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PHYSICAL AND CLIMATIC CHARACTERISTICS OF THE WESTERN AND HACKING CATCHMENTS OF THE UNIVERSITY OF NEW SOUTH WALES

by

D.H. Pilgrim

March 1972

THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL ENGINEERING

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PREFACE

From its foundation, the School of Civil Engineering of The University of New South Wales has pursued a vigorous programme of teaching and research in hydrology and water resources engineering. One of the features of this programme has been the operation of a network of research catchments, which have provided much of the data used in research and for tutorial purposes. Operation of the catchments has also kept academic staff in touch with the practical problems of hydrological data collection.

This report will serve a dual purpose. In addition to giving a general description of the University's catchments, it provides a source of more detailed background information for research workers and others interested in using the data from the catchments.

Most of the data collection on the catchments has been carried out by technical staff of the School of Civil Engineering under the general supervision of academic staff. However, a large number of private individuals regularly and conscientiously read instruments on a voluntary basis. The School is grateful for this help, for the catchment programme would not be possible without it. Similarly, instrumentation and operation have been funded primarily from the School's resources, but a few instruments have been purchased from research grants associated with particular projects. Financial assistance of this type from the Water Research Foundation of Australia and the Rural Credits Development Fund of the Reserve Bank of Australia is gratefully acknowledged.

H. R. VALLENTINE,
Professor and Head,
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1. INTRODUCTION

To provide data for its teaching and research programme in surface water hydrology, the School of Civil Engineering of The University of New South Wales has developed a network of gauged research catchments ranging in area from 16 acres to 35 square miles. These catchments were instrumented and are operated by the Hydrology Section of the Department of Water Engineering of the School. In the Sydney region, 15 catchments are instrumented and 13 of these are of a rural nature while the other two are urban catchments drained by stormwater channels.

The objective of this report is to give a detailed description of the physical and climatic characteristics of the rural catchment areas. This will provide not only a general description of the catchments, but also background information and a source of references to more detailed studies for research workers involved in actual use of data from the catchments.

With the aid of grants from the Water Research Foundation of Australia and the Forestry Commission of New South Wales, the School has also instrumented 11 catchments in the Lidsdale State Forest near Wallerawang, about 80 miles west of Sydney. These catchments are under eucalypt and exotic pine forest, and have been described by Bell (3) and Bell and Gatenby (4).

2. THE CATCHMENT AREAS

2.1 Location

The rural catchments are situated in the County of Cumberland within 30 miles of Sydney, and are located in two areas of limited extent, the two groups being known as the Western and Hacking catchments. Many characteristics are generally similar within each of the areas, but there is a marked difference between the two areas. These contrasting catchment areas were chosen to aid investigation of the effects of the different physical features on the hydrological characteristics. The general location of the catchments is shown in Fig. 1.

The four western catchments are located on the Cumberland Plain between St. Marys and Narellan. They lie within an area of 18 x 8 miles centred about 25 miles west-south-west of Sydney. Areas range from 16 acres to 34.6 square miles, these extremes also being the smallest and largest of all of the School's catchments. Streams in the area flow generally northwards and join into South Creek, which then flows into the Hawkesbury River just below Windsor. The catchments are shown in more detail on Fig. 2.

The other area is in the upper catchment of the Hacking River about 22 miles south of Sydney, and immediately to the south of the Royal National Park. The southernmost fringe of the Park lies within the area, which extends from the road crossing near Waterfall at the upper end of the Park in the north to Stanwell Tops in the south. Of the nine catchments, the largest has an area of 15.5 square miles, and the other eight are located within it. The smallest has an area of 94 acres. The Hacking River flows north from the catchments and discharges into the Pacific Ocean at Port Hacking. The individual Hacking catchments are shown on Fig. 3.

2.2 General Characteristics

The catchments and their general characteristics are listed in Table I. The numerical values in the table are given primarily to indicate the general nature and characteristics of the catchments rather than as definitive values to be used in quantitative studies. For a given catchment, numerical values of measures such as slope and stream length depend on the definition adopted, the map used, and the technique used in taking values off the map. In general, it is desirable for each investigator to derive or check measures of catchment characteristics for himself. Other sets of values for characteristics of some of the catchments have been published by Askew (1,2) and Cordery (15).

2.3 Instrumentation

The catchments are intensely instrumented to continuously record rainfall and streamflow. The location, type of water level recorder and period of record are listed for each of the catchments in Table II. Details and locations of pluviographs (recording rain gauges) and daily rain gauges on the Western catchments are given in Tables III and IV respectively, and the locations of these gauges are shown on Fig. 2. Similar data for the Hacking catchments are given in Tables V and VI, and the locations of these gauges are shown on Fig. 3. As indicated in the tables, a few of the daily rain gauges are operated by the Commonwealth Bureau of Meteorology, but all other instruments are operated by the School.

Evaporation measurements are also made at Badgerys Creek Flume. The University has operated a U.S. Class A pan at this location since 1955, and an Australian Sunken Tank since 1956. The Commonwealth Bureau of Meteorology also installed a U.S. Class A pan near Badgerys Creek Flume in 1967.

3. PHYSICAL CHARACTERISTICS

3.1 Topography and Drainage

The western catchments on the Cumberland Plain are in gently undulating country at from 150 to 650 feet above sea level. Land slopes are generally slight with an average of 2 to 3%, with some steeper slopes on the low hills which ring the catchments. Mt. Vernon catchment is in steeper country with moderate slopes of the order of 8% over much of the catchment. The drainage network in the area is reasonably developed and mature, and minor meandering is common. Generally, stream channels are rather inefficient from a hydraulic viewpoint, often being grassed and having trees and bushes in the beds due to the flat slopes and ephemeral nature of the streams. Considerable overbank flow often occurs at high discharges. Contours within the catchments are shown in Fig. 2.

Topography of the Hacking catchments is quite different,

being of a much more rugged nature. The area is on the coastal plateau surrounding Sydney, and the elevation of the top of the plateau here is from about 600 to 1100 feet above sea level. This plateau is heavily dissected by streams flowing into the Hacking River, which has an elevation of about 100 feet above sea level at the outlet of the catchment. Overall, the maximum elevation difference is about 1,000 feet. The catchment area is at the edge of the plateau and is immediately adjacent to the coastal scarp, which is very close to the coast at this point. Undulating and dissected sandstone plateau country occurs in the western half of the region, with some flattish swampy areas, especially in the south-west corner. The eastern half is much steeper and includes the valley of the Hacking River. Variations in topography are closely related to geology, as noted in Section 3.2. A reproduction of a detailed topographic map of the area is shown in Fig. 4.

Drainage of the majority of the Hacking area is efficient due to the steep dissection. Surface runoff travels only very short distances before it enters channels. Stream slopes are relatively steep, channels are well defined, and little overbank flow occurs even at high discharges. The only major variation from these conditions is in fairly small marshy patches near the ridges along the western edge of the area.

3.2 Geology

The catchment areas are located near the centre of the Permo-Triassic Sydney Basin. Three distinct geological strata outcrop widely in the County of Cumberland, and all three are found in the catchment areas. Sediments forming these strata were laid down in the Triassic period, being part of the Mesozoic era. Beginning with the uppermost and most recent, these three strata are:-

(i) The Wianamatta Series, which consists largely of interbedded shales and sandstones, and can be subdivided into two major divisions. The upper division,

or Camden Subgroup is composed of beds totalling more than 350 feet in thickness, sandstone and greywacke calcareous sandstone being dominant, although shales occur frequently. The lower division, or Liverpool Subgroup, is some 400 feet thick, shale being the predominant rock type with minor sandstone bands.

(ii) The Hawkesbury Series, consisting of massive coarse to medium quartz sandstone with a kaolinitic matrix, pebbly or conglomeratic in part. Occasionally, narrow shale bands occur, but these are not significant in the group. Passage beds approximately 50 feet thick of alternating shale and sandstone occur at the top of the series marking the major change from the Hawkesbury sandstone to the Wianamatta group.

(iii) The Narrabeen Series, comprising shales, claystones, sandstones, greywackes and fine conglomerates. The first two are often chocolate or reddish, or grey-green, and probably represent at least in part re-distributed tuffs. It is the lowest and oldest division of Triassic in the Sydney Basin and lies conformably over the top of the Permian series (formerly called the "Upper Coal Measures").

Descriptions of the geology of the areas in which the catchments are located are available in a number of publications. The geology of the western catchments is delineated in the map compiled by Bryan (6) and is discussed in detail in the accompanying Explanatory Notes by Bryan, McElroy and Rose. A similar map compiled by Rose (33) with Explanatory Notes to an earlier edition of the map by Joplin, Hanlon and Noakes covers the geology of the Hacking catchments. Both areas receive detailed coverage by McElroy, Lovering and Standard in the review edited by Packham (30). The Wianamatta series has been further described by Lovering (24) and the Narrabeen series by Hanlon et

al. (19). Other general descriptions of the geology of the Sydney region are given by Willan (39) and Osborne (29). Comprehensive bibliographies are included in the first three references. A more detailed delineation of the outcropping of the geological series in the Hacking area than is possible from any of the above references can be inferred from the soil survey by Walker (35).

The western catchments are located almost entirely on the Wianamatta series, except for some Quarternary alluvial terrace deposits along the lower sections of the streams. Upper division strata outcrop on some of the hills, notably at the head of Eastern Creek, the high section of Mt. Vernon, and along the south-western rim of South Creek. Over the remainder lower division shales occur. The gently undulating topography of the area is typical of the Wianamatta series.

On the other hand, Hawkesbury and Narrabeen strata occur in the Hacking area. Hawkesbury sandstone outcrops on the western half, and the ruggedly undulating topography with heavy dissection is typical of these strata. The eastern half of the catchment is mainly on Narrabeen strata, and the streams here have cut down into the softer material giving much steeper topography. The change in topography with the change of strata is generally quite marked.

Sediments composing the floodplain of South Creek have been examined at two sites by Riley (32) and the mode of deposition and the morphology of the stream are discussed. The general characteristics of the South Creek catchment are also described by Riley.

3.3 Sub-Surface Water

Knowledge of the underground water in the region encompassing the catchment areas has been summarised by Whiting (38). The Wianamatta shales are good host rocks for the retention of water, but are relatively impervious and yield very small flows. In dry weather, the creeks in the western area consist of series of pools, with little or no flow. Sandstones of the Hawkesbury and Narrabeen series are

excellent host rocks for the retention of water, but in general have low transmissivity. In the Hacking area, the rock is more pervious and jointed than in many other areas, and sustained yield to streams occurs. The calcareous and tuffaceous shales of the Narrabeen series also yield sustained flow.

The marine conditions under which the Wianamatta series sediments were laid down is reflected in the excessive salinity of sub-surface water in the western area. Old (28) has described a series of analyses of sub-surface waters from Wianamatta rocks, and this work is also referred to by Lovering (24). Average values of salinity over the area found in the analyses ranged from 12,000 to 24,000 parts per million of total salts, although some samples were more saline than sea water (35,000 parts per million). Also, water in the creeks in dry periods has a very high salt content. There is much evidence to indicate that this salinity is due to connate salt derived from the marine waters of the depositional area when the sediments were laid down.

