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GEOMORPHOLOGY OF NEW SOUTH WALES COASTAL RIVERS

by

H.A.Scholer

April, 1974

The University of New South Wales

WATER RESEARCH LABORATORY

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8. ABSTRACT

This research report deals with the effects of dams, land use, extractive industries and other activities on coastal rivers and their floodplains. Emphasis has been placed on the Hawkesbury-Nepean River.

In Chapter 1 physical features of the Hawkesbury-Nepean River system are described. Chapter 2 is a study of some land forms and soil stratigraphy associated with the river and Chapter 3 is a survey of the natural vegetation associated with the river and its tributaries. In Chapter 4 the effects of the Warragamba Dam and extractive industries on the river are described. In Chapter 5 the effects of speedboat waves on the river banks are described.

In Chapter 6 methods for predicting salinities and the dispersion of pollutants in estuaries are described. Chapter 7 is a regime study of rivers with natural levees. The processes of formation of leveed channels are described and regime expressions are derived. They include expressions for the levels of the levee crests and the channel bed. The results obtained from a laboratory model, simulating the processes involved in the growth of estuarine floodplains, are given in Chapter 8. Recommendations are given in Chapter 9 and Chapter 10 is a selected bibliography.

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Preface

This research project was carried out for an inter-departmental panel consisting of representatives of the University of New South Wales, the Public Works Department of New South Wales, the Metropolitan Water Sewerage and Drainage Board, the Water Conservation and Irrigation Commission, the Maritime Services Board and the Health Commission of N.S.W. The project, which was carried out under the supervision of Associate Professor R.T. Hattersley and the general direction of Professor H.R. Vallentine, Head of the School of Civil Engineering, The University of New South Wales, was financed by the Public Works Department of N.S.W.

The assistance is gratefully acknowledged of the Agriculture Department, the Lands Department, the Mines Department, the Library of N.S.W., State Fisheries, Windsor Municipal Council, Colo Shire Council, Penrith City Council and residents and organisation in the Hawkesbury Valley including students and teachers of Richmond High School.

D.N. Foster,
Officer-in-Charge,
Water Research Laboratory.

April 1974.

Summary

The object of this research project is to ascertain the effects of dams, land use, extractive industries and other activities on coastal rivers and their flood plains. Emphasis has been placed on the Hawkesbury-Nepean River. A dam impounds waters from most of the catchment upstream from the tidal limit and large quantities of sand and gravel have been removed from the river downstream from this dam.

In Chapter 1, features of the Hawkesbury-Nepean river system are described, including the catchments, the flood plain, the natural levees, changes which have occurred since the earliest days of white settlement, flood behaviour, the stability of river banks and the nature of the sediments in the bed and banks of the Hawkesbury River. Chapter 2, written in collaboration with Mr. A.M.H.Riddler of the N.S.W. Department of Agriculture, is a study of some landforms and soil stratigraphy associated with the river and Chapter 3, the subject matter of which was contributed by Mr.D. Benson, of the same department, is a survey of the natural vegetation associated with the river and its tributaries. In Chapter 4 the effects of the Warragamba Dam and extractive industries on the river are described. These effects are deduced from the alteration in the supplies of river sediments and from regime relationships derived in Chapter 7. In Chapter 5 the effects of speedboat waves on river banks are described.

In Chapter 6 there is a critical review of literature on the prediction of salinities, dispersion of pollutants and shoaling patterns associated with secondary currents caused by salinity gradients. Computer models and hydraulic models are discussed and the field observations, required for adequate records of salinity, are described. A new formula is derived for salinities at a station which is based on statistics of cumulative dry weather river discharges. This formula can be used to predict salinities at a station after the construction of a dam upstream has altered the discharge statistics.

Chapter 7 is a regime study of a river with natural levees. The levees on some of the rivers on the east coast of Australia are high by world comparisons. The crests of the Hawkesbury River attain a height of about 40 feet above the channel bed and a height of about 25 feet above the flood plain behind them. The processes of formation of leveed channels are described and regime expressions are derived. They include expressions for the levels of the levee crests and the channel bed. These expressions are based on the competence of a leveed channel to transport bed material and the proportion the average annual quantity of suspended sediment transported by the channel by the channel bears to the average annual quantity of bed material transported. The results obtained from a laboratory model, simulating the process involved in the growth of estuarine flood plains, are given in Chapter 8.

Recommendations for the Hawkesbury-Nepean River and other N.S.W. coastal rivers are given in Chapter 9 and Chapter 10 is a selected bibliography.

