WATER RESOURCES SYMPOSIUM

40th ANZAAS CONGRESS

PROCEEDINGS - PART 1

lincoln papers
in
water resources

1

WATER RESOURCES SYMPOSIUM

40th ANZAAS CONGRESS

WATER RESOURCES SYMPOSIUM
40th ANZAAS CONGRESS
PROCEEDINGS PART 1

Lincoln Papers in

Water Resources -

No. 1, April 1968.

Research Publication R/2 of the New Zealand
Agricultural Engineering Institute, Lincoln
College, Canterbury, new Zealand.

FOREWORD

Lincoln College, the College of Agriculture of the University of Canterbury, sponsors an active research and teaching programme in hydrology, soil conservation and water resources development. The purpose of these Papers is to communicate research results and new developments in these fields as rapidly as possible, and particularly to report the results of projects undertaken in conjunction by the Department of Agricultural Engineering and the New Zealand Agricultural Engineering Institute. From time to time the opportunity will be taken to publish material originating elsewhere in New Zealand with which the College is associated and which could not otherwise be made available.

The Lincoln Papers in Water Resources are published by the New Zealand Agricultural Engineering Institute and printed by the Lincoln College Press. All enquiries should be addressed to the Information Officer, New Zealand Agricultural Engineering Institute, Lincoln College Post Office, Canterbury, New Zealand.

. . . .

PREFACE

Volumes 1 and 2 of the Lincoln Papers in Water Resources comprise the papers presented at a Symposium on Water Resources Development which was arranged by the Engineering Section of the 40th ANZAAS Congress and organised by Lincoln College Staff. The full programme for the Symposium was as follows:

<u>Thursday 25th January</u>

Chairman: F.M. Henderson, University of Canterbury

(a) The Atmospheric Phase

1. Hydrometeorological contribution to the development and control of water resources - D.N. Body, Commonwealth Bureau of Meteorology.

2. Estimating the probable maximum precipitation in remote areas - C.J. Wiesner, University of New South Wales.

3. Rainfall variability and reliability in New Zealand - J. Coulter, N.Z. Meteorological Service.

Chairman: J.R. Burton, Lincoln College

(b) The Land Use Phase

4. Effects of agricultural land use on water quality - K. O'Connor, D.S.I.R., Lincoln.

5. Watershed management - problems and possibilities - J.F. Holloway, N.Z. Forest Service

6. Evaluation of changes in the land-use regime - W.C. Boughton, Lincoln College.

<u>Friday, 26th January</u>

Chairman: J.R. Burton, Lincoln College

(c) The Control Phase

7. Theory and practice in water resource system design - D.T. Howell, University of New South Wales.

8. The Tongariro Power project - H. James, Ministry of Works.

9. Irrigation development in the New Zealand environment - R. Lobb, N.Z. Department of Agriculture.

Chairman: T.D.J. Leech, Cooma, New South Wales.

(d) The Socio-Economic Phase

10. Economic evaluation for water resources development - R. Jensen, Lincoln College.

11. Legislation for water resources development - D.G. McGill, Ministry of Works.

12. Education for water resources development - J.R. Burton, Lincoln College.

CONTENTS

ABSTRACTS OF PAPERS

HYDROMETEOROLOGICAL CONTRIBUTION TO THE DEVELOPMENT AND CONTROL OF WATER RESOURCES.

Mr. D.N. Body
Hydrometeorological Section, Commonwealth
Bureau of Meteorology, Melbourne,
Australia.

Hydrometeorology can be considered to be the study of the occurrence and movement of water from the time it appears as precipitation until it is lost to either the ocean, groundwater storage or back to the atmosphere. It is during this phase of the hydrologic cycle that most use is made and the greatest control can be exercised on the water resource provided by precipitation.

If the water resource is to be used efficiently, both in terms of development and control, it will be essential for close co-operation to be maintained between meteorologists, hydrologists and agriculturalists.

Increased capacity for data collection and analysis and the introduction of numerical methods can be expected to lead to an improvement in objective forecasting techniques. Future research should also lead to a better understanding of precipitation producing mechanisms from which more adequate methods for providing hydrologic design criteria can be expected to emerge.

The paper describes the current situation in these fields and examines likely future developments.

ESTIMATING THE PROBABLE MAXIMUM PRECIPITATION IN REMOTE AREAS

Mr. C.J. Wiesner
Senior Lecturer, School of Civil Engineering,
University of New South Wales, Australia.

As part of the assessment of the water resources of a region, the probable maximum flood is required. A rational method of estimating this is through evaluations of the Probable Maximum Precipitation (P.M.P.)

In remote areas where data is absent, scanty, or poorly documented, it is possible to estimate the P.M.P. by using the data of other regions appropriately adjusted. Some of this data is given and described.

The temporal patterns of the probable maximum storms are discussed.

THE VARIABILITY AND RELIABILITY OF RAINFALL IN NEW ZEALAND

Mr. J.D. Coulter,
New Zealand Meteorological Service

A knowledge of the variability of rainfall in space and time is needed in planning water supply undertakings. Monthly rainfall variability in space and time and the variations of seasonal rainfalls from year to year are discussed using data from New Zealand rainfall stations.

EFFECTS OF AGRICULTURAL LAND USE ON WATER QUALITY

Dr. K.F. O'Connor,
Grasslands Division, D.S.I.R., Lincoln.

The quality of water as a resource for development may be affected by agriculture. This is seen in changes in discharge patterns of streams because of changes in runoff and infiltration characteristics, and in addition of materials to water bodies, either as solids in suspension or in solution. Additions to water may arise from erosion of soil, leaching or direct additions of agricultural chemicals, products or residues. Some of the principal dimensions of these phenomena are outlined for New Zealand in particular. Their significance for integrated water resource development and agricultural water use planning is discussed.

WATERSHED MANAGEMENT - PROBLEMS AND POSSIBILITIES

Mr. J.T. Holloway,
New Zealand Forest Service

Wherever the principal objective of watershed management is river control, action must primarily centre on the lands that produce the most water and/or the most sediment. In New Zealand, these are mountain lands.

Problems in New Zealand are those common to all high-rainfall, mountainous countries, compounded by the frequent occurrence of infertile soils of low erosion resistance and of strongly shattered bed-rock, by an exceptionally rapid worsening of climate with altitude gain, by frequent inaccessibility and by strict limitations of finance and manpower.

In these circumstances a severely realistic attitude is essential in considering possible management plans. The immediate task is to prevent further damage to watersheds. This must come from continued control of fire and better control of introduced domestic and wild animals.

Restoration of an adequate vegetation cover to lands already denuded will not be practicable without a much greater investment in research. Manipulation of vegetation to control water yield, as opposed to erosion control, is so far a theoretical possibility only.

EVALUATION OF CHANGES IN THE LAND-USE REGIME

Mr. W.C. Boughton,
Senior Lecturer, Agricultural Engineering
Department, Lincoln College.

Hydrologic evaluation of land-use changes encompasses a broad field of agricultural, forestry, and engineering activity. Because of the complexity of the hydrologic process, it is difficult to distinguish the effects of such changes from natural variations in quality, quantity, peak rates and other characteristics of runoff.

A variety of experimental methods ranging from the very simple to the very complex have been used in attempting to evaluate these effects. The variety of methods reflects the variety of problems encompassed and the number of different disciplines concerned with the problems.

The use of plots, experimental catchments, barometer watersheds, representative basins, benchmark and vigil networks and other methods for the collection of data, and methods of data analysis ranging from simple graphical correlations to multivariate analysis and mathematical catchment models are reviewed. Current use of catchment models as an experimental method is described and possible future developments of these models are explored. The need for integrated planning of data collection and data analysis is emphasised.

HYDROMETEOROLOGICAL CONTRIBUTION TO THE DEVELOPMENT AND CONTROL OF WATER RESOURCES

By D.N. Body

Bureau of Meteorology, Melbourne, Australia.

INTRODUCTION

Hydrometeorological effort has been traditionally oriented towards the engineering aspects of water resources development. This is understandable as engineering construction for the utilization of surface water resources has demanded design criteria which have required the combined efforts of meteorologists and hydrologists. However, it seems likely that the emphasis and direction of hydro-meteorological effort may be changed in the future to that area in which the vast majority of Australia's water resources are found and used.

It has been estimated that Australia's Average Annual Rainfall is near 17 inches while the surface runoff carried in the rivers is between 1 and 2 inches. Some of the difference between these figures is accounted for by deep seepage and evaporation from surface streams but by far the greatest proportion is utilized by vegetation at the point where the precipitation occurs. This water, which may be termed non-transportable water, cannot be affected or utilized by engineering construction. The magnitude of this resource indicates that any move to improve the manner in which it is utilized would be extremely rewarding and of the greatest significance to the national economy.

Because of the slower reaction time in agricultural and pastoral operations compared with that involved in reservoir operation, the time scale over which hydrometeorological forecasts are required is much greater in this context. In spite of this, there are some indications that the future holds promise for development of useful criteria in this field.

DESIGN ASPECTS OF ENGINEERING DEVELOPMENTS IN WATER RESOURCES UTILIZATION

The design process which leads to the construction of a water supply reservoir can be conveniently divided into two phases. The first of these deals with the provision of an inflow design flood for spillway design and the second involves the determination of reservoir capacity and operating procedures to meet the required demand. The various areas of investigation together with a suggested sequence in which these would be undertaken is given in Fig.1. Those investigations in which hydrometeorologists could be expected to make a major contribution are shown in the double outline.

Dealing firstly with the aspect of the spillway design flood, modern practice adopts the concept of the estimated extreme precipitation as the basis for the determination of this design parameter. Such a procedure is based upon the assumption that storms producing major rainfalls do so because of high efficiency and that had the air mass from which the rain was produced been at a higher dew point then an even greater depth of precipitation would have been produced. To this adjustment is added the concept of transposition in which provided the rainfall pattern produced is assessed as being little affected by orography, the storms are moved to the catchment under consideration from other localities.

The major disadvantages of this procedure have been its reliance on storms observed within the period of synoptic record and the difficulty of deciding the quantitative effects of orography in the observed storm and in the area to which transposition is required. Brunt (1967) in his paper presented to the Institution of Engineers' Hydrology Symposium found that, so far as tropical cyclones were concerned, the only two factors which were significant in regard to the rain producing capacity of these systems over areas up to 10,000 square miles, were dew point and orography. Orography in this case was measured by the rather simple procedure of determining the average elevation of the most intense rain centres.

Investigations of the behaviour of the atmosphere and the effect of vertical motion associated with orography which are at present under way in U.S.A. and India and which are planned also for Australia, should lead to the development of procedures which will allow orographically produced rainfall to be identified and separated from that produced by the dynamics of the storm mechanism. The successful separation of the rainfall from these two sources will enable a much more realistic application of the transposition part of the theory for the estimation of extreme precipitation.

There is another aspect of the provision of estimates of extreme precipitation which is becoming increasingly important with the construction of dams with large surface areas and small spillways. Under such conditions design floods over periods of up to 10 days are required. To provide these figures it is necessary to define the probability of two major rain producing storm occurring within such a period. Preliminary investigations indicate that the occurrence of such a sequence has a probability well in excess of that to be expected by chance. However, because of the fact that extremely rare events are being studied the sample is necessarily very small.

An extension of this same problem is faced in very large catchments where the extreme flood would be produced by a sequence of storm events extending over a period of weeks and perhaps months.

The introduction of large capacity computers of high speed has enabled meteorologists to model the atmosphere and to reach a stage of proficiency which allows synoptic sequences of up to some weeks to be successfully simulated. There appears to be a reasonable chance that these procedures will enable the establishment of an initial condition in which a major rain is inherent, and enable the study of the possibilities associated with the synoptic sequence following such an event.

The other phase involved in the design of engineering development of water resources is that of designing the capacity of the reservoir to serve the demand or perhaps to design the development to be based upon a given safe draft. This process is now generally recognised as being basically statistical rather than empirical.

In Fig. 1 the connection between the panels detailing a catchment runoff model and streamflow time series has been shown as dotted indicating that design of reservoir capacity does not necessarily involve a catchment model. However, it is interesting to speculate just how far any design can proceed using the historical streamflow record alone. As the reservoir will be required to supply demand in the future, then it is the future inflow sequence which is of interest. Two panels indicate possible modifications in the future which would be expected to produce variations in the streamflow regime and would need to be taken into account in any reservoir yield studies. These are precipitation modification and the change in evapotranspiration caused by changes in land use. A third modifying factor is the use of water upstream of the reservoir for pumped irrigation or perhaps in another reservoir.

It appears that the only satisfactory way in which the effects of the modifying influences can be established is to use a catchment runoff model to produce an estimate of the future streamflow time series on which to base the design.

OPERATION ASPECTS OF ENGINEERING DEVELOPMENTS IN WATER RESOURCES UTILIZATION

Forecasts of future precipitation and the consequent changes in streamflow would obviously be of very great assistance in the management of water resources. In the forecast content it is convenient to subdivide the problem into two categories based on the period of the forecast. Short-term forecasts relate to a period up to 10 days in the future while long-term forecasts are for periods beyond this time.

Fig.2 sets out possible sequences of events which could follow adequate forecasts of precipitation and runoff. In the short-term the main interest is in flood flows while in the longer term periods of less than normal rainfall assume the major importance.

Much of the consequent action to the issue of flood forecasts has already been developed successfully in many countries. In Australia, engineering authorities responsible for the operation of reservoirs have been singularly reluctant to accept forecasts as a basis for operating the dam as a flood control structure. However, there is no doubt that procedures are already available to allow adequate forecasts to be made, based upon observed rainfall, and precipitation forecasts giving some hours lead time are within sight.

U.S. workers have identified areas of precipitation and general quantities up to four days ahead with sufficient accuracy to allow emergency services to be alerted. The possibilities of this approach being adopted in the southern hemisphere would seem to be limited by the lack of observing sites with presently available instrumentation. Future developments will undoubtedly provide the opportunity of reaching a similar level of confidence in this hemisphere.

In regard to the longer term forecasts, there is no obvious method which at this time would lead one to prophesy that specific quantitative forecasts of precipitation could be given for periods covering a sufficient time in the future, to make it worthwhile for long term planning in the agricultural and pastoral sphere. While it is doubtful whether specific forecasts could be achieved, there does seem to be a possibility that an outlook based upon a probability approach could be given, which would be of assistance in the long term planning of water resources management in these important fields.

AGRICULTURAL AND PASTORAL PLANNING FOR WATER RESOURCES UTILIZATION

As already stated the response time for planning in agriculture and pastoral industries is such as to make the possibilities of specific quantitative forecasting rather remote. However, recognising that a major proportion of Australia's water resource is used by vegetation where it falls as precipitation, the Bureau of Meteorology has prepared on behalf of the Australian Water Resources Council a publication which sets out details of the distribution of monthly rainfall and evaporation. A sample of the form of tabulation used to display the rainfall data is given in Fig.3. Because of the marked skewness associated with monthly rainfall the data are presented in the form of percentiles with the median value being accepted as the "normal" rainfall. The most interesting part of these tabulations, from the point of view of water resources planning, is Part B of Fig.3. This gives the values of the 10th, 50th and 90th percentile rainfalls for runs of consecutive months. This allows rainfall statistics to be read directly for any continuous sequence of months.

An illustration of the use to which this form data can be put is the use of the data for the months November to March inclusive to provide an indication of the probability that the severe drought in western Vistoria and South-east South Australia might break before the Autumn of 1968. Fig. 4 shows the isohyets for the median rainfall for these five months while Fig. 5 shows the isohyets of the 10th percentile rainfall.

Using the average evaporation for each of these months the amount of rainfall required to promote and sustain growth was determined using the approach of Prescott et al. (1948). Isohyets of this rainfall are shown in Fig. 6. By using Figs. 4 and 5 it was possible to superimpose on this figure the areas in which there is at least a 50 per cent chance of achieving the required rainfall and the area where there is a 90 per cent chance. On the basis of this work it was possible for the Government to take steps to arrange continuing drought relief in the western district and for the movement of valuable stock to the eastern regions where the probability of receiving sufficient rainfall was higher.

This work does not mean that the drought will not break in western Vistoria or that there will not be a drought in eastern Victoria but it does provide an objective basis on which to base decisions.

Another project which may be mentioned under this heading is one which will be of assistance to farmers and all householders who rely for their domestic water supply on the runoff from the house roof. In its minor way it has all the essentials which are involved in the problem of designing a reservoir to meet a given demand.

For a selected daily demand it is possible to determine the basic impervious area which would be required to just meet this demand from the average annual rainfall if it is assumed that there is sufficient storage to damp out all variations from year to year. Fig.7 gives this relationship in graphical form.

In order to provide for periods when there is no rain and to make the most use of the rain when it falls, it is necessary to have some storage and to have an impervious area somewhat greater than the basic area given by this graph. Fig.7 is applicable in all regions as it depends only upon the average annual rainfall, but to determine the combination of storage and impervious area to meet the chosen demand for a given probability of providing full supply, it is necessary to consider the time distribution of the rain at the particular site.

Fig.8 shows the relationship between storage, impervious area and probability of providing full supply for Meekatharra in Western Australia where the mean annual rainfall is 8.28 inches.

For example, let us assume that the householder wishes to be assured of a daily demand of 20 gallons. Then for Meekatharra from Fig.7 the basic impervious area would be 1800 square feet. If our householder accepted a 95 per cent probability of full supply, then from Fig. 8 it can be seen that he has a number of combinations of storage and impervious area which will meet this level of guaranteed supply. If his roof area is twice the basic area of 1800 square feet, a large house, he can achieve his design performance with a storage of 120 times his chosen daily demand, i.e. 2400 gallons.

The interesting aspect of this apparently simple problem is that at any given combination of storage and impervious area, the probability of full supply is dependent upon the time sequence in which the rainfall occurs. As it is impossible to forecast this sequence, the values of the probabilities given in Fig. 8 are themselves subject to a probability distribution. In fact, a combination of storage and impervious area chosen from Fig.8 has a 95 per cent probability that it will reach the indicated level of performance. This probability is established by constructing from the existing historical record a series of new samples by a random selection of monthly rainfalls.

CONCLUSIONS

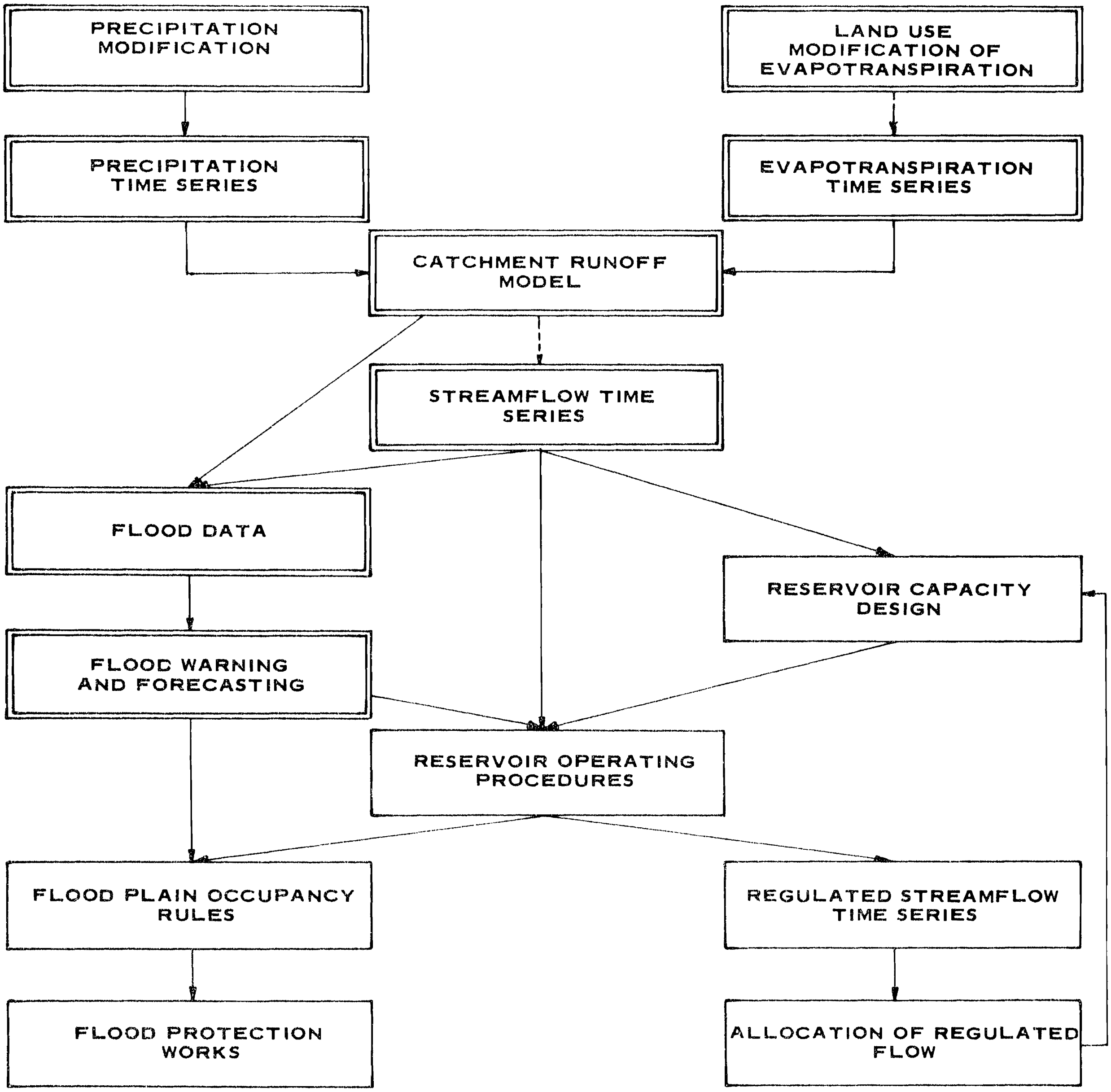
With the increasing understanding of the atmospheric processes which cause major rainfalls and the development of soundly based catchment runoff models, there is reason to believe that the design criteria for the engineering structures associated with the utilization of water resources will become more soundly based. This will apply to both the spillway design flood aspect and the yield problem.

The awareness that the vast majority of Australia's water resource is unavailable for control by engineering structures is expected to lead to a change in emphasis in hydrometeorological investigations. In this change, the problem of forecasting, or at least indicating the probabilities associated with seasonal rainfall, will assume greater importance.

REFERENCES

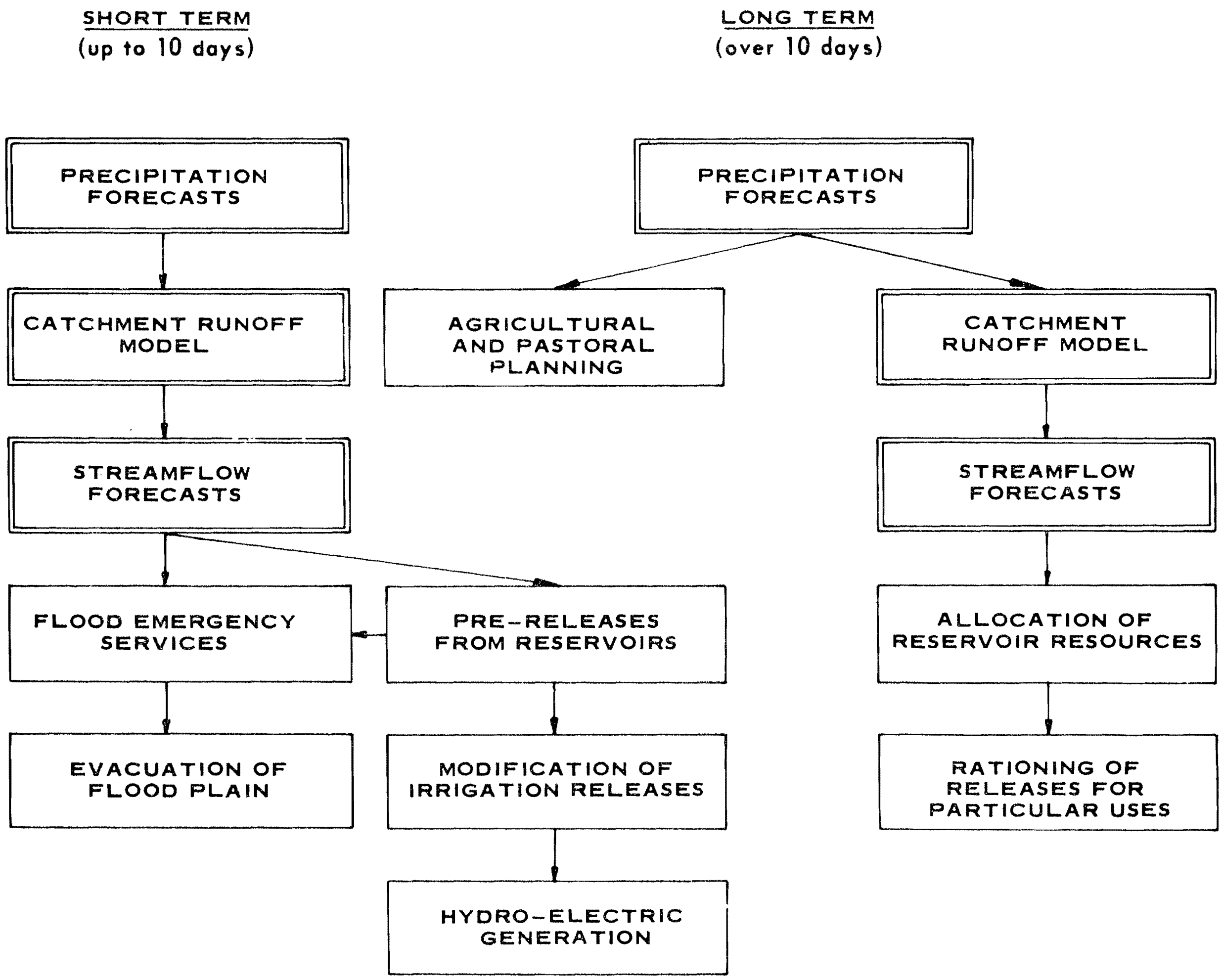
Brunt, A.T. 1967 Institution of Engineers, Hydrology Symposium (in press).

Prescott, J.A. and J.A. Thomas, 1948 Proc. Royal Geographical Society of Australia, South Australian Branch, Vol. 50.



Note *Boxes with double edging indicate those activities in which hydrometeorologists would make a major contribution.*

Fig. 1 Planning water resources utilization. The design process.



Note: Boxes with double edging indicate those activities in which hydrometeorologists would make a major contribution.

Fig. 2 Planning water resources utilization. Use of forecasts.

RAINFALL PERCENTILE INFORMATION IN POINTS

(100 points = 1 inch)

DRAINAGE DIVISION SOUTH AUSTRALIAN GULF (V)
CATCHMENT 12 EYRE PENINSULA

PART A

STATION	ITEM	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
PORT LINCOLN	LOW	0	0	0	3	53	39	76	35	51	15	4	0	1140
LATITUDE 34° 44′ S	10	4	1	8	32	102	110	159	131	81	39	14	8	1469
LONGITUDE 135° 52′ E	30	16	14	34	74	155	203	238	189	123	86	38	28	1473
1866-1965 100 YEARS	50	32	46	54	111	206	282	290	262	182	120	71	48	1848
STATION NO. 18070	70	60	77	83	181	249	356	333	305	238	167	155	87	2068
	90	115	142	153	268	372	497	479	388	334	262	207	153	2425
	HIGH	478	377	495	452	573	775	727	732	486	418	311	293	2999

PART B

DETAILS OF RAINFALL EXPERIENCE IN CONSECUTIVE MONTHS COMMENCING WITH THE MONTH INDICATED

	NUMBER OF MONTHS	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
10TH PERCENTILE VALUE	1	4	1	8	32	102	110	159	131	81	39	14	8
	2	18	38	82	178	275	330	334	266	173	102	51	31
	3	60	112	249	420	560	525	512	380	220	127	75	57
	4	158	304	454	654	759	723	659	462	294	151	107	98
	5	337	505	675	823	911	892	701	496	340	199	165	191
	6	545	730	847	1022	1052	942	752	549	354	245	260	374
	7	755	922	1033	1191	1149	971	811	587	423	376	452	407
	8	985	1107	1243	1255	1178	1012	831	642	550	598	715	843
	9	1139	1302	1304	1319	1198	1047	869	742	753	828	919	1030
	10	1328	1368	1343	1383	1257	1098	1008	947	976	1082	1117	1231
	11	1405	1437	1410	1402	1334	1258	1238	1163	1218	1328	1316	1370
	12	1469	1467	1433	1457	1452	1471	1470	1472	1463	1476	1492	1468
50TH PERCENTILE VALUE (MEDIAN)	1	32	46	54	111	206	282	290	262	182	120	71	48
	2	96	138	196	352	514	593	558	442	326	205	153	104
	3	174	243	413	670	803	847	741	577	416	299	197	152
	4	282	473	728	962	1081	1019	868	658	492	352	244	219
	5	520	776	1026	1235	1226	1134	981	738	541	394	322	351
	6	810	1085	1294	1378	1346	1226	1035	802	590	455	444	585
	7	1136	1351	1467	1500	1446	1341	1082	864	644	618	689	875
	8	1390	1543	1589	1568	1546	1372	1145	918	772	821	974	1190
	9	1597	1439	1654	1640	1607	1430	1201	1043	1035	1119	1309	1432
	10	1706	1723	1744	1699	1674	1535	1328	1270	1339	1422	1553	1674
	11	1807	1787	1805	1785	1721	1646	1554	1578	1628	1678	1753	1787
	12	1848	1855	1880	1964	1882	1891	1898	1874	1897	1905	1871	1865
90TH PERCENTILE VALUE	1	115	142	153	268	372	497	479	388	334	262	207	153
	2	214	251	407	575	814	912	785	637	476	390	294	227
	3	358	454	647	962	1177	1187	1047	786	587	472	365	321
	4	581	727	1079	1341	1486	1458	1212	920	675	586	454	467
	5	785	1115	1419	1727	1708	1608	1254	977	777	650	555	681
	6	1233	1529	1828	1919	1899	1700	1328	1059	871	745	778	879
	7	1586	1849	1973	2067	1984	1801	1459	1183	996	920	1006	1285
	8	1909	2005	2145	2177	2084	1911	1547	1240	1146	1154	1392	1608
	9	2050	2158	2309	2239	2176	1950	1606	1399	1409	1530	1778	1921
	10	2183	2339	2363	2334	2243	1984	1807	1693	1710	1896	2058	2095
	11	2373	2404	2434	2359	2280	2147	2082	1989	2033	2158	2188	2258
	12	2425	2440	2435	2407	2414	2398	2393	2368	2318	2295	2321	2413

Fig. 3 Sample tabulation of rainfall statistics published in Review of Australia's er Resources, Monthly Rainfall and Evaporation.

