 101 J = 1,31
      Y = 0.
      RUN = 0.0
      EX = 0.0
      DIF = 0.
      FALL = 0.0
      IF (RAIN(J,M))101,228,125
C THIS DIVIDES DAILY RAIN INTO 1.5INCH LOTS
  125 IF(RAIN(J,M) - 1.5)12,12,126
  126 FALL = RAIN (J,M) - 1.5
      RAIN (J,M) = 1.5
   12 AA = CEP
      AB = US
      AC = DR
      AD = SS
C ADD RAIN TO VARIOUS STORES TILL USED UP
      CEP=CEP + RAIN(J,M)
      IF(CEPMAX-CEP)13,228,228
   13 EX  = CEP - CEPMAX
      CEP = CEPMAX
      US  = US + EX
      IF(USMAX - US)14,228,228
   14 EX = US - USMAX  US = USMAX
     >DR = DR + EX
      IF(DRMAX -DR)15,228,228
   15 EX = DR - DRMAX
      CALL RATE(F,FO,FC,SS,SSMAX,AAK)
      A = EX/F
      RUN = EX - F*TANH(A)
      DR = DR - RUN
      SSING = F
      IF(SSMAX - SS - F)226,226,229
  226 SPILL = SS + F - SSMAX
      GO TO 229
  228 EX = 0.0
  229 CONTINUE
      RUN = RUN + GRUN
      ROF(J,M) = ROF(J,M)*0.0167
      ROFF = ROFF + ROF(J,M)
      GRUN = 0.0
      WRITE(3,2003)J,FEBETC(M),INIT,RUN,EX,SS,CEP,US,DR,SSING,SPILL,DEF,
     1GW,RAIN(J,M),ROF(J,M)
 2003 FORMAT(16X,13,A4,I5,12F7.3)
C THIS WRITES OUT VALUES UNDER OLD SYSTEM
      DIF = RUN - ROF(J,M)
      DIF = DIF*DIF
      DIFF = DIFF + DIF
```

```
      SPILL = 0.
      DEF = 0.
   11 CEP = CEP - EVAP(M)
      IF(CEP)16,117,117
   16 EP = ABS(CEP)
      CEP = 0.
      US = US - PCUS*FUNCT(US,USMAX,H,EP)/100.
      SS = SS - (100. - PCUS)*FUNCT(SS,SSMAX,H,EP)/100.
  117 IF(DR)18,92,19
   18 DR = 0.
      GO TO 92
   19 CALL RATE(F,FO,FC,SS,SSMAX,AAK)
      IF(DR - F)121,121,122
  121 SS = SS + DR
      DR = 0.
      GO TO 123
  122 SS = SS + F
      DR = DR - F
C THIS USES UP RAIN OVER 1.50. FALL IS RAIN OVER 1.50.