On the other hand, the acid, non-saline waters from the Hawkesbury and Narrabeen series reflect the fresh water origin of these formations.

3.4 Soils

A detailed soil survey of the County of Cumberland has been published by Walker (35) covering the two areas in which the University's catchments are located. The Hacking area is also covered by a reconnaissance survey of the South Coast by Walker (36). Further data on the soils of the catchment areas are given in two preliminary surveys of regional resources by the New South Wales Premier's Department (26 and 27). Detailed data on the soils of the Badgerys Creek Flume catchment are given by Watson (37).

The soil classifications are based on the great soil groups outlined by Stephens (34), Hallsworth and Costin (18) and Leeper (22). The soil types in the areas are delineated in detail on a set of

1 mile to 1 inch maps supplementary to the County of Cumberland soil survey report by Walker (35). Mapping units used are soil series associations, which are closely related to parent materials. Each association may contain a number of separate soil series whose distribution is determined by topography and parent material differences. Normally one series is dominant within each association, which is given the name of this dominant series. Great soil groups and soil series belonging to each group and occurring in the catchments are listed in Appendix A. Associations and the soil series present in them are noted in Appendix B.

Three associations are represented on the western catchments. Typical soil relationships along valley cross-sections, or "catenas", are given in Appendix C. The main soil series are Cumberland and Austral, which are red and yellow podsolic soils respectively. These are strongly leached soils, acid throughout, whose profile form is essentially a medium or lightish textured surface soil which becomes pale or bleached with depth (seen in the dry state), overlying a heavier textured plastic subsoil. The colour is the predominant hue of the subsoil. Red podsolic soils occupy the well-drained upper portions of the catena, and the more heavily leached yellow podsolic soils the lower, more poorly drained regions. The Menangle association occurs in the steeper districts where the Upper Wianamatta series with greywacke sandstone becomes dominant. This occurs around the rim of the Eastern Creek catchment, over the whole of Mt. Vernon, and on the south and south west edges of South Creek catchment. The Menangle series red-brown earth occurs on well-drained upper areas and Glenlee series solodic soil on lower poorly-drained areas in the same relation as the red and yellow podsolics. Where the lower Wianamatta shales appear on lower slopes the Cumberland series red podsolic soil occurs. Over the whole of the western catchment area, texture of surface soils is loam to clay loam, and subsoils vary from medium to heavy clay.

On the Hawkesbury sandstone of the western half of the

Hacking catchments, two soil associations occur. The Woronora association of podsolic lateritic soils occurs on the higher, flatter areas on mixed parent materials of shale and sandstone, and laterites and laterite detritus. It is a residual on ridges and remnants of the surface of the elevated coastal plateau. The Hawkesbury-Warumbul association occurs on the lower and relatively steeper sandstone dominated areas. Rock outcrops are a feature of the landscape and occupy possibly 10% of the surface area, and consequently there is not a continuous layer of soil over the geological strata. In general, stony soils of a number of series listed in Appendix B are found, belonging to the yellow podsolic, podsolic lateritic, skeletal and podsol great soil groups. Surface texture of the soils over the western half of the Hacking catchments is mainly sand with silty fines, but some loams occur and inclusions of small stones are common. Subsoil varies from sand to heavy clay, and a massive and dense ironstone horizon occurs in the lateritic soils. Sandstone underlies the whole area.

The Narrabeen association occupies most of the eastern half of the Hacking catchments over the Narrabeen geological series. The Lilyvale and Narrabeen soil series forming this association are both red podsolic soils, and no typical catenary sequences are evident. Surface soils are dark brown with a fine sandy clay loam to sandy loam or even sand texture, and subsoils are heavy clay.

Further detailed data on the soils of both areas are given by Walker (35), including soil profile descriptions and analyses, and pedogenesis of the soil types.

Sheet erosion of the soil of the western catchments is widespread, the red podsolic soils mainly being affected. Little gullying is evident due to the gentle slopes, although some has occurred on the steeper slopes. Natural vegetation on most of the Hacking area confines erosion here to roadside locations and other relatively small cleared areas.

With regard to fertility, there are widespread deficiencies of phosphate in the soils of both areas. Deficiencies also exist in

lime, molybdenum, copper and sulphur.

3.5 Vegetation

The vegetation of the Sydney district has been described in detail by the New South Wales Premier's Department (27), by Pidgeon (31), and in part by a number of other workers.

The western catchments contain mostly cleared country, with timber in relatively small belts and patches and along many of the watercourses. The timber is of poor quality, with grey box (Euc. hemiphloia) predominating and belts of red and narrow-leaf ironbark (Euc. siderophloia and creba), forest red gum (Euc. tereticornis), white stringybark (Euc. eugenioides), tea-tree (Melaleuca spp.), and occasional woolybutt (Euc. longifolia). Swamp sheoak (Casuarina glauca) and cabbage gum (Euc. amplifolia) occur along the watercourses, and acacias and rough barked apple (Angophora intermedia) are scattered throughout.

Most of the area is under a moderate to poor quality grass cover. The native kangaroo grass (Themeda australis) is being replaced by love grasses (Eragrostis spp.), coastal blue grass (Dichanthium affine), meadow rice grass (Microlaena stipoides), paspalum (Paspalum dilatatum), Parramatta grasses (Sporobolus spp.), spear grasses (Stipa spp.) and wire grasses (Aristida spp.).

There are small areas under improved pasture with irrigation, subterranean clover, red clover and phalaris being the main species, but the rainfall is too low for widespread improved pasture without irrigation.

The Hacking catchments are mainly under virgin timber with relatively small cleared and grassed areas in the south and south-west sections of the area, and in the township of Helensburgh. On the Hawkesbury sandstone of the western half, there is a moderate to poor cover of dry sclerophyll (eucalypt) forest of the smooth-barked apple association consisting of inferior eucalypts and angophora, sheoak, acacias and a dense ground cover of many shrubby plants. The main

trees are smooth-barked apple (Angophora costata), red bloodwood (Euc. gummifera), scribbly gum (Euc. Haemastoma), Sydney peppermint (Euc. piperita), grey gum (Euc. punctata), blue-leaved stringybark (Euc. agglomerata), narrow-leaved stringybark (Euc. sparsifolia) and silver-top ash (Euc. sieberiana).

On the Narrabeen series of the eastern half of the area, there is a dense forest cover. This is made up of areas of wet sclerophyll (eucalypt) forest and subtropical rain forest. The latter is common in the valleys, and sassafras (Doryphora sassafras) and scented satinwood (Ceratopelalum apetalum) are common species. The cabbage-tree palm (Livistona Australis) is a characteristic minor species. Turpentine (Syncarpia laurifolia) is common throughout the Narrabeen series area.

3.6 Population and Land Use

At the 1966 census, over 7,500 people lived on the western catchments. There are no large towns, and the population is fairly uniformly spread over the area in small villages and on farms. For the two large catchments, approximately 6,400 people lived in the South Creek area and 1,100 in the Eastern Creek area. Most of the area is used for grazing for beef and dairy cattle and sheep. Poultry farming is widespread and some pigs are raised. Small areas of vegetables and other crops are grown under irrigation on the Eastern Creek catchment. The only other agricultural production is a little hay, and small areas of improved pasture are grown under irrigation.

Nearly 3,200 people lived on the Hacking catchments at the 1966 census. These were concentrated in the southern half of the area, with the great majority living in the township of Helensburgh. Most of the remainder live in the villages of Otford, Bald Hill, Stanwell Tops and Waterfall Hospital. The great majority of the area is under virgin timber and is not used for agriculture, and the main industry is coal mining at Helensburgh. A small amount of timber is taken from the forests on the Narrabeen series for mine supports. A

few cattle are grazed on the clearings in the south of the area.

4. CLIMATE

4.1 General

The Sydney region is in the sub-tropics and has a typical temperate climate. Near the coast maritime influences give high humidity. There is a strong orographic influence and the average rainfall is high along the coastal scarp, and decreases rapidly to the west until the ascent of the Blue Mountains. Under the orographic influence of the coastal scarp, the Hacking catchments have an average annual rainfall of over 50 inches, making this the area of highest rainfall in the County of Cumberland. On the other hand, the western catchments lie in the centre of the rain-shadow area between the orographic influences of the coast and the Blue Mountains, and have an average annual rainfall of only about 30 inches.

Various systems of classification of climate have been proposed, but no simple system has been devised to give a complete and unique description of climatic characteristics. The best that has been achieved is a classification of climate for a specific purpose. One of the best known is the Koeppen system, which is an attempt to relate the extent and type of natural vegetation to climatic conditions. Koeppen's classification is described in various textbooks such as that by Berry, Bollay and Beers (5). Under this system and using average data, both the western and Hacking areas have a humid mesothermal type climate, with a moderate, oceanic climatic province. However, this classification has very wide limits.

A more detailed climatic classification of the areas in which the catchments are located has been published by the New South Wales Premier's Department (25) based on the work of Swain and de Beuzeville, and by the Forestry Commission of N.S.W. (17) based on de Beuzeville. A homoclimatic classification system developed by Swain for determining agriculturally equivalent locations is used as a basis. The system uses rainfall characteristics and mean tempera-

tures of the hottest and coldest months. The western catchments are in an area with a 2 to 4 months seasonal drought, defined as a period with mean monthly rainfall less than 2 inches. Mean temperatures of the hottest and coldest months are in the ranges of over 72°F and 46-55°F respectively. The Hacking catchments are in a zone of no seasonal drought, and mean temperatures of the hottest and coldest months are less than 72°F and 46-55°F respectively.

Due to the breadth of the divisions in the above systems and their consideration of a limited number of factors, the climatic characteristics of the areas are rather inadequately defined by the classifications. A more complete description is therefore given in the following sections, where the various climatic elements are listed in some detail and discussed.

Where not otherwise specified, publications referred to in the following sections have been issued by the Bureau of Meteorology, Commonwealth of Australia.

4.2 Rainfall

As mentioned previously, the average annual rainfalls over the western and Hacking areas are of the order of 30 and over 50 inches respectively. However when quoting averages, the period over which they are taken must be specified, as the average at a given station can vary appreciably with the period considered. The World Meteorological Organisation has emphasised that for effective comparison of the climatic elements of different locations, a standard period of 30 years should be adopted for the computation of average values. The current standard 30 year period used by the Bureau of Meteorology for rainfall averages is 1931-1960. Table VII lists average monthly and annual rainfalls over the 1931-1960 period for selected Bureau stations in the two areas from Ref. (12). These stations are shown on Figs. 2 and 3.