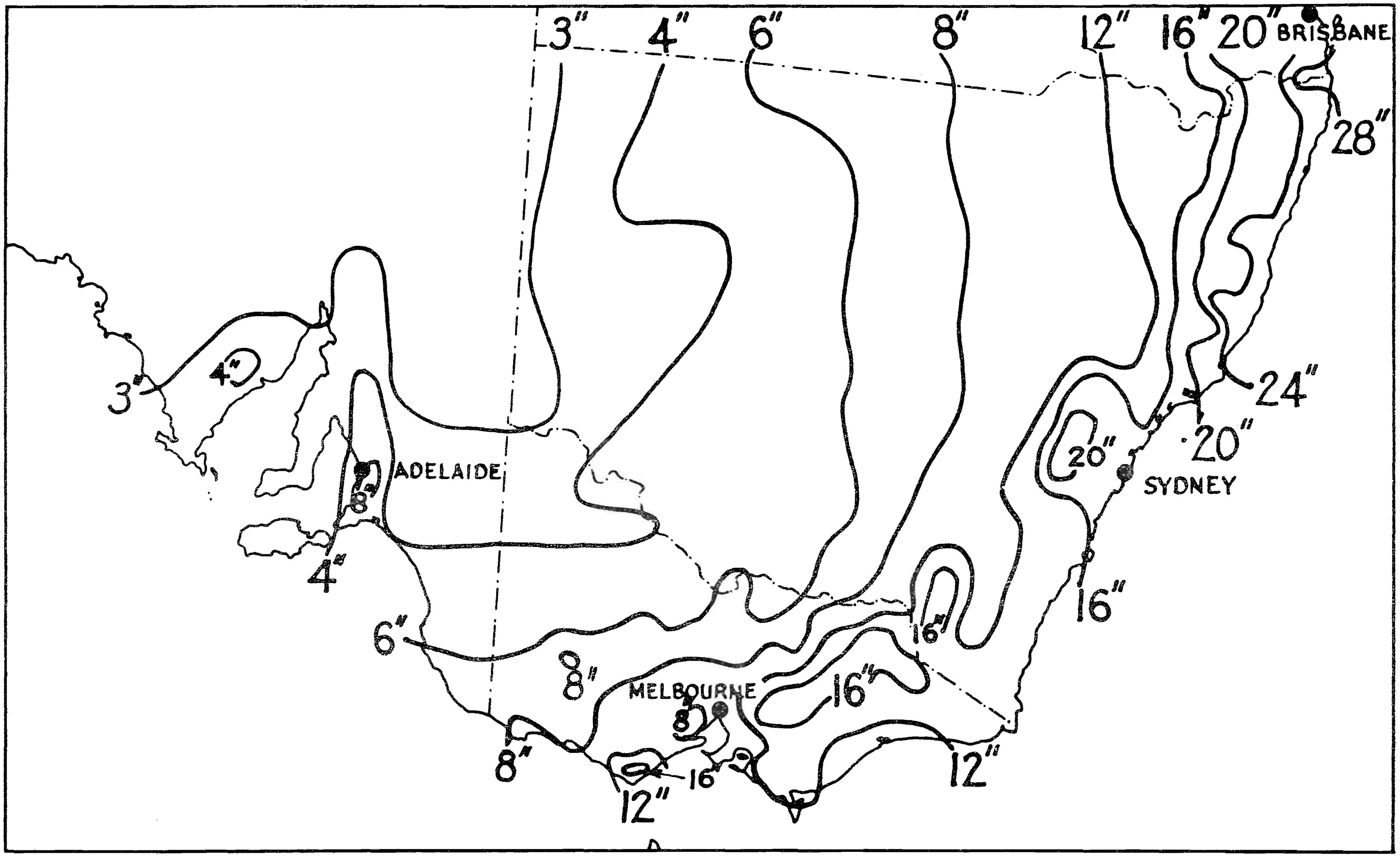


Fig. 4 Rainfall, November – March, in "normal" period.

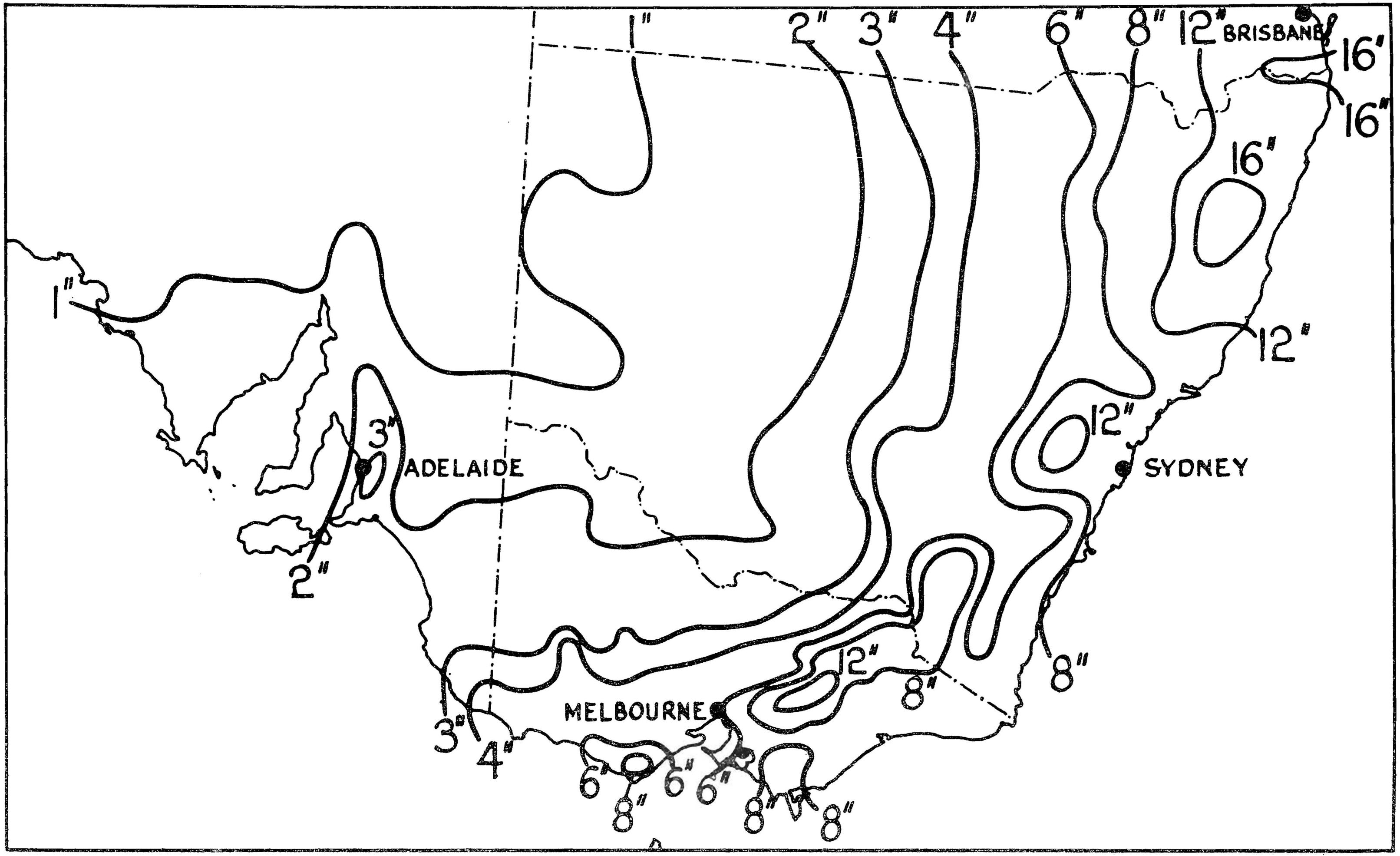


Fig. 5 Rainfall, November – March, not exceeded during one period in ten.

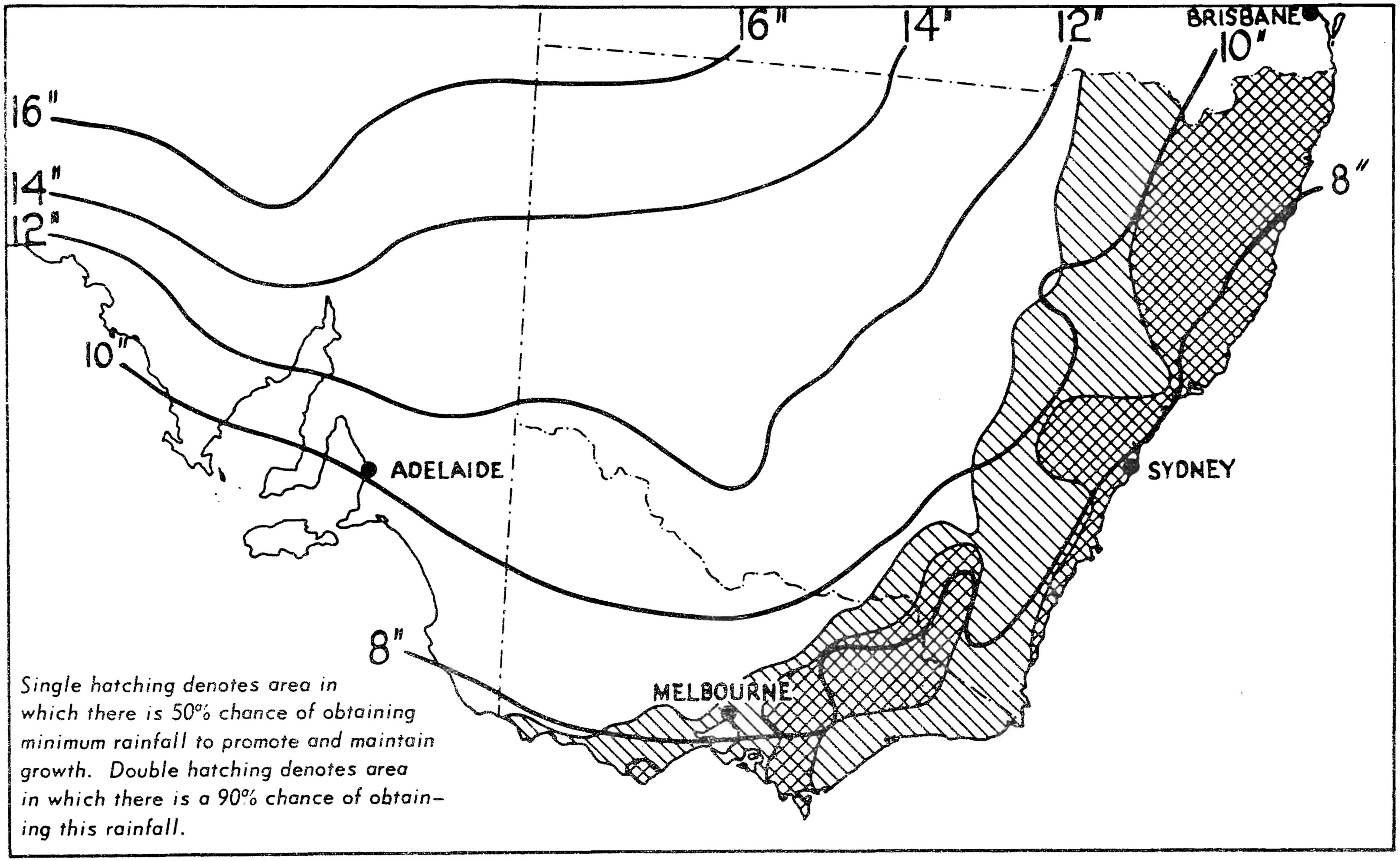


Fig. 6 Minimum rainfall required to promote and maintain pasture growth. (Prescott)

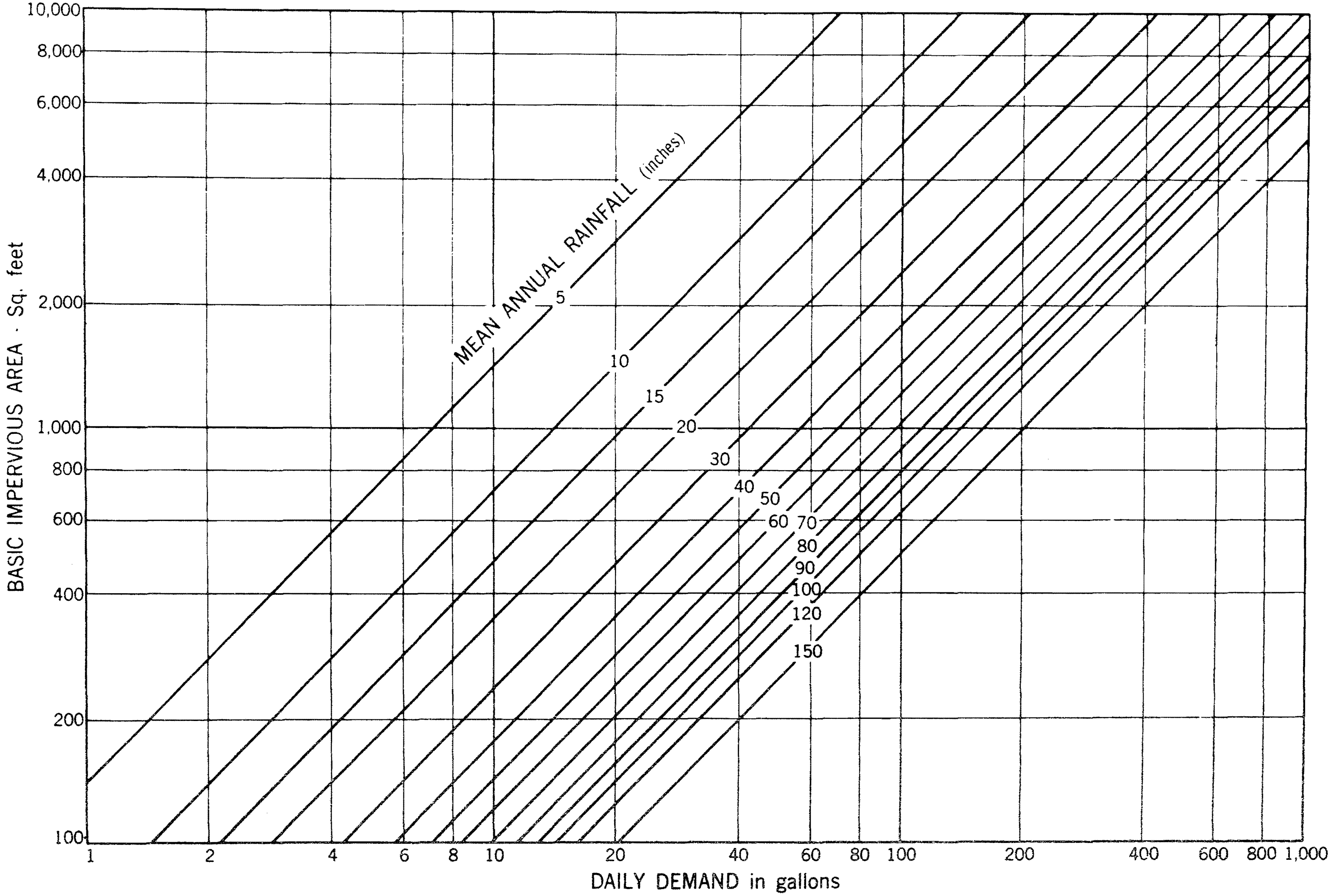


Fig. 7 Basic impervious area required for given daily demand and mean annual rainfall.

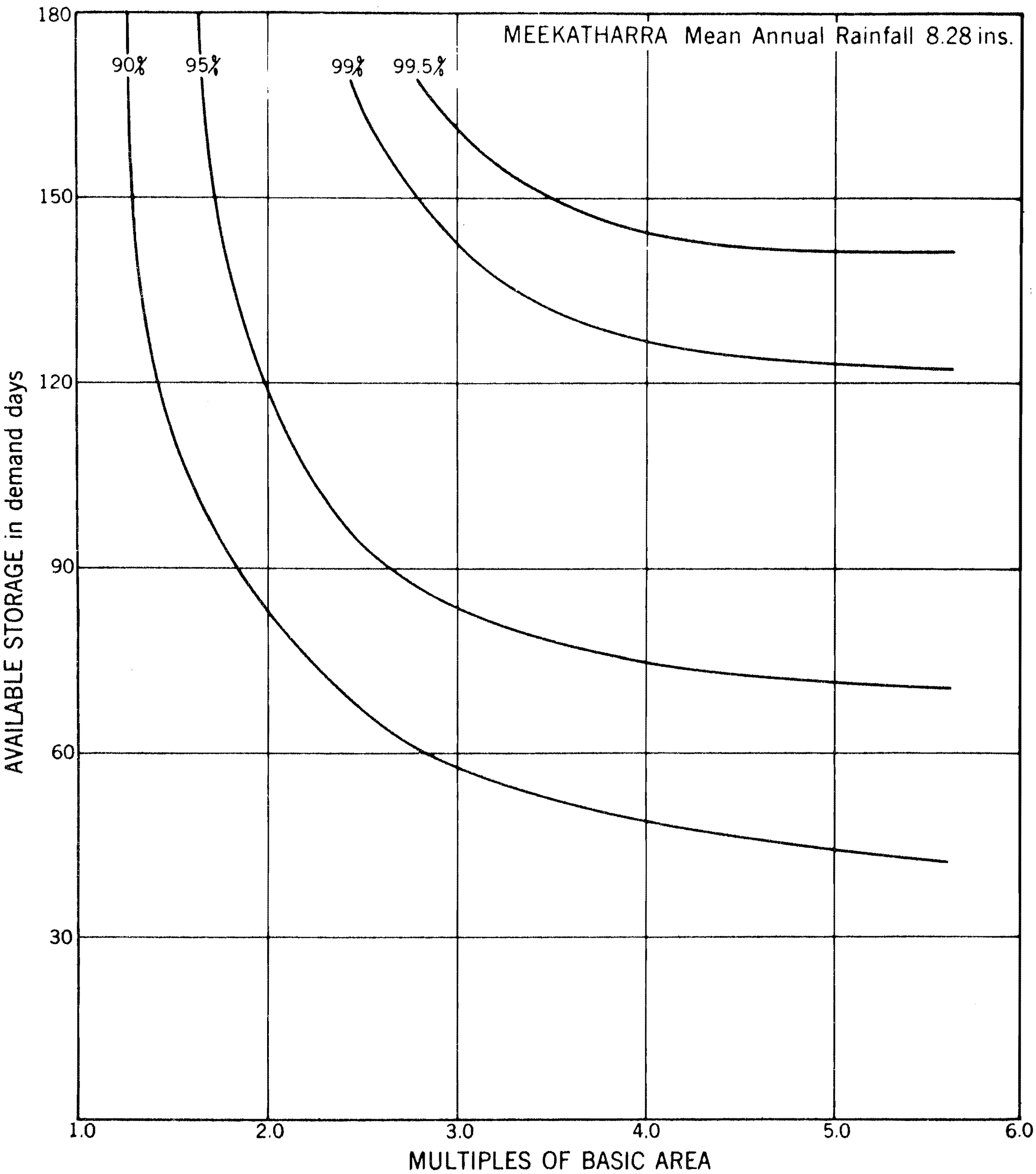


Fig. 8 Yield from impervious catchment Diagram shows the probability of supplying full demand with various combinations of impervious area and storage. Storage initially empty.

ESTIMATING THE PROBABLE MAXIMUM PRECIPITATION IN REMOTE AREAS

C.J. Wiesner,
University of New South Wales,
Australia.

INTRODUCTION

One of the features of the water resources of a region is its flood potential. This may be defined by estimates of floods of specified recurrence intervals and the probable maximum flood. These estimates are used in the design of water ways, dam spillways, river diversions, drainage works, and flood mitigation projects. The techniques used in estimating these floods are an important section of hydrology and are described in textbooks and their associated references.

A rational method of estimating the probable maximum flood makes use of the probable maximum precipitation (P.M.P.) This can be defined as that depth of precipitation, which, for a given area and duration, can be reached but not exceeded, under known meteorological conditions.

The estimation of the P.M.P. is one of the concerns of Hydrometeorology, defined in the restrictive sense as that study of the atmospheric processes which affect the water resources of the earth. P.M.P. is briefly discussed in the texts (1. 2. 3) and in more detail in the publications of the Hydrometeorological Branch of the U.S. Weather Bureau, and in numerous articles (4, 5, 6).

MAXIMUM DEPTH DURATION AREA DATA.

The methods of hydrometeorology require large amounts of data which must be processed and analysed. These are best handled by specialised groups of engineers and meteorologists combining in a hydrometeorological section. A successful method considers the intense storms which have occurred within a meteorologically homogeneous zone and expresses them in terms of the maximum depths of rainfall experienced over various areas. This is the storm's depth duration area (D.D.A.) data. (7.8). The conditions under which these storms can be transposed and maximized are determined. Information is needed on the properties of the air masses involved in the storm and region, the space-time relationships of precipitation, the storm mechanism and the storm's movements. It may then be possible to transpose and maximize the storms to the project basin and obtain estimates of the probable maximum precipitation. Thus a comprehensive observational network needs to be maintained for a considerable length of time to adequately document some of the more intense storms which are likely to occur. This and the lack of skilled staff limit the application of the method. It has been most thoroughly applied in the United States where the major storms have been analysed. The maximum depths achieved in these U.S. storms for the various durations and areas are given in Table 1. In other countries storms have approached but not exceeded these values which are taken as world maximum D.D.A. data.

MAXIMUM RAINGAUGE FALLS

The distinction between rain gauge falls or "point" rainfall and depth duration data is well known and both have their uses in engineering design. Raingauge figures lend themselves to statistical analysis and the estimation of rainfall of various return periods. Depth-duration-area data allow for the space variation of precipitation and are adapted to the determination of the probable maximum precipitation. The maximum depth-duration-area data are given in table 1 and it is as well to consider the world's maximum point rainfalls. These have recently been reviewed by PAULHAUS (1965)[9]., who fitted the equation $P = 16.6D^{.475}$ where P is the raingauge precipitation in inches over duration D in hours. From this equation the probable maximum raingauge depths or cloudburst rainfalls may be estimated and are given in table 2.

Table 2. Probable maximum cloudburst rainfall

Duration Min.	Depth in.	Duration (hr)	Depth in.
5	4.76	1	6.6
10	6.8	2	23.4
15	8.3	3	28.7
20	9.6	4	33.2
30	11.8	5	37.0
45	14.4	6	40.6

The extreme rainburst falls or cloudbursts are due to a combination of extraordinary circumstances. For example, air of very high moisture content flows into an efficient storm aided by favourable topography to give high rainfall at perhaps only one gauge of a network. Also, short duration cloudbursts can result when the liquid water, accumulated over a small area is suddenly released due to the collapse of the vertical supporting current.

The cloudburst rainfall is decidedly local and table 2 refers to raingauge depths. However, a detailed examination of cloudbursts in the U.S. has established an approximate relationship between the rainfall at a point and small areas. This is shown in figure 1 and can be used to extrapolate the intense point rainfalls to larger areas.

As table 2 is based on world figures, each of which is associated with peculiar conditions, it represents an overall upper limit to point rainfalls of the given duration. The amounts are so vastly greater than anything most people have experienced that the probability of their occurrence must be considered remote. However, the figures indicate an overall maximum and the only justification of using them in design is when the exceptional conditions described might occur in the project basin.

THE PROBLEM OF THE BASIN WITHOUT DATA

The problem of inadequate data is all too frequent in Hydrology as water projects are often planned in the isolated and unsettled portions of river valleys. Furthermore, in the under-developed and less sophisticated countries there is an urgent need for water conservation projects and data has not been collected in the past. It follows that it is necessary to consider the data which can be transposed and the conditions governing its use. In particular, tables 1 and 2 will be examined to see what parts of them can be used to estimate the P.M.P. in remote areas.

Earlier reports and papers (10, 11, 12) have made use of maximum D.D.A. data up to 1949, but these values were revised by the occurrence of the Yankeetown storm of September 3, 7, 1950. No higher values have been reported since. The generalised diagrams, maps, and formulae produced in the early reports are valuable but the direct transposition and maximization of the basic data is preferred as it eliminates smoothing errors and is applicable to all sites.

In order to know which parts of table 1 can be used the storms contributing to it must be examined and classified. This has been done by the Hydromet. Branch of U.S. Weather Bureau in their numerous reports (10. 13), and by the Corps of Engineers, (14).

THE STRUCTURE OF THE INTENSE STORMS

The storm mechanisms involved in table 1 were not simple and were particularly complicated in the long duration and large area storms. Quite often a number of storm models were involved, the topographical one being significant and unique to the area concerned. However, some generalisations can be made about the lower duration, small area storms. These were found to be predominantly of the convergent type described by the U.S. Weather Bureau [13] and Paulhaus and Gilman[4] (1953). In this model inflow occurs in the lower layers with high moisture inflow and outflow at high levels where temperatures and moisture contents are very low. This is the most efficient of the storm models and produces heavy rain over small areas and for short durations. The thunderstorm is a particular example of the model. This type of mechanism, which is independent of topography or latitude, can occur in all areas but not with the same intensity. The rainfall intensity has been successfully related to the moisture content of the inflowing air (4, 10, 12), and these efficient convergent models may thus be transposed into most areas with the necessary adjustment for moisture content of the air mass expected in the new site. The moisture factor is best expressed as the precipitable water above the storm base; thus the D.D.A. data of the efficient convergent storms can be maximized and transposed to most areas to obtain the P.M.P. The adjustment is -

$$\text{P.M.P.} = \begin{matrix}\text{Storm depth for} \\ \text{Area and duration}\end{matrix} \times \frac{\text{max. precipitable water above basin}}{\text{actual precipitable water above storm}}$$

DETERMINATION OF THE PRECIPITABLE WATER

The precipitable water, or perhaps, more correctly, the liquid equivalent of an air mass, is defined as the equivalent linear depth of water within a column if all the water vapour is condensed over the base area of the column. It can be determined from its vertical temperature and humidity structure.[15] In a storm situation when the air may be expected to be saturated the precipitable water may be estimated from a knowledge of the surface dew point and the assumed saturated pseudo adiabatic lapse rate. A suitable nomogram for this purpose is given in the texts (1, 2, 3) and is reproduced as figure 2.

It follows that to transpose and maximize a storm, the representative storm dew point and the maximum dew point at the project site are significant and must be carefully determined. In the United States, the dew point which persists for 12 hours is taken as representative of the air mass which flows into the storm or basin. It is quoted in terms of its 1000 mb equivalent for the sake of comparison and to give a base for adjustment.

In some countries the dew point persisting for other durations is used. An empirical relationship has been established to adjust these to the 12 hour dew point.[16] For example, if the precipitable water at the 12 hour dew point is represented by 1.00 then the corresponding fraction for a 6 hr dew point is 1.04 and for a 24 hr dew point is .95.

It is sometimes necessary to convert the dew point at a given height to the equivalent dew point at a different height assuming the air is saturated and the lapse rate is pseudo adiabatic. The appropriate pseudo adiabatic lapse rates in degrees F per thousand ft are 2.1° at 78°, 2.2° at 75°, 2.4° at 65°, and 2.6° at 60°.

USE OF THE U.S. MAXIMUM D.D.A. DATA IN REMOTE AREAS.

If, as stated in paragraph 5, the short duration (less than 24 hr) and small area (below 1000 sq. mi) storms are convergent types which can be transposed into all locations, then the United States maximum D.D.A. data for under 24 hr and less than 1000 sq. mi. may be used in other countries. There is controversy regarding the size and duration of the transposable storms and some workers restrict these to storms of area less than 500 sq. mi. and duration under 12 hr. A more conservative practice limits the transposable U.S. storms to durations below 6 hr and areas less than 200 sq. mi. and states that they should only be used on a coastal strip where high dew point air masses can be expected. However, there is little doubt that the U.S. D.D.A. values represent upper limits for the small area, short duration storms and can form a base for estimating P.M.P. in areas where there is no other data.