   92 SS = SS + XZ*US*US
      US = US - XZ*US*US
      IF(SS - SSMAX)700,700,701
  701 US = US + SS - SSMAX
      SS = SSMAX
  700 CONTINUE
      IF(FALL)123,123,130
  130 RAIN(J,M) = RAIN(J,M) + FALL
      IF(FALL - 1.00)131,132,132
  131 X= FALL
      GO TO 133
  132 X = 1.0
  133 FALL = FALL - X
      A = X/F
      RUN = RUN + X-F*TANH(A)
      SS = SS + F*TANH(A)
      WRITE(3,134)RUN
  134 FORMAT(24X,F7.3)
      IF(FALL)123,123,130
  123 IF(SSMAX -SS)140,141,141
  140 Y = SS - SSMAX
      SS = SSMAX
  141 QQ = QQ + 0.005*SS*SS + 0.1*Y
      RR = RR + 0.005*SS*SS + 0.1*Y
      ST = ST + 0.03*SS*SS + 0.05*Y
      TT = 0.05*Y
      GRUN = QQ
      QQ = RR
      RR = ST
      ST = TT
      TT = 0.0
      Q = Q + 0.1*Y
      R = R + 0.3*Y
      S = S + 0.3*Y
      GW = GW + Q
      Q = R
      R = S
      S = 0.0
      SS = SS - 0.04*SS*SS
      IF(GW - BBC)170,170,171
```

```
  170 GO TO 172
  171 GRUN = GRUN + ABC*(GW - BBC)*(GW - BBC)
      GW = GW - ABC*(GW - BBC)*(GW - BBC)
  172 IF(GRUN - 31.3)143,142,142
 >142 GW = GW + GRUN - 31.3
  143 GW = GW + SS*(1. -AAC)   GRUN = 31.3
      SS = SS * AAC
      IF(GWMAX - GW)146,147,147
  146 SS = SS + GW - GWMAX
      GW = GWMAX
  147 DEF = SUM - CEP - US - DR
      P = P + RAIN(J,M)
      ROM = ROM + RUN
      IF(DEFMAX - DEF)22,101,101
   22 DEFMAX = DEF
  101 CONTINUE
      WRITE(3,1007)P,ROM,ROFF,GW
 1007 FORMAT(53X,4F7.2)
      WRITE(3,530)DIFF
  530 FORMAT(10X,'SUM OF SQUARED DIFFERENCES IS', F10.4)
      DDIFF = DDIFF + DIFF
      USMAX = USMAX/C(M)
  102 CONTINUE
      WRITE(3,1019)DDIFF
 1019 FORMAT(10X,'TOTAL SS',F10.4)
      NM = 1
      INIT = INIT + 1
      NYEARS = NYEARS - 1
      IF(NYEARS)30,30,5
   33 GO TO 5
   30 CONTINUE
   32 CONTINUE
      END
/*
// EXEC FORTRAN
      FUNCTION FUNCT(SMLEY,SMMAX,H,ET)
      POINT = H*SMLEY/SMMAX
      IF(POINT-ET)1800,1800,1801
 1800 FUNCT = POINT
      RETURN
 1801 FUNCT = ET
      RETURN
      END
/*
// EXEC FORTRAN
      SUBROUTINE RATE(F,FO,FC,SS,SSMAX,AAK)
      IF(SSMAX - SS)301,301,302
  301 F = FC + 0.01
      RETURN
  302 IF(SS)303,303,304
  303 F = FO + 0.01
      RETURN
  304 F = FC + (FO - FC)/EXP(AAK*SS)
      RETURN
      END
```

APPENDIX II(6): DASTAT - statistical analysis of monthly flows (see Thomas & Fiering, 1962; Pearson, 1968). (Written in Fortran IV for the IBM 360 computer at Otago University)

```
C       DASTAT (STATISTICAL ANALYSIS OF RECORD OF MONTHLY RIVER FLOW
C       DECLARATIONS .
