# THE PHYSIOGRAPHIC AND CLIMATIC FACTORS CONTROLLING THE FLOODING OF THE HAWKESBURY RIVER AT WINDSOR.

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(*From the Department of Geography.*)

(Plate viii, and nine Text-figures.)

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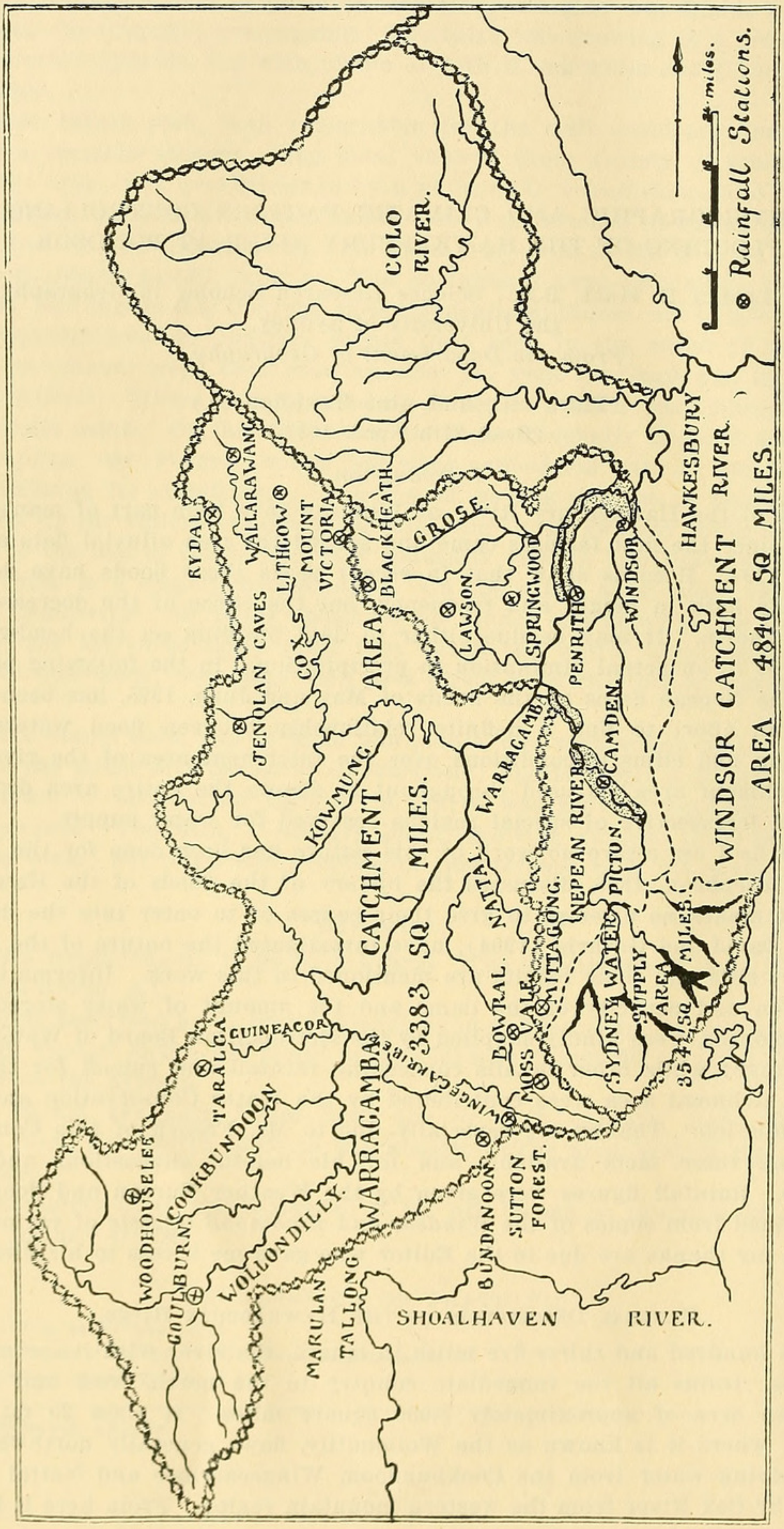
*Introduction.*

Floods of the Hawkesbury River at Windsor have been part of man's experience ever since the first farmers came and settled the rich alluvial flats along its banks in 1794. Records show that in recent years these floods have decreased considerably both in height and frequency, but the cause of the decrease is not definitely known. It may be due either to dam building on the headwaters of the river, or to an actual diminution in precipitation. In the following paper the effect of the Nepean dams on the floods of May and June, 1925, has been investigated in an effort to find a definite relationship between flood waters, water conservation and climatic conditions over the catchment area of the river. The term "catchment area" is used throughout to denote the entire area drained by the stream irrespective of special regions reserved for water supply.

So far as I am aware no work of this nature has been done for the Windsor district. Josephson, 1885, discusses the history of the floods of the Hawkesbury River, but makes no attempt to give their causes or to enter into the details of rainfall. David and Guthrie (1904), have investigated the nature of the Hawkesbury River silts and their results are mentioned in this work. Information as to the position and capacity of the dams and the amount of water stored during the flood months, were kindly supplied by the Metropolitan Board of Water Supply and Sewerage; while other details concerning rainfall and run-off for the whole Windsor catchment area were contributed by the Water Conservation and Irrigation Commission. Thanks are especially due to Mr. French of this Commission for making these facts available and for his helpful suggestions and kindly assistance. Rainfall figures were given by the Weather Bureau and flood details were obtained from copies of the *Windsor and Richmond Gazette* of various dates, for which my thanks are due to the Editor who gave me access to his files.

## General Description of the Hawkesbury River.

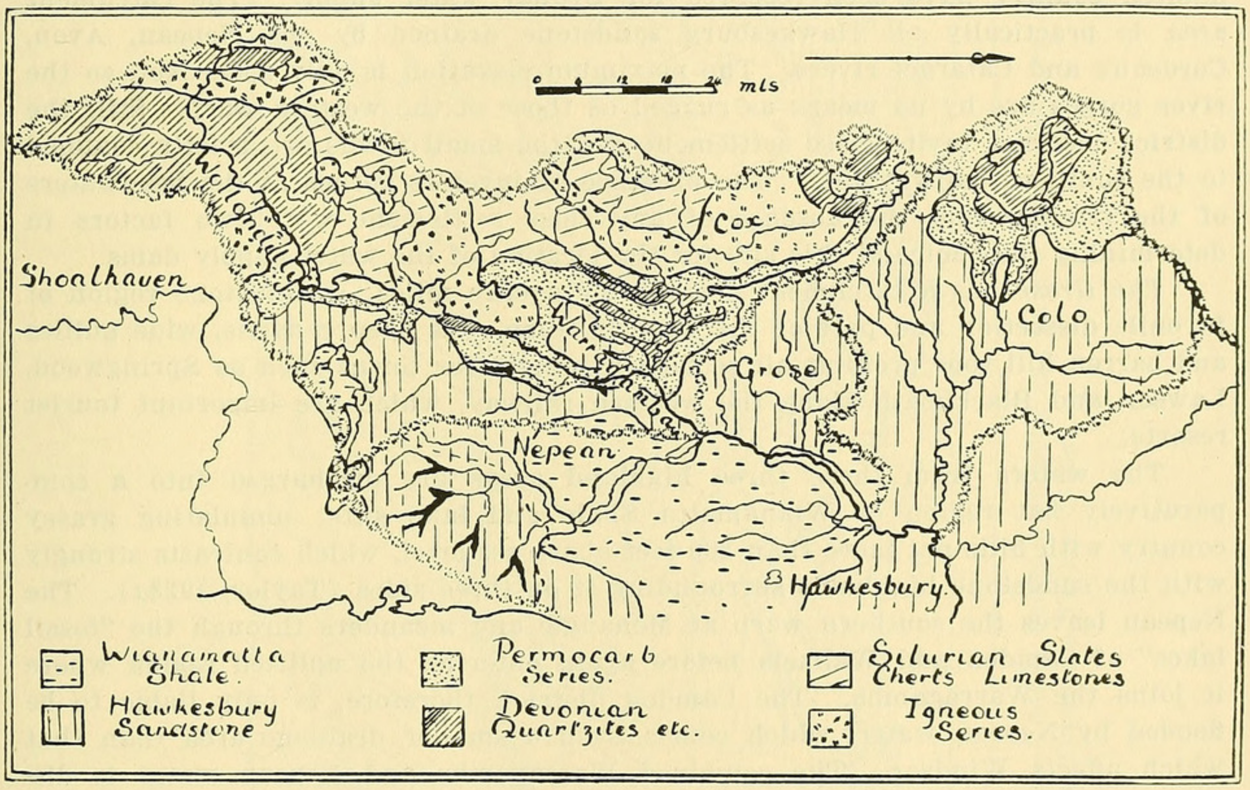
Three hundred and thirty-five miles in length, the river with its several large tributaries, drains all the immediate country to the north, west and south of Sydney, an area of approximately 8,000 square miles. It rises 20 miles from Goulburn. where it is known as the Wollondilly, flows generally northwards, and after receiving water from the Cookbundoon, Wingecarribee and Nattai streams, is joined by Cox River from the western mountain region. From here it is known