Appropriate adjustments are made for the precipitable water expected at the project site to the representative amount appropriate to the storms of table 1. In this way it is possible to obtain generalised estimates of P.M.P. for small areas and short durations. This has been done by the Hydrometeorological Branch of the U.S. Weather Bureau,[10, 13] and by Walpole in Australia.[11] Many studies have made use of this type of storm which is sometimes referred to as the thunderstorm model. It is doubted whether the high efficiency of these storms can be exceeded, and, therefore, the only adjustment required in new locations is that of inflowing moisture or the precipitable water of the significant air mass.

To determine the P.M.P. at a remote catchment it is necessary to select from table 1 the depths appropriate to the area of the catchment, interpolating where necessary. Depths for the durations significant to the catchment are taken so that a depth duration curve may be constructed for the area of the catchment. Each depth is multiplied by an adjustment factor as mentioned in paragraph 5. That is P.M.P. = depth for catchment area and duration from table 1, multiplied by the maximum expected precipitable water above the catchment divided by the actual precipitable water in the storm selected from table 1.

It will be noted that the storms of table 1 have occurred at different 1000 mb dew points. If it is assumed that the maximum dew point which may be experienced is 78°F (12 hr) then the figures of table 1 may be adjusted to the dew point of 78°F. This has been done in table 3.

Table 3 - Maximum Depth Duration Area Values for the U.S. adjusted to 12 hr 1000 mb dew point of 78°F

Area Sq. Mi	Duration hr.					
	1	3	6	12	18	24
10	9.3	19.8	30.0	31.3	40.0	42.6
100	6.3	15.5	20.6	29.0	35.8	38.8
200	5.8	14.2	18.8	28.2	34.6	37.3
500	4.9	12.4	16.2	27.1	32.7	36.0
1000	4.1	10.5	14.1	24.9	30.2	33.3

MAXIMUM D.D.A. VALUES FOR SHORT DURATIONS (LESS THAN 1 HR)

Table 1 has no maximum values below 1 hr and the 1 and 3 hr values may be suspect because of doubts concerning the techniques employed in evaluating depth duration area data. The usual method [7] considers the mass curves of rainfall at points within the storms and weights them for area. This may not fully allow for the storm movement or its areal and time variations. For example, an intense rain burst of 15 mins as indicated by a pluviometer is associated with a convergent cell which moves over the catchment. Without knowing the extent of the cell, its speed and direction of movement and the variation of rainfall with time within the cell, it is difficult to assess the maximum depth which would occur over a given area within a short period of time. Extremely dense pluviograph networks with accurately time synchronised instruments would be necessary to delineate the storm for simultaneous time periods. The maximum 15 min. depth over an area is a function of the cells history and movement in relation to that area. No comprehensive analysis of this type is known. The rapid and local variations in rainfall intensities are evidence of the quick fluctuations in moisture flow and vertical velocities common in convective cells and extremely hard to pin point.

In spite of the limitations mentioned above there is a need for maximum D.D.A. values for low durations and until better techniques and observational procedures are developed the values of table 1 for 1 and 3 hr will be accepted and values for lower durations estimated from the point mass curves of rainfall. A U.S. Weather Bureau report [17] gives a basis for estimation and it is concluded that for areas of from 10-200 sq. mi. and a 1000 mb dew point of 78°F, table 4 gives maximum D.D.A. values for durations less than 1 hr.

Table 4. Maximum D.D.A. values for U.S. storms adjusted to a 1000 mb dew point of 78°

Area Sq. Mi.	Duration - min.			
	15	30	45	60
10	4.1	6.2	8.0	9.3
100	2.4	3.8	5.8	6.3
200	1.9	3.3	4.6	5.8

These values may be used and adjusted for water content of the prevailing air mass in the same way as the data of table 1.

THE TEMPORAL PATTERN OF THE P.M.P.

The movement of a storm cell over a catchment can give almost any time distribution of the precipitation dependent on the storm's direction of movement and speed in relation to the catchment. Thus it is reasonable to impose that time pattern to the maximum precipitation as would produce a maximum flood provided the time pattern is not meteorologically impossible. In fact, in their procedures, the Corps of Engineers propose that the most critical rainfall pattern be used. However, a few generalisations can be made from studies of high intensity storms.

The mass curve of rainfall at a point does not necessarily represent the effect of a storm of known size and duration moving over a catchment of specified area. The type of storm, its size, movement and time variations in relation to catchment features such as shape, orientation and size are all significant and the net result might be obtained by translating a defined storm over a known catchment. This effect could be found in a practical way by using maps of simultaneous rainfall during small intervals of time. The effect of area is generally to damp out the point rainfall pattern and to give greater uniformity to the rainfall intensity. Also, as heavier storms occur, a more uniform pattern is to be expected.

Mass curves of 1 hr thunderstorms of varying intensities have been determined [13] and are shown in figure 3. These curves are similar to the maximum depth duration curve. Mass curves of longer duration storms have also been examined [18], and the average pattern for storms of 6, 12, 18 and 24 hr duration is shown in figure 3. The peak of maximum to the third quarter in the storm of duration greater than 6 hr. Figure 3 may be therefore used to estimate the mass curve of a storm in relation to its intensity and duration.

The translation of storms over a 375 sq. mi. catchment was examined [13], and a temporal pattern of the rainfall over the catchment during 6 hr was established. This is shown in figure 4 and demonstrates the damping effect of area upon the thunderstorm pattern.

Where data is available the time pattern of the P.M.P. should be similar to the intense storms which have occurred in the catchment. Where there is no data one of the patterns mentioned above can be adopted.

CONCLUSIONS

The P.M.P. may be estimated in remote areas by using the United States maximum depth, duration, area data for durations less than 12 hours and areas below 500 sq. mi., and by making an appropriate adjustment using figure 2 for the maximum depth of precipitable water in the remote area compared to that experienced in the storm chosen.

The temporal pattern of the P.M.P. can be taken as similar to the intense storms experienced in the area. If data on these is not available then a suitable temporal pattern may be deduced from that of heavy thunderstorms and general storms given in figures 3 and 4 with adjustments for area, rainfall intensity and storm duration.

REFERENCES

1. LINSLEY, R.K., KOHLER, M.A. and PAULHAUS, J.L.R. (1949) — Applied Hydrology. McGraw Hill.

2. LINSLEY, R.K., KOHLER, M.A. and PAULHAUS, J.L.H. (1958) — Hydrology for Engineers. McGraw Hill.

3. CHOW, V.T. (1964) — Handbook of Applied Hydrology, McGraw Hill.

4. PAULHAUS, J.L. and GILMAN, C.S. (1953) — Evaluation of probable maximum Precipitation. Trans. Am. Geophy. Un. Vol. 34, p 701-708.

5. SHOWALTER, A.K. and SOLOT, S.B. 1942) — Computation of the maximum possible Storm. Trans. Am. Geophy. Un. Vol. 23, p 258-274.

6. WIESNER, C.J. 1964) — Hydrometeorology and river flood Estimation. Proc. Inst. Civ.Eng. Vol. 27, pp 153-167.

7. U.S. WEATHER BUREAU (1946) — Manual for depth duration area analysis of storm precipitation. USWB. Co-op Studies Tech. Pap No.1

8. WIESNER, C.J. (1960) — Depth, Duration, Area Analyses of storms. Seminar on Rain. Sydney, Comm. Bureau of Met.

9. PAULHAUS, J.L. (1965) — Indian Ocean and Taiwan rainfalls set new records, Monthly Weather Rev. 93 p 331-335.

10. U.S. WEATHER BUREAU (1947) — Generalised estimates of Maximum possible precipitation. Hydromet. Report No. 23.

11. BUREAU OF MET. (AUST) (1958) J. WALPOLE. — Maximum Possible Rainfall over Australia, published in Conference on Estimation of Extreme Precipitation.

12. SHOWALTER, A.K. (1945) — Chapter on Hydrometeorology IN Handbook of Meteorology by BERRY E.A., BOLLAY, N. and BEERS, N.R. McGraw Hill.

13. U.S. WEATHER BUREAU (1947) — Thunderstorm Rainfall Hydromet. Report No. 5.

14. CORPS OF ENGINEERS. (to date) — Storm Rainfall in the U.S.

15. SOLOT S.B. (1939) — Computation of depth of precipitable water in a column of air. Monthly Weather Rev. V. 67, p 100-103.

16. U.S. WEATHER BUREAU (1961) — Interim report Probable Maximum Precipitation in California, Hydromet. Report No. 36.

17. U.S. WEATHER BUREAU (1945) — Revised report on Maximum Possible Precipitation Los Angeles Area, California. Hydromet, Report No. 21B.

18. HERSHFIELD, D.M. (1962) — Extreme rainfall relationships Jour. of Hyd. Div. of Proc. Am. Soc. Civ. Eng. HY 6, P 73-92.

Table 1. Maximum Depth, Duration, Area data for the United States (1960)

Area Sq. mi.	Duration, hr.								
	1	3	6	12	18	24	36	48	72
10	8.8	18.8b	24.7a	29.8b	36.3c	38.7c	41.8c	43.1c	45.2c
100	6.0b	14.7b	19.6b	26.3c	32.5c	35.2c	37.9c	38.9c	40.6c
200	5.5b	13.5b	17.9b	25.6c	31.4c	34.2c	36.7c	37.7c	39.2c
500	4.7b	11.8b	15.4b	24.6c	29.7c	32.7c	35.0c	36.0c	37.3c
1000	3.9b	10.0b	13.4b	22.6c	27.4c	30.2c	32.9c	33.7c	34.9c
2000			11.2b	17.7c	22.5c	24.8c	27.3c	28.4c	29.7c
5000			8.1bd	11.1b	14.1b	15.5c	18.7e	20.7e	24.4e
10000			5.7d	7.9f	10.1g	12.1g	15.1e	17.4e	21.3e
20000			4.0d	6.0f	7.9g	9.6g	11.6e	13.8e	17.6e
50000			2.5gh	4.21	5.3g	6.3g	7.9g	8.9g	11.5j
100000			1.7h	2.5hk	3.5g	4.3g	5.6g	6.6j	8.9j

Storm	Date	Location	Dew Pt.
a	July 17-18, 1942	Smethport, Pa	74
b	September 8-10, 1921	Thrall, Tex.	77
c	September 3-7, 1950	Yankeetown, Fla.	76
d	June 27 - July 4, 1936	Bebe, Tex.	78
e	June 27- July 1, 1899	Hearne, Tex.	75
f	April 12 - 16, 1927	Jefferson, Parish La.	72
g	March 13 - 15, 1929	Elba, Ala	67
h	May 22 - 26, 1908	Chattanooga, Okla.	74
i	April 15 - 18, 1900	Eutaw, Ala.	66
j	July 5 - 10, 1916	Bonifay, Fla.	76
k	November 19 - 22, 1934	Millry, Ala	69

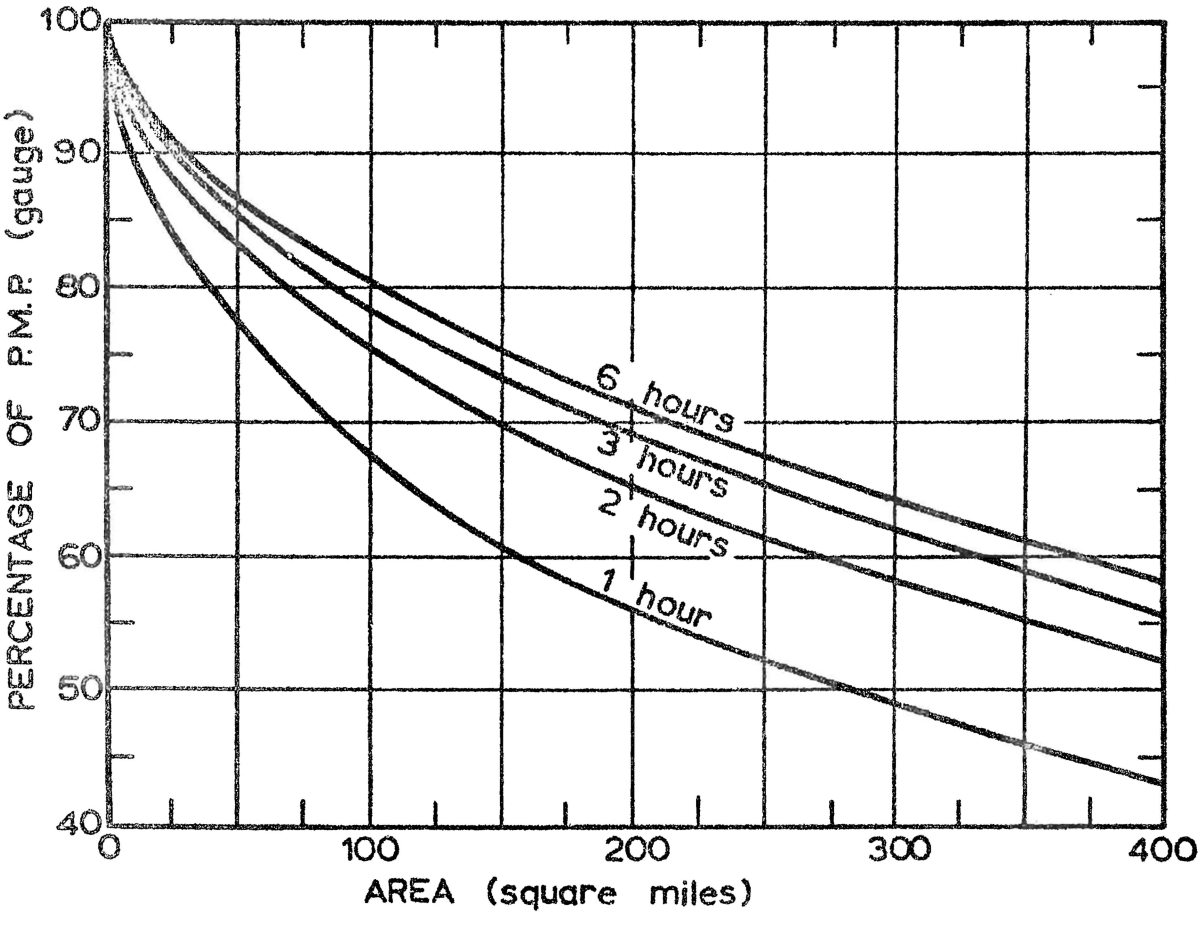


Figure 1 Depth - area relationship for cloud burst rainfall.

DEPTHS OF PRECIPITABLE WATER IN A COLUMN OF AIR OF GIVEN HEIGHT ABOVE 1000 MILLIBARS

Assuming Saturation with a Pseudo-Adiabatic Lapse Rate for the Indicated Surface Temperatures

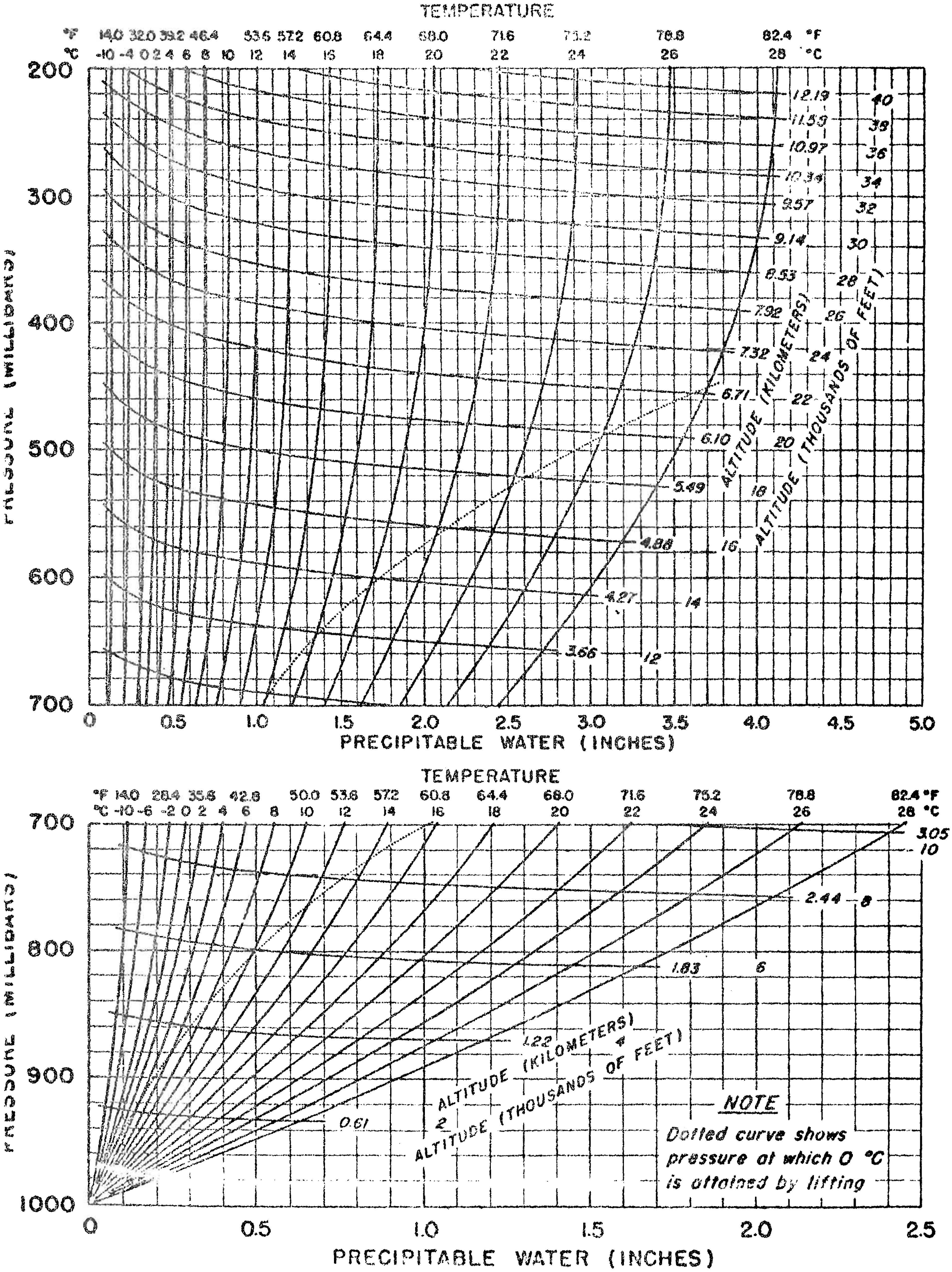


Figure 2 Depth of precipitable water in a column of air. 30

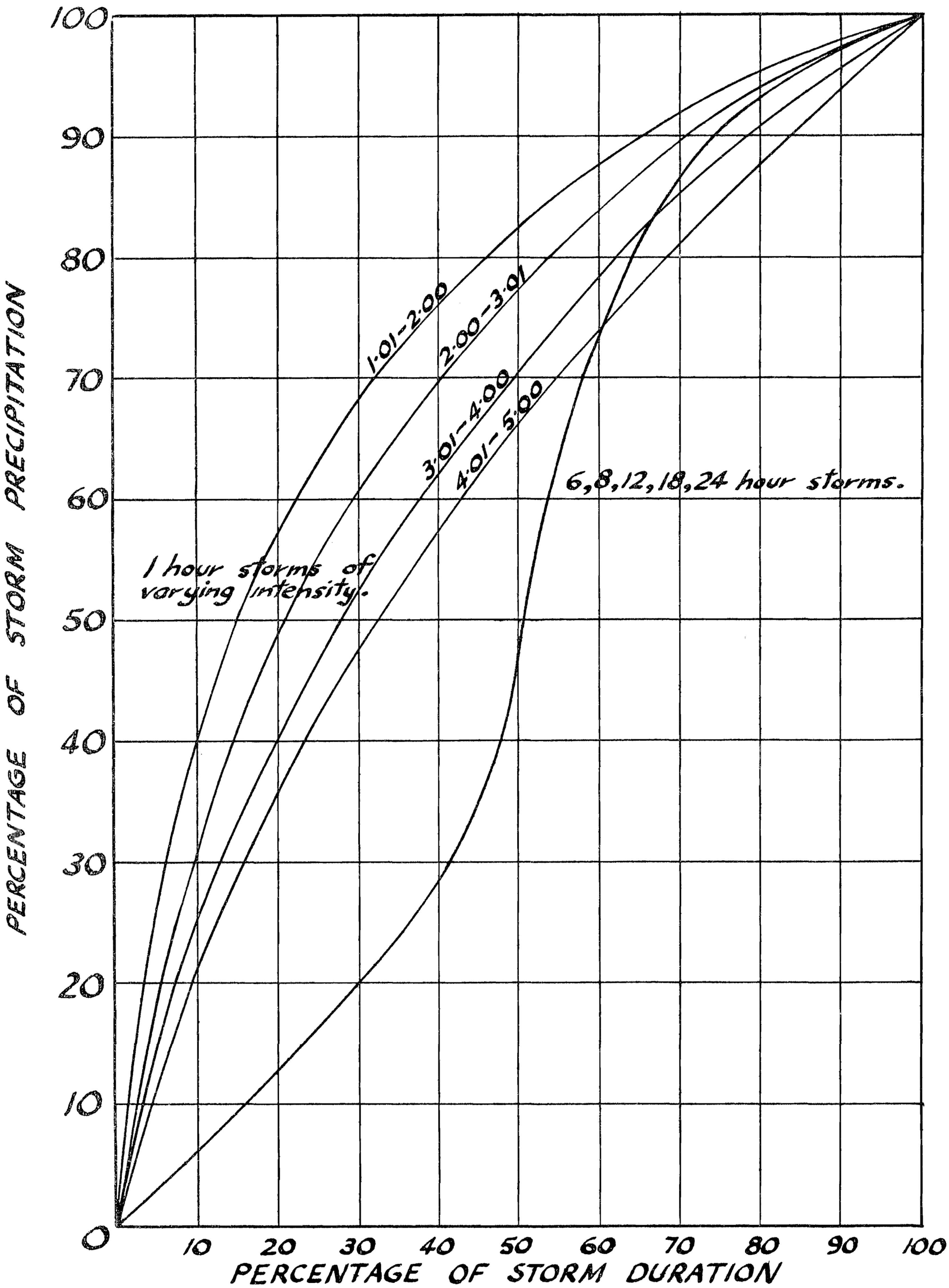


Figure 3 Mass curve of thunderstorm and general storm.

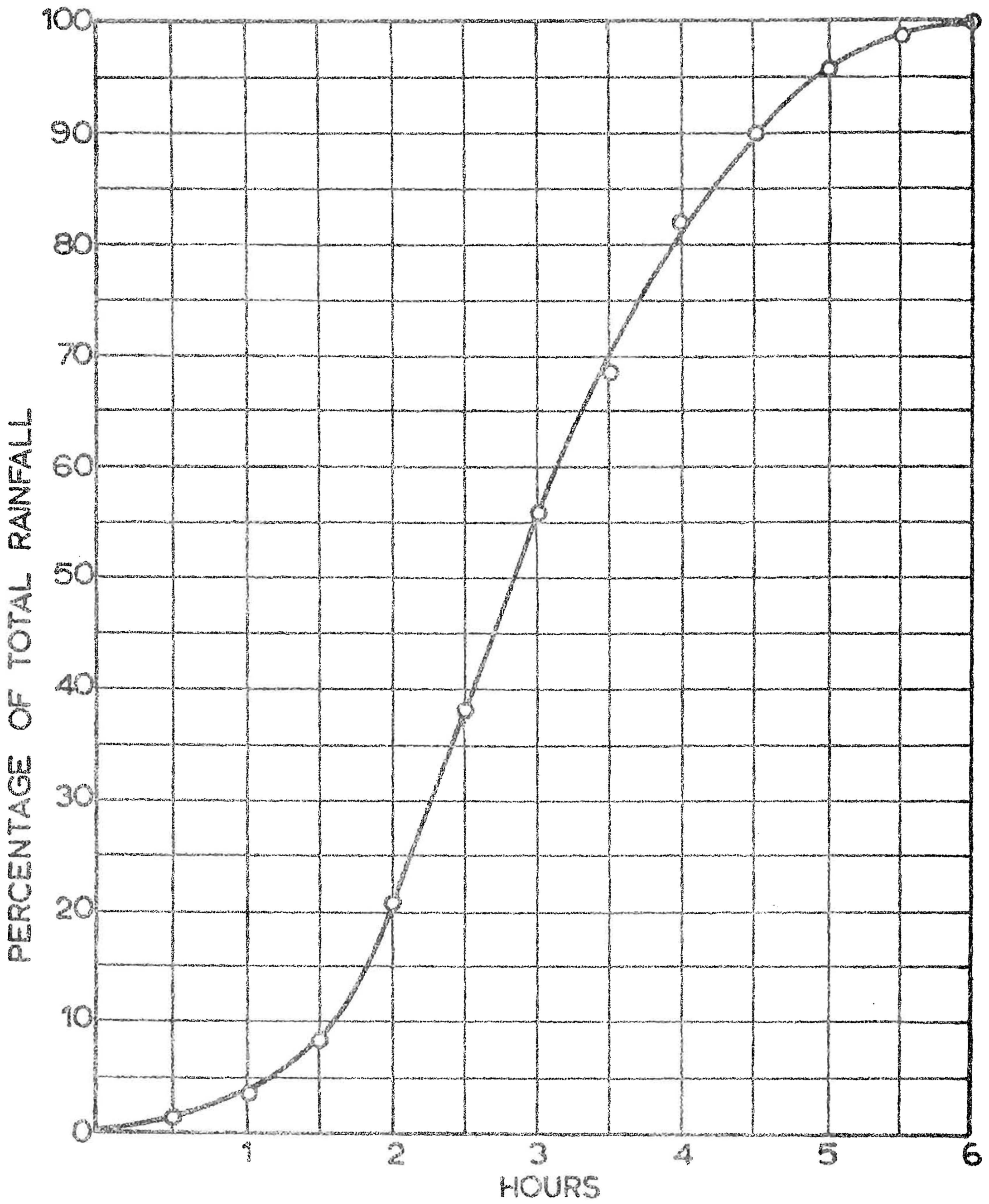


Figure 4 Mass curve of thunderstorm over 375 sq. mi and 6 hr.

ON RAINFALL VARIATIONS IN NEW ZEALAND

J. D. Coulter

N.Z. Meteorological
Service

INTRODUCTION

At last year's ANZAAS conference in Melbourne, drought was the main subject of at least one paper. In several others the effects on plants of water shortages during periods of low rainfall were discussed. Drought was then, as now, a matter of great concern in Australia. In parts of the southeast, unusually deficient rainfall for several years has had serious economic consequences.

In New Zealand, too, droughts and dry spells are important in the consideration of water resources, although on a shorter time scale. Here, except in the limited areas of lowest average rainfall, yearly rainfall totals are seldom much less than the annual water needs of vegetation. Thus, in New Zealand, for the most part, the dry periods of economic consequence for agriculture or engineering have durations of a few weeks or a few months.

Most rain in New Zealand is associated with relatively large scale weather systems - depressions or frontal low pressure troughs - which characteristically give one or more days of rain over large parts of the country. The intervening high pressure systems usually give several days without much rain. The obvious coherence in rainfall distribution associated with these moving systems is reflected in the statistical presistence found in daily rainfalls (see Finkelstein 1967). Dry and wet spells of longer duration appear to arise virtually at random, although Seelye (1946) demonstrated a small degree of persistence in monthly rainfall. (The probability of a drier than average month following a dry month was 0.59). During a typical drought the troughs and centres of low pressure are weak, or pass far from the areas concerned, and they come between persistent strong anticyclones. Thus apparently by chance a season occasionally occurs with very persistent or very widespread low rainfall. Such a season was experienced, for example, in 1963-64 when "drought disaster" was officially declared in a number of districts from Northland to Otago (Table 1), lasting from spring 1963 in some areas through the winter and spring of 1964 in others. (Fig. 1).

Table 1

Districts and seasons in which 'Drought Disaster' was declared, 1963 - 1964

District	Season
Northland	Spring (1963), Summer, Autumn, Winter
Thames (Auckland)	Summer, Autumn
Rotorua - Bay of Plenty - Taupo	Spring (1963), Summer
Wairoa (East Coast, N.I.)	Summer, Autumn, Winter
Hawkes Bay	Summer
Wairarapa	Summer
Ashburton County (Canterbury)	Autumn, Winter
Mackenzie Country(Canterbury)	Summer, Autumn, Winter
North-Central Otago	Winter, Spring (1964)

Rainfall records from a large number of stations in New Zealand are available for water resource studies. In the Meteorological Service recent work on rainfall has been concerned firstly with the distribution of seasonal rainfall over New Zealand, and secondly with the space relations of rainfall, on a monthly, seasonal and annual basis.

The first of these topics was chosen partly because the season of three calendar months is the order of duration of many of the major recorded droughts and the great mass of rainfall data is as yet available for electronic processing only as monthly totals. It was considered useful to prepare maps of average seasonal rainfall, and to determine the variability, and examine the frequency distributions of seasonal rainfall. This work is to be reported in more detail (Coulter and Finkelstein, in preparation), but some results are briefly outlined below.