Average monthly and annual rainfalls for the previously adopted 30 year standard peirod of 1911-1940 have been published in

Ref. (8). Average annual isohyets for the two areas for this period are shown on Fig. 5, and are based on these data and unpublished data compiled by the Bureau of Meteorology. The isohyetal map is given for the 1911-1940 period and not the current standard period as more detailed data are available at present for the former, and the data have been checked for consistency.

In Table VIII, average monthly and annual rainfalls from Ref. (12) are given for the selected Bureau stations for the periods from the commencement of record at each station to the most recent Bureau analysis of the data ending at 1964. While the data in Table VIII should not be used for comparative purposes, they may be useful as giving averages at individual stations over the longest available period.

The average monthly and annual numbers of rain days for the 1931-1960 standard period are given in the second line for each station in Table VII. A rain day is defined as a day when 1 point or more of rain was recorded.

Annual rainfalls and numbers of rain days for Bureau stations up to 1944 have been published in Ref. (7), together with averages for the complete periods of record to 1944.

Monthly and seasonal distributions of rainfall over the catchment areas are evident from examination of Tables VII and VIII. The highest average rainfall for both areas occurs in late summer and autumn, and the lowest in late winter and spring, although rainfall in the latter seasons is still appreciable. On the average, about 60% of the annual rainfall on the western catchments occurs in the six months January to June, and 34% in the three months January to March. For the Hacking catchments, about 64% of the annual rainfall occurs in the six months January to June, and 33% in the three months January to March. February has the highest average monthly rainfall for both areas, and a secondary peak occurs in June. The average driest three months are July to September for the western catchments, where approximately 16% of the annual average rainfall occurs. For

the Hacking catchments, the three driest months are August to October, when 17% of the annual average occurs. However heavy rainfalls can occur at any time of the year. These high rainfalls are normally derived from maritime air masses brought in from the Pacific Ocean.

Cumulative frequency curves of all recorded annual rainfalls are shown on Fig. 6 for the Bureau stations of Minchinbury, Bringelly (Maryland) and Helensburgh. As the first two stations are located at the northern and southern ends of the western area, and Helensburgh is near the centre of the smaller Hacking area, these curves may be used to indicate the frequency characteristics of annual rainfalls for the catchment areas. The curves for Minchinbury and Bringelly (Maryland) on the western area are very similar. The period and length of record for each station are noted on Fig. 6. Minor irregularities have been smoothed in drawing the curves. Various frequency data of annual rainfalls at the stations taken from the curves are presented in Table IX. Frequency data for Bringelly (Maryland) and a number of other Bureau stations in the Sydney region are also included in Ref. (7).

4.3 Temperature

Long temperature records are not available for any stations within either of the catchment areas. However, records for a number of stations near the areas are included in Ref. (10), which gives averages for all Australian stations for the standard 30 year period 1911-1940. Average monthly and annual maximum and minimum daily temperatures are listed, together with average daily mean temperatures calculated as the means of the maximum and minimum values. Similar average values for the complete period of record to 1940 are given in Ref. (7). Monthly average 9 a.m. and 3 p.m. temperatures for some stations are also given in this reference. More recent data have not been published, but average values at all stations for the complete period of record to 1956 are available at the Bureau of Meteorology. As temperatures are much more consistent than rainfall, the values averaged over the different periods show very little variation, and normally agree to within $1^{\circ}F$ or better.

Average temperatures at a location are related to its elevation and distance from the coast. To illustrate the effect of elevation, average monthly and annual mean daily temperatures from Ref. (10) have been plotted against elevation in Fig. 7 for twelve stations near the catchments. These stations are listed in Table X with their elevations and latitudes and longitudes. Values from all stations within 30 seconds of latitude and longitude of the catchment boundaries have been used, these limits being chosen to maintain consistency of the data, as 1 degree change in latitude causes approximately $1^{o}F$ change in temperature. Although the maximum elevation of the catchments is only 1100 feet, use of data from stations with elevations up to 3500 feet was necessary to define the relationships.

The plotted average daily mean temperatures show consistent decreases with increasing altitudes with only a small scatter of points. Dashed trend lines have been fitted by eye, and agree closely with the widely used approximation of 1,000 feet increase in elevation corresponding to $3^{o}F$ decrease in temperature. This decrease could have an appreciable effect in studies involving mean temperatures, such as evapotranspiration estimates and agricultural studies, especially in the Hacking area which is considerably higher than the surrounding Bureau stations.

Plotting of the values illustrated the moderating effect of the ocean on temperatures at locations close to the coast. Average daily mean temperatures at these stations were lower in summer and higher in winter than stations further from the coast but at the same elevation. The range of temperatures is thus less for the Hacking catchments near the coast than for the western catchments. The relatively large scatter of plotted points on Fig. 7 at low elevations is due to the effect of the ocean.

Differences in the range of temperatures for locations close to and away from the coast are more marked when average daily maximum and minimum temperatures are considered. Daily mean temperatures are more consistent, and for this reason were used in Fig. 7.

Values of average monthly and annual mean daily temperatures for the two catchment areas can be read from Fig. 7. To indicate the order of average daily maximum and minimum temperatures over the areas, values for surrounding stations are listed in Table XI. These are taken from Ref. (10), and are for the standard 30 year period 1911-1940 except where records for some years are missing, as noted in the Table. However, correction for elevation would be necessary in applying these values.

4.4 Humidity

Monthly and annual values of the average index of mean relative humidity for the standard 30 year period 1911-1940 are published in Ref. (10) for Bureau of Meteorology stations. This index is defined as the ratio of the average 9 a.m. vapour pressure to the saturation vapour pressure at the average mean temperature. Being thus related to the mean temperature, this value of relative humidity is claimed to be a good approximation to the daily mean. Also, little diurnal variation in vapour pressure has been found for stations near the coast, so that the index should give a good approximation to daily means for the catchment areas.

No records are available for stations within the catchments, but monthly and annual average values from Ref. (10) for stations in the surrounding area are listed in Table XI. Average 9 a.m. and 3 p.m. relative humidities are also given in Ref. (7) for Sydney and Wollongong for the total periods of record to 1940. Values for 9 a.m. only are also given for Parramatta and Richmond.

4.5 Evaporation

All evaporimeter stations in Australia as at October 1969 are listed in Ref. (13), and data from many of these stations are summarised by Hounam (20). Only reliable records from Sunken Tank (Australian Standard Tank) type evaporimeters are included in the latter publication, as results from different types of tanks or

different exposures cannot be compared. However, it should be noted that the standard instrument for measuring evaporation by the Commonwealth Bureau of Meteorology was changed to the Class "A" Pan evaporimeter in July 1968. Average monthly and annual evaporation figures from Ref. (20) are listed in Table XII for four stations near the catchment areas. Prospect is near the eastern boundary of the northern end of the western catchments, and thus gives an indication of evaporation in this area. Cataract Reservoir and Cataract River are approximately 10 miles west-south-west of the southern end of the Hacking catchments, and Sydney is 20 miles to the north of the area. Average evaporation for the Hacking catchments may be inferred from the values at these stations, but the effect of elevation should be recognised.

There is a strong tendency for an excess of potential evaporation over rainfall during spring and summer in both areas and this is a limiting factor on the growth of vegetation and pasture, particularly on the western catchments.

A series of small scale maps of average monthly and annual evaporation covering the whole of Australia has also been published (11). These maps are based on the Australian standard tank measurements published by Hounam.

4.6 Sunshine

A set of sunshine maps of Australia (9) is available giving isohels of average monthly and annual total hours of sunshine. These are based on an empirical relationship between available sunshine records and mean cloud amount observed at 9 a.m. and 3 p.m. Average monthly and annual total hours of sunshine for the western and Hacking areas read from these maps are listed in Table XIII.

4.7 Cloudiness

Data on monthly cloudiness at 9 a.m., 3 p.m. and 9 p.m. for the period of record to 1945 at Sydney are given in Ref. (7), and

these data should apply closely to both catchment areas.

4.8 Solar Radiation

Values of net solar radiation are necessary for estimating evapotranspiration by the Penman type approach and for other studies. A method for estimating solar radiation over Australia has been published by Hounam (21). This method, regarded only as an interim one, is based on records of less than 10 years from an Australia-wide network of six Robitzsch actinometers. The equation used for total radiation Q received at the earth's surface is of the modified Ångstrom form

$$Q/Q_A = a + b \cdot n/N$$

where

Q_A = the radiation received on a horizontal surface at the top of the atmosphere

n = actual duration of sunshine

N = maximum possible duration of sunshine

a and b = constants.

Using the actinometer records, monthly and annual values were found for the linear regression coefficients "a" and "b" for the whole of Australia. The range of monthly values was small, and in view of the small sample of data, Hounam recommended that for the present the annual relationship be adopted for each monthly value as well. The relationship for estimating radiation over Australia then is:

$$Q/Q_A = 0.26 + 0.50\ n/N\ .$$

Outgoing radiation is estimated by the Brunt type equation and net radiation is obtained using a universal albedo of 0.23.

Hounam published maps of net radiation over Australia for January and July based on his method. Values of average radiation from these maps for each of the catchment areas are 315 cal./sq.cm./day for January and 45 cal./sq.cm./day for July. Values for each

month for any point on the catchments could be calculated using average temperature corresponding to the required elevation from Fig. 7, sunshine hours from Table XIII, maximum possible sunshine hours from the Smithsonian Tables (23), and mean surface vapour pressure derived from the average indices of mean relative humidity in Table XI. However, great accuracy of calculation does not appear warranted in view of the interim nature of the method.

4.9 Wind

No wind data are available for stations within the catchments, but various data have been published for Sydney, and these should apply fairly closely to the catchment areas. Ref. (7) gives monthly wind data for Sydney for the period of record to 1945. Monthly 9 a.m. and 3 p.m. wind roses are given in Ref. (14), and prevailing directions are shown to be west for both 9 a.m. and 3 p.m. in the winter months and west for 9 a.m. and north-east for 3 p.m. for most of the remainder of the year. However, the influence of sea breezes on the 3 p.m. prevailing direction would not be as marked on the western catchments as at Sydney and on the Hacking catchments.

4.10 Frosts

Data on frosts are given by Foley (16).

5. MAP COVERAGE

The catchment areas are well covered by topographic maps. One mile series military maps with a scale of 1 mile to 1 inch and contour interval of 50 feet are available, and 1:25,000 series maps having a scale of approximately 0.4 miles to 1 inch and contour interval of 25 feet are also available for the South Creek and Mt. Vernon Creek catchments. As the military maps were inadequate for the rugged Hacking catchment, a special map of the area was compiled by the School of Surveying of the University. This map was drawn by photogrammetric methods using R.A.A.F. photographs taken from 16,000

feet altitude, and is to a scale of 1,000 feet to 1 inch and has a contour interval of 25 feet. A reproduction of this map is shown in Fig. 4. A tourist map of the Port Hacking District prepared by the N.S.W. Department of Lands also gives a useful qualitative coverage of the Hacking area.