Text-figure 1.—A general map showing the catchment area of the Hawkesbury River above Windsor. (From a map obtained from the Water Conservation and Irrigation Commission.)

as the Warragamba and flows through a deep gorge till joined by the Nepean near Mulgoa. The main river is now known as the Nepean and continuing northwards, is joined by the Grose a little above Richmond and by South Creek at Windsor. After the Grose junction it is called the Hawkesbury and is joined by two large streams, the Colo and the Macdonald, before reaching Wiseman's elbow, where it turns eastward and finally enters the sea at the beautiful drowned estuary of Broken Bay. A consideration of the map, Fig. 1, will show that the headwaters of the river above Windsor may be divided into three systems, namely, the Wollondilly-Cox, the Nepean and the Grose, each of which has its own definite catchment area.

*The Wollondilly-Cox* has a catchment area of 3,383 square miles including all the country drained by the Wollondilly, Cookbundoon, Wingecarribee, Nattai, Cox and Warragamba rivers. Part of the western warp, it is all highland, but varies




Text-figure 2.—Sketch map showing the approximate geology of the catchment area of the Hawkesbury River above Windsor.

somewhat geologically. The upper Wollondilly flows through a series of Palaeozoic rocks, so that its gorges are less striking than the huge canyons which have been cut in the Hawkesbury sandstone by the Cox. The lower Wollondilly, Nattai and Warragamba have also cut deep gorges in the sandstone. Thus the northern part of the catchment area is of a very rugged character making communication difficult. Within the area there is a comparatively small population and only a few large towns. Settlement has collected in three regions. On the Upper Wollondilly, beyond the limits of the sandstone, there is good agricultural land which supports a farming population. Goulburn, population 11,950, is an important inland town on the Great Southern Railway. Taralga is another large town in this district where grazing, dairy-farming and fruit growing are the chief industries. Good workable soil and a less rugged topography have led to settlement in this area.

In the Bundanoon-Mittagong district is a series of small towns along the Southern Railway, well within the sandstone area and important only from the tourist and residential aspect. Among these are Bowral (2,640), Moss Vale (2,030), and Mittagong (1,440). Round Sutton Forest is some good grazing land due to the presence of basalt and the intrusive rock of the Gib at Bowral is important commercially. On the headwaters of the Cox are several towns the most important of which is Lithgow (12,940). Here river erosion has caused the sandstone to be worn away and the coal measure series to be exposed. Coal is mined at Lithgow and is the cause of the industrial prosperity of that centre. Other towns on the Cox catchment area are Mount Victoria, Katoomba and Wentworth Falls, all of which are tourist resorts. Except for these regions, juvenile dissection and barren sandstone soils have prohibited settlement on the Warragamba catchment area.

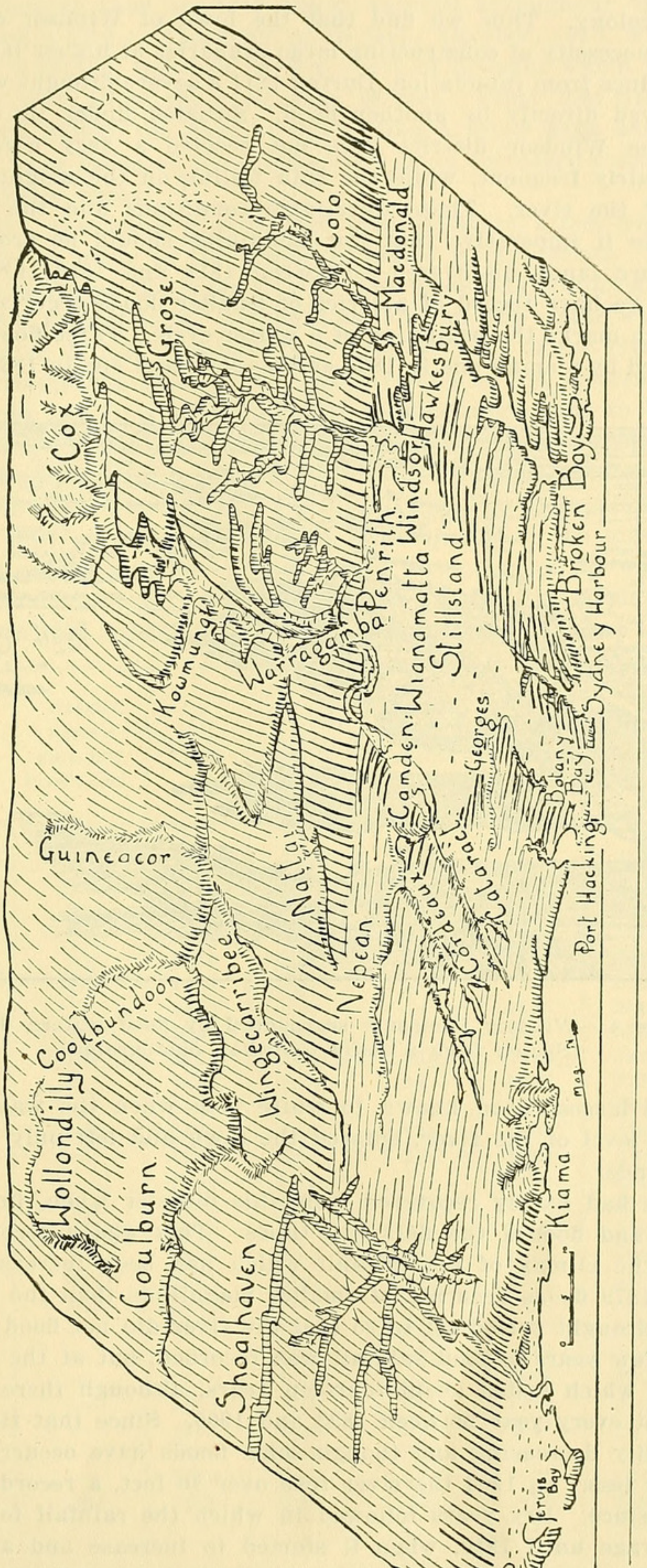
*The Nepean.*—On the headwaters of this stream 354 square miles of uninhabited country have been reserved for Sydney water supply. The catchment area is practically all Hawkesbury sandstone drained by the Nepean, Avon, Cordeaux and Cataract rivers. The maximum elevation is only 2,000 feet, so the river gorges are by no means as rugged as those of the western warp. Still the district does not invite close settlement and the small towns are mostly confined to the southern railway line. The presence of juvenile gorges at the headwaters of the streams and the absence of any close settlement were two factors in determining the choice of this site for the location of the water supply dams.

*The Grose* has a catchment area of 250 square miles; a sandstone region of juvenile dissection and part of the western warp. Its deep canyons, wide gullies and barren hill tops prohibit all settlement except for towns such as Springwood, Lawson and Blackheath along the western railway, which are important tourist resorts.

The waters from these three highland areas are discharged into a comparatively flat region of Wianamatta Shale and lake silts; undulating grassy country with hills not more than 200 feet above sea-level, which contrasts strongly with the sandstone highlands surrounding it on three sides (Taylor, 1923*a*). The Nepean leaves the southern warp at Menangle and meanders through the "fossil lakes" of Camden and Wallacia before again entering the uplifted region where it joins the Warragamba. The Camden district, therefore, is only liable to be flooded by Nepean water, which comes from a smaller drainage area than that which affects Windsor. The combined Warragamba and Nepean water is discharged on to the flats again at Penrith, causing floods here before it is joined by the waters of the Grose. The floods on the lowlands of Richmond and Windsor are caused by waters draining a total catchment area of approximately 4,840 square miles. At Cattai the river enters the northern warp and the flood waters are once more contained within the river valley.