The second is an attempted step towards answering the questions: How extensive are New Zealand droughts? If one district has a drought of specified severity, which other districts are likely to be affected, and which are likely to be having a wet or a normal season? If quantitative answers to such questions can be found they should have implications for economic planning, e.g. concerning stock movements and feed reserves required for optimum agricultural production.

SEASONAL RAINFALL DISTRIBUTION

The distributions of rainfall totals in the calendar seasons (Summer: Dec. Jan. Feb., etc.) have been studied to supplement previous work on monthly and annual rainfall. It may be desirable in future to extend to other groupings of months as well as to work with shorter time intervals. However, the seasons are for some purposes a convenient unit, and they are commonly used for comparisons.

The geographical distribution of average rainfall in New Zealand is well known, e.g. Fig. 2(a) shows average summer rainfall totals. These vary from more than 60 inches in Fiordland and the Alps to less than five inches in Central Otago. They are less than ten inches in most of Southland, Otago, Canterbury, Marlborough, the Wellington Province and Hawkes Bay, and in areas near Gisborne, Hamilton and Auckland. As the potential evapotranspiration total for summer is approximately 10 - 11 inches in most of these areas, an average summer rainfall, even if well distributed over the season, will provide less than full plant water needs, and little or no water will be available for runoff. Even a relatively small rainfall deficiency can then have significant effects on agricultural production.

Somewhat similar patterns of average rainfall are found in the other seasons. Figures 2(b) and 2(c) show the season of highest and lowest average rainfall, with the relevant percentage of the annual total shown where this exceeds 30 per cent or is less than 20 per cent. No season anywhere gets very much more or less than a quarter of the annual rainfall on average. Some extremes are:

> 16% in Central Otago in winter;
>
> more than 30% in the north and east of the North Island and in Banks Peninsula in winter;
>
> more than 30% in Central and North Otago in summer.

Winter rainfall predominates in the North Island and in the north of the South Island and about Banks Peninsula. In the remainder of the South Island summer or autumn rainfall predominates. (At many of the stations used in preparing these maps, 35 to 50 years of record were available. Another sample of similar length would not give precisely the same values. The probable sampling errors will be discussed in the paper on Seasonal Rainfall.)

The standard deviation of the seasonal rainfalls gives a measure of the scatter in individual seasonal totals. (Its value tends to be greatest where the average is greatest.) The ratio of standard deviation to the mean, or coefficient of variation, (v), is shown in figure 3 for summer and winter. It is generally greatest in the east of the country (and in the north in summer), exceeding 0.5 in a few places; and lowest in the south and west where it is often less than 0.2. There are seasonal differences. Except in Otago, spring and winter have generally the lowest values. This distribution is broadly similar to that of monthly variability (Seelye 1940). For comparison, values of seasonal variability index (the ratio of the average of departures from the mean without regard to sign, to the mean) have a maximum of approximately 40 per cent in summer and autumn in Hawkes Bay and Northland, and a minimum of 15 to 17 per cent on the west coast of the South Island in winter and spring. The range in monthly variability is from 18 per cent at Puysegur Point in May to 77 per cent at Waimarama in Hawkes Bay in January.

FREQUENCY DISTRIBUTION OF SEASONAL RAINFALL

Seasonal rainfall is not normally distributed, as the distributions are zero bounded but include occasional very large values. Histograms of the distributions at representative long period stations whose records are considered to be relatively reliable show a varying degree of positive skewness. They show also that even with 50 - 60 years of record there are large irregularities in the observed frequency distributions for a single station. The irregularities could be largely eliminated if the separate station data were combined into a single composite series, but this would obliterate any geographical differences which might exist.

Fitting of a theoretical curve has some value in that it can provide a compact representation of a large mass of data, and as it enables smoothed interpolations of quantile values to be made objectively. The theoretical "gamma" distribution (Thom 1958) has been found to give good fit to precipitation climatological series (Thom 1966). Applied to New Zealand seasonal rainfall series it appears to fit the actual distributions satisfactorily.

The gamma frequency distribution is defined by its probability density function

$$g(x) = \frac{1}{\beta^{\gamma}\Gamma(\gamma)} \cdot x^{\gamma-1} \cdot e^{-\frac{x}{\beta}}$$

where β is a scale parameter, γ is a shape parameter and $\Gamma(\gamma)$ is the ordinary gamma function of γ .

Estimates of the parameters may be obtained as follows (Thom 1966): $\gamma = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right)$ and $\beta = \frac{M}{\gamma}$

where $A = \ln \bar{x} - \sum \ln x / N$, M is the mean value of the variate x, and N the number of terms in the sample.

The distribution function $G(x) = \int_0^x g(t)\,dt$ Pearsons's (1951) "Tables of the Incomplete Γ - function" gives g (u,p) where $u = \frac{x}{\beta\sqrt{\gamma}}$ and $p = \gamma - 1$.

The gamma distribution is zero bounded. For $\gamma > 1$ it is bell shaped with mode at $\beta(\gamma-1)$. With increasing γ the distribution becomes more symmetrical and slowly approaches the normal distribution. If the variate is expressed in terms of the mean ($x' = x/M$), γ is unchanged and the mode becomes $1-\frac{1}{\gamma}$. In the gamma distribution the coefficient of variation (v) and the skewness parameter ($\sqrt{b_1}$) are determined by the value of gamma as follows:

$$\sqrt{b_1} = 2V = \frac{2}{\sqrt{\gamma}}$$

Two examples of observed and theoretical distributions, for Naper, summer and Ross, spring, are illustrated in figure 4. They were chosen as representing near extremes in the character of the distributions. The histogram gives the observed frequencies, the solid line the theoretical gamma frequency curve fitted to the data. The curve for Napier is highly skew ($\gamma = 4$), that for Ross is more nearly symmetrical ($\gamma = 23$).

Figure 5 gives the distribution function (cumulative probability curves) for selected values of γ for the variate x'. It may be used (by interpolating for γ) instead of the tables, from which it was constructed, to derive approximate values of the probability for the values of γ likely to be encountered with seasonal rainfalls in New Zealand.

Figure 6 shows for summer and winter the distribution of the gamma parameter found for some 135 stations in New Zealand. Of these 66 had records of at least 50 years while most of the remainder were of at least 30 years. The distribution of γ over the country shows, as expected, a rough correlation with the coefficient of variation. The isopleths have been smoothed to some extent, and as with other isopleths drawn on this scale they do not necessarily apply to areas of high elevation. The value of γ ranges from approximately 3.0 in a few places near Napier and East Cape in summer and autumn to more than 20 in western areas in winter and spring.

With values of γ taken from these maps, and values of seasonal rainfall (from, for example, maps such as Fig. 3a, or from average monthly rainfall tabulations), approximate quantiles of seasonal rainfall can be derived. For example, at places where $\gamma = 9$, the 20-percentile value (that exceeded four years out of five) is 72 percent of the mean.

SPACE CORRELATIONS OF RAINFALL

The spatial relationships of rainfall in New Zealand are determined by the interaction of topography and the various weather systems experienced. They are complex and it is not obvious how they can be subjected to statistical analysis that will be sufficiently discriminating but not so elaborate as to be unmanageable or to reduce sample sizes to an unacceptable level.

Geographical patterns of rainfall anomalies found in individual months, are illustrated for three recent months in figure 7. October 1967 was a dry month in many places, especially in the north. The two driest areas, near Kaitaia and near Auckland, had less than 25 percent of the average rainfall for the month. The areas were about a hundred miles in extent, and about the same distance apart. November was wetter than average in most of the country especially in middle areas of the South Island where rainfall exceeded 400 percent of average. Again the major anomaly elements cover half an island or more, but some features are on a smaller scale. In December the North Island was again largely wet, and the South Island variable. Major anomalies again cover about half an island. Details of the patterns are quite irregular and there is little apparent consistency in them from month to month.

As a first step in the statistical analysis, to seek broad relationships and their extent, correlation coefficients (r) have been calculated between monthly, seasonal, and annual rainfalls at a number of reference stations and at selected stations, mostly in the same province as the reference station in question. Figures 8 and 9 show some of the results, for Auckland and Christchurch as reference stations. Separate maps are given for annual totals, summer, January, and July. In all correlations the number of pairs was at least 30 and in most cases was more than 50. The shaded area is for $r > 0.7$ thus including areas where at least half the variance was in common with the reference station. Hatching indicates schematically the areas where correlation coefficients were less than the limiting significant value (at $P = 0.05$). The inset diagram shows confidence limits of r for 50 pairs.

In brief, the main features of these maps are as follows:-

The correlations fall off fairly rapidly with distance reaching 0.7 at distances of 15 to 140 miles from Auckland, and of 20 to 100 miles from Christchurch.

The area of high correlation is greatest for summer and summer months, lowest for annual and winter months.

The isopleths of **r** are roughly elliptical, with long axis parallel to the axis of the country, i.e. NW-SE at Auckland, NE-SW at Christchurch. The ellipses are roughly 2-3 times as long as broad.

With a few exceptions neighbouring stations give similar correlations, and the isopleths of r form reasonably consistent patterns which are related to topography. Although statistical confidence limits are wide (e.g. for $N = 30$, $r = 70$, the limits are 0.55 and 0.83 for $P = 0.05$) it is unlikely that this consistency is merely due to chance. It is not implied, however, that another sample of years would give exactly the same pattern.

In some few cases, mostly with Christchurch as reference station, statistically significant negative correlations were found.

CONCLUSIONS

Water resources planning is likely to be more concerned with the incidence of water shortage in times of deficient rainfall than with the occurrence of a surplus over a period of a month or more. Although the natural sequence of rainfall is measurable on a time scale of days at most, and although significant agricultural water shortage can arise in a shorter time than a month, useful information can be derived from rainfall statistics for months or seasons. The characteristics of point rainfall in New Zealand are by now reasonably documented for most of the country, both as to average amounts (N.Z. Met.S. unpublished maps and tabulations) and as to the variability and probability levels. (e.g. Seelye 1940, 1946), and also in relation to water needs of vegetation (e.g. Gabites 1956, Rickard 1960, Coulter 1966) chiefly for the month and longer groupings of months.

The associations from place to place of rainfall anomaly are less well known. The simple correlations between rainfall amounts now being evaluated provide some useful background for this problem. They also contain material for speculation on climatic differentiation within the country, and will need to be considered in terms of synoptic climatology. Further work on specific drought periods of the past record is clearly necessary, especially with regard to the area affected. If feasible it would be desirable to assess probabilities of drought for specified areas. Finally, one should mention the ultimate aim of long-term forecasting of rainfall anomalies in periods of a month or more. Although some hopeful signs are emerging from the theoretical study of the general atmospheric circulations in the light of improving global observations, there is as yet no indication that accurate long range forecasting will be realised in the very near future.

References

Coulter, J.D., 1966: Dry spells in New Zealand as a factor in plant ecology. Proc. N.Z. Ecol. Soc. 13: 4-8.

Finkelstein, J., 1967: Persistence of daily rainfall at some New Zealand stations, J. of Hydrol. (N.Z.) 6: 33-45.

Gabites, J.F., 1956: Estimation of natural evaporation and water need. Proc. Conf. on Soil Moisture Sept. 1954. N.Z.D.S.I.R. Inf. Ser. No. 2: 128-30.

N.Z. Meteorological Serv., Maps and tabulations of monthly and annual rainfall normals (unpublished).

Rickard, D.S. 1960: The occurrence of agricultural drought at Ashburton, New Zealand. N.Z. J. Agric. Res.3: 432-41.

Seelye, C.J., 1940: Variability of annual rainfall in New Zealand N.Z. J. Sci. Tech. 22B: 18-21.

Seelye, C.J., 1946: Variations of monthly rainfall in New Zealand. N.Z. J. Sci. Tech. 27B: 397-405.

Thom, H.C.S., 1958: A note on the gamma distribution. Monthly Weather Review. 86 (4): 117-122.

Thom, H.C.S., 1966: Some methods of climatological analysis. Tech. Note No. 81 W.M.O. Geneva, pp 52.

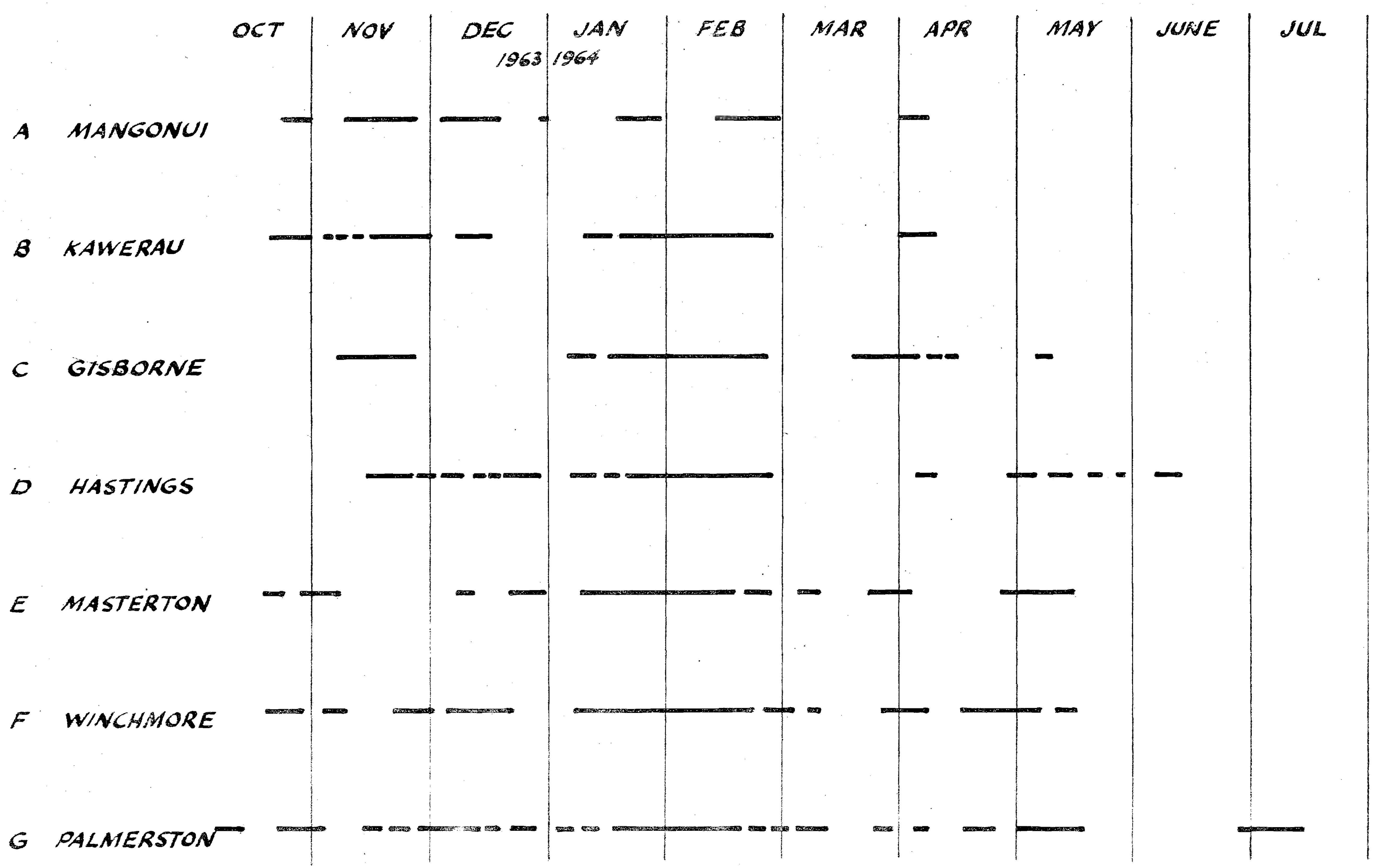

OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUNE
JUL
1963
1964
A MANGONUI
B KAWERAU
C GISBORNE
D HASTINGS
E MASTERTON
F WINCHMORE
G PALMERSTON

Figure 1

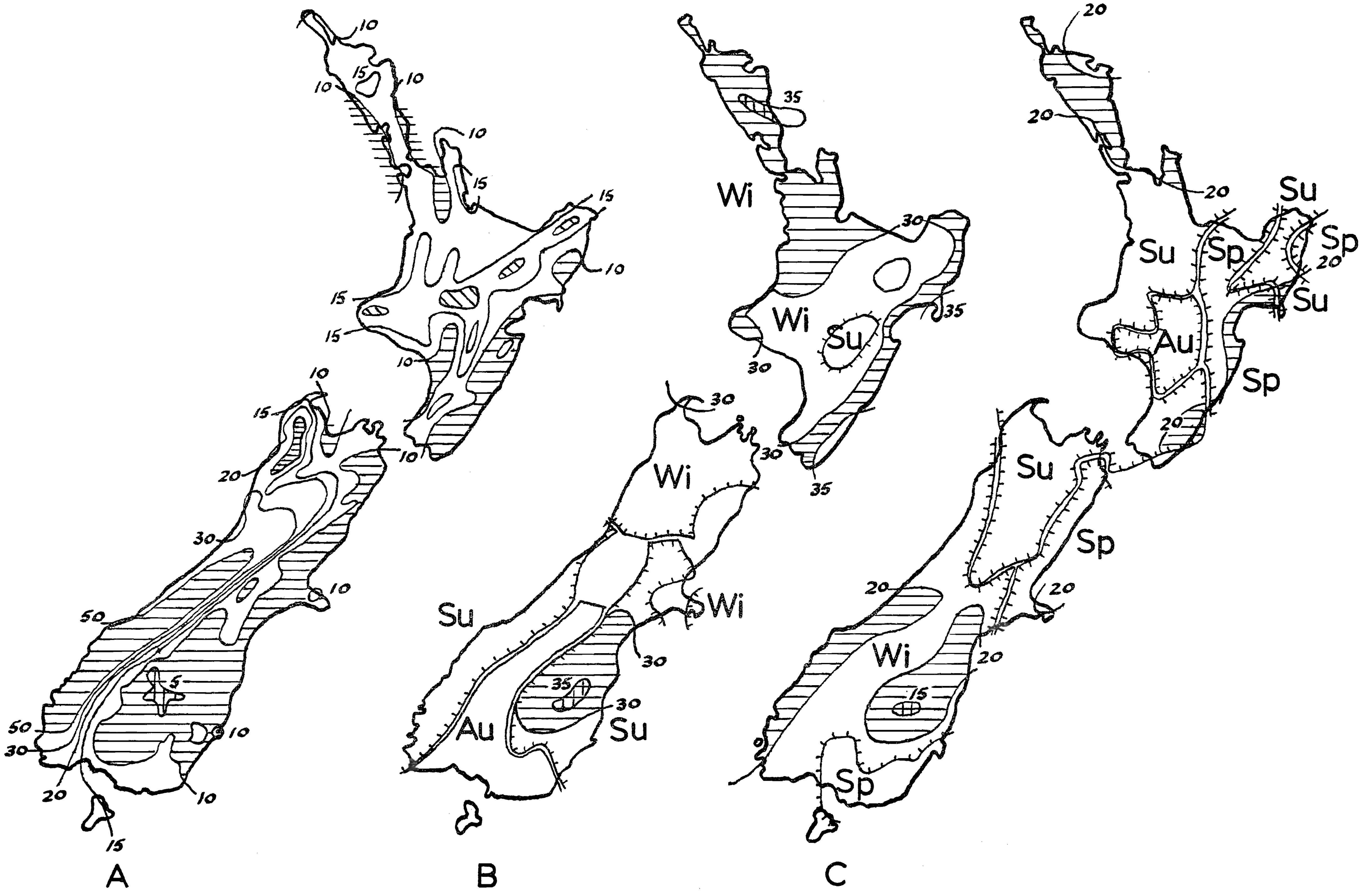
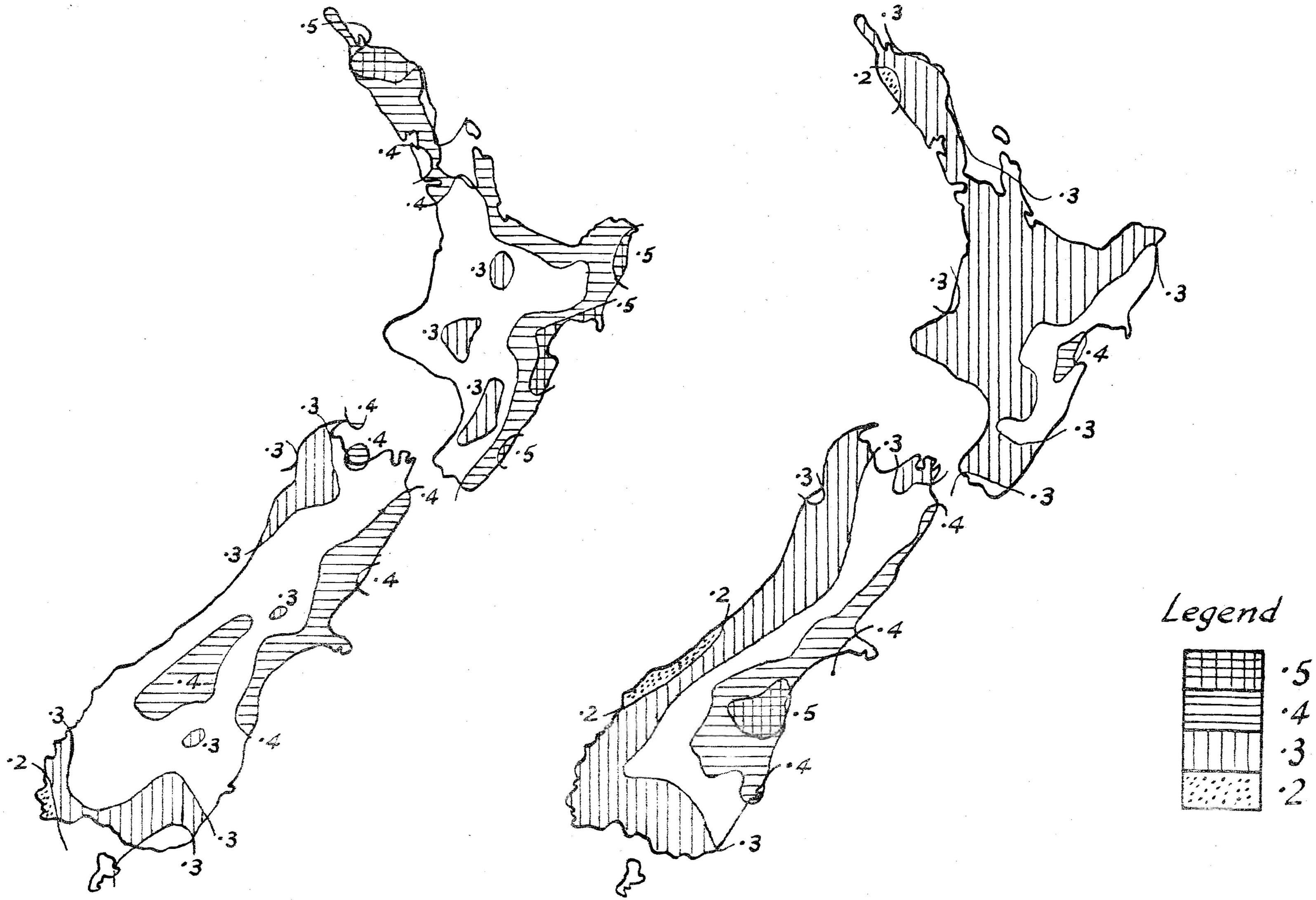