        REAL XX(100,13),A(13),B(13),C(13),F(13),QMAX(13),
      1 QMIN(13),FLOW,TOTAL,COL1,COL2,QBAR(12),SEBAR(12),QPOT(12),
      2 SEPOT(12),QSTD(12),SESTD(12),QVAR(12),SEVAR(12),QSKW(12),
      3 SESKW(12),QREG(12),SEREG(12),QCOR(12),SCOR1(12),SCOR2(12),M,K1,K2
      4,K3,K4,K5,K6,K7,K8,L,WP(12),WM(12),WPP(12),WPM(12),K9,ANTOT,K10,
      5 D(13),K11,QKUR(13),K12,SEKUR(13),K13,K14
        INTEGER RDS,HEAD(19),K,I,J,YI,YF,Y,KK
        DOUBLE PRECISION DT
C       READ LENGTH OF RECORD AND NAME OF STATION
   33 READ (1,2) RDS,HEAD
    2 FORMAT (I3,1X,19A4)
        IF (RDS) 4,4,6
C       READ INITIAL YEAR
    6 READ (1,50) YI
   50 FORMAT (I5)
C       READ RECORD
        READ (1,273) YF
  273 FORMAT (I2)
        IF (YF) 274,274,275
  274 CONTINUE
        READ (1,8) (XX(1,I), I = 1,12)
    8 FORMAT (2X,12F5.0)
        YF = RDS - 1
        DO 7 K = 2,YF
        READ (1,270) (XX(K,I), I = 1,12)
  270 FORMAT (2X,12F5.0)
    7 XX(K - 1,13) = XX(K,1)
        READ (1,271) (XX(RDS,I), I = 1,12)
  271 FORMAT (2X,12F5.0)
        XX(RDS - 1,13) = XX(RDS,1)
        XX(RDS,13) = XX(1,1)
        GO TO 276
  275 CONTINUE
        DO 157 K = 1,RDS
        READ (1,158) (XX(K,I), I = 1,13)
  158 FORMAT (13F6.0)
  157 CONTINUE
  276 CONTINUE
C       WRITE RECORD
        KK = 0
  208 CONTINUE
        HEADING OF DATA
        CALL SKIP
        WRITE (3,51) RDS
   51 FORMAT (' ',T40,'FLOW RECORD ',I3,' YEARS',/)
        IF (KK) 4,212,213
  212 WRITE (3,52)HEAD
   52 FORMAT (T40,19A4//,T40,'MEANFLOW (CUSECS)',/)
        GO TO 214
  213 WRITE (3,215) HEAD
  215 FORMAT (T40,19A4//,T40,'LOG BASE 10 OF MEAN FLOW (CUSECS)',/)
  214 CONTINUE
        WRITE (3,64)
   64 FORMAT ('YEAR',14X,'JAN      FEB      MAR      APR      ',
      1 'MAY      JUN      JUL      AUG      SEP      OCT      NOV',
      2 '      DEC         YEAR',/)
        L = RDS
        YF = YI + L - 1
C       DATA
        DO 53 Y = YI,YF
        K = Y - YI + 1
        ANTOT = 0
        DO 55 I = 1,12
```

```
   55 ANTOT = ANTOT + XX(K,I)
      ANTOT = ANTOT/12
      IF (KK) 280,280,281
  281 WRITE (3,282) Y, (XX(K,I), I = 1,12),ANTOT
  282 FORMAT (I5,T14,12F9.3,F9.3)
      GO TO 53
  280 WRITE (3,54) Y,(XX(K,I), I = 1,12),ANTOT
   54 FORMAT (I5,T14,12F9.0,F9.0)
   53 CONTINUE
C     INITIALISE WORKING PARAMETERS
      DO 10 I = 1,13
      A(I) = 0
      B(I) = 0
      C(I) = 0
      D(I) = 0
      F(I) = 0
   10 CONTINUE
      TOTAL = 0
C     SELECT MAXIMUM AND MINIMUM
      DO 9 I = 1,13
      QMAX(I) = -1.0