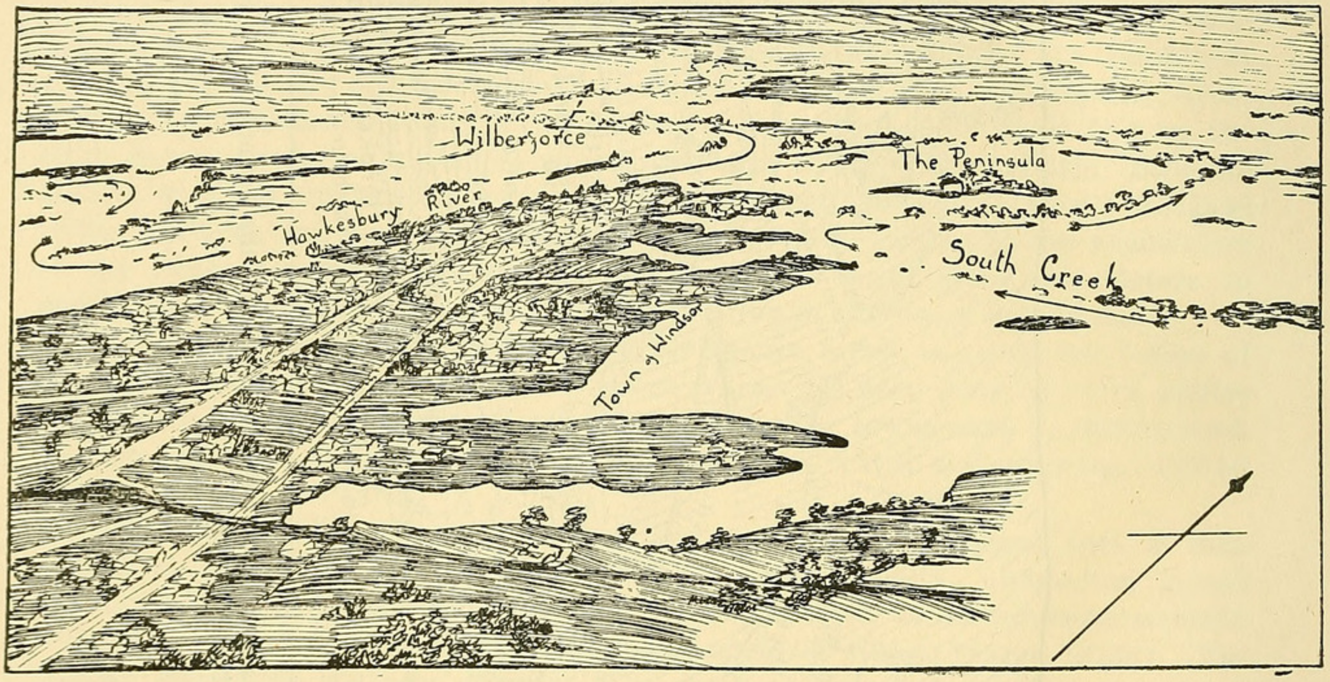
## History of Floods at Windsor.

The Hawkesbury River is recorded to have flooded for the first time in 1799, doing much damage and causing great distress among the people of the young settlement. This flood ushered in a series from 1799 to 1801 and then the river was normal till 1805 when another series of floods commenced. The records of these early floods are not accurate and no attempt was made to ascertain to what height the river rose above normal. In 1808 there was another flood and the frequency and destructive power of these floods was the cause of much anxiety




Text-figure 3.—A block diagram showing the nature of the country drained by the Hawkesbury River (based on Taylor, 1923*a*).

to the infant colony. Thus we find that the town of Windsor owes its origin directly to the necessity of constructing large granaries at higher levels in order to protect the produce from inundation. During 1811 a severe drought was experienced and was followed directly by another flood. Situated under the shadow of the great warp, the Windsor district does not receive a very high rainfall and droughts are fairly frequent, while the rain falling on the mountains will often cause floods of the river. These unsuitable conditions and the growth of the settlement made it imperative that the mountains should be crossed and more extensive pasture lands discovered. Between 1816 and 1819 three large floods occurred, then we have record of a series of smaller floods occurring at intervals until 1857 which marks the beginning of a wetter cycle. Three floods are recorded for 1860 followed by a small one in 1863 and a very large one in 1864. Three years




Text-figure 4.—Windsor Peninsula surrounded by flood waters, June, 1925. (Sketch from a *Daily Guardian* photograph.)

later came the largest flood known to white men when the water rose 63 feet above summer level of the river, entered the town and left only two parts of it exposed as islands.

The people had hardly recovered from this disaster when, in 1870 the river rose 15 times and flooded the flats five times. This was a record wet year at Windsor and the climax of the rainfall which had been increasing since 1857. From 1870 to 1879 floods occurred of smaller magnitude than the preceding ones, after which a drought period set in so that the river did not flood again till 1889. For the next few years a good rainfall was recorded, but at the close of 1893 a drought began which lasted about fourteen years, although there were floods at Windsor almost every year between 1893 and 1900. Since that time the rainfall has been steadily decreasing and though some floods have occurred their height has been much less. In 1904 the river rose over 40 feet, a record which has not been equalled since. Dry years followed in which the rainfall for the year was below the average until 1910, when it started to increase and a small flood of 21 feet occurred. 1911, 1912 and 1913 had small floods without much rain in the Windsor district, then in 1915 heavy rainfall throughout the Hawkesbury watershed caused a rise in the river of 25 feet. October, 1916, witnessed a high flood of 35 feet 6 inches, followed by five years of drought which were broken by heavy rains in 1921, when the river rose 20 feet. From this time onwards the rainfall has been better, the flood of 1922 being a fairly high one. There is no doubt, however, that floods of the Hawkesbury have decreased considerably during the last twenty-five years.

In May, 1925, the water rose 25 feet, that is, about 2 feet over the Windsor Bridge, and a great many of the low-lying places were covered. The water only broke over the banks of the river in very low spots and, running up the gullies, inundated a good deal of land. In the flood of June the water was 15 feet above Windsor Bridge, or 37 feet 3 inches above summer level of the river, which is the biggest flood experienced since 1904. Many people on the lowlands were driven from their homes and it is estimated that damage amounting to between £40,000 and £50,000 was done in the Windsor district and approximately £30,000 round Richmond. All the country round Cornwallis, Freeman's Reach, Pitt Town Bottoms, Wilberforce lowland, the Peninsula and the flats along South Creek were one vast sheet of water dotted here and there with the tops of houses and trees. Windsor was a complete island as the water backed up over the roads at the southern end of the town. The following is a list of the floods which occurred between 1795 and 1925 compiled from various sources:

| Year. | Month. | Height above summer level, feet. | Year. | Month. | Height above summer level, feet. | Year. | Month. | Height above summer level, feet. |
|---|---|---|---|---|---|---|---|---|
| 1795 | Jan. | — | 1857 | Aug. | 37½ | 1889 | May | 38½ |
| 1795 | Aug. | — | 1860 | Feb. | 26¾ | 1890 | Mar. | 38¾ |
| 1799 | Mar. | 50 | 1860 | Apr. | 36¾ | 1890 | Mar. | 34½ |
| 1800 | Mar. | — | 1860 | July | 34¼ | 1890 | June | 22¼ |
| 1801 | Mar. | — | 1860 | Nov. | 36 | 1891 | June | 35½ |
| 1805 | Feb. | — | 1861 | Apr. | 27¼ | 1892 | Sept. | 26½ |
| 1805 | Mar. | — | 1863 | — | — | 1893 | Mar. | 28¼ |
| 1806 | Mar. | 48 | 1864 | June | 48 | 1894 | Mar. | 31¾ |
| 1806 | Oct. | 30 | 1864 | June | 32½ | 1895 | Jan. | 30½ |
| 1808 | Nov. | 20 | 1864 | July | 36 | 1897 | July | 22½ |
| 1809 | May | 48 | 1866 | June | 26 | 1898 | Feb. | 31½ |
| 1809 | Aug. | 47½ | 1866 | July | 27¼ | 1899 | Aug. | 22 |
| 1810 | July | — | 1867 | Apr. | 21 | 1899 | Aug. | 26½ |
| 1811 | Mar. | — | 1867 | June | 63 | 1900 | July | 46 |
| 1812 | Mar. | — | 1869 | May | 36¾ | 1904 | July | 40 |
| 1816 | June | 45½ | 1870 | Apr. | 45 | 1908 | Aug. | 15 |
| 1817 | Feb. | — | 1870 | May | 35½ | 1910 | July. | 21 |
| 1819 | June | 46 | 1871 | May | 36¾ | 1911 | Jan. | 25¾ |
| 1820 | June | — | 1872 | — | — | 1912 | July | 22 |
| 1821 | Sept. | — | 1873 | Feb. | 41½ | 1912 | Aug. | 24 |
| 1826 | Jan. | — | 1875 | June | 38¾ | 1913 | May | 26¼ |
| 1826 | Sept. | — | 1876 | Sept. | — | 1913 | May | 20 |
| 1830 | Apr. | — | 1877 | May | 30 | 1915 | Jan. | 25 |
| 1831 | Apr. | — | 1877 | May | 20 | 1916 | Oct. | 35½ |
| 1832 | Mar. | — | 1878 | Feb. | 26½ | 1921 | — | — |
| 1833 | Apr. | — | 1879 | Sept. | 43¼ | 1922 | July | 31 |
| 1857 | July | 32½ | 1879 | Sept. | 34½ | 1925 | May | 25 |
| | | | | | | 1925 | June | 37¼ |

This list of floods records all those mentioned in the following references:

(1) 1799-1819: Articles in the *Nepean Times* for June, 1925, entitled "126 Years Ago."