Figure 2



A

B

Figure 3

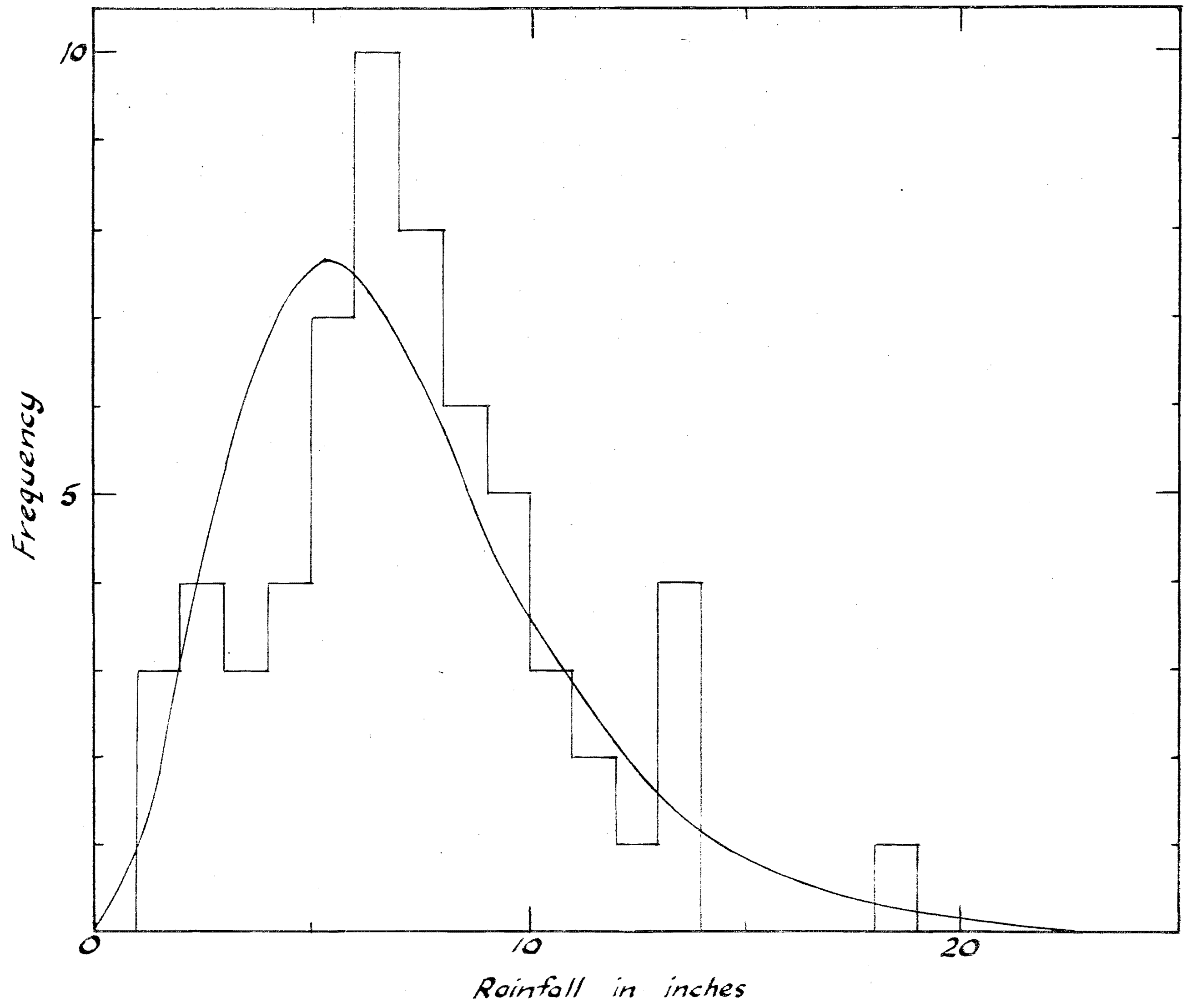


Figure 4A

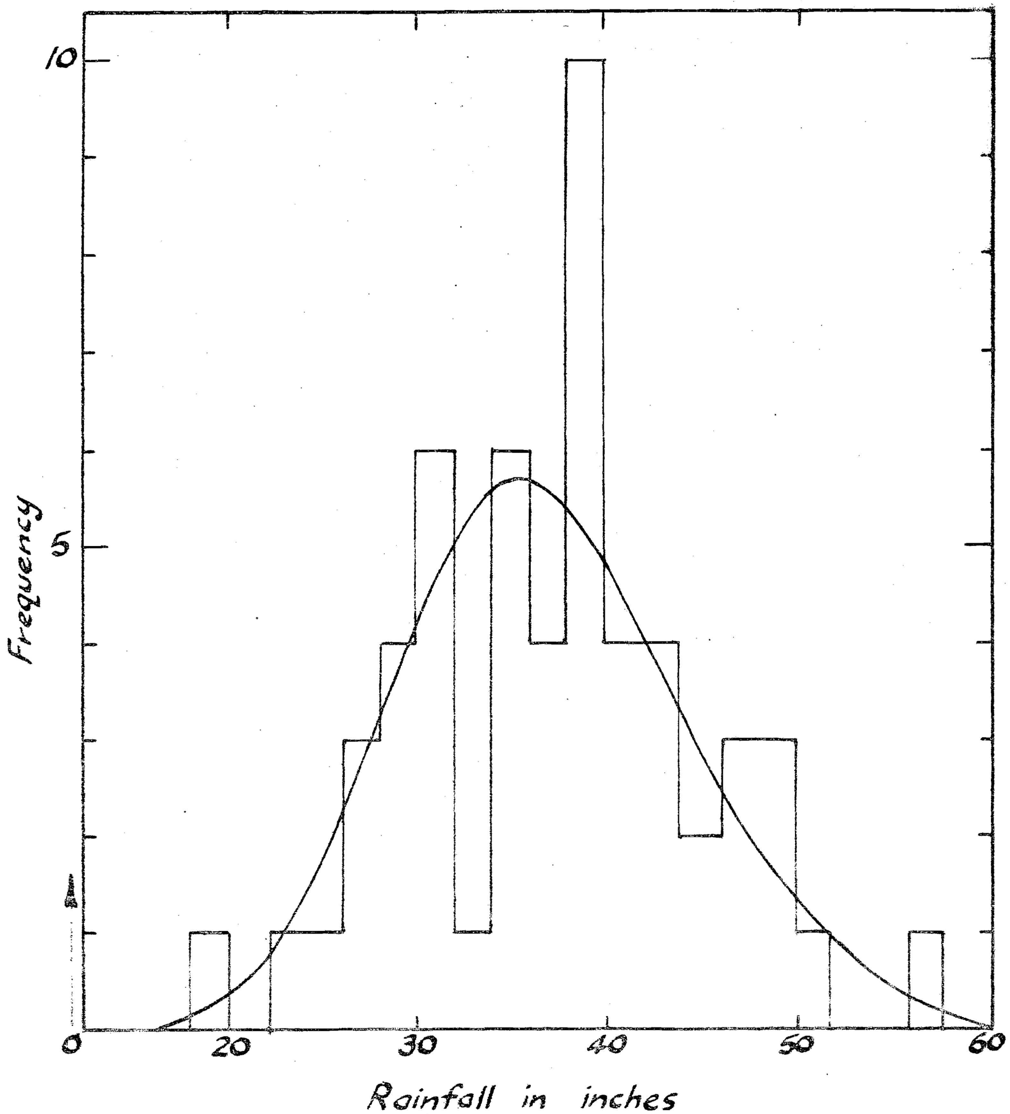
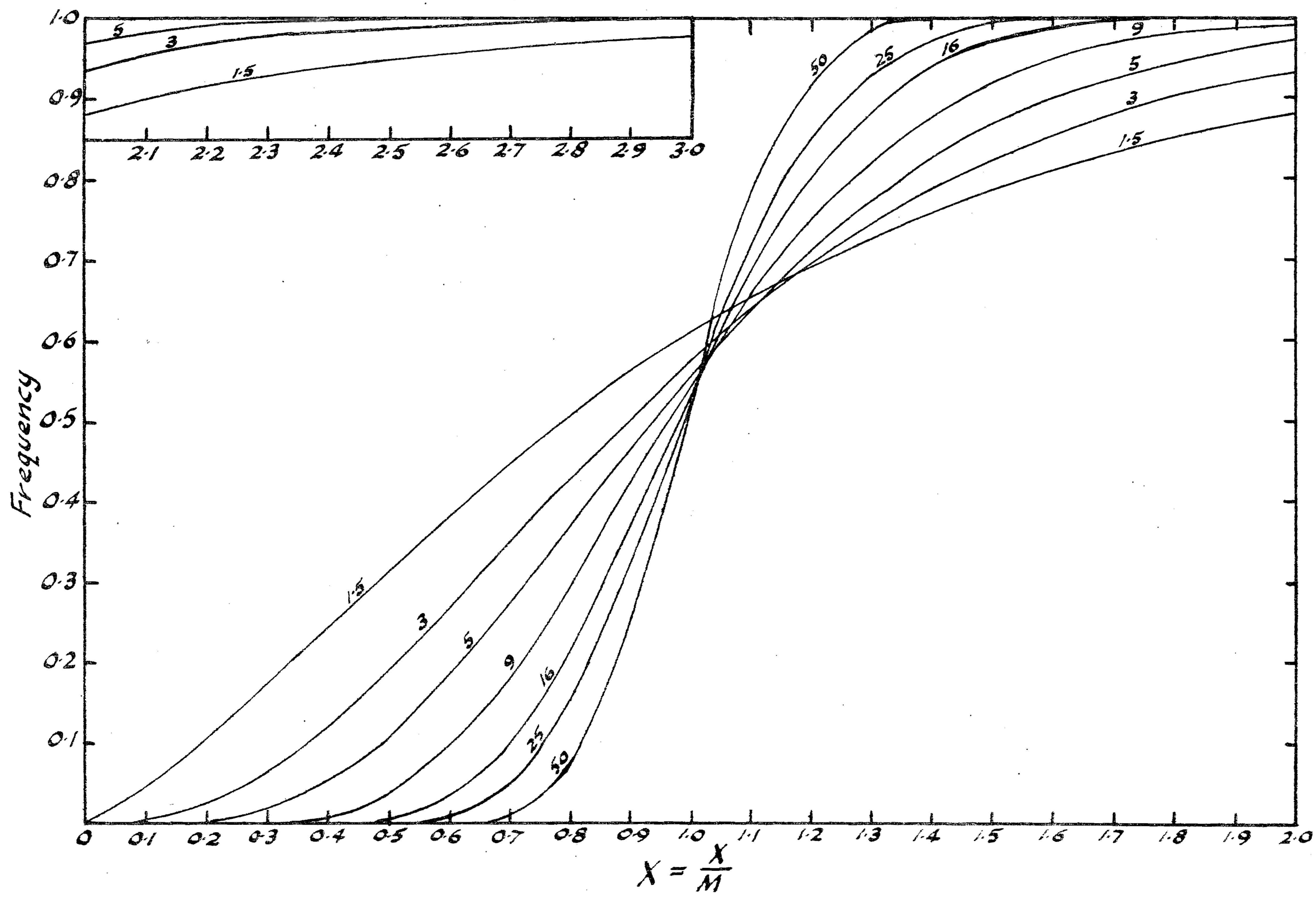


Figure 4B

Figure 5



Frequency
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
0·1 0·2 0·3 0·4 0·5 0·6 0·7 0·8 0·9 1·0 1·1 1·2 1·3 1·4 1·5 1·6 1·7 1·8 1·9 2·0
2·1 2·2 2·3 2·4 2·5 2·6 2·7 2·8 2·9 3·0
$X = \frac{X}{M}$
1·5
3
5
9
16
25
50

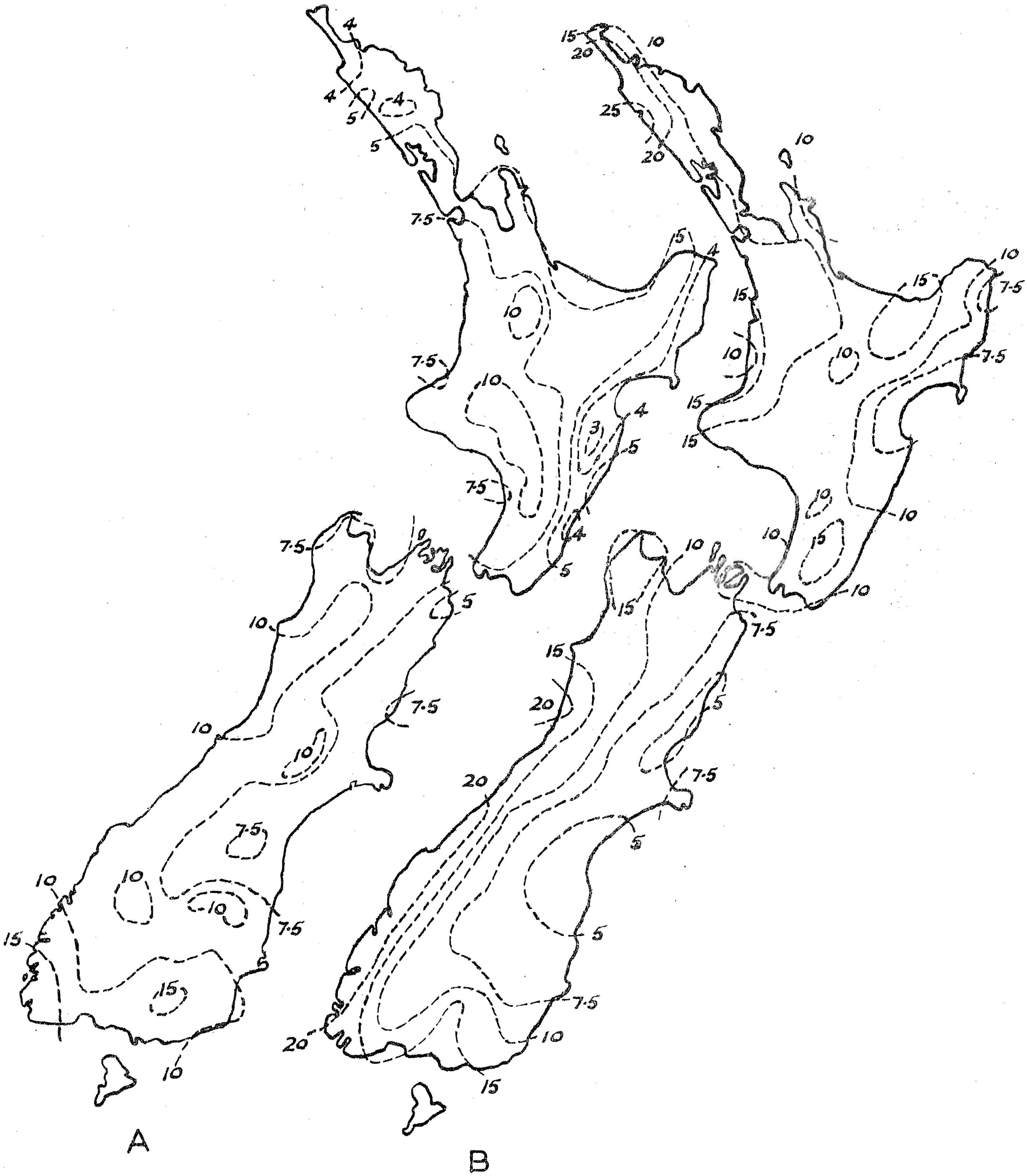


Figure 6

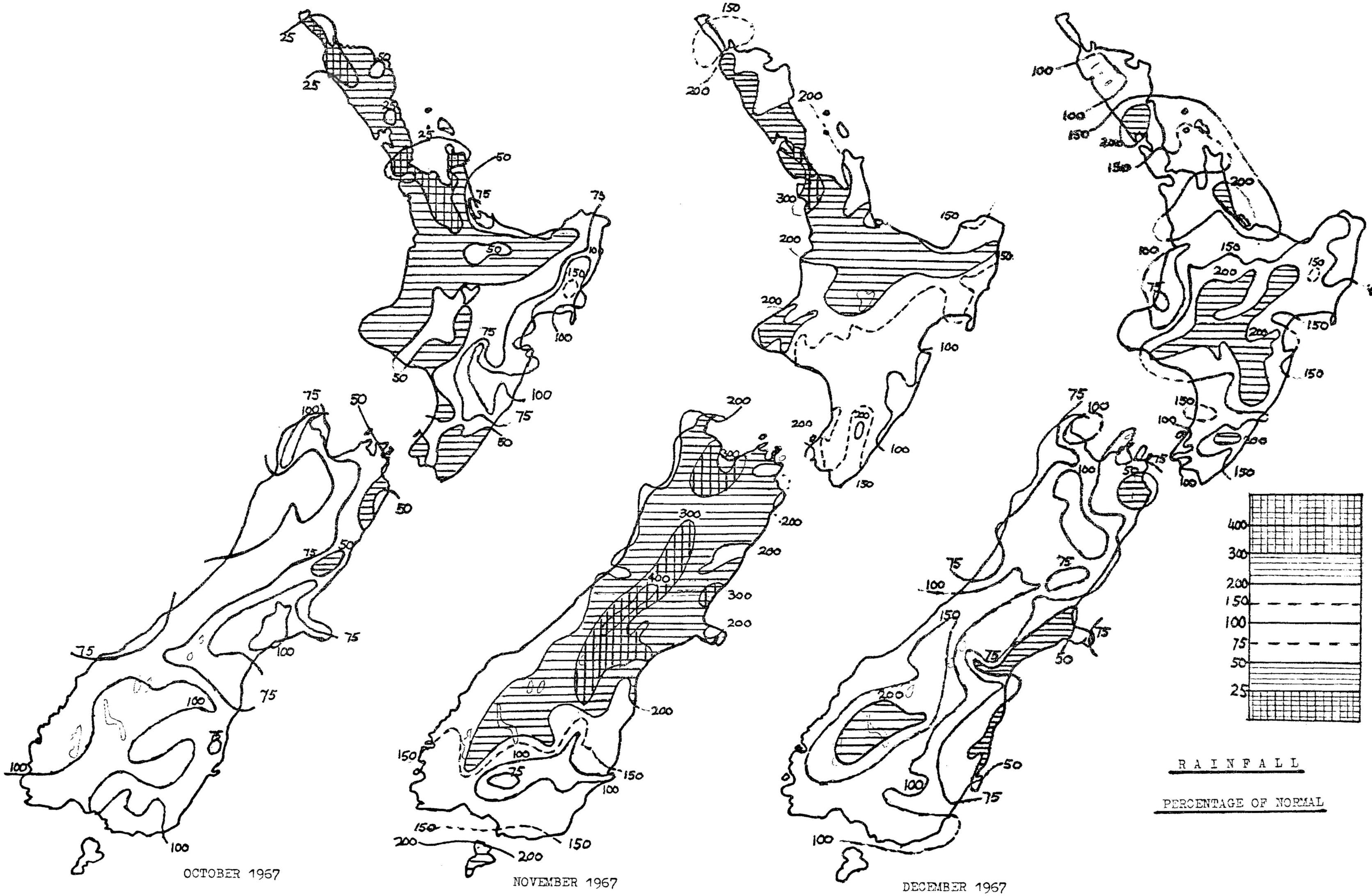
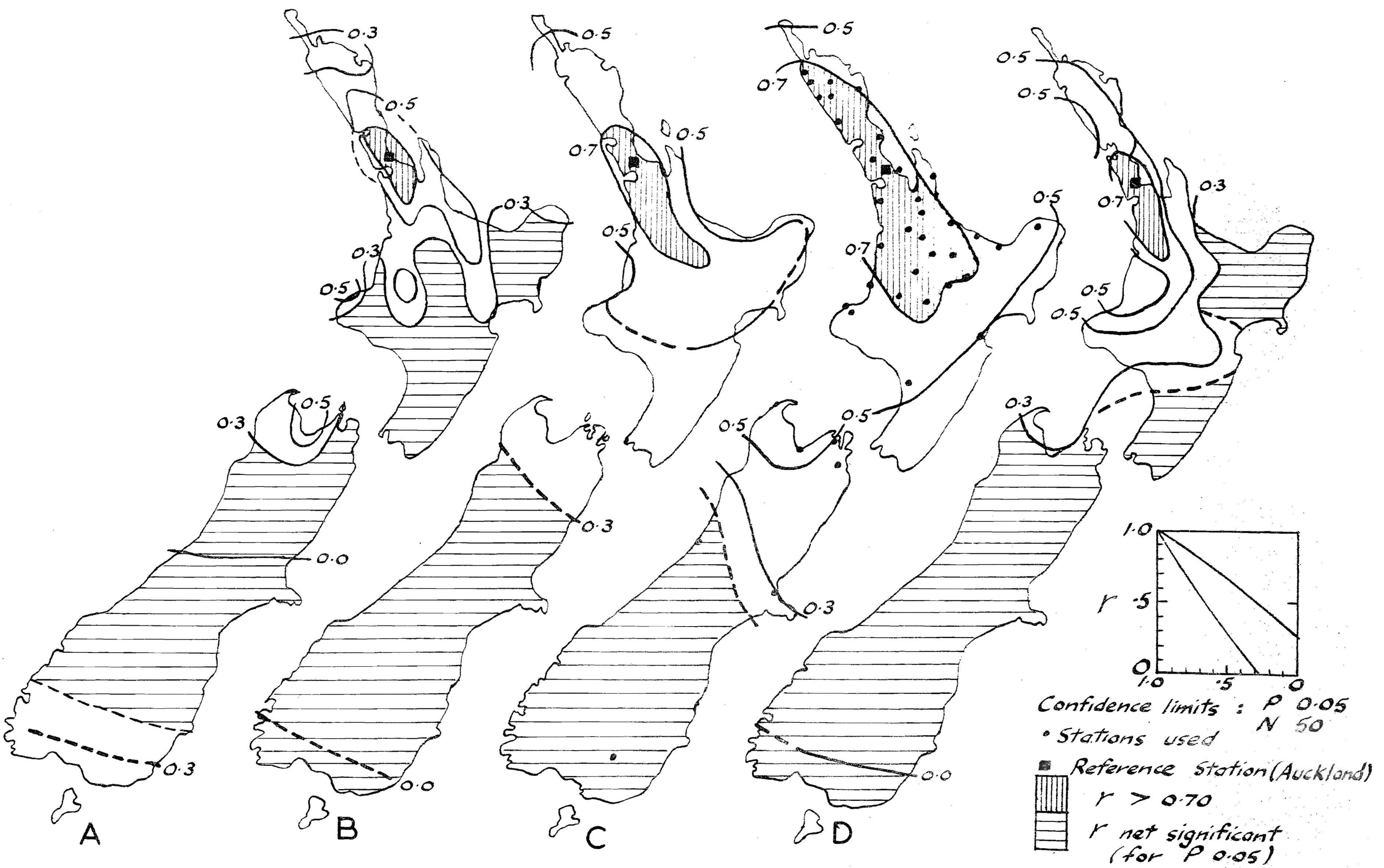

OCTOBER 1967
NOVEMBER 1967
DECEMBER 1967
RAINFALL
PERCENTAGE OF NORMAL
400
300
200
150
100
75
50
25

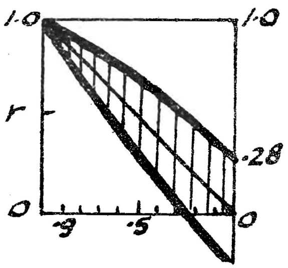
Figure 7



A
B
C
D
Confidence limits : P 0.05
N 50
• Stations used
Reference Station (Auckland)
r > 0.70
r not significant
(for P 0.05)

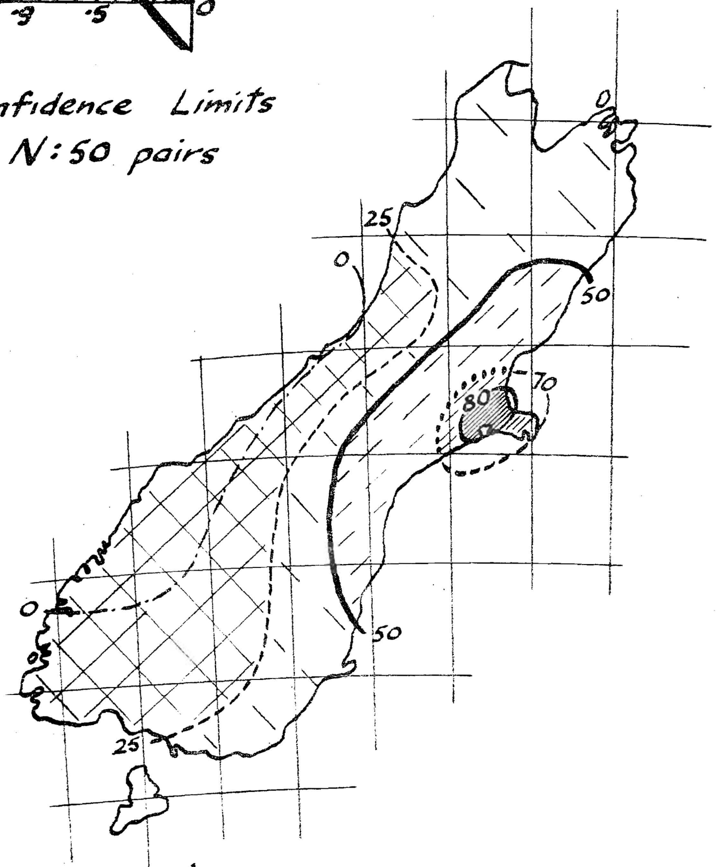
Figure 8

CHRISTCHURCH 100xr



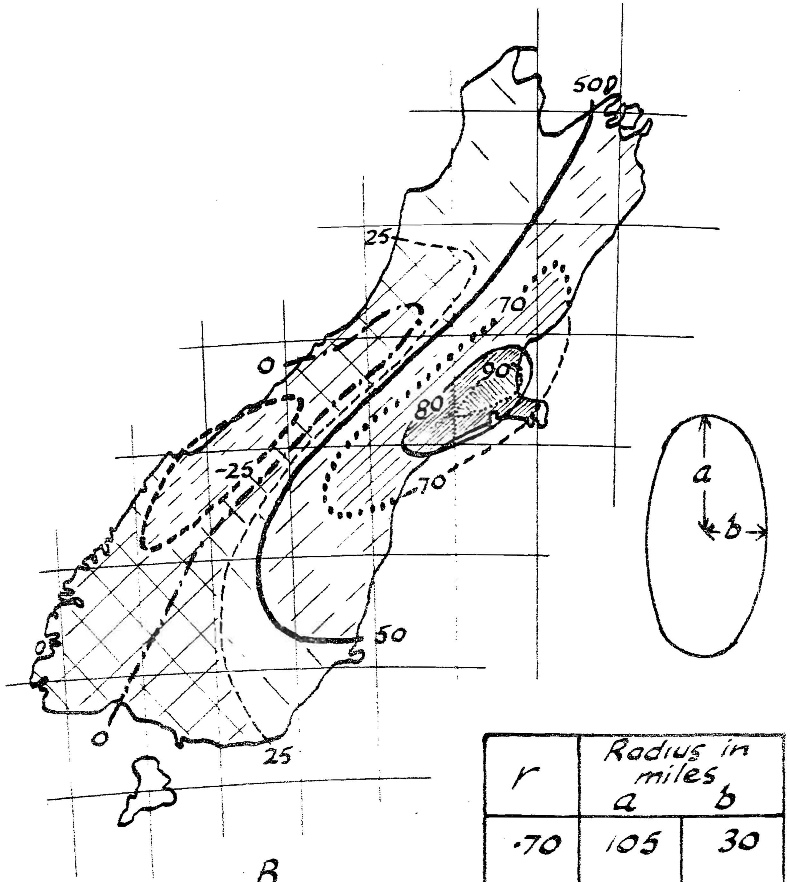
Confidence Limits
N: 50 pairs

Year



A

Summer



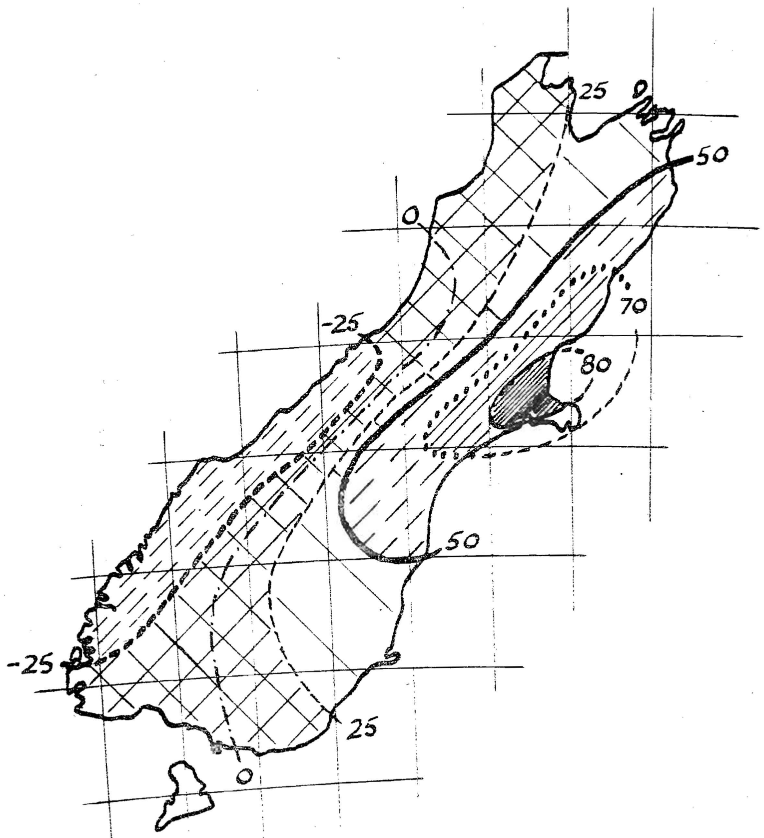
B

r	Radius in miles a	b
.70	105	30
.50	200	50

Figure 9A & 9B

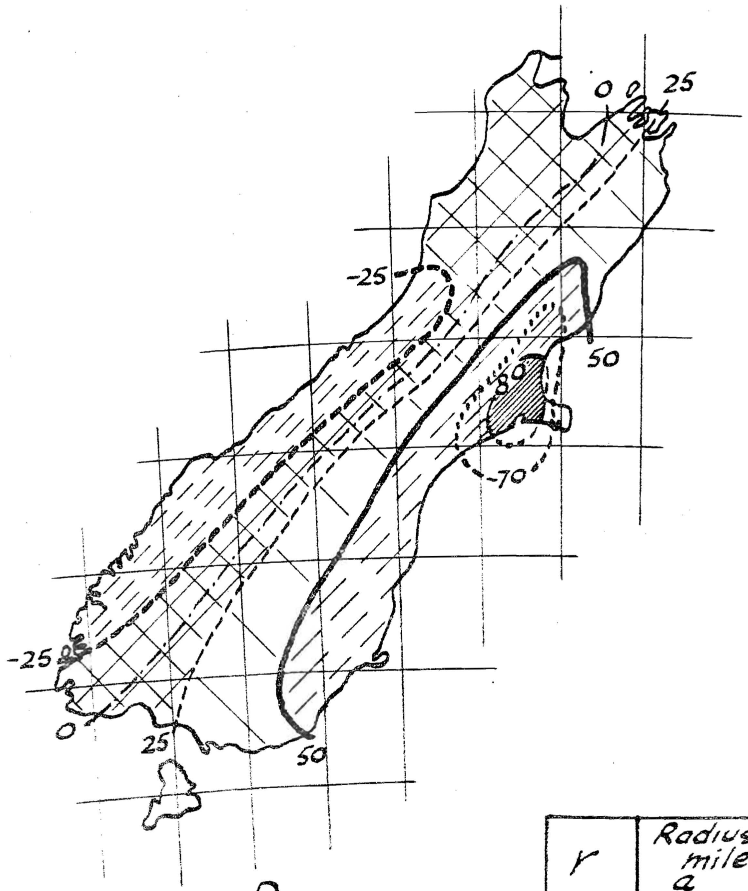
CHRISTCHURCH 100xr

January



C

July



D

r	Radius in miles a	b
·70	80	30

Figure 9C & 9D

THE ROLE OF AGRICULTURAL LAND USE

IN AFFECTING WATER QUALITY

Dr. K.F. O'Connor,
Grasslands Division,
D. S. I. R., Lincoln.

The purpose of this paper is to attempt a brief but integrated review of the deleterious and beneficial role that agricultural land use may have in affecting the quality of water in streams, lakes and other bodies. The viewpoint from which I shall attempt this integration is both biological and cultural - biological in that I shall take account of life processes in agriculture and of related natural forces which potentially affect water quality- cultural in that I show the ways in which these processes and forces can be modified by the actions on the environment of the responsible human community. My remarks are chiefly concerned with the New Zealand scene and they are designed to clarify the nature of the agricultural influences, highlight the significant aspects and leave the discussion of the details of water pollution and its treatment to those better qualified in the later symposium.

Any water user knows what water quality is, but most people know it only in a subjective sense. Like beauty, quality is in the eye of the beholder. Developing from Klein's (1962) definition of pollution, we might define water quality as the condition of water affecting adversely or beneficially any use or uses to which the water may be put. It is my thesis that agricultural land use may have substantial effects in pollution or decontamination of water. It is an integral part of water development to ensure that such effects are in community interest.

Effects on quality through effects on water quantity

As it is widely acknowledged by authorities on water quality, e.g. Phelps (1944), Lein (1962), Camp (1963), that dilution is an important factor in controlling water pollution, I shall first consider some of the implications of agricultural land use to quantities of water in water bodies. Diversion of water for irrigation is an obvious example. At the present time about half of the total fresh water use in the United States of America is for irrigation. Detailed information on the New Zealand scene is presented by Lobb (1968) in this symposium. If we consider the regional and seasonal implications of supplemental and full irrigation developed to potential, then we in New Zealand might appreciate the viewpoint of those Australians who are accustomed to regard some rivers as lines on a map rather than as bodies of flowing water. The implications of concentration of subsequently added wastes are clear. Disposal of wastes in rivers, at present a marginally safe practice in some low flow conditions, could become hazardous to downstream users if irrigation demand reduced South Canterbury rivers to the summer proportions of the Selwyn at the main highway bridge.

Intensification of agriculture can have some positive value for summer flow conditions, especially by development of alluvial lands bordering rivers for crops with lower consumptive use than hydrophytes and preatophytes (Lee, 1942, Fletcher and Elmendorf, 1955). The potential magnitude of losses from consumptive use by wild land vegetation is indicated by the estimate that "fully 50 per cent of the water supplied by Lakes Victoria, Albert and Edward and other sources never reaches the main stream of the Nile, being consumed in the papyrus swamps of the Sudd region covering over 3,200 square miles" (Lee, 1942). Waterspreading as an agricultural engineering device to recharge overdrawn groundwaters is of quantitative significance in several parts of the United States (Muckel and Schiff, 1955, Klein, 1962). When as in the pilot program at Pennsylvania State University it is using treated sewage effluent to recharge depleted groundwater and nourish productive ecosystems, then it has not only a quantitative effect, but a direct qualitative effect of enormous potential magnitude. Beneficial effects of such programs of sewage farming will be measured in the purity of the ground water replenishment They are dependent on the effectiveness of new production systems in taking up nutrients from applied water. In the ordinary practice of irrigation agriculture, it is commonly found that there is a substantial salt concentration increase in irrigation return flow (Sylvester and Seabloom, 1963).