      QMIN(I) = 99999.0
      DO 9 J = 1,RDS
      FLOW = XX(J,I)
      IF (QMAX(I) - FLOW) 12,11,11
   12 QMAX(I) = FLOW
   11 IF (FLOW - QMIN(I)) 13,68,68
   13 QMIN(I) = FLOW
   68 CONTINUE
C     COMPUTE WORKING PARAMETERS
      A(I) = A(I) + FLOW
      B(I) = B(I) + FLOW*FLOW
      C(I) = C(I) + FLOW*FLOW*FLOW
      D(I) = D(I) + FLOW*FLOW*FLOW*FLOW
    9 CONTINUE
      DO 14 I = 1,12
      DO 14 J = 1,RDS
      COL1 = XX(J,I)
      COL2 = XX(J,I + I)
   14 F(I) = F(I) + COL1*COL2
      K8 = EXP(SQRT(8/(L - 3)))
      K10 = SQRT(6*L*(L - 1)/((L - 2)*(L + 1)*(L + 3)))
      K12 = SQRT(96/L)
C     COMPUTE MEAN, SE OF MEAN, STD DEV, SE OF STD VAR, COEFF VARIATION,
C     ALSO SE OF KURTOSIS
C     SE OF CO VARI AND SE OF SKEW
      DO 15 I = 1,12
      K3 = A(I)
      QBAR(I) = K3/L
      K1 = B(I) - A(I)*A(I)/L
      QSTD(I) = SQRT(K1/(L - 1.0))
      K2 = QSTD(I)
      SEBAR(I) = K2/SQRT(L)
      SESTD(I) = 0.7071*SEBAR(I)
      QVAR(I) = K2*L/K3
      SEVAR(I) = SESTD(I)/QBAR(I)
      K4 = C(I) - 3.0*K3*B(I)/L + 2.0*K3*K3*K3/ (L*L)
      K11 = D(I) - 4.0*K3*C(I)/L + 6.0*K3*K3*B(I)/(L*L) - 3.0*K3*K3*K3
     1 *K3/(L*L*L)
      SESKW(I) = K10
      SEKUR(I) = K12
      K5 = B(I + 1) - A(I + 1)*A(I + 1)/L
C     SET SKEW AND REG CO TO ARBITRARY VALUES IF STD DEV IS ZERO
C     ALSO KURTOSIS
      IF (K2) 40,40,41
   40 QSKW(I) = 999.999
      QREG(I) = 999.999
      QKUR(I) = 999.999
      GO TO 45
```

```
C     COMPUTE SKEW AND REG CO IF STD DEV NOT ZERO
C     ALSO KURTOSIS
   41 QSKW(I) = K4*SQRT(L/(K1*K1*K1))
      QREG(I) = (F(I) - K3*A(I + 1)/L)/K1
      QKUR(I) = (K11*L)/(K1*K1) - 3.0
C     SET COR CO TO ARBITRARY VALUE IF STD DEV FOR THIS MONTH OR NEXT
C     MONTH IS ZERO
   45 IF (K2*K5) 42,42,43
   42  QCOR(I) = 999.999
      SCOR1(I) = 999.999
      SCOR2(I) = 999.999
      GO TO 15
C     COMPUTE COR CO AND TWO-THIRDS CONFIDENCE LIMITS IF NEITHER STD DEV
C      IS ZERO
   43 QCOR(I) = (F(I) - K3*A(I + 1)/L)/SQRT(K1*K5)
      K4 = QCOR(I)
      K6 = 1 - K4
      K7 = 1 + K4
      SCOR1(I) = (K7*K8 - K6)/(K7*K8 + K6)
      SCOR2(I) = (K7 - K8*K6)/(K7 + K8*K6)
C     COMPUTE SE OF REG CO
      K9 = QREG(I)
      SEREG(I) = SQRT((K9*K9*K6*K7)/(K4*K4*(L -2)))
   15 CONTINUE
C     COMPUTE MONTHLY PROPORTION OF ANNUAL TOTAL FLOW AND SE OF MPOT
      DO 16 I = 1,12
   16 TOTAL = TOTAL + QBAR(I)
      DO 17 I = 1,12
      QPOT(I) = QBAR(I)/TOTAL
   17 SEPOT(I) = SEBAR(I)/TOTAL
C     WRITE ANALYSIS
C     HEADING OF ANALYSIS
    5 CONTINUE
      CALL JOBDAY