(2) Tebbutt: Catalogue of the floods and freshes of the Hawkesbury River and South Creek at the Peninsula, Windsor, New South Wales. 1855-1903.

(3) "Results of Meteorological Observations at Mr. Tebbutt's Observatory. 1898-1915."

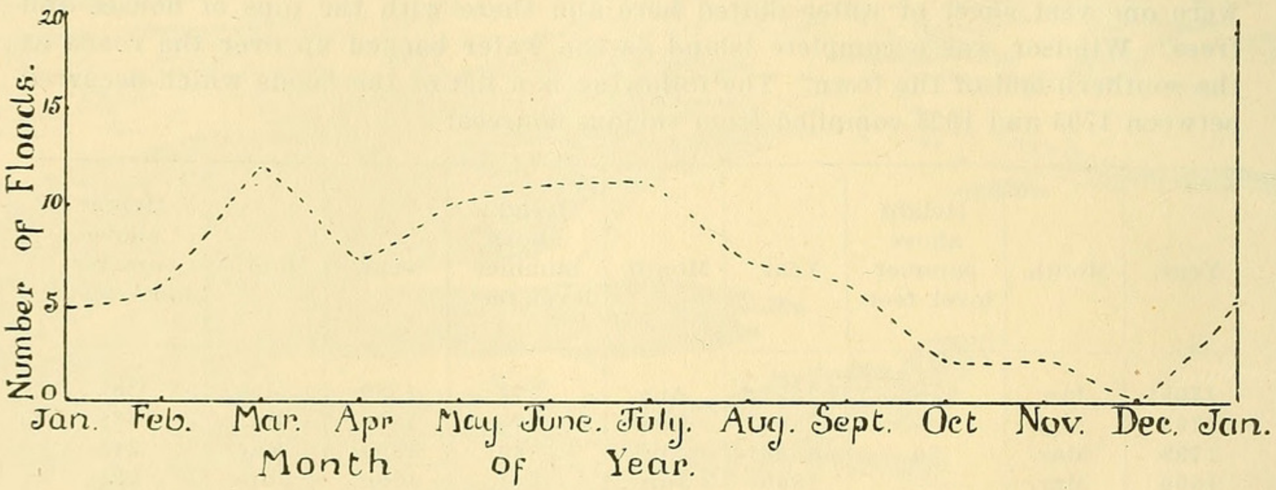
(4) Results of Rain and River Observations. 1903-1908.

(5) *Windsor and Richmond Gazette.* 1905-1925.

(6) Josephson, J. P., 1885: "History of Floods in the Hawkesbury River." *Proc. Roy. Soc. N.S.W.*, page 97.

### Relation of Flood Heights to Yearly Rainfall.

Floods in the Windsor district come at all seasons and have been known to occur in almost every month although the winter months, May, June and July, are the most common (see graph, Text-fig. 5). No flood has been recorded for

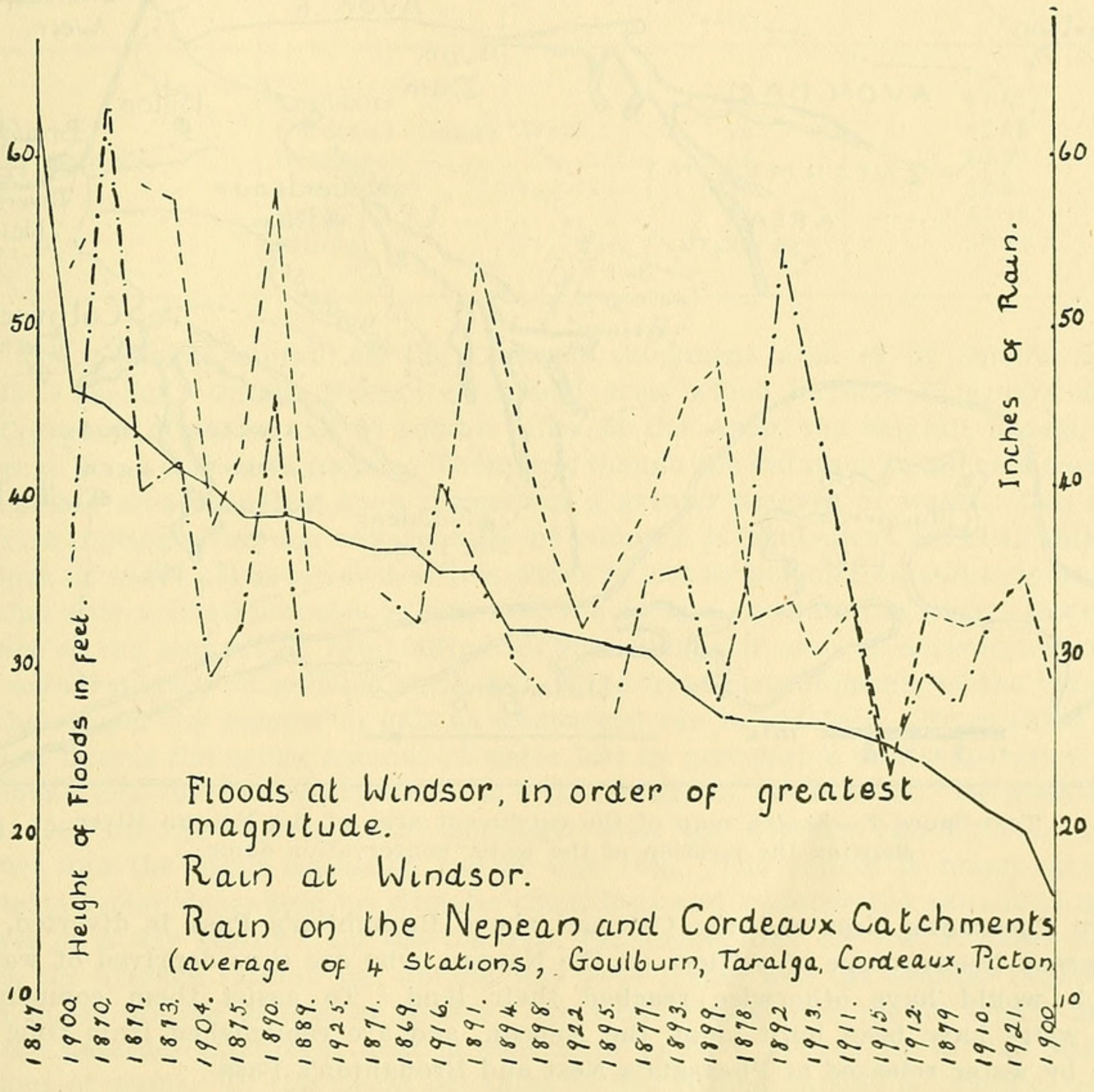



Text-figure 5.—A graph showing the number of floods occurring in each month of the year from 1795 to 1925.