Traditionally, considerable attention has been given to the influence of agricultural land use on particular aspects of water quantity, infiltration and runoff. The nature of changes in infiltration conditions arising from soil and vegetation changes has been debated at length, deduced at often greater length and occasionally measured. Infiltration behaviour may in particular circumstances affect water quality. Soils of low infiltration capacity, especially on landscapes with low depression storage, may give rise to accelerated overland flow and to accelerated stream flow. Rill erosion and bank erosion may develop with resulting increase in transported sediment and reduction in water quality for many uses. Management can control rilling in fields by using vegetation, furrows and other structures to reduce concentration, velocity and turbulence. Water rarely moves as a sheet over much of the soil surface because of lack of smoothness and uniformity. Such unconcentrated overland flow lacks the energy to detach soil particles even though it may transport them. The influences of infiltration behaviour on transported sediment are therefore governed by the subsequent conditions of micro- and macro-channel flow. If, therefore, agricultural land use is associated with a marked deterioration in infiltration behaviour it becomes all the more important for those responsible for water resources development to guard against the formation of unprotected micro-channels and also to protect stream banks themselves. Outstanding examples of such conditions are found in Central North Island pumice country. Table 1 is compiled from records obtained with the North Fork Infiltrometer by officers of the Soil Conservation and Rivers Control Council. The magnitude of the reduction in infiltration rate following agricultural development of scrublands and fernlands is indicated. The consequences of surface water flow in gully cutting, erosion and deposition have been observed by Blong (1966) and have been described in a wider context by Selby (1966).

The preliminary investigations of Nordbye and Campbell (1951) indicated a similar change in infiltration conditions with clearing and grassing in beech forest zones in Marlborough. As Nordbye and Campbell also suggested, the impact of pastoral use with increased grazing pressure and animal treading load is not irreversible. Figure 1 is compiled from Soil Conservation and Rivers Control Council records. I have reconstructed a cultural sequence on a range of slopes of Wither silt loam near Blenheim. As depletion of the Poa Caespitosa grassland has proceeded with increasing grazing pressure and reduced plant cover infiltration has apparently declined to low levels. With pasture improvement there is apparently some compensation, probably associated with higher biological activity.

As stock numbers are increased on our grasslands as they are improved and as treading loads are accordingly increased, it is commonly expected that infiltration will suffer. Increased live-stock numbers are not without compensation. Sears and Evans (1953) have demonstrated the effects of full return of dung and urine from clover-grass pasture in increased soil organic matter, in high percentage of water-stable aggregates and in weight of earthworms. All of these factors tend to compensate for the increased treading load. Vegetation itself cushions the effects of treading on infiltration. This phenomenon is illustrated in Figure 2 which is derived from an animal treading experiment on Fulton silty clay loam in New York State (O'Connor, 1956). The data illustrated are from paddocks mown every four weeks. Treading with dairy cows was experimentally applied at these intervals at two levels. The high level which is illustrated here was equivalent to double that involved in intensive break-grazing. Relative infiltration was estimated after 20 weeks' treatment by using tubes. 36 2-in. diam. tubes per treatment were inserted into the soil to a depth of 2 in. and the rate at which water diminished in the tube from an initial head of ten inches was measured. While it is clear that treading of the freshly mown sward greatly altered the distribution of samples among infiltration classes, very little influence of the same treading was detected when mowing of the sward was delayed until the treading was completed. Further differences in infiltration were found to be attributable to moisture at treading time. Areas mown and watered before treading were found to be more seriously affected in infiltration than areas simply mown, even though there was no difference between moisture classes in bulk density induced by treading. This appeared to be due to puddling at the soil surface by hoof slipping rather than to compaction. Analagous effect of different moisture conditions have been described for New Zealand by Edmond (1958) and Scott (1963). It is indicated that the potentially massive adverse effects on infiltration of treading by both animals and machines are amenable to management, by avoiding treading unprotected soil, especially when it is wet and by ensuring that the whole life system is maintained in vigorous condition. It may be noted in passing that as soil physical conditions are dynamic, studies at one point in time of otherwise comparable pastures, one having just been hard grazed, the other having been spelled for several weeks, may not be true comparisons of the average condition of such pastures. More likely, they may be measures of the range in infiltration in a normal course of partial pugging and structural restoration by biological agencies.

The attention given here to treading as a factor affecting infiltration and consequent water quality does not mean that it is the only factor affecting these phenomena in agricultural land use. Changes in soil physical conditions can be brought about by other agencies such as cultivation. As Sherman and Musgrave (1942) commented: "The commonly observed higher infiltration and lower runoff for virgin soils, native grass, forest, or rotated-crop land, in contrast to low infiltration and high runoff for intensively cultivated land is fully in harmony with the known effects of these practices upon soil structure." If, however, we analyse the factors involved in such structure-reducing practices as row-crop farming we find that the reduction in protective cover is probably of primary importance. There is a widespread tendency to regard accelerated erosion as a mechanical consequence of runoff. It might be nearer the mark to regard accelerated runoff as a physical consequence of primary erosion, soil detachment by raindrop impact. As soil detachment is not only a major cause of reduced infiltration but also the primary source of themajor pollutant of the world's waterways - sediment, let us consider the influence of agriculture on water-transported sediment.

Influence of agriculture on transported sediment

Just as the role of vegetation in protecting the soil is seen in the reduction of treading damage and in overland flow, so also it is seen in protection of soil from erosive forces. Examples of such forces are needle ice and solifluction, wind especially involving saltation by sand particles, and above all, raindrop splash. The familiar progression of sheet erosion and consequent forms increasing from dense swards, to open swards, to row crops, to bare fallow is a progression of increased exposure. As Osborn's (1955) review indicates, compensating protections against soil splash take the form of reducing the detaching energy of raindrops or reducing the detachability of the soil particles. There can be little doubt that the detachment of soil particles by raindrop impact is the largest and most widespread agency affecting water quality. Suspended sediment is the greatest enemy of so many water users from electric power design engineers to weekend fishermen. Suspended sediment is chiefly caused by water erosion, principally associated with agricultural land use. Suspended sediment can be reduced to negligible proportions by positive cultural land use by ensuring protection of soil against detachment by raindrop splash and other agencies.

Influence of agricultural land use on dissolved solids in water

Erosion of agricultural and pastoral land contributes more than sediment to water. Soluble components are also eroded. Erosion is not, however, the only mechanism by which solutes are delivered to water bodies. Others arrive in solution following leaching and by overland flow. From the point of view of agricultural loss as well as from the point of view of water quality for subsequent users perhaps the two most important elements involved are nitrogen and phosphorus. Table 2 is compiled from a recently published report of a United States Task Group investigating sources of nitrogen and phosphorus in water supplies. The group concluded that agricultural runoff (in the broad sense) is the greatest single contributor of nitrogen and phosphorus to water supplies. They estimated that about 5,000 million lb of nitrogen and 1,000 million lb of phosphorus reach United States water supplies each year. If this were distributed through the 4.5×10^{14} gallons of annual stream flow the average concentration would be 1.35 mg N/1 and 0.27 mg P/1, an order of magnitude above those cited as limiting for algal growth.

What of the New Zealand scene? There is a dearth of published information of nitrogen and phosphorus contents of waters not subject to domestic sewage or industria pollution but there are many data from work in progress which implicate current agricultural practice. Matthews (1967) reported phosphorus concentrations of from 0.006 ppm P to 0.07 ppm P in waters from various types of watersheds contributing to Lake Rotorua where the concentration was 0.004 ppm P. Fish (1963) stated that regular analyses during 1962 of the waters of Lakes Okaro and Ngapouri showed the presence of up to 0.2 ppm of free phosphate, especially in the hypolimnion of the two lakes. Fish implicated the recent history of land development and aerial topdressing with superphosphate in the land surrounding these lakes in their observed eutrophication and poorer thrift of trout in contrast with the neighbouring undisturbed and oligotrophic Lake Okataina. Fish and Will (1966) found that <u>Elodea canadensis</u> had significantly lower contents of nitrogen and phosphorus when sampled from Lake Okataina than when sampled from Lake Rotorua. A progress report on research on the <u>Ceratophyllum demersum</u> weed problem in the Waikato hydro-lake Ohakuri (Hill, 1967) indicated that tributary streams such as the Whirinaki in a zone of new land development contained phosphate at frequently five times the level of the lake proper. Phosphate contents further up the Waikato river to Taupo were negligible. Hill had not obtained clear evidence of further increase in phosphate level below Ohakuri where land settlement was longer established but he did find evidence of increasing nitrate from Taupo (0.05 mg) down the Waikato chain to 0.5 mg at Karapiro and Meremere. In current research in Canterbury lakes (D.J. Hogan and L. Wilkinson, 1968, pers. comm.) generally low levels of free phosphate and mineral nitrogen are found in mountain lakes whereas nitrate nitrogen in waters closer to the coast and subject to agricultural influence may approach 1 ppm. Drainage waters at the commence of late autumn flow from grazed pastures in the Manawatu have been found to have as much as 20 ppm of nitrate (G.W. Butler, 1967, pers. comm.). Thompson and Coup (1943) have reported rapid nitrification of NH_4-N at levels of 600 ppm in 0 - 3 in. horizon in urine patches. Downward movement of nitrate and its disappearance would be expected with heavy rain. Wilkinson (1964) reported on the nitrogen transformations in the Avon-Heathcote estuary enriched with nitrogen from agricultural, industrial and domestic sources (Hogan and Wilkinson, 1959) and drew attention to the evidence that nitrogenous material from fertile farms may be increasing the productivity of onshore waters of the west coast of the North Island.

It is clear that much more research is called for in this topic but there is sufficient information now available in New Zealand and overseas to allow useful interpretation of the overall pattern. Surface runoff may involve losses of nutrients depending on their abundance at the surface. There is some evidence in New Zealand (R.C. Dixie, pers. comm.) that with heavy rain substantial losses of freshly applied superphosphate may occur from steep slopes under pasture. Where soil erosion accompanies runoff then nutrients may be lost in the soil. Machenthum (1965) cites annual losses of 18 lb/A of nitrogen and 0.5 lb/A of phosphorus from plantings of corn on 8 percent slope, increasing to 38 lb and 1.8 lb respectively on 20 percent slope. Fippin (1945) recorded average losses in silt and water for 1939 for row crops in the Tennessee River system as 23.8 lb N/A and 13 lb P_2O_5/A, with much higher losses of CaO, MgO and K_2O. It is not always easy to distinguish whether losses from soil have occurred as a result of leaching of solutes or from washing over the surface or into field drains of solids, especially as colloids. It is known that soils differ greatly in their ability to retain phosphorus, but in many agricultural conditions and especially in New Zealand it is unlikely that much phosphorus will be lost from soils by leaching. So long as nitrogen in soil is in the ammonium form or in organic forms it is unlikely to be leached in large quantities from soils with medium to fine textures. Nitrate, however, is gradually diluted out of the topsoil when rainfall is sufficient to percolate through the soil profile (Allison, 1966). During very wet periods, water may move most of the nitrate from topsoil to lower layers where it can either accumulate as in northern Australia (Wetselaar, 1961) or be lost in drainage or suffer denitrification. Drainage losses are likely to be most serious in soils which are well drained naturally or artificially and which are at least periodically well furnished with nitrate. Table 3 is derived from Sylvester's (1961) data from irrigation return flow drains in the Takima River Basin in comparison with streams from areas under forestry with some logging in Washington State. It indicates the preponderance of nitrate losses in drainage from irrigated areas. The lowest proportion of soluble phosphorus occurred in streams from forested areas. Between irrigation drains, surface drains, which had the higher concentration of total phosphorus, had a lower proportion of soluble phosphorus. Table 4 compiled from the data of Sylvester and Seabloom (1963) shows some of the anionic contribution to return flow from an irrigated area of 375,280 acres. Again nitrate dominates over phosphate in leaching losses. Such loss of anions from soil implies not only enrichment of the receiving water but also the depletion of bases K, Ca, Mg and Na from soil.

The story of water enrichment from agricultural land may well be summarised as follows. Infertile soils may contribute little nutrients of themselves except by way of erosion. Their days of giving are over. Younger, fertile soils may lose phosphorus and nitrogen as well as other ions if the leaching of the wasting regime (Taylor and Pohlen, 1962) is not counteracted by effective plant uptake in a vigorous organic regime. They may lose nitrogen and phosphorus and other elements by the erosion of fertile topsoils arising from bad management. From steeper soils in particular nutrients may be lost from applied fertiliser, probably while still in particulate form. Fertilisers may also be lost by erosion. As infertile soils undergo development, as in New Zealand and Australia, by topdressing with superphosphate, phosphate losses to water may accompany runoff and erosion, especially where the land is cleared and cultivated. From soils with high phosphate retention such as on the pumice lands, losses of phosphorus by leaching are not likely but losses of sulphate probably occur on many such soils of high porosity. As land development proceeds and the nitrogen deficiencies of the system are corrected by vigorous clover growth, symbiotic fixation and return of dung and urine by livestock, the likelihood increases of nitrogen losses by leaching of nitrate, especially following dry summers and on limed soils. As leaching of nitrate increases so too will losses of bases especially potash, magnesium and calcium. If irrigation is applied, losses of nutrients in leachates from a particular soil will depend on the levels of ions available for leaching and on the volume of through-flow. If fertilisers are applied to achieve very high fertility levels in soil, the risk of nutrient leaching will increase both from irrigation and from natural precipitation. It becomes difficult to have highly fertile land drained by infertile rivers. A chronosequence may be expected in waters following their enrichment with phosphate only, similar to that observed in land development. Nitrogen fixing organisms such as blue-green algae would initially dominate, parallel to clover dominance in pastures. If waters are directly enriched with nitrogen as well as phosphate then rapid eutophication may be expected with a wider range of plant forms, parallel to application of nitrogen fertiliser bringing about strong growth in pastures.

Influence of agriculture on organic pollution

Klein (1962) outlines some of the sources in agriculture of organic pollution. Among them are pea vining and silage drainage with very high biochemical oxygen demand; waste liquors from washing cattle sheds and piggeries which may be 10-20 times as strong as ordinary sewage; spent liquors from sheep dips which may be highly poisonous and grossly polluting. Some estimates of these kinds of potential pollutants have been made in New Zealand (Interdepartmental Committee, 1951). The trend to larger herds in the dairy industry and the use of loafing platforms is causing concentration of animals and their manure. Disposal of such residues into groundwater or into drainage ways involves large nutrient losses as well as water pollution. Beyond the farm gate some of the most important localised pollution problems of New Zealand arise from disposal of cannery, tannery, dairy factory, abbatoir and wool scouring primary wastes. Rapid increases in scale characterise these agriculturally based industries. Most of these organic pollutants not only have fairly high B.O.D. but they also contribute markedly to enrichment with nitrogren and phosphorus. Continuing developments are being made to fully utilize their by-products to avoid stream abuse by pollution.

In recent years a new form of organic pollution has developed. The most important biocides of 20 years ago were arsenic or copper compounds or natural organic materials, such as pyrethrum and nicotine. New synthetic organics used as insecticides or herbicides include many which are poisonous to fish, birds and mammals. When they enter water, whether as a result of heavy rain or by carelessness or accident, they may soon disappear but some of the chlorinated hydrocarbons being fat-soluble are accumulated and pass through food chains. In water, such agents are potential or actual hazards to water users.

Conclusion

The main features of the outline I have given of the role of agriculture in affecting water quality can be summed up under six headings - concentration, infiltration, sediment, enrichment, organics and poisons. An enlightened community of water users will summarily object to poisons. It will also wish to see that infiltration is promoted to ensure more manageable waterflows in streams. It will want sediment reduced to low levels because it represents a waste of soil as well as a cost, a nuisance, and an ugliness to water users. It will also recognize that if the use of water for agriculture induces concentration and increases the problem of stream sanitation, then agriculture itself should be expected to control enrichment with nitrogen, phosphorus and other nutrients and eliminate the addition to water of obnoxious or hazardous organic residues. The motivation for the agricultural industry to take up this challenge lies above all in nutrient economy. This will call for new perspectives in plant breeding and management, animal management, water control in irrigation and drainage and above all in the understanding and management of soil biology. Those who would plan the development of water resources in the midst of agriculture must first ensure that the agricultural industry is enabled to work with them, not left aside to work against them. The alternatives are silent springs, silted dams, triffids, dead fish and some very obnoxious effluvia.

REFERENCES

Allison, F.E. 1966 : Adv. Agron. 18 : 219-58.

Blong, R.J. 1966 : J. Hydrol. (N.Z.) 5 : 87-99

Camp, T.R. 1963 : Water and its impurities. Reinhold, N.Y. 355 pp.

Edmond, D. 1958 : N.Z. Jl. Agric. Res. 1 : 652-9

Fippin, E.O. 1945 : Soil Sci. 60: 223-39.

Fish, G.R. 1963 : Proc. N.Z. Ecol. Soc. 10 : 1-7.

Fish, G.R., Will, G.M. 1966 : Weed Res. 6 : 346-9.

Fletcher, H.C., Elmendorf, H.B. 1955 : USDA Yrbk of Agric. 1955 : 324-9.

Hawkes, H.A. 1962 : "Biological Aspects of River Pollution" pp.311-432 in Klein R. (cit. infra.)

Hill, C.F. 1967 : "Investigation of the weed problem at Lake Ohakuri". pp 15-8 in "Rotorua and Waikato Water Weeds." Univ. of Auckland 76 pp.

Hogan, D.J., Wilkinson, L. 1959 : N.Z. J. Sci. 2: 506-29.

Interdepartmental Committee 1951 : 2nd interim report on the utilization of organic wastes in N.Z. N.Z. Eng. 6: 396-424.

Klein,.L. 1962 : "River Pollution II. Causes and Effects". Butterworths, London. 456 pp.

Lee, C.H. 1942 : "Transpiration and total evaporation" pp.259-330 in "Hydrology" O.E. Meinzer ed. Dover, N.Y. 712 pp.

Mackenthun, K.M. 1965 : "Nitrogen and phosphorus in water" USDHEW Public Health Service Publ. 1305, 112 pp.

Matthews, L.J. 1967 : "Further results of spraying lake weeds" pp.40-44 in "Rotorua and Waikato water weeds". Univ. of Auckland 76 pp.

Muckel, D.C., Schiff, L. 1955 : USDA Yrbk. Agric. 1955 : 302-10.

Nordbye, D.J., Campbell, D.A. 1951 : C.R. Ass. gen. d'Assoc. Int. d'Hydrol. sci. Bruxelles 2 : 98-101.

O'Connor, K.F. 1956 : "Influence of treading on grasslands" Ph.D. Thesis, Cornell Univ., Univ. microfilms. Ann Arbor, Michigan.

Osborn, B. 1955 : USDA Yrbk Agric. 1955 : 127-35.

Phelps, E.B. 1944 : "Stream sanitation" Wiley, N.Y. 276 pp.

Scott, R.S. 1963 : Proc. 25th conf. N.Z. Grassld. Assn. : 119-26.

Sears, P.D., Evans, L.T. 1953 : N.Z. J. Sci. Techn. 35A (Supp. I) : 42-52.

Selby, M.J. 1966 : N.Z. Geographer 22 : 194-6.

Sherman, L.K., Musgrave, G.W. 1942 : "Infiltration" pp.244-58. in Hydrology" D.E. Meinzer ed. Dover, N.Y. 712 pp.

Sylvester, R.O. 1961 : "Nutrient content of drainage water for forested urban and agricultural areas". Algae and Metropolitan Wastes U.S. Pub. Health Service Sanitary Engineering Center Tech. Report W61-3, pp.80-7.

Sylvester, R.O., Seabloom, R.W. 1963 : J. Irrigation & Drainage Div. ASCE 89 (IR3) : 1-27.

Task Group 2610 P Report 1967 : Jour. AWWA 59 : 344-66.

Taylor, N.H., Pohlen, I.J., 1962 : "Soil survey method". N.Z. DSIR Soil Bureau, Bull. 25 : 242 pp.

Thompson, F.B., Coup, M.R. 1943 : N.Z. J. Sc. Techn. 25A: 118-24.

Wetselaar, R. 1961 : Plant and Soil 15 : 121-33.

Wilkinson, L. 1964 : "Nitrogen transformation in a polluted estuary" pp. 405-22 Intl. Conf. on Water Pollution Research, London 1962. Pengamon Oxford.

TABLE 1 Mean infiltration rates in undeveloped and developed pumice lands

(Inches per hour)

	Taupo ash shower (21°)	Rotomahana mud (18°)	Kaharoa ash shower (15 ± 2°)
Undeveloped (Scrub and fern)	3.7	6.8	4.5
Developed (5 yr old pasture)	1.8	1.9	0.8

TABLE 2 <u>Estimates of nutrient concentrations in discharges (mg/l)</u>

	Nitrogen	Phosphorus
Domestic waste	18 - 20	3.5 - 9
Agricultural runoff	1 - 70	0.05 - 1.1
Other rural runoff	0.1 - 0.5	0.04 - 0.2

TABLE 3 Mean nutrient concentrations (mq/1) in some Washington State Drainage

	Phosphorus			Nitrogen		
	Soluble	Total	Sol.%	NO_3-N	Total	NO_3%
Forestry streams	.007	.069	10	0.130	.204	64
Irrigated agriculture subsurface drains	.184	.216	85	2.690	2.862	94
Surface drains	.162	.251	65	1.250	1.455	86

TABLE 4 Contribution of some anions from irrigated area during irrigation and non-irrigation seasons in Yakima River Basin, Washington.

(lb/A)

	HCO_3	Cl	NO_3	Sol. PO_4
Irrigation season 6 mos.	575	37	33	1
Non-irr. season 6 mos.	715	63	35	1.2

WATERSHED MANAGEMENT - PROBLEMS AND POSSIBILITIES

J.T. Holloway
N.Z. Forest Service.

INTRODUCTION

Watershed management is currently a fasionable subject. As such, it attracts a full quota of faddists, extremists, do-gooders and hangers-on. In recent years, in both scientific and lay circles, more impractical nonsense has been poured forth on this topic than on any other. Grandiose schemes and counter schemes, utterly divoiced from reality, have been concocted and propounded *ad nauseum*.

This is not good enough. The subject is too important to be left abandoned in a morass of loose talk and woolly thinking. The immediate and urgent need is the dispassionate appraisal of problems and possibilities in order that available technical and financial resources can be intelligently directed and applied with a minimum of wild-goosing around problem peripheries.

When we look at the broad field of watershed management in New Zealand, we can all place a finger on localities that are seasonally water deficient and that cry out for better catchment management aimed at improvement of dry-season water yields or more effective on-the-spot use of what water there is. Similarly, we can all point to localities where the better regulation of hill-country run-off is essential if problems of soil loss and local flooding are to be overcome. Or, again, we are all increasingly aware of the threat of water pollution and can name localities where we teeter on the brink of real pollution trouble. Nevertheless, these are all local or regional problems. They demand attention, sometimes urgent attention, but they must be seen in true perspective. There is a constant danger that, because they are often right on our doorsteps, we will permit them to occupy so much of our time and consume such a disproportionately large share of our technical and financial resources that only token effort can be applied elsewhere.

This elsewhere, in our case, is the mountain country. The national water problem is control of the major mountain-derived rivers. The national watershed management problem is the management, the maintenance in or the restoration to a satisfactory condition, of the mountainous upper catchments of these rivers.

The area of land involved is approximately one-third of the total land area of New Zealand. It receives, in all probability, in excess of two-thirds of the total rainfall. Topographically and climatically it is inhospitable country that, except from the air or from the few transalpine highways, remains a *terra incognita* to most New Zealanders.

KEY PROBLEMS IN MOUNTAIN-LAND MANAGEMENT

The mountain-lands, particularly the very-high-rainfall wild-lands beyond the limits of pastoral occupation, are unquestionably our most important water-source flood-source lands. The paradox is that, despite frequent expressions of opinion to the contrary, these are the lands for which we have least need for accurate information concerning the effects of land management operations on water yield or stream flow. Under the prevailing rainfall conditions, depletion or destruction of the vegetation may or may not adversely affect the yield or season of yield of water or result in heightened flood peaks but, under the prevailing topographic, geological and pedological conditions it does, without question, result in the significant acceleration of the processes of normal mountain-land erosion and consequently in the aggradation of stream channels.

Examples of spectacular accelerated erosion accompanied by dramatic stream-channel aggradation are, unfortunately, all too many. This sets the course of action we must take. Our first task is control of the agents of depletion and destruction, notably control of the many species of grazing and browsing animals that have been introduced. And our second task is the planned restoration of an adequate cover of vegetation to critically eroded areas that are unlikely to heal as a result of animal control alone. Both tasks must be undertaken primarily for erosion control, not water yield regulation. Both are far from accomplishment.

Populations of introduced game animals have been reduced in selected river catchments to the point where recovery of the vegetation, at least on the most favourable sites, is slowly becoming apparent; but the maintenance of this level of control, whilst concurrently seeking its achievement over wider areas, presents many difficulties. Indications are that control must be maintained for very long periods of time if there is to be a significant reversal of downward trends in the condition of forests at or near to the timberline. Once forests at this altitude have been reduced to an empty shell devoid of undergrowth, very few animals are sufficient to keep them in this condition.

The removal of domestic animals, mainly sheep, from the erosion-prone uplands is, at first sight, a much simpler matter. They can be mustered off. For valid political, sociological and economic reasons, however, this is not something that can be accomplished overnight or with a wave of a dictatorial wand. Any such major change in the system of land-use has manifold and far-reaching repercussions far beyond the area immediately concerned. In general it is not practicable to withdraw the high alpine grasslands from pastoral use unless and until equivalent grazing can be provided elsewhere. This means that the route to withdrawal must be through research into pasture development, pasture management and stock management, and into supplementary winter feed production, at lower levels. The revolution must be a slow and quiet one, neither drastic nor impetuous. It is well under way.

The most difficult problem is that of restoring an adequate cover of vegetation to critically eroded areas. The classical techniques of mountain-land restoration employed in western Europe, modified to suit local soil and climate conditions, would undoubtedly work well but we coult not afford to employ them. They demand the mechanical stabilisation of slopes, the reduction of torrent profiles, gully plugging, and similar engineering works as a prerequisite to revegetation measures. But if we threw our total resources into work of this nature we could not treat one per cent of the areas requiring treatment over the next one hundred years.

Our solution must, in fact, be a wholly indigenous one that, if we are to overcome the acute problems of difficult access and labour shortage, makes the maximum possible use of aircraft. In lieu of slope stabilisation by mechanical means, we must discover how, where and to what extent we can induce a sufficient degree of site stability, by the application of fertilisers and direct seeding, to provide a firm base for the re-establishment of a permanent soil cover. The key factor will be speed: the speed of establishment of the pioneer cover, the speed with which a good mulch of litter is formed, the speed of accumulation of soil organic matter, and the speed with which an effective nitrogen cycle is reconstituted.

Research along these lines is in progress. It may not be long before firm recommendations can be made relative to the treatment of eroded sites at altitudes up to, approximately, 3000-3500 ft. But it is likely to be many years before the effective treatment of critical debris-source areas at high altitudes is possible. In the meantime we must avoid the expenditure of effort on the development of techniques that, because of their cost, stand a negligible chance of practical application.

HYDROLOGICAL RESEARCH NEEDS

It has frequently been suggested that we need hydrological data if we are to determine accurately the levels to which populations of introduced animals should be reduced. The proponents of this notion have clearly, however, given little if any thought to the problems involved in the conduct of the required research. Populations of wild animals, or even of free-ranging merino sheep, cannot be manipulated and controlled in the necessary manner. Small catchment studies using fenced animals would, for example, be so completely artificial that data extrapolation would be even more dangerous than usual.

Similarly, it has frequently been suggested that hydrological data, relative to the probable effect upon water yield of the various classes of vegetation, should be obtained before we decided whether to establish a forest, shrubland or grassland cover on denuded areas. This, however, is putting the cart well in front of the horse. We do not yet know how to re-establish any class of cover on a practical scale at reasonable cost. Comparative studies cannot be initiated until a choice is available. Even then, the cost factor will be the critical one. If we can provide an effective soil cover, any class of cover, at a price the country can afford, our great grandsons can modify this in line with the water control needs of their time. We will have done our job in leaving them something capable of modification. Proposals that existing stable grassland should be converted to forest are, of course, patently absurd. A forest cover might be preferable, hydrologically speaking, but the operation would have to be a very large-scale one to mean anything at all in terms of river control. The cost could not be justified while there are so many other things to do that are far more urgent. If there is to be such a replacement, it must be justified on the purely economic grounds of timber production versus pastoral production.

Finally, it has been suggested that pasture development work in the high country should proceed with the utmost caution pending full evaluation of the possible hydrological consequences of work of this type. This is nonsense. The urgent need is the withdrawal of stock from the high-altitude, high-rainfall, high-erosion-risk alpine and subalpine grasslands to lower levels where rainfall is generally less and erosion risks are comparatively negligible. By raising the carrying capacity of these lower-level grasslands in order to permit this withdrawal, we may, conceivably, adversely influence their hydrological characteristics but the alternative is even less acceptable. A moderate loss in the hydrological efficiency of the valley grasslands will be a very small price to pay for the retirement of the real problem country.