      IF (KK) 4,203,204
  203 WRITE (3,1)
    1 FORMAT (' DASTAT',T40,'STATISTICAL  ANAYSIS OF RIVER FLOW'/)
      WRITE (3,18) HEAD
   18 FORMAT (T40,'ANALYSIS OF MEAN MONTHLY RIVER FLOW',
     1 ' (CUSECS)',//,T40,19A4/)
      GO TO 207
  204 WRITE (3,205)
  205 FORMAT ('ODASTAT',T40,'STATISTICAL  ANAYSIS OF LOG BASE 10 '
     1 'OF RIVER FLOW',//)
      WRITE (3,206) HEAD
  206 FORMAT (' ANALYSIS OF LOG BASE 10 OF MEAN MONTHLY RIVER FLOW ',
     1 ' (CUSECS)',//,T40,19A4/)
  207 CONTINUE
      WRITE (3,19)
   19 FORMAT (' STATISTIC',11X,'JAN      FEB      MAR      APR      ',
     1 'MAY      JUN      JUL      AUG      SEP      OCT      NOV',
     2 '      DEC',/)
C     ANALYSIS
C     MEAN AND 2/3 CONFIDENCE LIMITS
      DO 30 I = 1,12
      WP(I) = QBAR(I) + SEBAR(I)
      WM(I) = QBAR(I) - SEBAR(I)
      WPP(I) = QPOT(I) + SEPOT(I)
      WPM(I) = QPOT(I) - SEPOT(I)
   30 CONTINUE
      WRITE (3,20) QBAR,SEBAR,WP,WM
   20 FORMAT (' MEAN(D)',T17,12F9.2/,' SE OF MEAN',T17,12F9.2/,
     I ' MEAN + SE',T17,12F9.2/,' MEAN - SE',T17,12F9.2//)
C     MONTHLY PROPORTION OF ANNUAL TOTAL AND 2/3 CONFIDENCE LIMITS
      WRITE (3,21) QPOT,SEPOT,WPP,WPM
   21 FORMAT (' MPOT(N)',T17,12F9.3/,' SE OF MPOT',T17,12F9.3/,
     1 ' MPOT + SE', T17,12F9.3/,' MPOT - SE',T17,12F9.3//)
```

```
C     STANDARD DEVIATION AND COEFFICIENT OF VARIATION WITH 2/3 CLS
      DO 31 I = 1,12
      WP(I) = QSTD(I) + SESTD(I)
      WM(I) = QSTD(I) - SESTD(I)
      WPP(I) = QVAR(I) + SEVAR(I)
      WPM(I) = QVAR(I) - SEVAR(I)
   31 CONTINUE
      WRITE (3,22) QSTD,SESTD,WP,WM
   22 FORMAT (' STD DEV (D) ',T17,12F9.2/,' SE OF STD DEV',T17,12F9.2/,
     1 ' STD DEV + SE',T17,12F9.2/,' STD DEV - SE',T17,12F9.2//)
      WRITE (3,23) QVAR,SEVAR,WPP,WPM
   23 FORMAT (' CO VARI (N)',T17,12F9.3/,' SE OF CO VARI',T17,12F9.3/,
     1 ' CO VARI + SE',T17,12F9.3/,' CO VARI - SE',T17,12F9.3//)
C     SKEW AND KURTOSIS WITH 2/3 CLS
      DO 32 I = 1,12
      WP(1) = QSKW(I) + SESKW(I)
      WM(I) = QSKW(I) - SESKW(I)
      WPP(I) = QKUR(I) + SEKUR(I)
      WPM(I) = QKUR(I) - SEKUR(I)
   32 CONTINUE
      WRITE (3.24) QSKW,SESKW,WP,WM
   24 FORMAT (' SKEW (N)',T17,12F9.3/,' SE OF SKEW',T17,12F9.3/,
     1 ' SKEW + SE',T17,12F9.3/,' SKEW - SE',T17,12F9.3//)
      WRITE (3,82) (QKUR(I), I = 1,12),(SEKUR(I), I = 1,12),WPP,WPM
   82 FORMAT (' KURTOSIS (N)',T17,12F9.3/' SE OF KURTOSIS',T17,12F9.3/,
     1 ' KURTOSIS + SE', T17,12F9.3/,' KURTOSIS - SE',T17,12F9.3//)