Large-scale aerial photographs of the areas are also available from the N.S.W. Department of Lands. New series of photographs are taken at intervals of about five years. The three most recent series covering most of the period of record were flown in 1961, 1965 and 1970, with scales varying from 16 to 25.3 chains to one inch. The Department of Lands has also produced photomaps with a scale of 20 chains to one inch, made up as mosaics of aerial photographs flown in 1955-56. These cover the western catchments and the northern third of the Hacking catchments, but are not available for the remainder of the area. New photomaps of the entire area are being prepared by the Department of Lands from the 1970 series aerial photographs.

Detailed topographic maps have been prepared by the Hydrology Section of the two smallest catchments, Badgerys Creek Flume and Research Creek. The map of the latter was based partly on large-scale photogrammetric maps of the western fringe of the Hacking catchments prepared by the N.S.W. Department of Main Roads for highway reconstruction.

A summary of the various topographic maps and aerial photographs available for the catchments is given in Table XIV.

Geological and soil maps are also available for the areas in which the catchments are located, as has been previously described in Sections 3.2 and 3.4.

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TABLE I - Characteristics of Individual Catchments

Catchment	Area - Sq. Miles	Length of Main Channel L-Miles	Elevation Diff. - Divide at Head of Main Channel to Gauge. H-Feet	Slope of Main Channel H/L - %	Approx. Average Overland Slope. - %
Western:-					
South Ck at Mulgoa Road	34.6	14.2	400	0.5	3
Eastern Ck at Gt. Western Hwy	9.6	5.8	300	1.0	3
Mt. Vernon Ck	0.27	0.6	175	5.6	8
Badgerys Ck Flume	0.025	No Natural Channel			6
Hacking:-					
Hacking R. at Upper Causeway	15.5	11.1	1025	1.8	14
Cawleys Ck at Lower Cawleys	2.13	3.4	880	5.0	12
Cawleys Ck at Railway	1.02	1.4	450	6.3	10
Research Ck	0.15	0.5	185	7.1	10
Hacking R. at Ferndale	8.7	8.3	1000	2.3	14
Boora Ck	0.36	1.0	780	14.8	30
Hacking R. at Otford	3.1	3.8	810	4.0	12
Kellys Ck	0.98	1.7	370	4.1	8
Gills Ck	0.33	0.8	260	6.2	7

TABLE II - Instrumentation At Gauging Stations

Catchment and Station	Aust. Water Resources Council Number	Military Map Coordinates *	Type of Water Level Recorder	Float or Pressure Type	Period of Records
Western:-					
South Ck at Mulgoa Road					
- Bridge	212320	765148	Bristol (0-20')	Pressure	10/55 - Present
- Weir	212321	765149	Bristol (0-6')	Pressure	10/66 - Present
	212321	765149	Negretti & Zambra (0-20')	Pressure	9/65 - Present
Eastern Ck at Gt. Western Hwy	212340	860251	Bristol (0-20')	Pressure	2/57 - Present
	212340	860250	Bristol (0-6')	Pressure	3/69 - Present
Mt. Vernon Ck	212333	805144	Bristol (0-6')	Pressure	3/56 - Present
Badgerys Ck Flume	212330	740156	Leupold & Stevens 2A35 Duplex	Float	12/56 - 6/71
Hacking:-					
Hacking R. at Upper Causeway	214340	029812	Bristol (0-10')	Pressure	5/61 - Present
	214340	029812	Bristol (0-20')	Pressure	7/68 - Present
Cawleys Ck at Lower Cawleys	214334	012795	Leupold & Stevens A35	Float	7/61 - Present
Cawleys Ck at Railway	214333	987800	Leupold & Stevens A35	Float	6/61 - 10/71
Research Ck	214330	987804	Leupold & Stevens A35	Float	3/61 - 12/70
	214330	987804	Bristol (0-6')	Pressure	2/63 - 12/70
Hacking R. at Ferndale	214324	022782	Bristol (0-20')	Pressure	1/61 - 11/69
Boora Ck	214320	026780	Ott	Float	9/62 - 9/69
	214320	026780	Leupold & Stevens A35	Float	9/69 - Present
Hacking R. at Otford	214314	005743	Bristol (0-20')	Pressure	4/61 - Present
Kellys Ck	214310	979740	Bristol (0-10')	Pressure	4/61 - Present
Kellys Weir	214311	979741	Leupold & Stevens Type F	Float	7/68 - Present
Gills Ck	214312	973747	Leupold & Stevens 2A35 Duplex	Float	10/65 - Present

* Liverpool, Camden and Port Hacking 1 Mile to 1 Inch Military Map Coordinates.

TABLE III - Pluviograph Stations on Western Catchments

Station	Reference Number On Fig. 2	Military Map Co-ordinates *	Instrument Type	Period of Record
Narellan	1	763978	Mort	10/55 - Present
Pondicherry	2	735015	Casella (Natural Siphon) Mort	5/56 - 12/64 12/64 - Present
Kelvin	3	742094	Casella (Natural Siphon)	5/56 - Present
Kelvin	4	742094	Mort	8/70 - Present
Badgerys Creek No. 1	5	740160	Mort	2/54 - Present
Badgerys Creek (Intensity Recorder)	6	740160	D.S.I.R.	12/56 - 12/67
Badgerys Creek No. 2	7	740160	Mort	12/67 - Present
Mt. Vernon	8	816150	Casella (Dines Tilting Siphon)	3/56 - Present
Watertower	9	849177	Mort	2/59 - Present
Horsley	10	832196	Mort	2/59 - 2/62
Eastern Creek	11	858250	Mort	2/57 - Present

* Liverpool and Camden 1 Mile to 1 Inch Military Map Co-ordinates.

TABLE IV - Daily-Read Rain Gauges on Western Catchments

Station	Reference Number On Fig. 2	Military Map Co-ordinates *	Period of Record
Blairmount	21	798940	1/56 - 1/65
Marist Brothers	22	785949	1/59 - 12/64
Studley Park	23	722939	8/64 - Present
Harrington Park No. 1	24	740969	1/56 - Present
Harrington Park No. 2	25	777992	7/65 - Present
Narellan	26	763978	3/56 - 1/63
Springfield	27	767992	1/57 - 2/59
Gledswood	28	782992	1/57 - Present
Pondicherry	29	735014	2/57 - Present
Bringelly (Maryland) (C.B.M.)	30	721034	1867 - Present
Noonoora	31	735036	1/56 - 10/64
Wyld	32	806034	1/56 - Present
Romney	33	741050	1/56 - 12/58
Newstead	34	717054	1/56 - Present
Rossmore School	35	768062	5/60 - 9/62
Bringelly P.O.	36	729069	10/65 - 12/66
Kelvin	37	742095	2/57 - Present
Shepherd	38	700107	9/57 - 2/63
Crosby	39	758120	1/56 - Present
Clarke	40	784112	3/59 - 4/64
Neville	41	737127	1/56 - 7/57
Barber	42	774146	1/56 - 11/65
Kemps Creek School	43	789142	3/59 - Present
Badgerys Creek (C.B.M.)	44	735156	1919 - 1928; 1936 - Present
Mt. Vernon	45	816149	1/59 - 1/60
Horsley	46	832196	5/62 - 2/71; 6/71 - Present
Moultspiers	47	845190	8/59 - 5/63
Thomas	48	858197	2/57 - 6/59
Redmayne	49	868193	7/71 - Present
Davis	50	856205	2/57 - 2/59
Prospect Dam (C.B.M.)	51	911211	1887 - Present
Dobson	52	864228	5/71 - Present
Poole	53	868228	3/57 - 11/70
Southridge	54	839225	1/59 - 7/60
Masters	55	852244	5/60 - 9/65
Eastern Creek	56	860251	7/57 - 6/62
Minchinbury (C.B.M.)	57	834252	1903 - Present

* Liverpool and Camden 1 Mile to 1 Inch Military Map Co-ordinates.

TABLE V - Pluviograph Stations on Hacking Catchments

Station	Reference Number On Fig. 3	Military Map Co-ordinates *	Instrument Type	Period of Record
Research Creek No. 1	1	984808	Mort	8/62 - Present
Research Creek No. 2	2	987808	Mort	9/68 - 6/70
Research Creek No. 3	3	984802	Mort	10/68 - Present
Upper Cawleys	4	987804	Negretti Zambra	1/63 - 12/66
Waterfall Hospital	5	972798	Mort	6/61 - Present
Lower Cawleys	6	012795	Casella (Dines Tilting Siphon)	9/69 - Present
Garrawarra	7	039775	Mort	1/61 - Present
Telosa	8	015776	Mort	1/61 - Present
Gills Creek	9	973747	Mort	8/61 - Present
Gills Creek Duplex	10	973747	Leupold & Stevens 2A35 Duplex	10/65 - Present

* Port Hacking and Camden 1 Mile to 1 Inch Military Map Co-ordinates.

TABLE VI - Daily-Read Rain Gauges on Hacking Catchments

Station	Reference Number On Figure	Military Map Co-ordinates *	Period of Record
Waterfall Home (C.B.M.)	11	972798	1907 - Present
Helensburgh (C.B.M.)	12	990880	1889 - Present
Otford No. 1	13	000741	5/62 - Present
Bald Hill	14	995726	5/62 - Present
Otford No. 2	15	010743	3/67 - Present
Waterfall	16	995835	12/61 - Present
Helensburgh (Coffee)	17	990880	5/62 - 6/63
Gills Creek	18	973748	10/61 - Present
Illawarra	19	939693	3/67 - Present
Telosa (Weekly)	20	015777	3/61 - Present

* Port Hacking and Camden 1 Mile to 1 Inch Military Map Co-ordinates.