In all these respects it may be said, therefore, that hydrological research, though theoretically desirable, is not essential. Realistic land management objectives can be set without it. It may be added that it is very fortunate indeed that this is so because, if we did need the data, I doubt very much that we could obtain it. Thus I doubt that, for the New Zealand mountain country proper, we can measure either the input water in the form of rain or, especially, snow, or the output as streamflow, with sufficient accuracy to pretend to be able to evaluate the effects on water yield of land management operations. The one real hydrological research need is, in fact, the development and testing of research techniques for use when the time is opportune. I would suggest that effort in land-use hydrology can, in the meantime, be most profitably directed toward solution of the local and regional problems already mentioned. For solution of these problems, currently available techniques should prove adequate. The only exception that I would make is that we should proceed, as vigorously as possible, with the collection of mountain-land climate data, especially precipitation data. It will be too late to initiate this work, on the required scale, when we do have both the need and the technical ability to undertake purposeful research in mountain-land hydrology.

CONCLUSION

I do not propose to attempt a summary of this already over-brief account. But if there is one point above everything else that I have tried to make, it is this: that there is much in common between watershed management and politics. Both can be defined as the art of the possible. It is right and proper that we should have ideals: in the case of watershed management the ideal is that the land should be managed in such a way as to ensure the best possible control of water. But we must, at the same time, be hard-headed realists. The goals we set ourselves should be attainable ones. Fresh objectives can readily be set when immediate tasks are completed.

EVALUATION OF CHANGES IN THE LAND-USE REGIME

Walter C. Boughton,
Lincoln College

THE PROBLEM

Most hydrologists would accept that complete removal of vegetation from a steep catchment is likely to result in increased runoff and soil loss. Yet, it is virtually impossible with present knowledge to estimate in advance what the magnitude of such effects might be, or to extend the results from an experimental area to an ungauged catchment. When less extreme conditions or changes are considered, it is rarely possible to predict the probable effects even in a qualitative way.

Evaluation of changes in the land use regime is one of the less developed aspects of hydrology. Although considerable effort has been and continues to be applied to this problem, little satisfactory progress has been made. Renne (1967) comments that "although millions of dollars have been spent on watershed surveys, data collection, and research in the past 30 yr., there has been only a very small rate of return on such investments." The fact that considerable amounts of both money and effort continue to be spent on the problem in the face of such incompetence illustrates the importance of the problem.

One reason for the difficulty is the range of different aspects of the problem encountered in different fields such as forestry, agriculture, conservation, and engineering. Conservationists and agriculturalists may be interested in the effects of terracing and contour farming, strip cropping, or different farm management practices, while foresters pursue studies into the effects of logging, change from native trees to plantation crops of exotic species, or the exchange of forest for grassland and vice versa. Neither may consider the effects of changing river channels by clearing, straightening or lining, of urban development into rural areas, or of constructing works such as expressways, which might be of most concern to some engineers.

Similarly, different workers are interested in different effects produced by these different changes. In areas of abundant water, change in the timing of runoff can be of major concern for power generation or in the operation of flood control works. In areas of water scarcity, total yield can be more important than the timing of runoff. In alpine areas, erosion and sediment movement can be of greater interest than runoff.

The difficulties encountered are partly due to a lack of formal treatment of the subject in hydrologic texts. Few texts even mention experimental design and none give adequate treatment. This paper reviews the problems encompassed, past efforts and methods used, the present situation, and suggests where future investigations might be directed.

A REVIEW

In the U.S.A., the two agencies most directly concerned with evaluation of changes in the land use regime are the Bureau of Reclamation of the Department of the Interior and the Soil Conservation Service of the Department of Agriculture. The Bureau of Reclamation is concerned with estimating streamflow changes that may result from land treatment because of the need to determine availability of a firm water supply for its projects. The Soil Conservation Service has similar responsibilities for the development of water use projects for both irrigation use and municipal water supply.

In 1957, these two agencies and the Agricultural Research Service of the Department of Agriculture jointly formed the Cooperative Water Yield Procedures Study for the primary purpose of developing and testing procedures for evaluating the effects of watershed treatment on the yield of streamflow. Watershed treatment included land treatment measures such as changed land use, strip cropping, terracing and contour farming, and structural measures such as retention and retardation reservoirs and water spreading systems. Watershed studies ranged from the very small upstream watersheds to major river basins.

The two-year Progress Report prepared by Sharp, Owen and Gibbs (1959) is impressive for the effort applied in this project to the problem, but is discouraging for the lack of success which is reported. The following is quoted from the Summary and Conclusions of the Report:

"In its first two years of effort Cooperative Water Yield Procedures Study has not been able to conclusively demonstrate that water yielded by streamflow is significantly affected by the conservation use and treatment of land, except for some areas where research data are available from small watersheds. Since decreases in streamflow of river basins by conservation treatment have not been found significantly measurable, the objective of Cooperative Water Yield Procedures Study, to develop methodology for estimating such effects, has not been attained. This does not mean that there are no such effects. Nor does it mean there are. It simply demonstrates that the limitations of the data and methodology are such that the effects, if any, have not been depicted."

A more recent review of the problem was provided in 1965 at the International Symposium on Experimental and Representative Catchments held in Budapest (International Association of Scientific Hydrology, 1965). In the 75 papers given at this symposium, more detailed descriptions were given of individual aspects such as criteria for the selection and location of experimental and representative watersheds, newer developments such as multiple-watershed experiments, and the use of more sophisticated analytical techniques such as factor analysis.

These papers provide a wider review of the problem than given by Sharp, Owen and Gibbs, and describe the experimental activities then current (1965) in many parts of the world.

Immediately following the Budapest symposium, an International Symposium on Forest Hydrology was held in Pennsylvania, U.S.A. at which

85 papers dealing with many aspects of forest hydrology were presented. The proceedings of this symposium were recently published with discussion, the editors being Sopper and Lull (1967). This publication provides the most up-to-date and complete review of forestry aspects of land use changes and the endeavours to evaluate the hydrological effects involved.

In September, 1967, the Coordinating Council of the International Hydrological Decade at its 3rd session (UNESCO, 1967) reported on two important publications. The Council was presented with the final draft of the "Guide for Research in Representative and Experimental Basins" to be published in English, French and Spanish. In addition, the Council received the 1st edition of the "World Catalogue of Representative and Experimental Basins" which had just been prepared. Copies of the Catalogue were to be forwarded to all National Committees for the IHD.

There are a number of national catalogues and inventories of hydrological experiments which supplement the World Catalogue. The predominance of American activities in water research is evidenced by the massive Catalogue of Water Resources Research (U.S. Dept. of the Interior, 1967). The 3905 research projects listed in this publication include many directed towards land use studies. The American Geophysical Union (1965) has published an inventory of representative and experimental watershed studies conducted in the United States, and Rothacher (1965) lists the experimental watersheds used for research by the U.S. Forest Service.

The Australian Water Resources Council has published (1965) an Inventory of Research into Water Resources and Directly Related Matters. Section 1 of this Inventory lists projects dealing with catchment behaviour and characteristics, and this includes land use studies.

New Zealand activities have been summarised by Toebes (1965) and current work and results are reported periodically by the N.Z. National Committee for the IHD (1965).

There is a profusion of individual papers and reports dealing with the hydrological effects of land use changes. Generally, these are referred to in later sections of the paper which deal with detailed aspects.

THE METHODS

In the hydrological literature related to land use studies, there is a profusion of methods and techniques, both for the collection of data and for the analysis of data. Land use studies have included collection of data from fractional-acre plots, unit source areas, small experimental catchments, large representative basins, and such others as barometer watersheds, vigil networks, and benchmark catchments. Data analysis ranges from simple graphical techniques relying on visual examination of plotted data to the most sophisticated of statistical procedures.

The literature dealing with studies of hydrological effects from changes in land use lacks a systematic classification of the different methods used. Some ordering of the methods is desirable in order to see each method in perspective and to make comparisons. Existing classifications do not seem adequate. For example, the American Geophysical Union (1965) classes watersheds used in research studies into two principal categories:- experimental watersheds and representative watersheds. They state -

"an experimental watershed is one that has been chosen and instrumented for study of hydrologic phenomena; a representative watershed is one that has been chosen and instrumented to represent a broad area in lieu of making measurements on all watersheds."

The Director of the Office of Water Resources Research of the U.S. Department of the Interior (Renne, 1967) quotes this classification and comments that -

"studies using experimental watersheds imply a search for principles, relationships, and factors for prediction schemes; studies using representative watersheds imply that data are transferred quite directly to other watersheds where similar measurements are not available."

This classification has some weaknesses. Apart from being very broad, it is not well defined. Some groups of representative basins are specifically intended for study of basic relationships, for example, the Australian system of representative basins is being selected "for detailed study, particularly of rainfall-runoff relationships." (Australian Water Resources Council, 1967, p.4).

The following classification system, which encompasses both methods of data collection and methods of data analysis, is proposed as an alternative.

- Collection of data
  - Observational Methods
    - Plots
    - Unit Source Areas
    - Barometer Watersheds
    - Representative Basins
    - Vigil Basins
    - Benchmark Basins
  - Experimental Methods
    - Calibrated Catchments
    - Paired Catchments
    - Multiple-catchment experiments
- Analysis of data
  - Statistical
    - Graphical Analysis
    - Single-variable analysis
    - Multi-variable analysis
  - Physical
    - Catchment Models

The separation of data collection from data analysis serves principally for the review of past studies which is made here, but is not the most suitable approach to planning of land use experiments. Integrated studies where collection of data is planned in conjunction with analysis of data are described later in this paper.

COLLECTION OF DATA - OBSERVATIONAL METHODS.

A variety of methods of data collection have been used in experiments and projects to evaluate land use effects. The methods range from the purely passive, or observational, to the active, or experimental, approach. This distinction between observational and experimental is adopted as a primary separation in the classification of methods of data collection.

With observational methods, the observer plays a passive role by observing the behaviour of different catchments, and attempting to deduce by analysis the influence of catchment characteristics or land use on the observed variable, usually runoff or sediment yield. With experimental methods, the experimenter introduces a deliberate change to some part of the catchment system, and then attempts to monitor the effects produced by that change.

Observational methods encompass both large complex situations as in representative basins and smaller, more homogeneous situations as in runoff and soil loss plots. Unit source areas are between these extremes in both size and homogeneity. Experimental methods include "before and after" studies of a single catchment, comparisons of different catchments in paired-catchment studies, and multiple-watershed experiments in which many catchments and many treatments are involved. These methods are described in the following sections.

Plots

The two basic ideas behind the use of small plots for hydrologic studies are firstly that, being small, it should be possible to select different sites with variation in only one factor (such as slope, soil type, land use, etc.), and, secondly, being cheap, sufficient replications could be made to ensure statistical significance of the results. Rarely, if ever, are these ideals attained or even adequately pursued in practice.

Haywood (1967a and 1967b) has made a comprehensive review of plot experiments, particularly those directed towards soil loss. This study has shown the wide range of plots which have been used, ranging from a few square feet to several thousand square feet in area.

This review has also shown up two major weaknesses which typify most plot studies - lack of statistical design and analysis of the experiments, and, more specifically, disregard for any bias created by the boundaries of the plot. Fractional-acre plots in particular are so small that boundary effects can completely dominate natural effects. Interference with the natural overland flow pattern and wind blow of rain and soil particles into the collecting gutters can create quite considerable errors in the data collected from plots. The need to allow for such effects in plot experiments has been set out elsewhere. (Boughton, 1967b).

There are few results from plot studies related to land-use evaluation which are valid, quantitative, and statistically significant. In addition, the study by Minshall and Jameson (1965) shows clearly the differences which can occur between watershed runoff and runoff from plots within the watershed due to both interflow and transmission losses. The problems of bias interent in the collection of data from plots are thus compounded by the problems of extrapolation from the plot to the whole watershed.

Before plots could be used with confidence for land-use evaluation studies, some basic investigations of the following would be needed:-

(a) to establish the degree of bias to data caused by the nature of the plot construction.

(b) to establish the variance within so-called homogeneous areas which plots are used to sample.

(c) to clarify the differences between plot runoff and watershed runoff due to interflow and transmission losses.

Unit Source Areas

The unit source area is an approach to isolation of the factors affecting runoff and soil loss which is intermediate between plots and large catchments.

A unit source area is presumed to have relatively homogeneous soils and vegetation cover, uniform precipitation, and geologic influences on the surface outflow which are areally representative (Kincaid et al, 1966). Amerman (1965) defines a unit source area as "a subdivision of a complex watershed which, ideally, has a single cover, a single soil type, and is otherwise physically homogeneous."

The underlying concept is that complex watershed runoff is essentially a summation of the runoff contributions from its component unit source areas. Unit source areas that are sufficiently alike are assumed to react in a similar manner hydrologically when they are subject to storms that are alike. Amerman says:-

"by prediction and combination of unit source area runoff, it should be possible to predict runoff from ungauged complex watersheds. In this manner, the integrated effects on runoff of various combinations of land use changes on a complex watershed may be calculated without actually measuring the evaluating runoff from other complex watersheds to which the several plans have been applied."

The runoff computed from unit source areas at Coshocton did not agree with observed runoff in the examples quoted by Amerman, but linear regression equations between computed and observed data gave correlation coefficients of 0.98 for a 76 acre watershed and 0.99 for a 7.4 acre watershed. Amerman suggests that the disagreement in direct comparison may be due to:-

(1) interflow
(2) partial area runoff
(3) influence of runoff from upslope areas upon runoff production on downslope unit source areas.

Amerman and McGuinness (1966) discuss this problem of extending from small areas to large complex watersheds. These authors give the following definition of unit source watersheds:-

"Unit source watersheds are defined as all research watersheds, plots included, whose data are to be applied directly to larger watersheds."

Robins, Kelly and Hamon (1965) propose the use of unit source watersheds as a basis for hydrologic study of a 93-sq.mile experimental catchment in Idaho, but this report and the others cited omit any detailed specification for delineating unit source types and for classifying sub-areas of catchments into these types. Amerman (1965) also cites unit source studies by Rowe (1943) and Allis (1962). Doty and Carter (1965) use unit source areas for study of the rates and particle size distributions in soil erosion.

A Unit Source Watershed Conference was held at St. Louis, Mo., U.S.A., in February 1965, indicating the American interest in this method of research; however, unit source methods are virtually unknown in Australia and New Zealand. While the concept is attractive because of its relative simplicity, the following apparent weaknesses require some resolution before the method would be satisfactory for land use studies:-

(a) the present lack of specifications for classifying and identifying unit source areas.

(b) the lack of data on differences in the response of unit source areas of the same type, i.e. the within-type variation which will determine the significance of between-type variation.

(c) the unknown effects of interflow, partial area runoff, and transmission loss in extrapolation from unit source areas to whole catchments.

Barometer Watersheds

Dortignac and Beattie (1965) describe a catchment unit that seems to be a special type of representative basin. These watersheds, used by the U.S. Forest Service, are termed "barometer watersheds" and are stated to be "50,000 to 150,000 acres in area (80 sq. miles to 240 sq. miles) selected to represent a broad climatic-physiographic region."

These catchments are surveyed in detail with measurements of water storage capacities of soil and rock, vegetative composition, ground cover, etc. Sampling techniques are applied to the measurements to ensure accuracy. The data obtained are combined in a water balance analysis which accounts completely for the disposition of precipitation from the moment snow or rain strikes water surface, soil, rock or vegetation, through all of the runoff or percolation processes until the precipitation is accounted for as runoff past the gauging station or as deep percolation.

Parameters in this analysis are adjusted (not stated how) until hydrographs are reproduced "with reasonable accuracy" whence the watershed is "adequately characterised or calibrated". Extrapolation to other areas is not clearly explained.

The approach described in the paper by Dortignac and Beattie could be sound. The problem in reviewing the concept of "barometer watersheds" is that insufficient information is available on two important fundamental aspects:-

(a) how parameters in the water balance model are adjusted in order to calibrate the catchment

(b) what criteria and methods are used to extrapolate the results from one watershed to other areas.

Representative Basins

The concept of a representative basin arises from the fact that the land surface of the earth contains a number of recognisably different landscapes, i.e. types of country as determined by geology, topography, land-use etc., and that within each landscape a catchment or catchments may be selected which are representative of the catchments which form the landscape. Hydrological similarity among the catchments of the region is presumed.

Generally, the boundaries of such regions are determined by climatic zones, lithology, and landform. The region need not be in a virgin condition and, usually, virgin-condition catchments of a representative nature are treated separately as Benchmark or Vigil Basins (see later sections). However, a representative basin should be developed to the same extent as, and have the same land-use, as the region in general.

Representative basins form the other extreme in size and complexity to plots in the range of observational methods used in land-use studies in hydrology. The concept of a representative basin may have preceded the International Hydrological Decade (I.H.D.) but it was the I.H.D. programme in which this terminology was formalised. Descriptions contained in I.H.D. reports give a wide range of sizes of representative basins, recently given as generally from 1 to 250 sq. km. and rarely in excess of 1000 sq. km.

In countries where a network of representative basins is to be gauged, data will be recorded from a wide range of catchments, and it is probable that data will be obtained from some landscapes that otherwise may not have been included in the national network. However, the scientific merit of representative basins is not at all clear and the value of the data collected, beyond routine assessment of national water resources, is open to question.

The underlying concept that repeating units in a landscape are hydrologically identical, or at least sufficiently similar for one catchment to be representative of the group, has never been established. The few studies which have examined catchments on a regional basis and examined the differences between regions, for example Sopper and Lull (1965) or Ivanov and Romanov (1965), give the impression that there is as much hydrological variation among the catchments in a region as there is between different regions.

It would be wrong to condemn the collection of data from catchments in such diverse landscapes as will be included in representative basin networks. Indeed, there is still a great need for collection of data on many such catchments in Australia and New Zealand. However, there could be danger in use of the term "representative" if it is allowed to convey the impression that hydrological similarity of catchments in a region is a proven fact, and that data from one such catchment may be extrapolated directly to other catchments in the same region.

The greater danger is that, if such an impression became established without argument to the contrary, there could be increasing difficulty in obtaining funds for some basic research in hydrology, particularly research which is needed to check the very concept which is being adopted.

The report of the 1st Session of the Coordinating Council of the I.H.D. held in Paris in May 1965, mentions Decade Stations, Benchmark Basins, and Vigil Basins in addition to Representative Basins.

Decade Stations describe the minimum essential stream gauging network, i.e. the stations of major significance for defining the water resources of a country, or stations which are established to assess the resources of an area which is under special examination for development purposes. It seems that this class of station is of more concern to countries with stream gauging networks less developed than in Australia and New Zealand. Benchmark and Vigil Basins are more related to the topic of this paper and are described separately in the following sections.

Benchmark Basins

The following is quoted from the Report of the 1st Session of the Coordinating Council of the I.H.D. :-

"By exploitation of resources, man's mark upon his own environment becomes ever deeper and more drastic. On the other hand, changes in climatic patterns, through their effects on the hydrological cycle, on soil, and on vegetation can produce results remarkably similar to those caused by the works of man. Among natural phenomena, the most pervasive and probably the most important are the slow and subtle changes in land, vegetation and water which result directly or indirectly from variations in climate. Over periods of time, pulsations in precipitation and temperature regimes cause changes in evapotranspiration, in soil-moisture recharge, in groundwater recharge, and in streamflow. Climatic variations also cause changes in patterns of erosion, of which spectacular consequences can be observed in arid areas.

Hydrologic benchmarks are basins and associated stations established to provide simple measures of time trends in the secular march of hydrologic events unaffected by the works of man. Beyond simple measurements, however, they provide the means for more sophisticated uses such as direct comparison with other records. For example, records of streamflow at a regular gauging station may show a downward trend relative to flow at a nearby hydrologic benchmark. In suitable circumstances, this would be direct evidence of streamflow depletion.

Hydrologic benchmarks would help unravel the interrelations among climatic and hydrologic variables with confidence that the results are not biased by effects of human activity. The interrelations thus demonstrated could provide the base or datum for distinguishing natural from artificial phenomena elsewhere."

This quotation illustrates the concept behind benchmark basins for use in land-use studies. Their use is not sufficiently widespread or well-established to give much indication of their value at this time.

Vigil Basins

The following is quoted from the Report of the 1st Session of the Coordinating Council of the I.H.D. :-

"The purpose of (the Vigil) network is to establish stations and make observations generally similar to those established for the benchmark networks, but with no attempt either to protect the station from artificial changes or to deliberately introduce special changes. Vigil basins may be regarded as a special type of representative basin.

The purpose of the vigil basins is to collect data that will clarify relations between man, the land and the hydrological cycle. The network will include areas, therefore, that are subject to such uses as farming, grazing, deforestation, afforestation, community development, and other activities of man."

The Coordinating Council of the I.H.D. recognised Vigil Basins as a special type of catchment for data collection, but did not recommend special attention to this form of catchment during the I.H.D.

Even with the description given, the concept and exact purpose of Vigil Basins are somewhat vague, and their relation to benchmark and representative basins also cloudy. The proposals given by Slaymaker and Chorley (1964) for establishment of a Vigil Network in Great

Britain give the impression that these basins are intended wholly for geomorphological studies, but this may have been just the special interest of these authors.

Vigil Basins appear to be midway in size between unit source areas and representative basins. They are about the same size as catchments generally used in experimental studies, but are an observational type of catchment. They complete a series, arranged in order of size, of plots - unit source areas, vigil basins, representative basins - general streamgauging networks.

COLLECTION OF DATA - EXPERIMENTAL METHODS

With experimental methods, as distinct from the observational methods described earlier, the experimenter observes a catchment during a calibration period until he is satisfied that he is able to determine the "normal" response of the catchment under given conditions of rainfall and evaporation, either by comparison with the behaviour of another catchment nearby or from some relationship with rainfall, evaporation, etc., established during the calibration period.

The experimental catchment is then treated in the required manner and the runoff or sediment yield observed after treatment is compared with estimates of the normal or without-treatment behaviour of the catchment obtained from the earlier comparisons or calibrations.

The basic experimental methods used are -

(i) Calibration of Single Catchment
(ii) Paired Catchments
(iii) Multiple Catchment experiments.

Calibration method

This method is also referred to as "Before and After" technique, "Single Basin" technique and by some other titles. Essentially, a single catchment is calibrated for a number of years until its behaviour can be predicted from its past performances. A treatment is imposed and its effect is measured in terms of the deviation from the expected behaviour.

Success or failure of this method depends wholly on the ability to predict the behaviour of the catchment from climatic variables, usually rainfall and evaporation. The two approaches to relating runoff to climatic variables are by linear regression (for example, see Reigner, 1964) or by use of a catchment model.

Reigner describes the single watershed approach as -

"...less costly because no control is involved, and the analysis is more informative because it relates streamflow to the factors that influence it rather than to streamflow from another watershed only. Its principle disadvantage is its complexity; considerably more tabulation and analysis of data are required than with the control watershed system."

However, the single watershed approach is not well regarded generally. Sharp, Owen and Gibb (1959) conclude "... it is not believed this method of testing effects of land use and treatment changes on water yield is either logical or practical, hence, although it has been tried, is not being used by this project."

Paired Catchments

This method involves the use of an untreated control catchment (sometimes more than one) in conjunction with the experimental catchment which is to be treated. This method is also called "Comparative Basins" technique, "Control Watershed" method, etc., but all names refer to the same concept and method.

Two catchments are selected for their similarity in size, shape, topography, plant cover, land-use, climate, and general location. First, they are calibrated for a period of years to establish the response of each to a variety of storm conditions. The period of calibration is long enough that the behaviour of one can be predicted from the behaviour of the other. Criteria and methods for determining the required length of calibration have been proposed by Wilm (1949), Kovner and Evans (1954), Bethlahmy (1963) and Reinhart (1965). The period appears to range from about 3 to 10 years.

Following the calibration, a treatment is applied to one catchment while the other is left as a control. The effects of the treatment are measured as departures from the predicted behaviour of the catchment. The predictions of expected behaviour are based on the control catchment, but may be supported by predictions based on the period of calibration. If the climatic conditions are the same for the treatment and calibration periods, and the characteristics of the control catchment have remained unaltered, then changes in the characteristics of streamflow or sediment yield are attributed to the treatment.

This technique was first used in the Wagon Wheel Gap study of 1911 (Bates and Henry, 1928). Hibbert (1965) lists 32 paired-catchment studies of the effect of forest treatments on water yield.

The most comprehensive study of this method has been made by Sharp, Owen and Gibbs (1959). They found that the ratio of flow on one catchment to flow on another was not constant during periods of calibration before any treatments had been applied. They reported that "the reactions of small watersheds ... are so erratic that direct comparisons are not safe".

Ivanov and Romanov (1965) also give examples to show that the use of comparisons between catchments can be meaningless. They used various pairs of catchments to illustrate the relative evaporation rates from swamps and swampless areas. Three pairs of catchments were used in the example, and, according to the authors, "each pair of comparative basins is selected within a homogeneous physiographical region which is homogeneous not only in climatic conditions but also in relief, geologic structure and some other characteristics. The selection was performed on the basis of usual qualitative areal descriptions without any quantitative measures of relief and other characteristics."

Comparison of the second pair of catchments showed that normal annual evaporation from swamps is greater than from swampless areas, comparison of the third pair of catchments showed that it is less, while comparison of the first pair showed that normal annual evaporation from swamps was a negative amount.

Multiple Catchment Experiments.

Wicht (1965) describes multiple catchment experiments in South Africa designed to overcome the deficiencies of paired catchment experiments. These are afforestation experiments on a group of 6 catchments, designed to compare the hydrological effects of deliberate controlled burning in spring, summer and autumn on 4 to 12-year cycles, and indefinite protection of the scrub.

An integrated pattern of treatments is applied to the complex of watersheds, in which the components are closely comparable in geology, topography, and initial vegetal cover, and simultaneously subject to the same or related uncontrolled, extraneous, climatic influences. Related treatments on related watersheds are expected to produce related effects.

The experiments are designed for a major rotation cycle of 40 years and, on the 6 watersheds included, an 8-year secondary planting-cycle permits the progressive development of a complete series of age classes. The burning experiments are designed to include indefinite protection with which burning can be compared.

The comparison of identically treated watersheds and of diversely treated watersheds with two or more under the original treatment will be used to test whether discharge relationships have changes due to influences other than that of the treatment. The treatments are replicated and the results checked by repeated comparison of different watersheds variously treated.

Striffler (1965) describes experimental work on forested catchments in the central and southern United States where the effects of disturbances, such as roading and strip mining, on water yield and water quality, is evaluated by the multiple catchment technique. Data from a large number of catchments are analysed statistically to determine the influence of the disturbances.

In New Zealand, Yates (1962) describes a series of multiple catchment experiments (called "comparative catchment studies") designed to assess the effects of grazing, oversowing and topdressing, and cultivation and conservation structures (such as pasture furrows and graded banks) on runoff and soil loss. These experiments were planned by the Department of Agriculture, to be undertaken on groups of catchments at

Makara and Moutere. At Makara, eight catchments were to be combined in a 2 x 2 factorial experiment, and similar experiments were proposed for the 16 catchments at Moutere.

These examples portend the development of more complex experimental methods in hydrology, beyond the traditional calibration and paired catchment techniques.

ANALYSIS OF DATA

The variables used as criteria to illustrate the effects of land-use changes are numerous. For example, a few of the variables used in simple comparison studies of runoff (neglecting the many variables in catchment models, and sediment yield variables) are:-

volume of runoff

peak rate of runoff

coefficients of runoff

seasonal distribution of runoff

half-flow time

flow duration distribution

groundwater recession constant

There are also ratios of runoff from one catchment to runoff from control catchments, residuals of rainfall minus runoff, etc. To simplify the profusion of variables used as these criteria, the following classification is proposed for methods of analysis:

1. Statistical
    - (i) Graphical Methods
    - (ii) Single variable analysis
    - (iii) Multi-variable analysis

2. Physical
    - (i) Catchment models

Statistical methods treat the data as abstract variables without concern for cause and effect relationships. The emphasis is on testing the significance of differences between data obtained after change in land use from data obtained before the change. The major abuse of statistical methods occurs when attempts are made to use the results from an arbitrarily selected model (e.g. multiple linear regression) from which wild speculations about physical behaviour of the variates are made.

Physical methods, on the other hand, begin from known or postulated cause and effect relationships and are generally used to demonstrate that the proposed physical relationships reproduce observed hydrological behaviour to a satisfactory degree. Statistical and physical methods are described in more detail in the following sections.

ANALYSIS OF DATA - STATISTICAL METHODS

Graphical

The use of graphical methods of analysis such as double-mass plots (plotting cumulative runoff from one catchment against cumulative runoff from another catchment) is common in land use studies. Graphs are used both to find and to illustrate the changes thought to be caused by the change in land use.

Graphical methods have a place in preliminary analyses and for illustration of results after more comprehensive analyses. However, graphical methods only supplement the final statistical analysis of data and are not an alternative. It is unfortunate that graphical methods are often proposed as the sole analysis of data that may have taken 10 or more years to collect.