C     REGRESSION AND CORRELATION COEFFICIENTS WITH 2/3 CLS
      DO 80 I = 1,12
      WPP(I) = QREG(I) + SEREG(I)
      WPM(I) = QREG(I) - SEREG(I)
   80 CONTINUE
      WRITE (3,25) QREG,SEREG,WPP,WPM
   25 FORMAT (' REG CO (N)',T17,12F9.3/,' SE OF REG CO',T17,12F9.3/,
     1 'REG CO + SE',T17,12F9.3/,' REG CO -SE',T17,12F9.3//)
      WRITE (3,26) QCOR,SCOR1,SCOR2
   26 FORMAT (' COR CO (N)',T17,12F9.3/, ' .16 PROB HI CC',T17,12F9.3/,
     1 ' .16 PROB LO CC',T17,12F9.3//)
C     MAXIMUM AND MINIMUM
      WRITE (3,27) (QMAX(I), I = 1,12),(QMIN (I), I = 1,12)
   27 FORMAT (' MAX VALUE (D)',T17,12F9.2/,' MIN VALUE',T17,12F9.2//)
C     MEAN ANNUAL FLOW
      FLOW = TOTAL/12
      WRITE (3,28) FLOW,RDS
   28 FORMAT (' MEAN ANNUAL FLOW (D)',T26,F9.2//,' LENGTH OF RECORD',
     1 ' (YEARS)', I9,//,' (D) = DIMENSIONAL  (N) = NON-DIMENSIONAL',//)
C     TRANSFORM FLOW RECORD TO LOG FLOW RECORD
      IF (KK) 4,210,211
  210 DO 200 K = 1,RDS
      DO 200 I = 1,13
      IF (XX(K,I)) 150,150,151
  150 XX(K,I) = 1.0
  151 CONTINUE
      XX(K,I) = ALOG10(XX(K,I))
  200 CONTINUE
      KK = 1
C     REPEAT FOR LOG FLOW RECORD
      GO TO 208
  211 CONTINUE
C     REPEAT FOR NEXT RECORD
      GO TO 33
C     CLOSE DOWN
    4 END
```

APPENDIX II(7): GENSYN - sequential generation of synthetic flow record (see Thomas & Fiering, 1962; Pearson, 1968). (Written in Fortran IV for the IBM 360 computer at Otago University)

```
C     GENSYN (GENERATES SYNTHETIC RECORD OF RIVER FLOW)
C     DECLARATIONS
      REAL Q (101,13),QBAR (13),QSTD(13),QSKW(13),QREG(13),QCOR(13),Z,
     1N,E(13),G,R(13),A(25),B(25),C(14,13),K1,QMIN(13)
      INTEGER L,I,K,M(13),XO,P,HEAD(19),O,W,LL,IX,T,K2,KK,QQ(13)
      DOUBLE PRECISION DT
      CALL JOBDAY
C     READ LENGTH OF SYNTHETIC RECORD AND NAME OF RIVER AND STATION
   69 READ (1,2) L,HEAD
    2 FORMAT (I3,IX,19A4)
      IF(L) 111,111,3
    3 CONTINUE
      W = 6
      IF (100 - L) 1,99,99
   99 CONTINUE
C     QUERY ARE DATA BASED ON LOG TRANSFORMED FLOW RECORD
      READ (1,200) KK
  200 FORMAT (I2)
C     QUERY IS SKEW TO BE MODIFIED TO ELIMINATE NEGATIVE OR ZERO FLOW
      READ (1,130) LL
  130 FORMAT (I2)
C     WRITE HEADING FOR STATISTICS OF FLOW RECORD
C     HEADING
      WRITE (3,4)
    4 FORMAT (' GENSYN', T40,'SYNTHETIC RECORD OF RIVER FLOW',//)
      WRITE (3,5) HEAD,L
    5 FORMAT (T40,19A4//,T40,'INPUT STATISTICS',
     1'OF MONTHLY FLOWS',//,I3,' YEAR SYNTHETIC RECORD',/)
      IF (KK) 111,201,202
  202 WRITE (3,203)