December and very few in October or November. Floods are caused by heavy rain falling on the watershed of the river and are not affected by precipitation at Windsor. A fall of rain on the southern drainage area sufficient to cause floods is usually due to a cyclonic disturbance whose influence is felt all along the coast; thus it often has rained or is raining at Windsor during the rise of the flood waters. Cases have been known, however, when the river rose without any rain having fallen in the immediate district. The graph, Text-figure 6, shows the floods at Windsor in order of decreasing magnitude, with rainfall at Windsor for the corresponding years superimposed. It is obvious that the two lines bear no relation to each other. The third line shows the rainfall over the Nepean and Warragamba catchment areas, calculated as an average from the four stations, Goulburn, Taralga, Cordeaux and Picton. In this the relationship is more apparent as the rainfall curve is composed of a series of maxima and minima, with a general decrease in the height of the maxima, which corresponds to the decrease in height of the floods. The minima mark those years when the heavy rainfall was more coastal and all the flood waters came from the Nepean. The association between the rainfall and the flood line is not very close, for a flood does not depend on the amount of annual rainfall, but on a very heavy fall over a short period. Constant precipitation may give a high annual total with not enough at any one time to cause a flood, while flood rains followed by droughty conditions will result in a low yearly average. If heavy rain falls at a time when evaporation and percolation factors are high the run-off may not be sufficient to cause a flood.

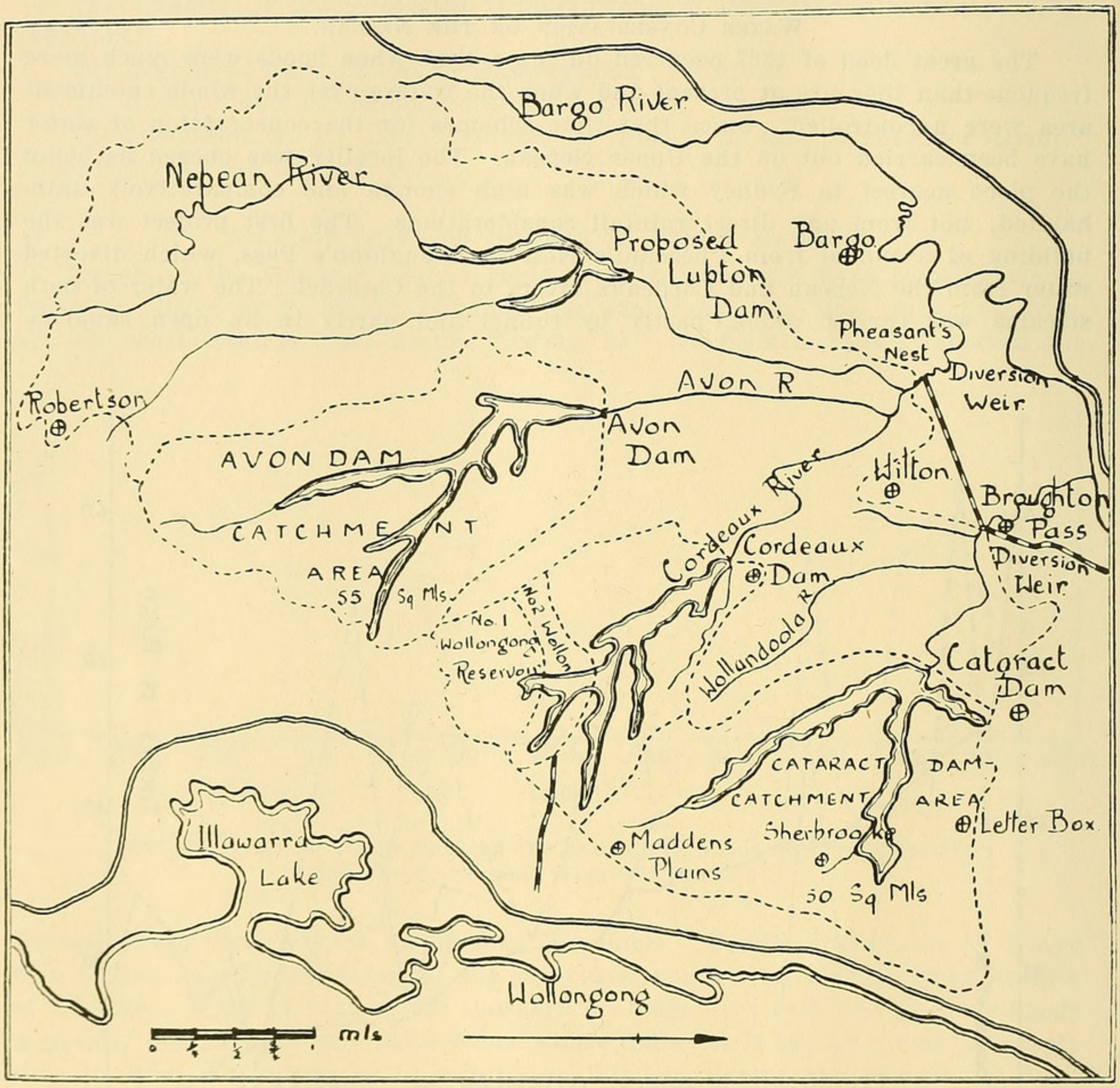
### Water Conservation on the Nepean.

The great flood of 1867 occurred during a time when floods were much more frequent than they are at present and when the waters over the whole catchment area were uncontrolled. Since that time schemes for the conservation of water have been carried out on the Upper Nepean. The locality was chosen as being the place nearest to Sydney which was high enough and comparatively uninhabited; not from any direct rainfall considerations. The first project was the building of a tunnel from Pheasant's Nest to Broughton's Pass, which diverted water from the Nepean and Cordeaux rivers to the Cataract. The water of both streams was carried along, partly by tunnel and partly in an open canal to




Text-figure 6.—A graph showing the relation of flood heights at Windsor to the yearly rainfall. In this figure the continuous graph represents the floods at Windsor, the dot and dash graph the rain at Windsor and the broken line the rain on the Nepean and Cordeaux Catchments.

Prospect and so to Sydney. Then the Cataract dam was built and stored water first in 1906. It was filled for the first time in 1911. In time of flood or fresh only a fraction of the flow of the Nepean River can be diverted to Sydney and the same might have been said of the Cataract River before the completion of the dam. In dry weather, however, practically the whole flow of the Cordeaux




Text-figure 7.—Sketch map of the catchment area of the Nepean River showing the position of the water conservation dams.

above Pheasant's Nest and the Cataract above Broughton's Pass is diverted, to the great disadvantage of settlers on the Nepean, who are thus deprived of water which would have otherwise reached their land. To assist them compensation weirs have been built along the Nepean, and are replenished from time to time by water released at Pheasant's Nest and Broughton's Pass.

The catchment area of the Cataract Dam is 50 square miles and, when full, it backs up the water to a depth of 150 feet and stores 20,743 million gallons. Construction of dams on the Cordeaux and Avon rivers is now almost complete and during the flood rains of May and June, 1925, they stored a great deal of water. As soon as these dams are finished one is to be constructed at Lupton on the Nepean proper, and with the four dams in working order a continuous flow of 108 to 110 million gallons of water per day will be able to be maintained to Sydney as well as the coastal supply to Mt. Kembla and Wollongong. In 1871 there were only two rainfall observing stations in the catchment area but at various times since then others have been established. The following is a list of these recording stations:

| Catchment Area. | Rain Gauge Stations. | No. of Years. | Yearly Average. |
|---|---|---|---|
| Cataract. | Sherbrooke | 32 | 59·16 |
| | Madden's Plains | 17 | 58·47 |
| | Letterbox | 16 | 49·43 |
| | Mount Pleasant | 17½ | 57·13 |
| | Cataract Dam | 20 | 34·82 |
| | Broughton's Pass | 36 | 33·16 |
| Nepean. | Cordeaux | 53 | 61·01 |
| | Cordeaux Gauge Weir | 15 | 42·04 |
| | Robertson | 34 | 57·69 |
| | Mittagong | 28 | 33·61 |
| | Bargo | 22 | 30·22 |
| | Wilton | 28 | 27·23 |

The average rainfall on the Cataract catchment area of 50 square miles is 48·69 inches. On the Nepean catchment area, which includes 35 square miles of Cordeaux drainage and 55 square miles of the Avon, the rainfall is less, the average being only 41·98 inches. Therefore, though the Cataract Dam has a smaller catchment area than the Avon it receives a greater amount of water. One inch of rain falling over one square mile of country is equivalent to 14·52 million gallons of water. A great deal of this water is lost by percolation and evaporation so that only a small percentage runs over the surface and into the river. Measurements of the amount of rain falling on the catchment area of a river will give the actual number of gallons which fell, while from measurements of the velocity of the stream the number of gallons discharged can be obtained. From these two sets of figures the actual amount of water lost by percolation and evaporation can be found and the run-off expressed as a percentage of the rainfall. Between 1887 and 1906 on the Warragamba catchment area the average rainfall was 32·45 inches and the mean estimated run-off was 16%. The run-off is found to be a variable factor depending on climatic conditions and whether the rain falls after a wet or a dry season. On the Cataract catchment area for the 25 years since 1900, the average rainfall per annum was 50·56 inches and the average discharge was 13,358 million gallons or 33·64%. An inch of rain over the 50 square miles of the Cataract catchment area is equivalent to $50 \times 14{\cdot}52 \times 10^6$ or 726 million gallons of water. Of this about one-third or 242 million gallons is available to be stored in the dam. The average fall of 50 inches of rain over the whole area will only produce 12,100 million gallons of water to be stored and, as this is only about half the capacity of the dam it seems evident that its catchment area is not large enough. Yet the Avon Dam with about equal available water is twice as big as Cataract with a total capacity of 47,159 million gallons. The heavy rains of May and June, 1925, were not sufficient to fill the Avon and Cordeaux dams which would seem to be too large for their catchment areas. In this connection it is necessary to remember the purity of the water which flows into the Avon Dam, an important factor in a country where settlements are to be found on most of the rivers.