TABLE VII - Average Monthly and Annual Rainfalls and Rain Days
(One Point or More) at Selected Bureau of Meteorology Stations.
Standard 30 Year Period 1931-1960

1st line - Rainfall in Points 2nd line - Number of Rain Days

Station	Approx. Elevation - Feet	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Western Catchments:-														
Minchinbury	150	344 5	426 6	333 6	265 6	258 5	311 5	185 4	165 5	179 5	234 5	257 6	298 6	3255 64
Prospect Dam	190	377 10	426 10	357 10	283 9	290 8	348 9	210 7	196 8	190 9	241 9	268 9	271 9	3457 107
Bringelly (Maryland)	420	346 8	367 8	310 8	243 7	242 6	281 6	178 5	153 6	164 7	215 7	261 7	259 7	3019 82
Camden	222	363 8	404 8	303 9	258 7	252 6	268 7	179 6	146 6	166 7	217 8	269 8	268 7	3093 87
Brownlow Hill	305	354 6	380 7	302 7	239 6	243 5	264 6	155 4	134 5	151 6	216 6	241 6	251 7	2930 71
Cobbity	200	341 8	395 9	308 9	215 8	265 7	255 7	167 7	149 7	170 8	213 9	254 8	261 8	2993 95
Hacking Catchments:-														
Helensburgh	600	572 7	707 8	683 8	517 7	615 7	697 7	366 5	306 5	349 6	348 6	368 7	345 6	5873 79
Waterfall Home	930	509 8	617 8	572 9	442 8	489 6	607 7	337 6	300 6	302 6	308 7	310 8	333 7	5126 86
Woronora Dam	660	415 10	507 11	419 11	364 10	412 9	541 9	294 8	259 8	240 9	311 9	280 9	295 9	4337 112

TABLE VIII - Average Monthly and Annual Rainfalls at Selected Bureau of Meteorology Stations. Commencement of Record to Most Recent Analysis (1964)

Station	Bur. of Met. Identification No.	Period of Record	Number of Years	Average Monthly Rainfall - Points												Average Annual Rainfall - Points
				Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Western Catchments:-																
Minchinbury	67016	1903-1964	62	315	330	320	270	255	268	231	160	161	214	238	322	3084
Prospect Dam	67019	1887-1964	78	354	343	365	295	300	314	264	200	189	219	254	311	3408
Bringelly (Maryland)	67015	1867-1964	98	318	313	311	278	259	261	209	163	182	211	249	260	3014
Camden	68011	1883-1964	81	339	297	320	271	237	277	236	169	155	200	247	285	3033
Brownlow Hill	68007	1882-1964	82	343	296	316	249	227	252	198	155	154	202	232	275	2899
Hacking Catchments:-																
Helensburgh	68028	1889-1964	75	545	599	677	571	593	624	470	356	324	324	368	424	5875
Waterfall Home	68063	1907-1964	56	506	504	530	520	553	556	411	300	289	290	331	424	5214
Woronora Dam	68070	1927-1964	37	410	514	431	386	424	580	284	293	235	305	307	329	4498

TABLE IX - Frequency Data of Annual Rainfalls at Selected Bureau of Meteorology Stations

Station	Period of Record	Number of Years	Annual Rainfall - Inches						
			Median (Nearest 0.5in.)	Maximum (All in 1950)	Minimum (Year of occurrence)	Quartiles (Nearest 0.5in.)		Deciles (Nearest 0.5in.)	
						Upper	Lower	Upper	Lower
Minchinbury	1903-1965	63	30.0	81.03	11.88 (1944)	37.0	22.5	42.5	18.0
Bringelly (Maryland)	1867-1970	104	28.0	66.92	12.80 (1944)	36.0	23.5	43.0	20.0
Helensburgh	1890-1970	81	56.5	140.86	25.98 (1968)	68.0	45.5	82.0	36.5

TABLE X - Commonwealth Bureau of Meteorology

Climatological Stations

Latitudes 33° 30' to 34° 30', Longitudes east of 150° 15'

Station	Elevation - Feet	Latitude S	Longitude E
Bowral	2171	34° 28'	150° 26'
Centennial Park	150	33° 54'	151° 15'
Katoomba	3349	33° 38'	150° 18'
Manly	50	33° 48'	150° 42'
Mount Victoria	3490	33° 36'	150° 15'
Parramatta	169	33° 49'	151° 00'
Pennant Hills	538	33° 42'	151° 06'
Picton	552	34° 10'	150° 36'
Richmond (Agric. Coll.)	73	33° 36'	150° 44'
Riverview	71	33° 50'	151° 10'
Sydney	138	33° 51'	151° 13'
Wollongong	33	34° 25'	150° 56'

TABLE XI - Average Temperatures and Humidities from Ref. (10).
Standard 30 Year Period 1911-1940

Line 1 - Average Daily Max. Temperature. Line 2 - Average Daily Min. Temperature
Line 3 - Average Daily Mean Temperature ($\frac{\text{Line 1 + Line 2}}{2}$). Line 4 - Average Index of Mean Relative Humidity

Station	Item	No. of Years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Western Region															
Parramatta	1	24	83.2	82.3	79.9	74.7	69.0	64.0	62.7	66.2	71.3	75.4	78.8	82.1	74.1
	2	24	62.1	61.4	58.4	52.6	46.7	42.0	40.5	41.6	46.3	51.5	56.3	60.4	51.7
	3	24	72.7	71.9	69.1	63.7	57.9	53.0	51.6	53.9	58.8	63.5	67.5	71.3	62.9
	4	24	67	70	71	72	73	67	70	67	65	64	64	64	68
Richmond (Agric. Coll.)	1	30	85.0	85.1	81.0	74.4	68.4	63.5	62.8	66.2	72.1	77.3	81.2	84.2	75.1
	2	30	61.8	61.9	58.5	52.3	45.1	39.5	38.2	39.7	44.6	50.7	55.6	59.8	50.6
	3	30	73.4	73.5	69.7	63.4	56.8	51.5	50.5	52.9	58.4	64.0	68.4	72.0	62.9
	4	30	68	70	73	76	76	73	70	71	69	67	66	67	70
Picton	1	30	85.0	84.6	81.2	74.5	68.6	63.2	62.3	65.3	70.9	76.1	79.9	83.3	74.6
	2	30	59.8	59.9	56.0	49.5	42.6	37.5	36.1	37.5	41.8	48.1	53.3	58.0	48.3
	3	30	72.4	72.2	68.6	62.0	55.6	50.4	49.2	51.4	56.4	62.1	66.6	70.6	61.5
Hacking Region															
Sydney	1	30	78.6	78.7	76.6	72.0	67.0	62.8	61.8	64.3	68.3	71.7	74.5	76.9	71.1
	2	30	65.1	65.5	62.9	57.7	52.4	48.1	46.4	47.6	51.4	55.9	59.8	63.2	56.3
	3	30	71.8	72.1	69.8	64.9	59.7	55.5	54.1	56.0	59.9	63.8	67.1	70.1	63.7
	4	30	68	71	72	71	70	68	67	64	62	63	65	68	66
Wollongong	1	30	78.4	78.4	76.3	72.1	67.1	62.5	61.7	64.1	68.4	71.8	74.3	76.7	71.0
	2	30	62.6	63.1	60.9	56.4	51.9	48.3	47.1	47.7	50.7	54.1	57.3	60.8	55.1
	3	30	70.5	70.8	68.6	64.3	59.5	55.4	54.3	55.9	59.5	63.0	65.8	68.7	63.0
	4	31	78	78	78	75	73	72	71	70	71	74	75	79	75

TABLE XII - Average Monthly and Annual Evaporation at Selected Bureau of Meteorology Stations Near the Catchments. From Ref. (20)

Station	Elevation - Feet	Period of Reliable Record	No. of Years	Average Evaporation - Inches												
				Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Prospect	205	1893-1926	34	5.98	4.69	4.27	3.12	2.24	1.70	1.72	2.15	3.16	4.42	5.24	5.89	44.58
Sydney	138	1944-1959	16	5.03	3.77	3.54	2.82	2.11	1.58	1.54	2.10	2.66	4.02	4.87	5.33	39.37
Cataract Reservoir	960	1908-1938	31	4.32	3.76	3.21	1.99	1.31	0.87	0.83	1.17	1.95	3.19	3.90	4.39	30.89
Cataract River	490	1888-1942	55	4.94	3.94	3.39	2.35	1.58	1.16	1.23	1.70	2.48	3.41	4.18	4.99	35.35

TABLE XIII - Average Monthly and Annual Hours of Sunshine. From Ref. (9)

Region	Average Hours of Sunshine												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Western	250	210	210	195	190	175	195	210	225	245	245	250	2600
Hacking	240	210	205	200	200	175	195	215	230	240	240	250	2600

TABLE XIV - Topographic Maps Covering the Catchment Areas

Compiling Authority	Name of Map or Map Series	Scale Generally Referred to	Scale - Feet to 1 Inch	Representative Fraction	Contour Interval - Feet	Area to Which Map is Applicable
Royal Aust. Survey Corps.	Military Map, 1 Mile Series	1 Mile to 1 Inch	5280	1:63,360	50	All Catchments
Royal Aust. Survey Corps.	Military Map, 1:25,000 Series, Training Ed.	---	2083	1:25,000	25	South Creek and Mt. Vernon Creek
The University of New South Wales	Hacking River: Hydrologic Exptl. Catchment	---	1000	1:12,000	25	Hacking Catchments
Dept. of Lands	Tourist Map of the Port Hacking District	---	3960	1:47,520	--	Hacking Catchments
Dept. of Lands	Aerial Photos:					
	1961 Series	16 Chains to 1 Inch	1056	1:12,672	--	All Catchments
	1965 Series	25.3 Chains to 1 Inch	1670	1:20,040	--	All Catchments
	1970 Series	18.2 Chains to 1 Inch	1201	1:14,410	--	All Catchments
Dept. of Lands	Photomaps (Based on 1955-56 Aerial Photos)	20 Chains to 1 Inch (approx.)	1320 (approx.)	1:15,840 (approx.)	--	All except south part of Hacking Catchments
The University of New South Wales	Badgerys Creek Experimental Catchment	---	40	1:480	1	Badgerys Creek Flume
The University of New South Wales	Research Creek Catchment	---	200	1:2,400	25	Research Creek

APPENDIX A - GREAT SOIL GROUPS AND THEIR SERIES - AFTER WALKER (35)

Great Soil Group	Series	General Features	Remarks
Podsol	Commodore	Podsolisation minimal, organic A_1 and B horizons not well developed	Immature soil of sandstone detritus
Podsolic Lateritic	Pittwater	Well developed, deep A_1 hor., little or no A_2, bright red B hor. with abundant ironstone	Podsolic of laterite detritus
	Terrey	Shallow, sandy soil, narrow A_1 hor., no A_2, slight texture profile	Weakly podsolised soil of laterised shale and sandstone. Derived from weathered indurated zone
	Warrawee	Stony soil of indistinct A hor., drab brown heavy clay B hor.	Almost skeletal soil of laterised shale beds
	Warumbul	Almost peaty A hor., rusty mottled clayey B hor., water table at 30 inches, weathered sandstone C hor.	Upland swamp soil of deeply laterised sandstone
	Woronora	Deep A hor. well developed heavy clay B overlying mottled and indurated hor. Ironstone abundant throughout	Podsolic soil of laterised shale over sandstone

APPENDIX A (cont.)

Great Soil Group	Series	General Features	Remarks
Red Podsolic Soils	Cumberland	Deep clay loam A hor., heavy clay B hor., with grey weathered shale C hor.	Podsolic soil of Wianamatta shale
	Lilyvale	Deep highly organic A hor., A_2 absent, heavy clay B hor., profile stony throughout	Podsolic soil of Narrabeen chocolate shales
	Narrabeen	As for Lilyvale series	Podsolic of Narrabeen tuffaceous beds
Yellow Podsolic Soils	Austral	Narrow A_1 and A_2 hor., sharply defined heavy clay B hor., organic and iron enriched B hor.	Podsolic of present meadow landscape on Wianamatta, frequently wet throughout
	Birrilee	Shallow profile, deep A hor., little or no A_2 hor., texture rise gradual to sandy clay B hor., sandstone D hor.	Podsolic of mixed shell and sandstone of elevated coastal plateau
	Cowan	Narrow A hor., deep A_2 sharply defined clayey B hor., organic B absent or weak, massive sandstone D hor.	Mixed shale and sandstone soil of elevated coastal plateau

APPENDIX A (cont.)