  203 FORMAT (T40,'(STATISTICS OF LOG 10 TRANSFORM OF FLOW RECORD)',/)
  201 CONTINUE
      IF (LL) 111,131,132
  132 WRITE (3,133)
  133 FORMAT (' SKEW VALUES MODIFIED BY PROGRAM TO ELIMINATE ZERO OR ',
     1'NEGATIVE FLOWS IN SYNTHETIC FLOW RECORD',/)
  131 CONTINUE
      IF (LL) 90,90,91
   91 CONTINUE
      WRITE (3,6)
    6 FORMAT (T32,'MONTH',T46,'MEAN',T55,'S DEV    SKEW    REG C       ',
     1'COR C',/)
      GO TO 94
   90 WRITE (3,93)
   93 FORMAT (T32,'MONTH',T46,'MEAN',T54,'ABS MIN', T65,'S DEV    SKEW   ',
     1'REG C    COR C',/)
   94 CONTINUE
C     READ STATISTICS OF FLOW RECORD
      DO 7 I = 1,12
      READ (1,17) QBAR(I),QSTD(I),QSKW(I),QREG(I),QCOR(I),QMIN(I)
   17 FORMAT (6F9.3)
      R(I) = 1 - QMIN(I)/QBAR(I)
      IF (R(I)) 101,101,102
  101 R(I) = 1
  102 CONTINUE
    7 CONTINUE
      QBAR(13) = QBAR(1)
      QSTD(13) = QSTD(1)
      QSKW(13) = QSKW(1)
      QREG(13) = QREG(1)
      QCOR(13) = QCOR(1)
      R(13) = R(1)
```

```
C       MODIFY SKEW IF NEGATIVE FLOWS ARE TO BE ELIMINATED
        IF (LL) 111,134,135
  134   CONTINUE
        DO 100 I = 1,12
        K1 = QCOR(I)
        Z = 2*QSTD(I + 1)*SQRT(1 - K1*K1)
        N = QBAR(I + 1)*R(I + 1) - QREG(I)*QBAR(I)*R(I)
        QSKW(I + 1) = Z/N
  100   CONTINUE
        QSKW(1) = QSKW(13)
  135   CONTINUE
C       WRITE STATISTICS OF FLOW RECORD
        DO 103 I = 1,12
        IF (LL) 95,95,96
   96   CONTINUE
        WRITE (3,8) I,QBAR(I),QSTD(I),QSKW(I),QREG(I),QCOR(I)
    8   FORMAT (T33,I2,T40,5F9.3/)
        GO TO 97
   95   CONTINUE
        WRITE (3,98) I,QBAR(I),QMIN(I),QSTD(I),QSKW(I),QREG(I),QCOR(I)
   98   FORMAT (T33,I2,T43,6F9.3/)
   97   CONTINUE
C       TEST STATISTICS OF FLOW RECORD AND FAIL IF STATISTICS INADMISSIBLE
        W = 1
        IF (QBAR(I)) 1,9,9
    9   W = 2
        IF (1.0E5 - QBAR(I)) 1,1,20
   20   W = 3
        IF (QSTD(I)) 1,21,21
   21   W = 4
        IF (1 - QCOR(I)*QCOR(I)) 1,23,23
   23   W = 5
        IF (KK) 111,88,89
   89   IF (5.0 - QBAR(I)) 88,1,1
   88   CONTINUE
C       CALCULATE THE ORDER OF GAMMA
        IF (QSKW(I)) 24,25,24
   24   N = QSKW(I)*QSKW(I)
        R(I) = 8/N
        M(I) = 8/N
        GO TO 103
   25   M(I) = 100
        R(I) = 100
  103   CONTINUE
        M(13) = M(1)
        R(13) = R(1)
C       INITIALISE FLOW RECORD
        Q(1,1) = QBAR(1)
C       INITIALISE RANDOM SEQUENCE
        READ (1,26) XO
   26   FORMAT (3X,I9)
        IF (XO - 100000000) 80,80,81
   81   IF (MOD(XO,2)) 82,80,82
   80   XO = 100000001