### The Action of the Dams During the 1925 Floods.

Heavy rains were experienced on the Nepean catchment area during May and June, 1925, the total precipitation over the whole area for the two months, as calculated from four rainfall stations on the Cataract catchment and three on the Avon and Cordeaux, being 37·08 inches. Of this 22·84 inches fell during May as compared with the 14·24 inches which fell in June. At the time of the May fall, however, the ground was dry and a great deal of the water was lost by percolation and evaporation. For this month the average run-off over the whole area was 63·6% of the rainfall, while during June when the ground was still moist the average run-off was 76·9%. On the Cataract catchment area the mean precipitation for the month of May was 25·24 inches and the run-off was 66% of the rainfall. There were 5,470 million gallons of water stored at the beginning of the rain and the increase was 6,263 million gallons. The dam did not overflow during the May flood and the water continued to rise during the rest of the month owing to run-off from the hills which continues for a good while after rain has fallen. At the beginning of the heavy June rains there were 17,954 million gallons in storage and the dam was filled within three days. The overflow at the time of the June flood is estimated at 4,421,324,500 gallons. The rainfall for that month was 13·95 inches and the run-off was 74·7%. The total amount of water stored in the Cataract dam in May and June was 15,273,000,000 gallons.

On the Cordeaux catchment area records from three stations only are known and their readings give a mean rainfall of 23·19 inches for May. The increase in storage of the dam was 6,848,000,000 gallons and the run-off was 58·4% of the rainfall. The June rains averaged 15·29 inches but the run-off was higher, 70·3%, and increased the storage by 5,439,000,000 gallons, making a total increase of 12,287,000,000 gallons in the Cordeaux storage for May and June. The dam did not reach its full capacity. Records from the Avon catchment area are also very approximate, being based on observations from three stations only. For May a mean precipitation of 20·1 inches is recorded, 25% less than that of Cataract, while the run-off was 66% and gave an increase in the storage of 10,625 million gallons. In June the rainfall of 13·47 inches with a high run-off of 85·8% gave an increase in storage of 9,193,000,000 gallons. The total increase in the Avon storage was 19,816,000,000 gallons, but as the dam was almost empty at the beginning of the rains it did not then reach its full capacity. Storage was commenced on the Avon River at the end of May, 1924, and by the end of June, 1925, 22,308 million gallons had been impounded; practically the whole yield at the catchment, as only a trifling amount was sent to Sydney. Another 71 inches were then required to fill the storage. It is calculated that the mean precipitation over the whole catchment area of 354 square miles for May and June was 18·54 inches, giving a run-off of 105,372 million gallons, of which 48,233,000,000 gallons, or nearly 50% was caught and held in the Cataract, Avon and Cordeaux reservoirs. Some of the excess water not held by the dams was probably discharged down the canal to Prospect, but in quantity so small as not to affect the calculations, since at the height of the flood the gates are closed to prevent the blocking of the canal by debris.

Details as to the rainfall and discharge from the Warragamba and Grose catchment areas are supplied by the following letter from the Water Conservation and Irrigation Commission: "The most notable falls on the Warragamba River catchment area during the months of May and June were:

| | |
|---|---|
| Robertson .. .. .. .. .. .. | 44·27 inches |
| Goulburn .. .. .. .. .. .. | 16·38 ,, |
| Katoomba .. .. .. .. .. .. | 24·78 ,, |
| Mount Victoria .. .. .. .. .. | 15·59 ,, |
| Bowral .. .. .. .. .. .. .. | 22·49 ,, |
| Taralga .. .. .. .. .. .. | 15·26 ,, |

The rainfall stations are not evenly distributed over the catchment area; on the sparsely settled districts the records are scanty, but by giving each station its proper 'zone of influence' the mean depth of precipitation over the catchment area is estimated at 17 inches. The amount of water discharged by the Warragamba at a point a litttle up stream from its junction with the Nepean, during May and June is estimated at 297,715,000,000 gallons or enough to supply Sydney for 14 years at the present annual consumption rate. About 35·5% of the rainfall was discharged by the Warragamba, the rest being lost by percolation and evaporation. There are no reliable measurements of the amount of water contributed by the Grose River to the floods of May and June. The catchment area of the stream at its affluence with the Hawkesbury above Richmond is 250 square miles. A conservative estimate of the discharge, basing it on the relation of its area to that of the Warragamba, would be 22,000 million gallons of water, which is little more than the capacity of Cataract Dam. Rainfall stations on the Grose catchment area are Springwood, Lawson and Blackheath."

From a combination of the figures for the three catchment areas the following table is derived:

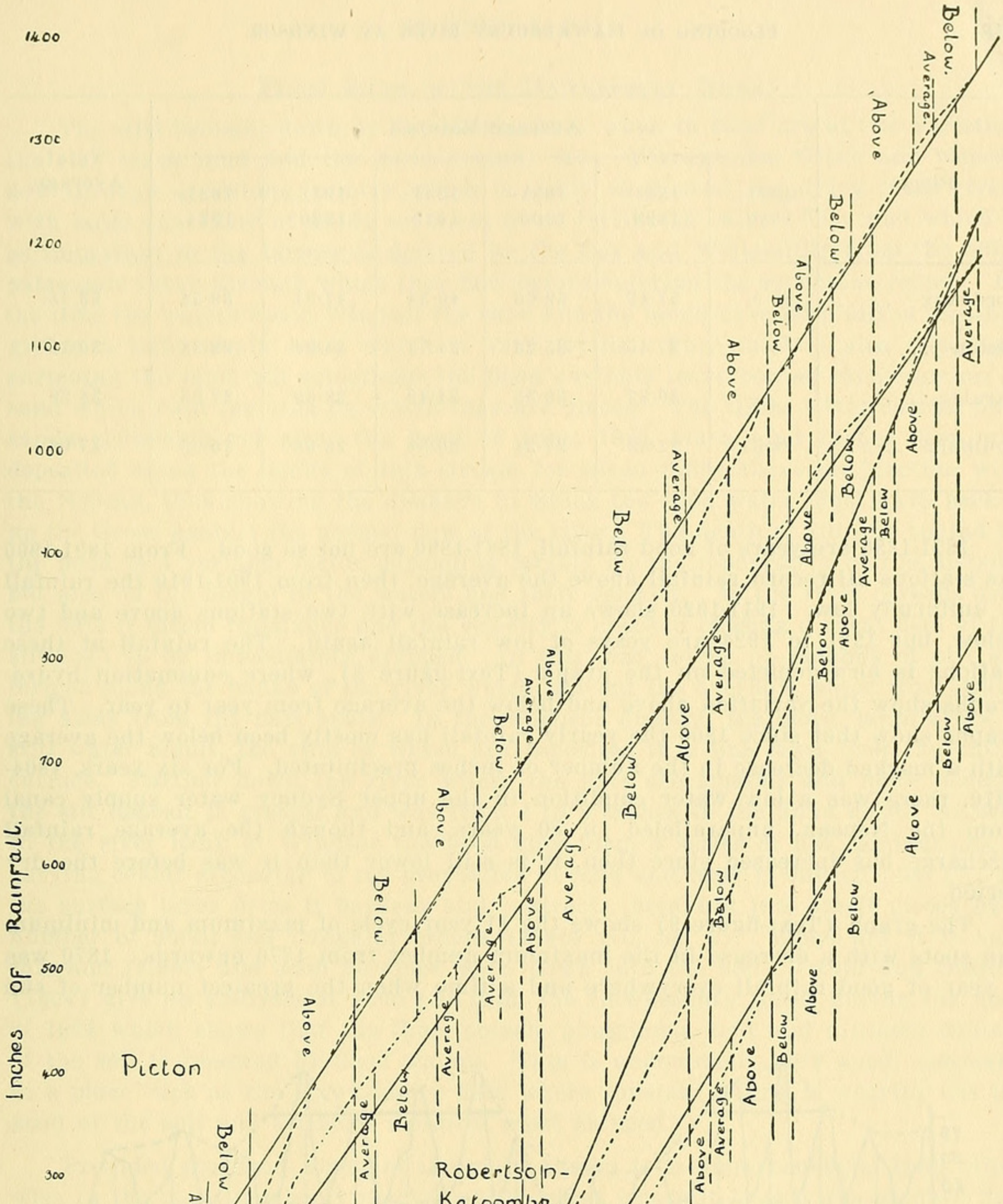
| Catchment. | Area in square miles. | Run-off, million gallons. | Storage, million gallons. | Storage %. |
|---|---|---|---|---|
| Warragamba .. .. .. .. .. .. | 3,383 | 297,715 | — | — |
| Nepean .. .. .. .. .. .. .. | 354 | 105,372 | 48,233 | 45·7 |
| Grose .. .. .. .. .. .. .. | 250 | 22,000 | — | — |
| TOTAL .. .. .. .. .. .. .. | 3,987 | 425,087 | 48,233 | 11·3 |