Great Soil Group	Series	General Features	Remarks
Yellow Podsolic Soils (cont.)	Hammondville	Well developed A, bleached A_2, heavy clay organic and iron B hor., with sandstone at 42 to 48 inches	Podsolic of mixed shale and sandstone of elevated coastal plateau
	Warriewood	Well developed sandy A_1 and bleached A_2 hor., heavy clay iron and organic enriched B, some orstein in lower A_2 and upper B hor., profile deep	Podsolic of sandy material overlying weathered Narrabeen shale material
Red-brown Earths (non-calcareous)	Menangle	Well developed A hor., no A_2, well structured heavy clay B hor., lime usually absent	Soils of hilly regions of calcareous upper Wianamatta beds (well drained)
Solodic Soils	Glenlee	Well developed A_1 hor., weak A_2, domed heavy clay B hor., lime often present in deep subsoil	Soils of hilly regions of calcareous upper Wianamatta beds (poorly drained)
Skeletal Soils	Hawkesbury	Slight A_1 development, usually grey or yellow sandy solum, profile shallow and stony	Soils of the sandstone plateau

APPENDIX B - SOIL SERIES ASSOCIATIONS - AFTER WALKER (35)

Soil Series Associations	Soil Series Present
Western:-	
Austral	Austral
Cumberland	Cumberland, Austral, Warrawee
Menangle	Menangle, Glenlee, Cumberland
Hacking:-	
Hawkesbury - Warumbul	Hawkesbury, Warumbul, Birrilee, Hammondville, Cowan, Commodore, Warriewood
Woronora	Woronora, Terrey, Pittwater
Narrabeen	Narrabeen, Lilyvale

APPENDIX C - TYPICAL CATENARY RELATIONSHIPS - WESTERN CATCHMENTS

Association	Nature of Catena	Characteristic	Crest and Upper Slope Soils	Mid-Slope Soils	Slope Base Soils
Austral	Wianamatta shale (slope ½ mile long)	Series:	Austral	Austral	Austral
		Profile:	Medium	Deep	Deep
		Soil group:	Yellow podsolic	Yellow podsolic	Yellow podsolic
		Surface texture:	Loam	Loam	Loam
		Subsoil texture:	Heavy clay	Heavy clay	Heavy clay
Cumberland	Wianamatta shale (slope ¼-½ mile long)	Series:	Cumberland	Cumberland	Austral
		Profile:	Shallow	Deep	Deep
		Soil group:	Red podsolic	Red podsolic	Yellow podsolic
		Surface texture:	Stony, fine sandy clay loam	Fine sandy clay loam	Loam
		Subsoil texture:	Heavy clay	Heavy clay	Heavy clay
Menangle	Wianamatta grey-wacke sandstone - upper division (slope usually ¼ mile long)	Series:	Menangle	Menangle	Glenlee
		Profile:	Shallow, non calcareous	Deep, lime occasionally present	Deep, lime occasionally present
		Soil group:	Red-brown earth	Red-brown earth	Solodic
		Surface texture:	Clay loam	Clay loam	Fine sandy loam
		Subsoil texture:	Clay	Clay	Clay

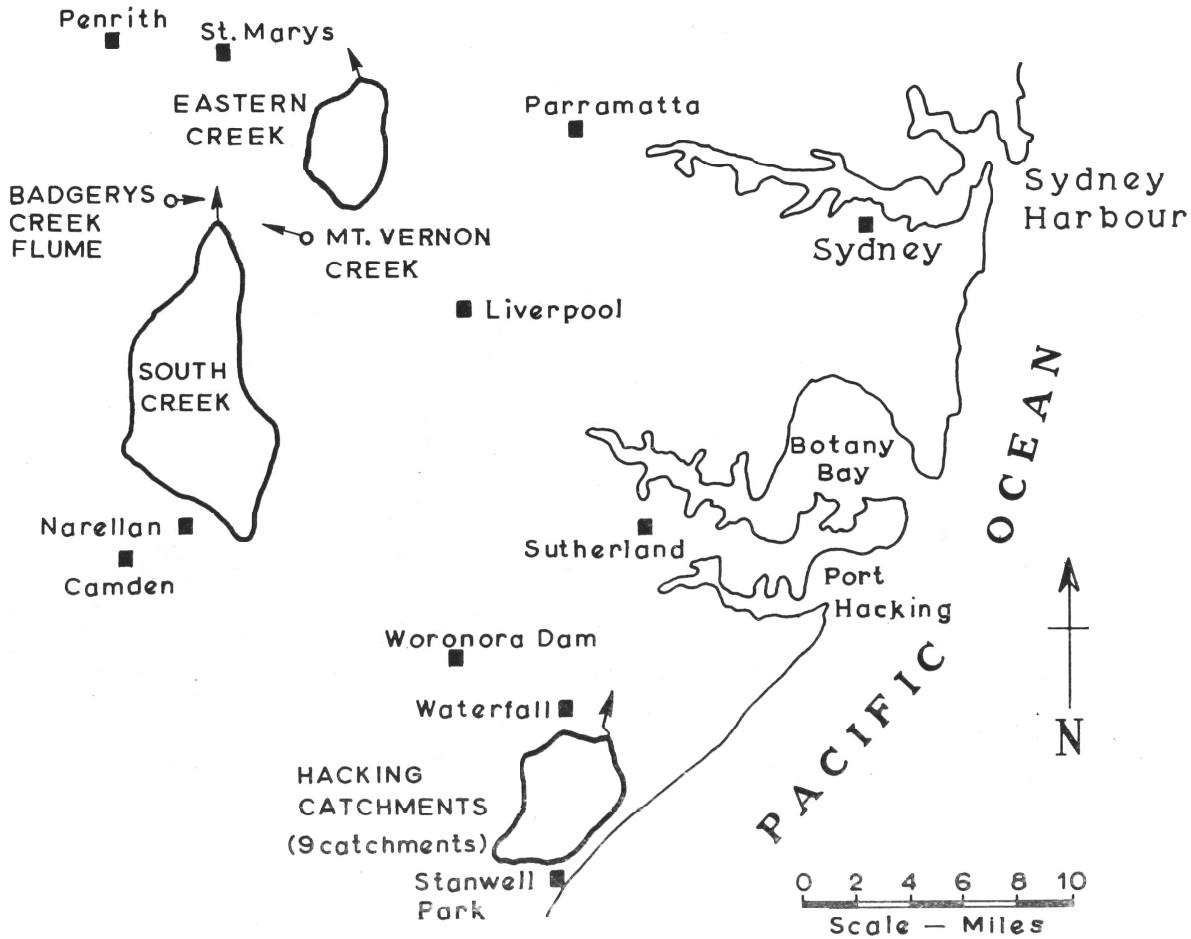
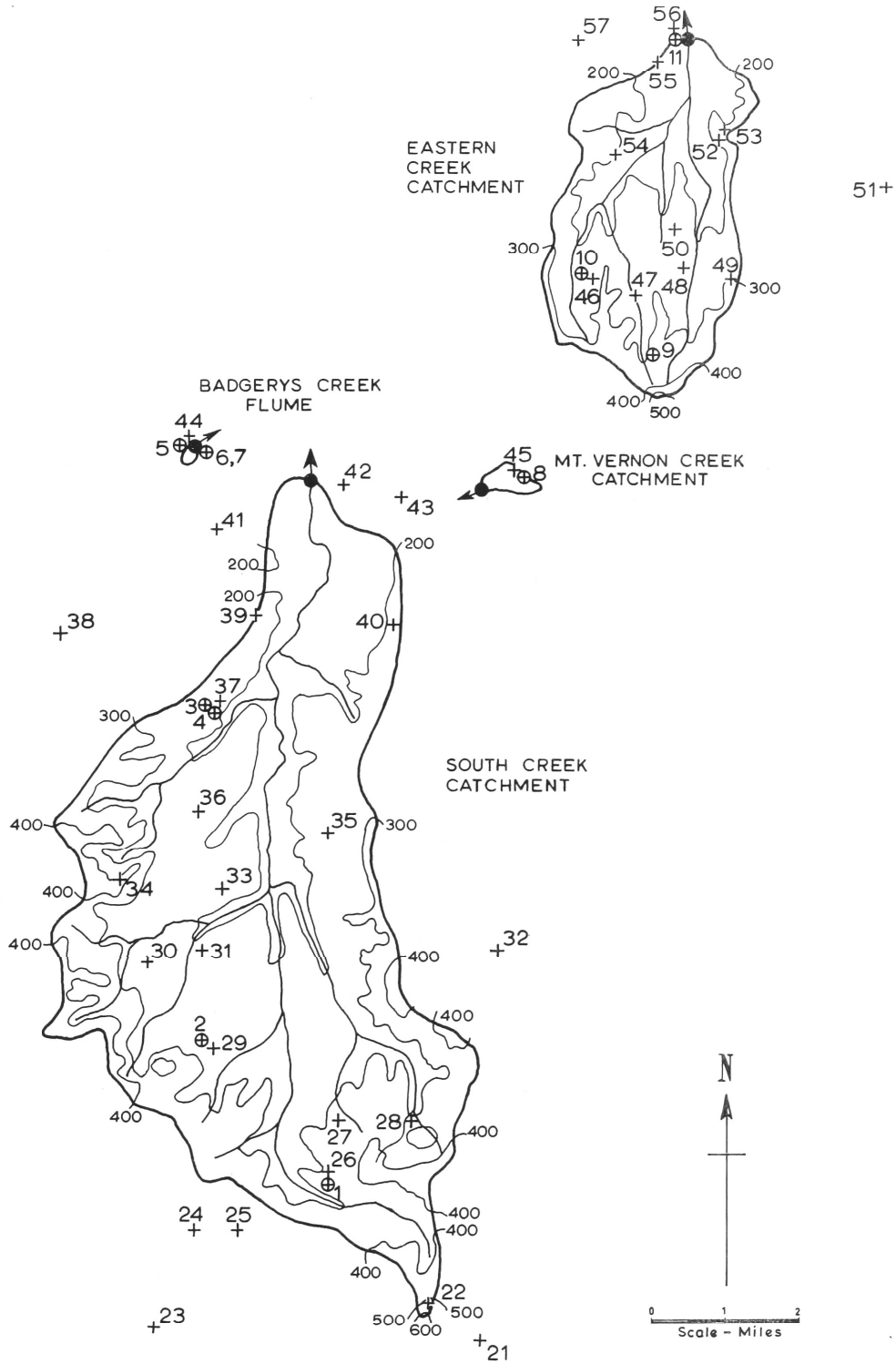


FIG. 1: LOCALITY MAP OF WESTERN AND HACKING EXPERIMENTAL CATCHMENTS OF THE UNIVERSITY OF NEW SOUTH WALES.