Most graphical methods have a statistical equivalent from which numerical values can be given to the variations detected on a graph. This can be illustrated by considering the common graphical method of plotting cumulative runoff from one catchment against cumulative runoff from a second catchment. This method is usually associated with paired catchment experiments and involves two assumptions:

(a) the ratio of runoff from one catchment to runoff from the second catchment is relatively constant and so the cumulative plotting results in a relatively straight line.

(b) following treatment of one catchment (or change in its land use) the ratio of runoff will still be relatively constant but at a different value, the difference appearing as a different slope on the graph, and being due to the treatment.

In reality, the runoff ratio before treatment is not a single value but will have a distribution of values about a mean value. After treatment, there will still be a scatter or distribution of values of the runoff ratio, but the hypothesis to be tested is that the mean has changed to a different value.

This resolves into a simple exercise in statistics. There are two groups of values for the runoff ratio (before treatment and after treatment) and we can test the probability that both groups are drawn from the same population, i.e. the difference between them is due to chance fluctuation and not conclusively attributable to the change in land use. If the Student's t test shows that the probability of the two groups being drawn from the same population is very small, then the hypothesis that the difference in mean value is due to the treatment is substantiated. The difference between the means of the two groups of values may then be accepted as the difference produced by the treatment or change in land-use.

However, fluctuations in runoff due to differences in rainfall can be significant, and statistical checking of the homogeneity of the climate before and after treatment should be made to avoid introduction of such errors. Unfortunately, there is no established methodology for analyses such as these.

Another method of graphical analysis which has been used is to plot flow duration curves for both before and after treatment and to attribute differences in the curves to the treatment. This also ignores natural variations in flow durations on untreated catchments and can allow natural variations to be interpreted as being due to the applied treatment. A conversion to a statistical equivalent may be made by examining the differences between the before treatment distribution and the after treatment distribution using the chi-square test of significance.

Single Variable Analysis

The most important aspect of data analysis is to take account of natural variations and to ensure that other variations, which are to be attributed to change in land use, are significantly different from the natural fluctuations. Not all of the variables which are encountered in these studies are constant from storm to storm or from year to year. Volumes and peak rates of runoff, coefficients of runoff and distribution of runoff throughout the year, etc., all show differences from one period of record to another. It is human nature that the fluctuations which veer towards the direction we hope for are accepted as proof of our hypothesis while fluctuations which veer away from the desired direction are discarded as errors in measurement.

Simple statistical techniques are available to help distinguish variations caused by change in land use from natural variations in the variable being analysed. The two techniques which are most useful for the tests of significance needed in these studies are the Student's t test and the Chi-square test.

In records collected over a number of years, a variable such as the date when half of the yearly flow has passed (half-flow date) will have a mean value and a standard deviation of the values. Following a change in land use, a new mean value is observed. The Student's t test will give a test of significance of the difference in the mean values. Half-flow date was proposed by Court (1962) for studying possible changes in streamflow regime caused by watershed management practices, especially vegetational manipulation aimed at increasing snowpack and delaying snowmelt.

The problem of significant differences in distributions such as change in a flow duration distribution, is more readily examined using the Chi-square test. Changes in flow duration curves have been used by Reinhart (1965) and others.

Knisel (1963) and Brown (1965) used the slope of the recession curve as an indicator variable, while Schneider (1965) uses a low flow index defined as the "average annual minimum daily flow". There are a multitude of coefficients based on the ratio of runoff to rainfall; for example, Dunin (1965) uses 3 yield coefficients - on an annual basis, on a storm basis and on a rate of flow basis - in analysis of a paired-catchment experiment in Victoria.

Hewlett and Hibbert (1965) define two response factors which describe the ratio of surface runoff to total runoff (surface runoff plus groundwater flow) and the ratio of surface runoff to precipitation. These measures are meant to indicate the effects of forests in ameliorating flood flows from a catchment.

These examples may give some idea of the range of variables used as indicators, either of the effects of a change in land use or of the difference between catchments having different characteristics. There is a need for a more detailed review of these variables than is given here and of some sorting and classifying.

Multivariable Analysis

Multivariable analysis is most common in analysis of observational-type experiments. Data are recorded from a number of variables, and the data are analysed to determine what correlations exist among the variables. An illustration is the equation used by Musgrave (1947) for predicting soil loss:

$$E = I.R.S.^{1.35} . L^{0.35} . P_{30}^{1.75}$$

where

E = soil loss in acre inches

I = inherent erodibility of soil in inches

R = a cover factor

S = degree of slope in percent

L = length of slope in feet

P_{30} = maximum 30 minute rainfall amount for a two year frequency, in inches.

The most popular method used for multivariable analysis is multiple linear regression. It has increased in popularity since the introduction of digital computers, undoubtedly due to the prepared regression programs which are now available at most computer installations and the ease with which they can be used.

Multiple non-linear regression is not common except for logarithmic transformation of a linear regression, which results in equations of the type illustrated in the soil loss equation above. Graphical multivariable non-linear correlations are not common but graphical methods are flexible to use. The accuracy obtainable with graphical methods is frequently equal to the accuracy of the data used.

Multiple regressions are useful in deriving prediction equations where the value of one variable, e.g. soil loss, can be predicted from values of other variables, e.g. slope, cover, etc., based on past relationships of the variables. However, much confusion arises when attempts are made to interpret these prediction equations as cause and effect relationships.

As an example of the difference, it might be observed that the sale of blankets in Canada rises when weather in England is very cold. Given data for a number of years, a regression equation could be derived to estimate sales of blankets in Canada from temperatures in England. Now, it would be absurd to postulate a cause and effect relationship that Canadians buy blankets because Englishmen are cold. Yet because cold weather in England is highly correlated with cold weather in Canada, the prediction equation could give good results.

While this example may show clearly the difference between prediction equations and causal relationships, the difference becomes clouded in land use hydrology where the physical process is complex and not well understood. A recent example (Taylor, 1967) illustrates the absurd misinterpretations that can occur with indiscriminate use of multiple linear regression. By attempting to correlate mean annual discharge in cusecs with mean annual rainfall and catchment area as independent variables, Taylor found that rainfall was not a significant factor in causing runoff. To quote:

"Rainfall emerges as a significant factor only when the effect of area is incorporated in the dependent variable as a runoff/area ratio; the mean annual rainfall then becomes of prime importance. To a large extent, however, the effects of catchment size overrule the effects of local climatic variations."

A little reasoning in advance should have dictated that the volume of runoff should have been correlated with the volume of input, i.e. the product of rainfall and area, and not with rainfall and area as independent factors. Misuses of multiple linear regression such as this have resulted in many hydrologists discarding the method altogether.

In an endeavour to find a statistical method by which causal relationships might be established, some hydrologists have turned to factor analysis (Snyder, 1962, Wong, 1963, Eiselstein 1966). In multiple regression, the contribution of a number of predictor variables to the variance of the dependent variable is expressed in the prediction equation. In factor analysis, principle components are found which describe the variance of all of the variables. The principle components or factors are the eigenvectors of the correlation matrix of the variables.

Unfortunately, there is no direct physical significance of the eigenvectors. To quote from Eiselstein:-

"The interpretation of the eigenvectors is somewhat subjective and consists of determining which of the original independent variables are primary contributors to each eigenvector and from this information deciding which quantities of variance each eigenvector is mainly concerned with."

It is this subjective interpretation that is the major weakness of factor analysis. This method, therefore, offers no more information on physical relationships than does multiple linear regression. Both methods can establish that there is some correlation between the variables but neither can determine whether this is spurious (e.g. Canadian blankets and English weather) or causal.

ANALYSIS OF DATA - CATCHMENT MODELS

The difference between mathematical catchment models and the previously described statistical methods of analysis is one of the most important distinctions in modern hydrological analysis. Catchment models are deterministic instead of probabilistic, parametric instead of stochastic, and are based on a specified structure of physical processes rather than on a manipulation of independent and abstract data sets.

The purpose of a catchment model is to simulate the physical processes of the land phase of the hydrological cycle, from input of rain and snow to final disposition as runoff, evapotranspiration loss, deep drainage, or change in the moisture storage of the catchment.

In essence, a catchment model may be regarded as having two major components - one to carry forward a sequential water balance and so determine what losses occur when rain falls; and the second to rout the excess rainfall after losses through surface and channels storages to determine the shape of the outflow hydrograph.

Sequential water balances to determine volumes of runoff are not new. Many attempts have been made to determine annual yield as the residual of annual precipitation minus annual evapotranspiration loss. However, differences in the carryover of catchment storage from year to year can produce substantial errors, and even with monthly water balances, the errors can be very high, particularly in areas of water deficient summers.

For accurate estimates of runoff, it is necessary to use daily increments of time. Chapman (1963) demonstrated the use of a daily water balance involving only a single moisture store to represent catchment storage, in a study of runoff from the Upper Goulburn River catchment. In order to simulate the variation of infiltration rate during a storm, and the action of interflow and similar processes, it is necessary to have a more complex representation of the moisture holding capacity of a catchment than a single moisture store. In addition, to simulate these processes with any accuracy, it is necessary to use time increments in the order of one hour or less.

The water balance components of a typical modern catchment model will probably contain about four moisture stores with the movement of water into, out of, and between the stores specified by operating rules. Calculation of rainfall excess during storms for determining the shape of the runoff hydrograph may use time increments as small as 15 minutes but more likely one hour. Between storms, simulation of drying and drainage will probably revert to a daily basis.

Because of the amount of calculation involved, catchment models are generally prepared as programs for operation on an electronic digital computer. The first and most detailed catchment model prepared in this way was at Stanford University by Crawford and Linsley (1962). Much work has been done in developing and extending the early model to the present Stanford Watershed Model Mark IV (Crawford and Linsley, 1966). In Australia, Boughton (1966a, 1966b) developed a model using only daily data for estimation of catchment yield, and this model is being developed further at Lincoln College in New Zealand.

If the use of a digital computer speeded up water balance calculations by only two or three times, the improved speed could be regarded as simply an improvement of existing techniques. However, the operating speeds of current 3rd generation computers is faster than manual or electro-mechanical calculating speeds by 4 to 5 orders of magnitude. This has introduced not only the facilities for handling much more complex water balance and hydrograph calculations, but has introduced completely new concepts in the approach to data analysis. Crawford (1965) describes these developments as "revolutionary rather than evolutionary", and he uses the term "digital simulation" to describe the new process.

As might be expected with a new development such as catchment models, there is no established methodology or framework which can be assessed in the same way as statistical methods. However, two aspects of this approach are crucial, where models are to be used for evaluating changes in land use, and these are briefly discussed here.

First, the selection or design of the structure of a catchment model is decided in an arbitrary way. What moisture stores or physical processes to include, how water will move through the system, what allowance is made for areal variation in infiltration and other parameters, are all decided by the designer of the model. It is an analytical method which makes each man an artist, and provides for maximum use of preconceived ideas.

A wide variety of different model structures can be used to give equally good results in simulating the runoff pattern from rainfall and evaporation data. While this flexibility may be attractive to the individual worker, it is not conducive to clearly defined analysis, and is more open to misinterpretation than any other method.

The second aspect of major concern is the difficulty of interpreting values of the parameters in the model. Where models are to be used for evaluating land use changes, one set of values of the model parameters are used to simulate "before treatment" catchment behaviour and a second set of values are used to represent the "after treatment" condition. The difference in the simulated outputs from the model, using first one set of values and then the other, is assumed to be the effect caused by the treatment. The Stanford Watershed Model is being used in this way to investigate a variety of applications ranging from the response of catchments to weather modifications, to the hydrological changes caused by urban development (Crawford and Linsley, 1966).

(i) The land phase of the hydrologic cycle is too complex. It will never be possible to achieve a worthwhile definition of all the physical processes occurring in a catchment.

(ii) Even if it were possible to define sufficient of the physical processes for an adequate approximation to be made, the amount of calculation involved would still make it impossible to answer realistic problems.

(iii) Even if arguments (i) and (ii) could be overcome, the cost of collecting sufficient data on all of the variables concerned would be prohibitive, and sufficient replications of the experiments for valid statistical significance could not be afforded.

The application of second generation digital computers to hydrological problems became common about 1960. It was about this time that Crawford and Linsley (1960) introduced the concept of watershed models and digital simulation of the land phase of the hydrological cycle. Third generation computers now provide even faster calculating facilities and still higher speeds seem imminent. The use of catchment models has developed with the development in computers and there is no longer any doubt that we now have adequate computational facilities to handle the simulation of very complex watershed models.

In addition, experimental methods in hydrology have developed beyond the traditional paired-catchment, graphical analysis concepts. Multiple-catchment experiments are already under way in South Africa and the U.S.A. as described earlier. These experiments are approaching a stage equal to the randomised block design of experiments that are common in agricultural science, and indicate that resources are available for satisfactory experimentation in hydrology once a valid methodology is clearly established.

Experimental hydrology is a neglected field in Australia, except for some soil conservation work in Victoria and New South Wales, but is more developed in New Zealand. The 16 small catchments which have been gauged at Moutere since 1959, 6 catchments at Taita gauged since 1955, and others, indicate that the resources currently available here, if correctly applied, could be sufficient for valid statistical design of experiments of some changes in land use.

The argument which has not yet been adequately answered is that we do not have sufficient knowledge of the physics of the problem to design experiments correctly or to set up a simulation model of a catchment that can reproduce the effects of change in land use. It is the lack of understanding of the physical processes involved that at present provides the limit to our abilities, not money or ability to handle the computations.

THE FUTURE

As the author has served on national committees dealing with the

However, it has been demonstrated (Boughton, 1967c) that catchment models can contain compensating parameters where, for example, change in the value of a moisture storage capacity can be compensated by change in value of the infiltration parameters to give nearly similar output. Change in value of a moisture storage capacity from 10 inches to 20 inches with small change in output was demonstrated. The opportunities for misinterpretation, where small variations in output are sought among wide natural fluctuations, are obvious.

One urgent need at the present time is for collection of intermediate data between rainfall and runoff, particularly soil moisture and groundwater storage, in order to obtain a firmer basis for design of model structures. Although some data collecting programs, such as the experimental catchment program in New Zealand, include measurements of soil moisture and groundwater storage, there is no integration of data collection with data analysis, i.e. the selection of data to be recorded is made quite independently of how the data will be analysed. Pious hopes of the future development of improved methods of analysis abound in hydrology.

Catchment models are still very new and their full potential and best uses are still unknown. It will be some little time yet before the opportunities for analysis presented by digital simulation are formulated into a systematic methodology and can be reviewed with assurance.

THE PRESENT SITUATION

Ackermann (1965) draws an interesting analogy between watershed research and weather modification programs. To quote from his report:

"The history of watershed studies is quite parallel with our efforts in the field of weather modification in which we have attempted operational programs and field experiments before we understood the basic cloud physics and mechanisms of drop coalescence. As a consequence, the results of most cloud seeding applications have been clouded by the inherent natural variability. Much controversy and lost motion has resulted in the rush to achieve effects, but in the end we will need to understand the mechanisms before we can successfully modify them to our advantage."

This could be summarised in a catch-phrase "Physics first, statistics second". Early statistical analyses of land use experiments are clouded by misinterpretation and doubts of validity, due to doubts about the nature of the problem. If this is to be avoided in future, a much fuller understanding of the physics of the problem must be achieved.

Three arguments have often been used to justify short-cut empiricism and an ad hoc approach to this problem of change in land use. These are:

planning of catchment studies in two countries (The Australian Water Resources Council's Advisory Panel on Representative Basins and the New Zealand Sub-Committee on Hydrological Decade Experimental Basins) the urge to speculate idealistically about what ought to be done is tempered by thoughts about what might actually be achieved.

In Australia, there is an obvious lack of interest at administrative level in hydrologic effects of land use changes, and little understanding of the depth of the problem of evaluating the effects. The streamgauging networks, operated by the State and Federal Governments, are engineering-dominant and orientated towards the major water supply works. Land use hydrology is studied in a small way by Soil Conservation, Forestry and Agricultural authorities who operate a few experimental catchments.

The Australian Water Resources Council has initiated some studies of runoff estimation for farm dam design, effects of soil conservation works on catchment yield, and the selection of 50 to 100 representative basins. These studies have progressed very slowly, even by standards of inter-department government committees, and it would be extremely optimistic to predict that any significant increase in Australian activity in experimental land use hydrology will be initiated in the foreseeable future.

In New Zealand, problems of soil conservation are more severe, and interest in watershed management covers a wide range of disciplines. Experimental catchment studies within the national International Hydrological Decade program are accorded more importance and attention than representative basins, but both are included. The series of experimental catchment studies which have been initiated to date are specifically designed to evaluate effects of changes in land use, and these studies reflect the interest of conservationists, agriculturalists, and foresters in the problem.

The major criticism which might be made of the New Zealand program is that the emphasis is very much towards empirical studies, such as paired catchment experiments with scant planning of the study of basic processes. While a number of individual workers are undertaking fundamental investigations, there is no coordinated program of such work. Current experiments appear to be based on principles of data collection similar to earlier overseas studies which have not produced expected results in other countries. While interest is being shown in the use of mathematical catchment models for analysis of data, there is little experience in the use of such techniques, and the collection of data does not appear to be well integrated with proposed methods of data analysis.

Planning of a program of fundamental hydrologic research involving experimental catchments is a major task. The specification of what fundamental studies of physical processes should be made, in what order of priority, how each study should be undertaken, etc., are questions that form a research program by themselves. Planning of the program, collection of data, and analysis of data, should be allocated equal shares of the available resources, rather than the predominant allocation to data collection as at present.

The principal problems in land use hydrology are usually concerned with the short term pattern of flood runoff, or the long term pattern of yield, or the quality of runoff, the latter including sediment problems. As an example of the type of study and type of planning mentioned above, consider how a study to improve current models of flood hydrograph production (unit hydrograph, runoff routing, kinetic wave, and conservation-momentum) might be planned.

The original concept might be for additional streamflow gauges to be installed within a catchment to examine the sources of runoff, to collect data for hydraulic computation of build-up of the hydrograph, and to study those measures of channel storage which could be used to extrapolate the results to other catchments.

Such a study would involve collection of data for several years, and considerable cost for equipment and labour in installation and data handling. It seems reasonable that this and similar proposals would be given detailed study before a decision is made to proceed (perhaps 6 to 12 months full-time investigation). In this planning stage, the objectives of the study would be defined in precise detail, the data to be collected and how it is to be analysed would be set out, comparisons made of alternative means of collecting the data and the optimal method selected, and the coordination of the study with other parts of the overall research program worked out.

Data collection must be fully integrated with data analysis, and it is in the planning stage that this integration should be ensured. In no other science is the tradition of data collection without set purpose so ingrained as in hydrology.

It must be recognised that the problem of evaluating changes in the land use regime is an extremely complex one and more attention must be given to fundamental studies of physical processes than is done at present. Planning of what studies to undertake, and how they should be undertaken, is a full research project in itself, as should be evident by the scope of existing methods and techniques covered in this paper. Yet, the method of planning which has been chosen in both Australia and New Zealand is to set up committees. To repeat what has been said many, many times before, research by committee is futile and ridiculous.

In the U.S.A., the three government agencies participating in the Cooperative Water Yield Procedures Study each provided a technical expert full time for two years to investigate and report on how to study the effects of land treatment on water yield. The difference between the time allocated to this planning and the time allocated to similar planning in New Zealand and Australia is most marked.

ACKERMANN, W.C. 1965. Guidelines for research on hydrology of small watersheds. University of Minnesota, Water Resources Research Center, Information Circular, No. 46, 13 pp.

American Geophysical Union. 1965. Inventory of experimental and representative watershed studies conducted in the United States.

AMERMAN, C.R. 1965. The use of unit-source watershed data for runoff prediction. Water Resources Research 1 : 499-507.

AMERMAN, C.R. and McGUINNESS, J.L. 1966. Plot and small watershed runoff and its relation to larger areas. Paper presented at the 1966 Winter Meeting ASAE, Chicago.

ALLIS, J.A. 1962. Comparison of storm runoff volumes. Agr. Eng. 43 : 220-223.

Australian Water Resources Council. 1965. Inventory of research into water resources and directly related matters. Canberra, Australia.

Australian Water Resources Council. 1967. Water resources newsletter No. 8, April 1967, Canberra, Australia.

BATES, C.G. and HENRY, A.J. 1928. Forest and stream flow experiments at Wagon Wheel Gap. United States Weather Bureau Monthly Weather Review. Suppl. No. 30, 79 pp.

BETHLAHMY, N. 1963. Rapid calibration of watersheds for hydrologic studies. Internatl Assoc. Sci. Hydrol. Bull. 8 : 38-42.

BOUGHTON, W.C. 1966a. A new simulation technique for estimating catchment yield. University of New South Wales, Water Research Laboratory, Report No. 78.

BOUGHTON, W.C. 1966b. A mathematical model for relating runoff to rainfall with daily data. Civil Eng. Trans. I.E. Aust. CE8 : 83-97.

BOUGHTON, W.C. 1967a. Hydrologic characteristics of catchments. Paper presented at the Symposium on Streamflow and Catchment Characteristics, N.Z. Hydrol.Soc., Wellington, 1967.

BOUGHTON, W.C. 1967b. Plots for evaluating the catchment characteristics affecting soil loss. 1. Design of experiments. J.Hydrol. N.Z. 6 : 113-119.

BOUGHTON, W.C. 1967c. Evaluating the variables in a mathematical catchment model. Paper presented at the Inst.Engs.Aust.Hydrol.Symp., Brisbane, 1967. Civil Eng.Trans. I.E.Aust. CE10 (To be published)

BROWN, H.E. 1965. Characteristics of recession flows from small watersheds in a semiarid region of Arizona. Water Resources Research. 1 : 517-522.

CHAPMAN, T.G. 1963. Rainfall - run-off relations in the Upper Goulburn River catchment. Civil Eng.Trans. I.E. Aust. CE5 : 25-35.

COURT, A. 1962. Measures of streamflow timing. J.Geophys.Res. 67 : 4335-4339.

CRAWFORD, N.H. 1965. Digital simulation methods in hydrology. In "International Symposium on Forest Hydrology" ed. W.E. Sopper and H.W. Lull. Pergamon Press, Oxford, 1967. pp 761-769.

CRAWFORD, N.H. and LINSLEY, R.K. 1960. Computation of a synthetic streamflow record on a digital computer. International Association of Scientific Hydrology. Publ. No. 51 : 526-538.

CRAWFORD, N.H. and LINSLEY, R.K. 1962. The synthesis of continuous streamflow hydrographs on a digital computer. Tech. Report 12, Dept Civil Eng., Stanford University.

CRAWFORD, N.H. and LINSLEY, R.K. 1966. Digital simulation in hydrology : Stanford Watershed Model IV. Tech. Report No. 39, Dept Civil Eng., Stanford University.

DORTIGNAC, E.J. and BEATTIE, B. 1965. Using representative watersheds to manage forest and range lands for improved water yield. In "Symposium of Budapest. Representative and Experimental Areas", Inter.Assoc. of Sci.Hydrology, Belgium, pp 480-488.

DOTY, C.W. and CARTER, C.E. 1965. Rates and particle size distributions of soil erosion from unit source areas. Trans. ASAE 8 : 309-311.

DUNIN, F.X. 1965. The effect of vegetative changes on parameters for estimating runoff near Bacchus Marsh, Victoria. Civil Eng.Trans. I.E. Aust. CE7 : 16-22.

EISELSTEIN, L.M. 1966. Experimental design of hydrologic land-use studies. Thesis (M.Agr.Sc.) University of Canterbury.

HAYWOOD, J.A. 1967a. A critique of soil-loss plot studies. N.Z. Agr.Eng.Inst.Res.Report R/2. Lincoln College. (In press)

HAYWOOD, J.A. 1967b. Plots for evaluating the catchment characteristics affecting soil loss. 2. Review of plot studies. J. Hydrol. N.Z. 6 : 120-137.

HEWLETT, J.D. and HIBBERT, A.R. 1965. Factors affecting the response of small catchments to precipitation in humid areas. In "International Symposium on Forest Hydrology" ed. W.E. Sopper and H.W. Lull. Pergamon Press, Oxford, 1967. pp 275-290.

HIBBERT, A.R. 1965. Forest treatment effects on water yield. In "International Symposium on Forest Hydrology" ed. W.E. Sopper and H.W. Lull. Pergamon Press, Oxford, 1967. pp 527-543.

International Association of Scientific Hydrology : International Symposium on Experimental and Representative Catchments. Budapest. 1965.

IVANOV, K.E. and ROMANOV, V.V. 1965. Quantitative water budget criteria of evaluation of representativity of drainage areas in studying the influence of physiographical factors upon hydrological regime elements. In "Symposium of Budapest. Representative and Experimental Areas", Inter.Assoc.Sci. Hydrology, Belgium, pp 669-675.

KINCAID, D.R., OSBORN, H.B. and GARDNER, J.L. 1966. Use of unit-source watersheds for hydrologic investigations in the semiarid southwest. Water Resources Research 2 : 381-392.

KOVNER, J.L. and EVANS, T.C. 1954. A method for determining the minimum duration of watershed experiments. Trans.Amer.Geophys.Union 35 : 608-612.

KNISEL, W.G. 1963. Baseflow recession analysis for comparison of drainage basins and geology. J.Geophys. Res. 68 : 3649-3653.

MINSHALL, N.E. and JAMISON, V.C. 1965. Interflow in claypan soils. Water Resources Research 1 : 381-390.

MUSGRAVE, G.W. 1947. The quantitative evaluation of factors in water erosion - a first approximation. J.Soil and Water Conserv. 2 : 133-138.

New Zealand National Committee for the IHD. 1965. IHD Bulletin New Zealand No. 3 in J.Hydrol., N.Z. 4 : 40-49.

REIGNER, I.C. 1964. Calibrating a watershed by using climatic data. United States Forest Service Research Paper NE - 15, 45 pp.

REINHART, K.G. 1965. Watershed calibration methods. In "International Symposium of Forest Hydrology" ed. W.E. Sopper and H.W. Lull. Pergamon Press, Oxford, 1967. pp 715-723.

RENNE, R.R. 1967. Research guide lines to sound watershed development. Journal of the Irrigation and Drainage Division. ASCE 93 : 53-58.

ROBINS, J.S., Kelly, L.L. and HAMON, W.R. 1965. Reynolds Creek in southwest Idaho : an outdoor hydrologic laboratory. Water Resources Research 1 : 407-413.

ROTHACHER, J. 1965. Streamflow from small watersheds on the western slope of the Cascade Range of Oregon. Water Resources Research 1 : 125-134.

ROWE, P.B. 1943. A method of hydrologic analysis in watershed management. Trans.Amer.Geophys. Union 2 : 632-649.

SCHNEIDER, W.J. 1965. Areal variability of low flows in a basin of diverse geologic units. Water Resources Research 1 : 509-515.

SHARP, A.L., OWEN, W.J. and GIBBS, A.E. 1959. Cooperative water yield procedures study. Agr.Res.Service USDA, Lincoln, Nebraska, July 1959.

SLAYMAKER, H.O. and CHORLEY, R.J. 1964. The vigil network system. J.Hydrol. 2 : 19-24.

SNYDER, W.M. 1962. Some possibilities for multivariate analysis in hydrologic studies. J.Geophys.Res. 67 : 721-730.

SOPPER, W.E. and LULL, H.W. 1965. Streamflow characteristics of physiographic units in the Northeast. Water Resources Research 1 : 115-124.

SOPPER, W.E. and LULL, H.W. (ed.) 1967. "International Symposium on Forest Hydrology" Pergamon Press, Oxford.

STRIFFLER, W.D. 1965. The selection of experimental watersheds and methods in disturbed forest areas. In "Symposium of Budapest. Representative and Experimental Areas", Inter.Assoc.of Sci.Hydrology, Belgium, pp 464-473.

TAYLOR, C.H. 1967. Relations between geomorphology and streamflow in selected New Zealand river catchments. J.Hydrol.N.Z. 6 : 106-112.

TOEBES, C. 1965. The planning of representative and experimental basin networks in New Zealand. Paper presented at the Symposium on Representative and Experimental Areas; Budapest. 1965.

UNESCO 1967. Nature and Resources. Bulletin of the IHD 3(3).

United States Department of the Interior 1967. Catalogue of Water Resources Research, vol.2.

WICHT, C.L. 1965. The validity of conclusions from South African multiple watershed experiments. In "International Symposium on Forest Hydrology" ed. W.E. Sopper and H.W. Lull. Pergamon Press, Oxford. 1967. pp 749-760.

WILM, H.G. 1949. How long should experimental watersheds be calibrated? Trans.Amer.Geophys.Union. 30

WONG, S.T. 1963. A multivariate statistical model for predicting mean annual floods in New England. Annals Assoc.Amer.Geog. 53 : 298-311.

YATES, M. 1962. Comparative catchment studies. In "Hydrology and Land Management" Soil Con. and Rivers Control Council, N.Z. pp 10-12.

LINCOLN PAPERS IN WATER RESOURCES

A publication of the New Zealand Agricultural Engineering Institute

No. 1: Water Resources Symposium, 40th ANZAAS Congress: Part 1. (April 1968)

No. 2: Water Resources Symposium, 40th ANZAAS Congress: Part 2. (April 1968)

No. 3: Flood flows from rural catchments: J.R. Burton and T.D. Heiler (in press).