This gives approximately the total run-off from a catchment area of 3,987 square miles, figures for the other 853 square miles of the Windsor catchment area not being recorded. Yet considering that the dams caught and held almost half the water discharged from the Nepean catchment area and practically 10% of the total water discharged at Windsor, it is obvious that if these dams had not been in existence the magnitude of the floods at Penrith and Windsor would have been greatly increased. The dams on the Nepean cannot prevent floods at Windsor, nor decrease the number experienced there, but their existence is felt in a tendency towards modification during a flood period, although their effect is a variable factor depending on a number of conditions. The Nepean drainage is only about 10% of the Warragamba, but its area is nearer the coast and consequently receives more rainfall, so that in the June, 1925 flood its run-off was equal to 35% of the Warragamba run-off. It is possible for coastal rains to cause floods of the Nepean without additional water from the Warragamba and in such cases there is no doubt that the effect of the dams is very great. The actual amount of water which is held back by the dams depends on the number of gallons already stored at the beginning of the rains. The heavy rains of May were preceded by a dry period and the water in Cataract Dam was low. Also dams at Cordeaux and Avon were only on the verge of completion and almost empty, so that a considerable quantity of water was capable of being stored.

A flood of any magnitude at Windsor is due to a cyclonic disturbance, which causes sudden heavy rain of only short duration over the whole catchment area. As a result a great deal of excess water is discharged in a few days, causing an abrupt rise and fall in the river level. The dams, therefore, by holding back water at the time of general discharge decrease the height to which the flood would have risen and the consequent damage which would have been done. Even if the dams are full and cannot hold back the water from the flood they decrease its peak discharge, because the whole surface of still water must be raised above the level of the dam before the overflow takes place and the drainage from such a surface is necessarily slower. It is not the actual amount of water but the rate of discharge which causes the river to rise and flood the lowlands and an arrangement whereby the water is delayed and caused to pass more slowly down the river does much to lessen its evil effects.

## Decrease in Rainfall.

The decrease in the number of floods experienced at Windsor of late years seems rather to be a factor of the decreasing rainfall than to be due to dam building on the Nepean. At Grove Farm the river rose to 67 feet 10 inches on the present gauge in 1867 and only 35 feet 4 inches in 1925. This difference could not be accounted for by the building of the dams. It must be associated with a diminution in rainfall, a factor not due to deforestation as this area, being rugged inhospitable country, is still uncleared to a large extent. The difficulty in this connection is the absence of long time rainfall records by which a decline in precipitation might be verified. Goulburn is the oldest established rainfall station on the Warragamba catchment area. The records commenced in 1858 and the average for 67 years was 25·41 inches, while for the last 30 years the average has been 22·83 inches, a falling off of about 10%. Rainfall records at Cordeaux gauging weir were started in 1872, the average rainfall for 53 years being 53·58 inches, while the average since 1900 shows a decrease of about 20% and is only 44·45 inches. The following table shows how the ten yearly averages compare with the total averages since the formation of the station at various places on the catchment area (figures obtained from Hunt, 1916, and from the Weather Bureau).



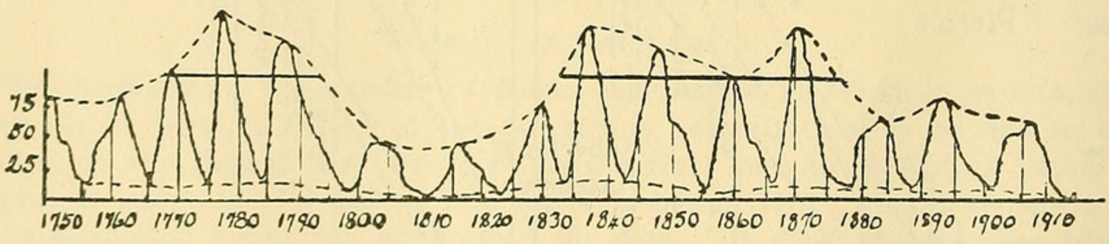

Text-figure 8.—Summation hydrographs showing the variation in the rainfall above and below the average for a number of years, of six stations on the Windsor catchment area.

The summation hydrograph is made by adding together the averages of the rainfall at a certain place over a number of years and then plotting the result as a rising graph. The final point on the graph is joined to the first point by a straight line which is the general average rainfall over the total number of years. When the graph line is parallel to the average line the years were ones of normal rainfall. Where it inclines away from the average the rainfall during those years was above normal and where it inclines in to the average the rainfall was less than normal.

| Place. | Average Rainfall. | | | | | | Total Average. |
|---|---|---|---|---|---|---|---|
| | 1871–1880. | 1881–1890. | 1891–1900. | 1901–1910. | 1911–1920. | 1921–1924. | |
| Cordeaux ..... | 60·0 | 57·42 | 69·66 | 46·34 | 47·91 | 39·58 | 53·48 |
| Picton ......... | — | 27·45 | 35·26 | 24·74 | 34·94 | 28·38 | 30·15 |
| Taralga ....... | — | 30·87 | 30·35 | 24·49 | 28·69 | 27·05 | 28·28 |
| Goulburn ...... | 28·51 | 22·53 | 27·21 | 20·39 | 23·58 | 26·03 | 27·06 |

1871-1880 are years of good rainfall, 1881-1890 are not so good. From 1891-1900 the stations all record rainfall above the average, then from 1901-1910 the rainfall is uniformly low. 1911-1920 shows an increase with two stations above and two below, but 1921 to 1924 are years of low rainfall again. The rainfall at these stations is also depicted on the graph (Text-figure 8), where summation hydrographs show the variation above and below the average from year to year. These graphs show that since 1900 the yearly rainfall has mostly been below the average with a marked decrease in the number of inches precipitated. For six years, 1904-1910, there was a low water condition in the upper Sydney water supply canal from the Nepean, unparalleled in 80 years, and though the average rainfall discharge has increased since then, it is still lower than it was before the dry period.

The graph (Text-figure 9) shows the 11 year cycle of maximum and minimum sun spots with a decrease in the maximum number from 1870 onwards. 1870 was a year of good rainfall everywhere and a time when the greatest number of sun




Text-figure 9.—Major and minor sun spot cycles (Huntington, 1915).

spots have been recorded. From 1881 to 1890 the rainfall was not so good, but at that time the sun spot maximum was not nearly so large as the one preceding. Between 1891 and 1900 the maximum was greater and the rainfall recorded is better, but from that time onwards there has been a steady decline both in sun spots and precipitation. Thus rainfall does seem to vary, not only with the eleven years' cycle but possibly also in accordance with a superimposed major cycle as shown by Huntington, 1915. If this is the case the recent floods of 1925 might be taken to indicate the beginning of a new cycle in which the seasons would gradually improve. Such conclusions are necessarily very tentative as it is difficult to arrive at any definite principle.