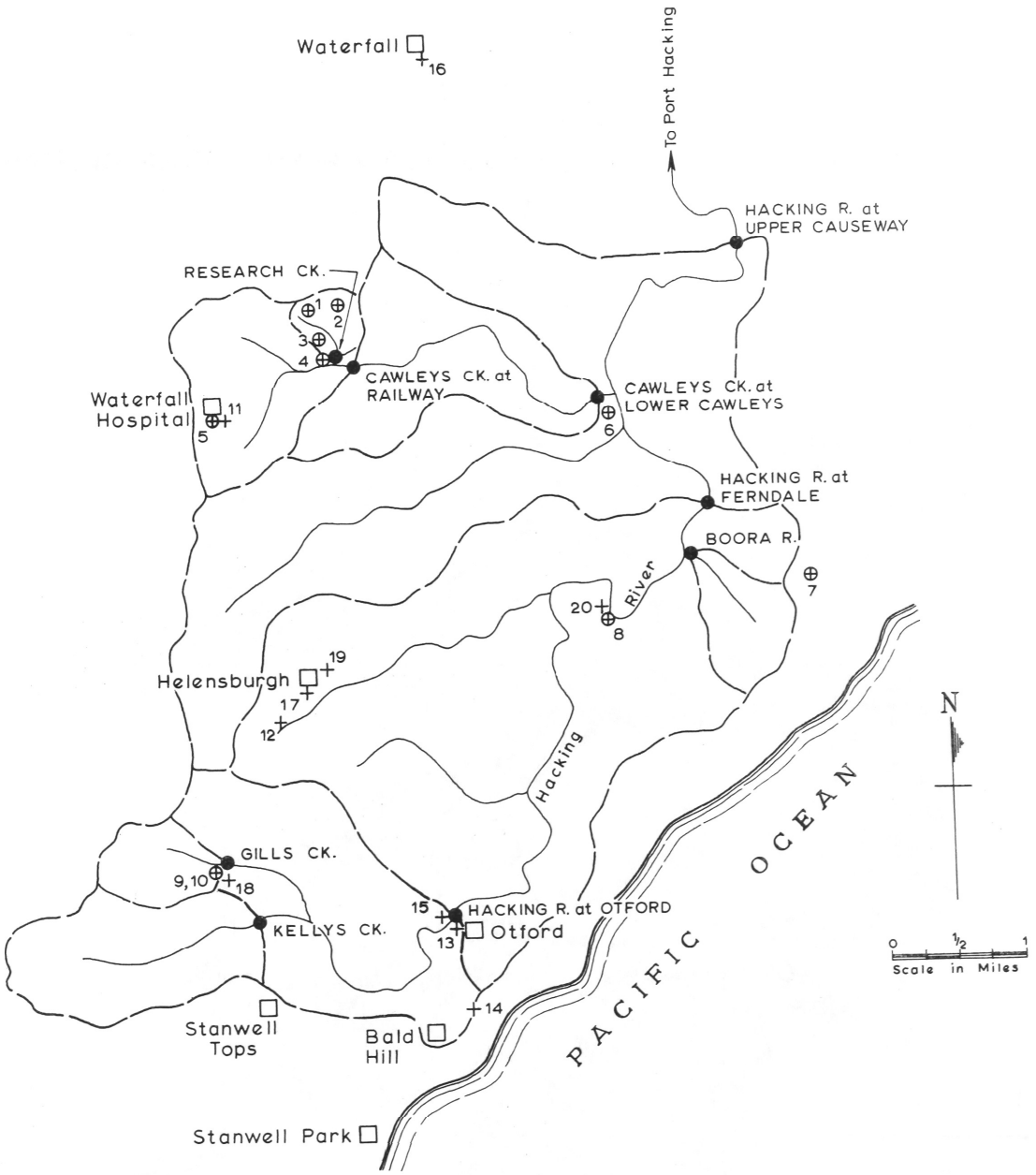


LEGEND:

⊕.....Pluviographs
+.....Daily rain gauges

Station names and details are listed in Tables III & IV

FIG. 2: WESTERN CATCHMENTS – RAIN GAUGES AND TOPOGRAPHY



LEGEND:

- Catchment Boundaries.
- Gauging Stations at Catchment Outlets.
- ⊕ Pluviographs.
- \+ Daily Rain Gauges.
- □ Towns or Villages.

PLUVIOGRAPHS.

1. Research Creek No. 1.
2. Research Creek No. 2.
3. Research Creek No. 3.
4. Upper Cawleys.
5. Waterfall (Hospitall.)
6. Lower Cawleys.
7. Garrawarra.
8. Telosa.
9. Gills Creek.
10. Gills Creek Duplex.

DAILY RAIN GAUGES.

11. Waterfall Home (C.B.M.)
12. Helensburgh (C.B.M.)
13. Otford 1
14. Bald Hill
15. Otford 2
16. Waterfall
17. Helensburgh (Coffee)
18. Gills Creek
19. Illawarra

WEEKLY RAIN GAUGES.

20. Telosa.

FIG. 3: HACKING CATCHMENTS.

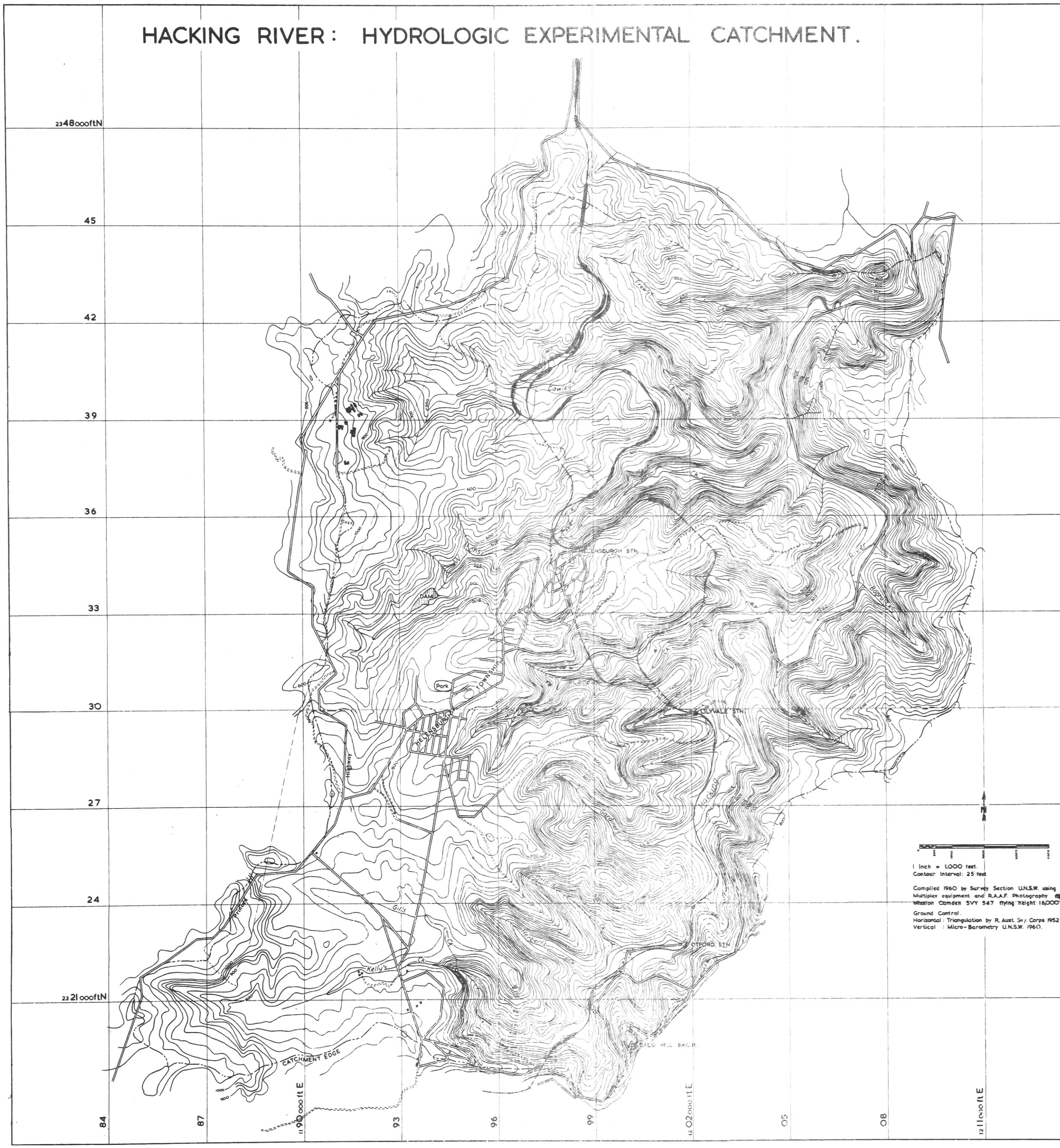
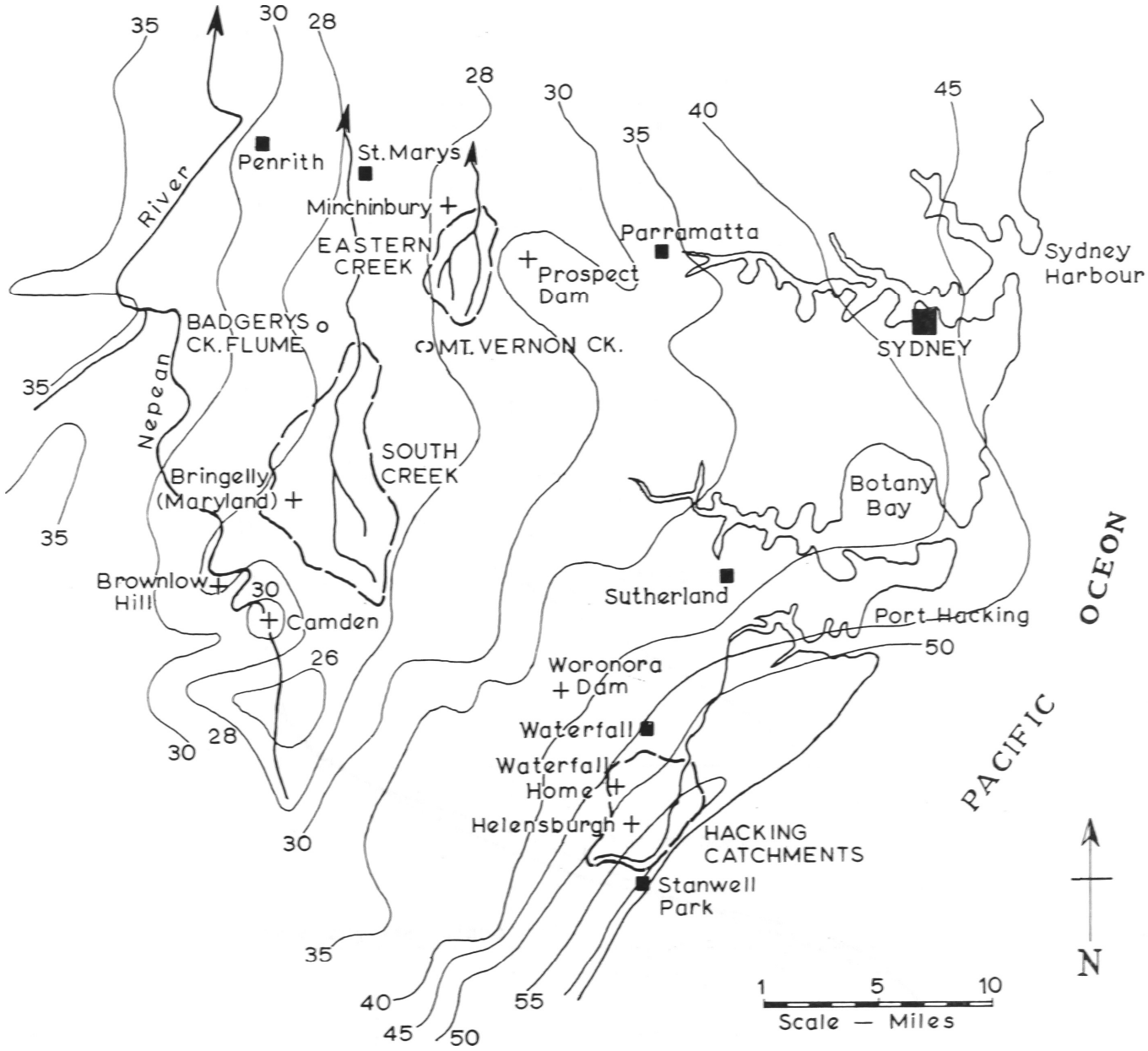