   82   CONTINUE
        IX = XO
        WRITE (3,171) IX
  171   FORMAT (' RANDOM SEQUENCE INITIALISING VALUE = ',112,/,' NINE ',
       1'DIGIT ODD INTEGER',//)
C       GENERATE SKEWED RANDOM DEVIATE WITH ZERO MEAN AND UNIT VARIANCE
        K = 0
   60   CONTINUE
        K = K + 1
        DO 27 I = 1,12
        T = M(I + 1)
        S = R(I + 1)
        Z = 0
   29   IF (25 - T) 42,42,41
   41   IF (T) 43,43,40
```

```
   40 DO 48 P = 1,T
      CALL GAUSS (XO,1.0,0.0,G)
   48 Z = Z + G*G
   43 CALL GAUSS (XO,1.0,0.0,G)
      Z = Z + (S - T)*G*G
      E(I) = (Z - S)/SQRT(2.0*S)
      GO TO 50
   42 CALL GAUSS (XO,1.0,0.0,G)
      E(I) = G
C     THOMAS AND FIERING SYNTHESIS EQUATION
   50 CONTINUE
   45 Q(K,I + 1) = QBAR(I + 1) + QREG(I)*(Q(K,I) - QBAR (I))
     1 + E(I)*QSTD(I + 1)*SQRT(1 - QCOR(I)*QCOR(I))
C     SET NEGATIVE FLOWS TO ZERO
      IF (Q(K,I + 1)) 46,47,47
   46 Q(K,I + 1) = 0.0
   47 CONTINUE
C     RECYCLE THROUGH SYNTHESIS OR PASS OUT TO PRINT
   27 CONTINUE
      Q(K + 1,1) = Q(K,13)
      IF (L + 1 - K) 61,61,60
C     ANTILOG TRANSFORM OF FLOW RECORD
   61 CONTINUE
      LL = L + 1
      IF (KK) 111,204,205
  205 CONTINUE
      WRITE (3,170)
  170 FORMAT ('FLOW RECORD TRANSFORMED FROM LOG SCALE TO NORMAL ',
     1'SCALE BY ANTILOG TRANSFORMATION',//)
      DO 206 K = 1,LL
      DO 206 I = 1,12
      Q(K,I) = EXP(2.3025*Q(K,I))
  206 CONTINUE
  204 CONTINUE
C     LINE PRINTER OUTPUT OF FLOW RECORD
      CALL SKIP
      WRITE (3,62)
   62 FORMAT (' ',T40,'SYNTHETIC FLOW RECORD ')
      WRITE (3,63) HEAD
   63 FORMAT (T40,19A4/,T40,'MEAN MONTHLY FLOW (CUSEC)')
      WRITE (3,64)
   64 FORMAT ( ' YEAR       JAN     FEB     MAR     APR     MAY       ',
     1'JUN     JUL     AUG     SEP     OCT     NOV     DEC',/)
      DO 85 I = 1,12
   85 QQ(I) = Q(1,I)
      WRITE (3,65) (QQ(I), I = 1,12)
   65 FORMAT (' PRERUN', T8,12I8)
      DO 72 K = 2,LL
      DO 86 I = 1,12
   86 QQ(I) = Q(K,I)
      O = K - 1
   72 WRITE (3,66) O,(QQ(I), I = 1,12)
   66 FORMAT (I3,T8,12I8)
C     PUNCHED CARD OUTPUT FOR ANALYSIS BY DASTAT
      WRITE (2,67) L,(HEAD(I), I = 1,16)
   67 FORMAT (I3,1X,16A4,' (SYNTHETIC)')
      WRITE (2,73)
   73 FORMAT ('1000')
      WRITE (2,472)
  472 FORMAT (' 2')
      DO 71 K = 2,LL
      DO 87 I = 1,13
   87 QQ(I) = Q(K,I)
   71 WRITE (2,68) (QQ(I), I = 1,13)
   68 FORMAT (13I6)
      GO TO 69
C     FAIL ROUTINE
    1 WRITE (3,70) W
   70 FORMAT (//' ERROR EXIT ',I3//)
C     CLOSE DOWN
  111 CALL EXIT
      END
```