## Flood Silts of the Hawkesbury River.

The silts brought down by the Hawkesbury when in flood are of two varieties, the rich black mud and the useless sand. The Warragamba, Grose and Nepean flow through sandstone country which is easily weathered, supplying these rivers with large quantities of sandy sediment of no fertilizing value. The mud which is so important to the farmer is derived by the Cox and Wollondilly from the older palaeozoic rocks through which they flow before entering the sandstone region. By the time the waters reach Windsor the sand and the muds have been mixed together giving a light sandy loam which is very fertile. Pure mud is also deposited, enriching the land, but sometimes the flood currents leave behind them patches of sand which ruin the area on which they are placed. The Grose River carries only sandy sediments yet after the flood of June, 1925, black mud inches deep was deposited along the banks of this stream for seven miles above its junction with the Nepean, thus showing the distance to which the flood water must have backed up the Grose against the normal flow of the river. The depth of silt left behind by the flood is a variable factor depending largely on the topography of the district, but also on the height of the waters and their velocity. As the river spreads over the flats it meets resistance and the velocity is checked causing a great deal of the silt load to be immediately dropped. In this way levees or mounds of silt are formed along the banks of the river which prevent the overflow water from draining away from the flats again. In the Windsor district, therefore, large areas of still water result, the silts of which are deposited in a fine layer over the entire surface. Farther down the river where the flats are smaller and more isolated the silt deposit is greater and was from 4 to 6 inches in the June flood. As seen in the river bank at Windsor the flood silts form a series of fine laminations of varying colour according to the proportion of mud and sand (Plate viii, fig. 1). As the surface layer dries it hardens and contracts, breaking into small pieces by a number of small and irregular cracks (Plate viii, fig. 2). When dry it is very soft and friable and soon becomes worn down into the soil. David and Guthrie (1904) give an analysis of flood silt from the Hawkesbury water during the flood of 1904 which shows that the lime, potash, phosphoric acid and nitrogen content of the soil is renewed by flood waters. This is undoubtedly very good, especially in a place such as the Hawkesbury flats where constant tilling is wearing out the good of the soil and artificial manures must be used.

Provided the flood comes at the right season it is more beneficial than otherwise in the more northerly reaches of the river where it is only the orchard flats which are covered by the waters. Here the houses are built on the higher sandstone terraces and so escape damage. The fruit trees are grown in the long flat gullies at the base of the sandstone hills where the flood forms quiet backwaters in which silt is deposited inches deep over the farms. However, floods are very uncertain in their coming and on the low flats between Wilberforce and Windsor often large areas of growing crops are destroyed in addition to other extensive damage which tends to outweigh any good effect. After the flood of June, 1925, the water remained on the surface for days which, although impeding the work of reconstruction, enabled the subsoil to become thoroughly wet. As a result it was possible for the farmer to grow valuable areas of lucerne, a crop which cannot be grown there under ordinary rainfall conditions as rain does not penetrate deeply enough into the soil. Moreover, throughout the dry summer which followed the crops flourished on water stored beneath the surface of the ground. Therefore, although the general opinion is one of censure against the floods, there is always some benefit to be derived from them. In the Windsor district another difficulty at flood times is the shifting of the land as the river increases the scope of its meanders. The velocity of the flood waters gives them great erosive power and as they swing round a meander the river bank is washed away on one side while sand and debris are deposited on the other. During the June flood a land slide occurred in which 200 yards of the road along the bank was completely washed away. With every flood the channel of the river is altered, the meanders becoming more and more curved and unless they are prevented by artificial means the meanders will become cut off with resulting ox-bow lake formation. This action of the river is a source of great difficulty in a region where the land is divided into private farms whose owners lose large blocks of land with every flood.

## Flood Prediction and Control.

As floods in the Windsor district are due to irregular cyclonic disturbances on the coast, to forecast their occurrence would be a matter of some difficulty. At one time the people were caught by the water when quite unprepared, but they are now warned by telephone communication which gives them about 24 hours in which to evacuate. The warnings, however, are never very accurate and the people do not know how high the water may be expected to come, nor will they leave their homes till they are quite sure that it will be necessary. The best way of controlling flood waters is to build levees along the river banks high enough to prevent the water from coming over. In the Windsor district this would be an enormous task owing to the great extent of flat land through which the river flows in that locality. Moreover the expense of such an undertaking would not be justified by the value of the land. It is doubtful whether any farmer round Windsor would be willing to go to the expense of erecting a bank to protect his property against the ravages of the river even if it did not do good as well as harm. The risk of life does not even cause them to take precautions, for many still live in houses well within the danger zone and do not even keep a boat when their only means of escape at flood times is by water. The rescue work is carried on by special boats which have to be sent to the afflicted areas from Sydney.

To control floods in the Windsor district it has been suggested to build a dam in the Warragamba gorge to collect all the run-off from the Wollondilly watershed and permit of it being released in more or less regulated volumes. A wall 300 feet high in this gorge would impound the water for 25 miles up the Wollondilly and 20 miles up the Cox. Such a dam might not actually prevent floods for the Burrenjuck Dam, which captures nearly all the headwaters of the Murrumbidgee, was unable to prevent flooding of that river in 1925. However, besides lessening the discharge by an amount proportional to the number of gallons already in the dam at the beginning of the rains, it would offer a very large surface of still water over which the excess would have to pass and would thus make the floods less intense and therefore lower in height. If the overflow water were to be discharged down the river more slowly it might possibly be contained within the river banks. The dam would give a continual flow of 200 million gallons per day to Sydney. It is calculated by water supply experts that up to 1967 Sydney, with the 80 million gallons from the Nepean, will only require 160 million gallons from the Warragamba, and if the surplus is not used it will bank up and overflow. This will decrease its usefulness in the prevention of floods and in order to use the excess water schemes for the generation of electric power and for the irrigation of the lowlands have been suggested. The water from the dam on the

Murrumbidgee is used to irrigate land which is naturally fertile and only requires water to make it good for agriculture. It is well drained with uniform surface levels which make redistribution easy, while the low rainfall insures a constant demand for water. Conditions are different in the county of Cumberland. Here there are 26,390 acres of good river land, 14,300 acres of second class river land and the rest is Wianamatta shale, poor soil almost worthless for cultivation with unequal levels which would make the application of water a costly process. The area supports 778 persons per square mile, including the city of Sydney and only 98 per square mile if that town is excluded. Also the rainfall is a very variable factor and the demand for irrigation water would fluctuate. Yet on the river flats the dam would greatly decrease the possibility of floods and irrigation, though costly, would increase the productivity of the land which is the closest agricultural region to the city of Sydney. Nevertheless the proposal to dam the Warragamba is not much favoured by people of the Windsor district, who depend on the river for their water supply. The towns of Richmond and Windsor both obtain water from the river by electric pumps and anything which would check or interfere with the flow of the river or any of its tributaries upstream must seriously jeopardize the supply from the Hawkesbury, especially in dry seasons when the salt water works its way towards Windsor rendering the river water unfit for use.

## Summary and Conclusions.

Floods in the Windsor district are due to the presence of a river with widespread upland drainage, discharging its waters from the mountains on to the flat lands of this locality. They are caused mainly by heavy coastal storms of short duration and result from the sudden and simultaneous discharge of excess water from the large number of tributary streams. This gives a typical high peaked flood wave which passes very quickly so that the rise and fall of the waters is only a matter of days. A high flood is very destructive covering the crops and often entering the homes of the farmers, who are forced to seek shelter on higher ground. The black mud left behind by the waters is fertile and the ground is improved by the moisture yet the damage of the flood outweighs its good effects. Prevention, however, is a difficult matter. The flats are far too extensive and not rich enough to pay for the building of levees. Also floods are not nearly so numerous or so high as they used to be. The best method of controlling floods is by water storage. There are at present three dams on the Nepean which hold back some of the water at time of flood and, by thus knocking off the peak of the flood wave, do much good by making the rise of the waters less abrupt. The river is the one nearest to Sydney and therefore its natural source of water supply, while the inhospitable character of the rugged mountainous area through which it flows prevents settlement and keeps the water fairly pure. It is suggested to build a large dam on the Warragamba River which will assure an ample supply of water to Sydney and at a time of heavy rain will help to smooth down the flood wave so considerably that the water may possibly be contained within the river banks. Dams, however, cannot actually prevent floods and those built on the Nepean have not been the cause of the decrease in the number of floods experienced at Windsor of late years. This decrease is rather a factor of declining rainfall for precipitation on the catchment area has been steadily less ever since the heavy rainfall of 1870.

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## DESCRIPTION OF PLATE VIII.

Figure 1.—Flood silts on a grassy bank at Windsor showing the laminated character of the deposits.

Figure 2.—Irregular cracks due to drying in the flood silts at Windsor.