HACKING RIVER: HYDROLOGIC EXPERIMENTAL CATCHMENT.
23 48 000 ft N
45
42
39
36
33
30
27
24
23 21 000 ft N
84
87
11 90 000 ft E
93
96
99
12 02 000 ft E
05
08
12 11 000 ft E
Cowley's
HELENSBURGH STN.
DAM
Park
TOWNSHIP
HELENSBURGH
Highway
LILYVALE STN.
Gardiner's
Hacking
Gills
Kelly's
Ck.
OTFORD STN.
CATCHMENT EDGE
1 inch = 1,000 feet.
Contour interval: 25 feet
Compiled 1960 by Survey Section U.N.S.W. using
Multiplex equipment and R.A.A.F. Photography
Mission Camden SVY 547 flying height 16,000.
Ground Control.
Horizontal : Triangulation by R. Aust. Svy. Corps 1952.
Vertical : Micro-Barometry U.N.S.W. 1960.

FIGURE 4



LEGEND:—

+ ..... Rainfall Stations in Tables VII and VIII

□ ..... Towns.

FIG. 5: AVERAGE ANNUAL RAINFALL IN INCHES
– 1911 – 1940 STANDARD PERIOD.

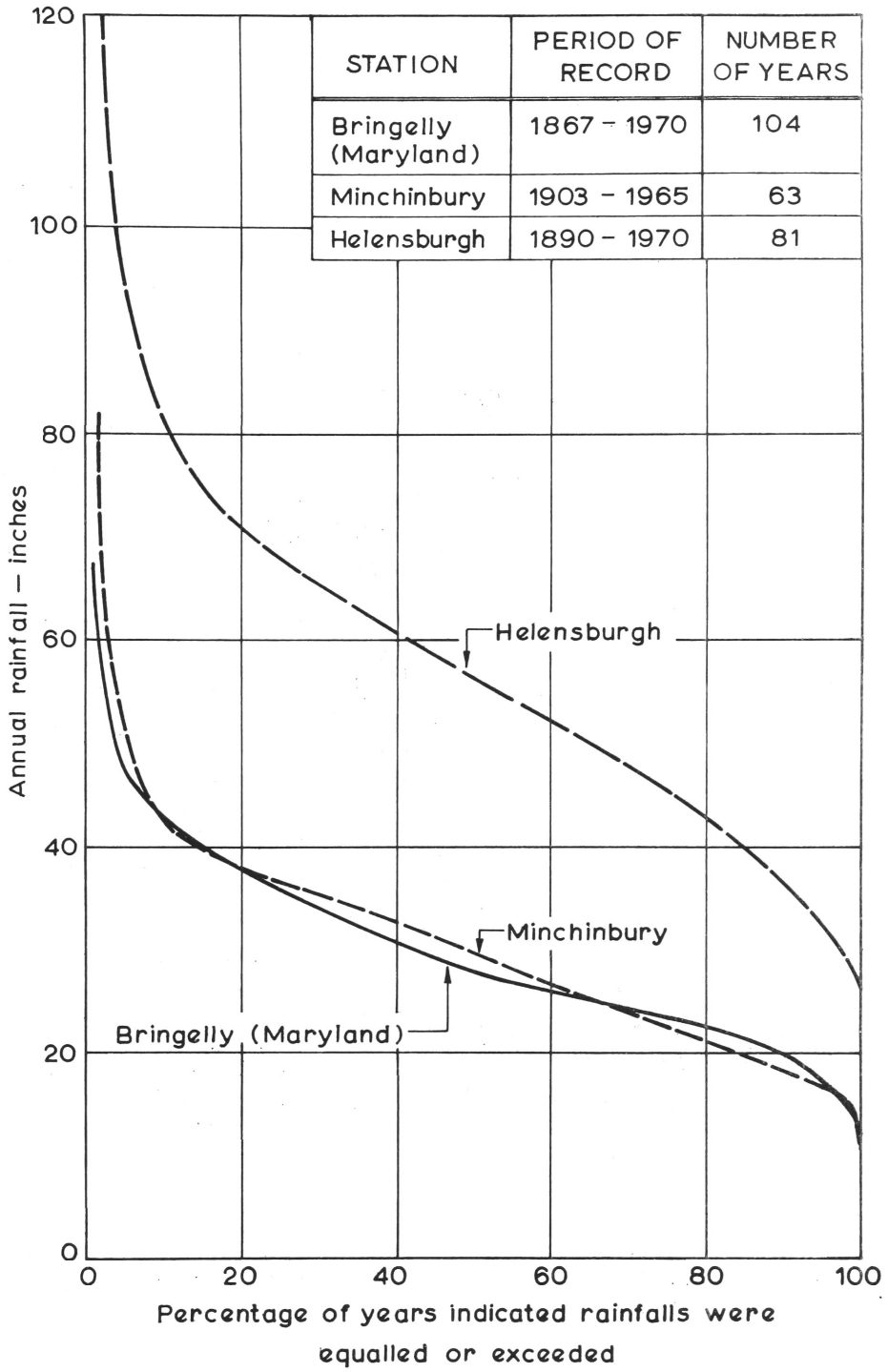


FIG. 6: CUMULATIVE FREQUENCY CURVES OF ANNUAL RAINFALL

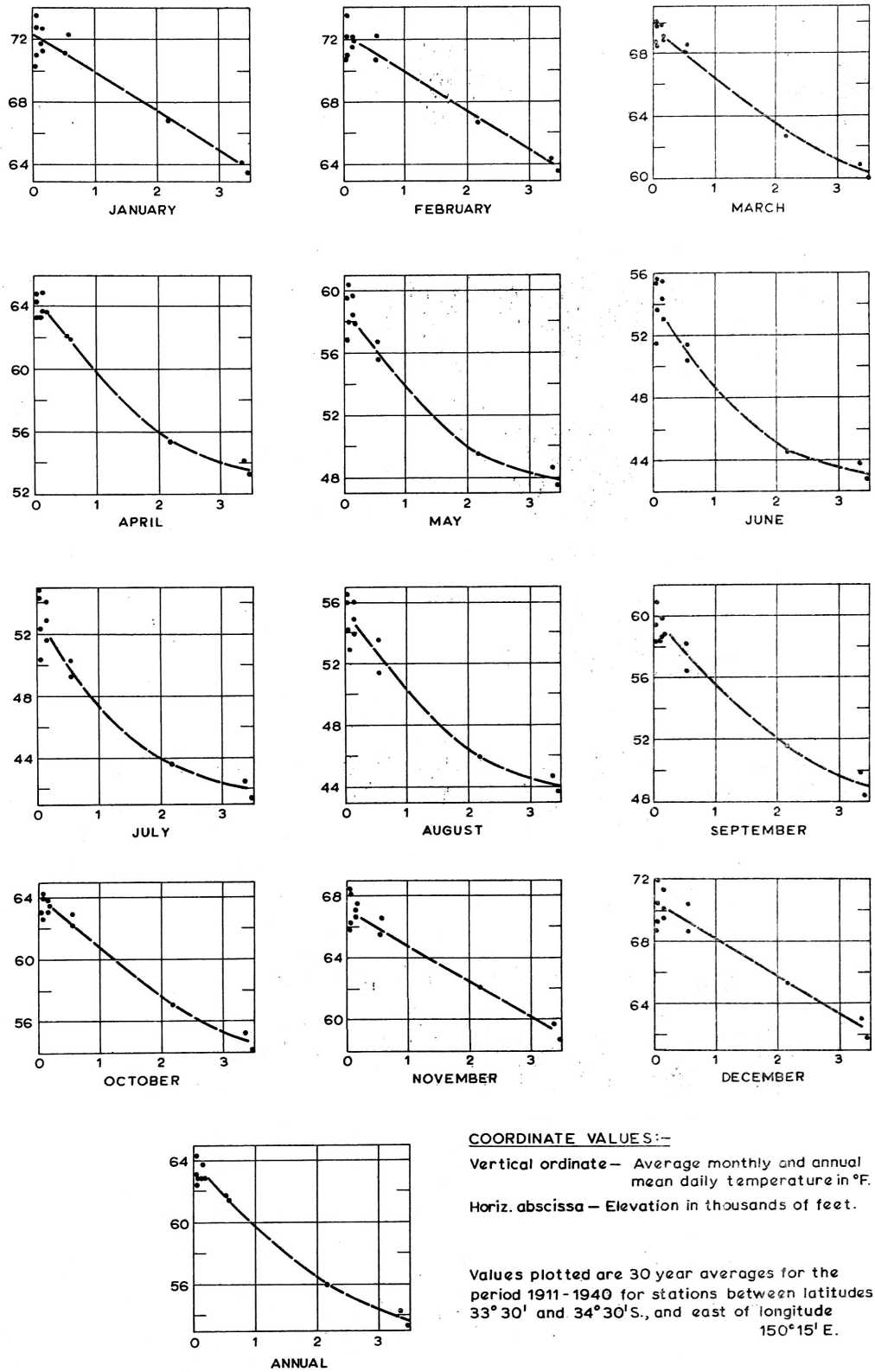


FIG. 7: RELATION BETWEEN ELEVATION AND AVERAGE MONTHLY AND ANNUAL MEAN DAILY TEMPERATURES.