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CHAPTER 1 - PHYSICAL FEATURES OF THE HAWKESBURY RIVER AND ITS TRIBUTARIES.

Introduction

By the most common usage the name "Nepean" is given to the main river above its junction with the Grose River and the name "Hawkesbury" is given to the main river below this junction. Generally in this report the entire river, for convenience, will be named the Hawkesbury River.

The river and its tributaries drain an area of about 8400 sq. miles. The area is shown on Fig. 1.1. It extends from the southern boundary of the Hunter Valley near Cessnock southwards to the vicinity of Goulburn. It is bounded on the west by the Great Dividing Range and on the east by the Illawarra Range and a line of low hills rising from the Cumberland Plain. On the upper Nepean River and its headwater tributaries the Avon, Cordeaux and Cataract Rivers there are water storage dams under the control of the Metropolitan Water Sewerage and Drainage Board. The total capacity of these dams is about 390,000 acre feet. Eight weirs have been constructed on the main river between Menangle and Wallacia to offset the reduced flow resulting from the construction of these dams. The total catchment area above these dams (about 350 sq. miles) is small, however, compared with the catchment area (about 3500 sq. miles) above the Warragamba Dam (42% of the entire catchment area of 8400 sq. miles). This dam, which is on the Warragamba River about two miles from its junction with the main river, has a storage capacity of about 1,665,000 acre feet. It is operated by M.W.S. & D.B. to supply a large proportion of Sydney's water needs. The dam has a gated spillway to control the discharges of excess flows and has outlets for the release of water for hydro-electric power generation and for riparian usage. The tributaries of the Warragmaba River, namely the Cox, Wollondilly, Kowmung and Nattai river now flow directly into the storage behind this dam. The Wollondilly and the Nattai Rivers drain the undulating country to the south east of the valley; the Cox's and the Kowmung Rivers drain the mountainous western regions of the valley.

The Grose River, with a catchment area of about 250 sq. miles, joins the main river about two miles upstream from North Richmond. Between Windsor and Wiseman's Ferry the main river is joined by the Colo and Macdonald Rivers. The areas of the catchments of these two rivers are, respectively, about 1700 sq. miles and 350 sq. miles.

Between Penrith and Richmond, large quantities of sand and gravel are being removed by extractive industries from the river and from areas adjoining the river. Significant quantities of sand and gravel are also being removed from the river between Richmond and Pitt Town.

Included in this chapter is a description of the composition of the river bed and banks, the sedimentation of the river and tributaries, unstable portions of the river, causes of bank failure, river flooding and flow behaviour. There are four appendices:-

Appendix 1.I: Bores associated with the Hawkesbury River and its tributaries.

Appendix 1.II: Inspection of sand deposits in the Macdonald River and Webb's Creek.

Appendix 1.III: Samples of river bed and bank material.

Appendix 1.IV: Information disclosed by the dredging undertaking of W. Davidson Pty. Ltd.

Geographic and Geological Features

The greater part of the northern and western areas of the Hawkesbury Valley are heavily timbered and comprise rugged and mountainous terrain with land slopes greater than 15 degrees (1). The undulating to hilly areas are mostly found in the south-west of the valley near Goulburn and Moss Vale. The relatively gentle sloping or flat terrain borders the Hawkesbury River from the vicinity of Camden to Wallacia and from Penrith to a location about 5 miles downstream from Windsor. Figure 8 in Reference 2 is a block diagram which gives an excellent visualisation of the topography associated with the Hawkesbury River between Broken Bay and the Blue Mountains.

Downstream from Penrith and located roughly between the Grose River junction and Wilberforce is a broad flood plain which embraces large areas adjacent to the towns of Richmond, Windsor and Wilberforce. There are smaller areas subject to inundation around the lower reaches of the Colo River, Webb's Creek, the Macdonald River and other creeks downstream from Wilberforce. Figure 1.2 shows the Recent silts constituting the present flood plain between the Grose River junction and Wilberforce and the Pleistocene silts and river gravel outcrops in the vicinity of Windsor and Wilberforce. The high ground on which is situated the town of Windsor is part of what was once an extensive alluvial plain, but is now thoroughly dissected by the Hawkesbury River and its tributaries: South Creek and Rickaby's Creek. The towns of Richmond, Clarendon, Pitt Town and Wilberforce are built on these old high level alluvials which give place to the rounded grassy hills of the Wianamatta Shale country.

Downstream from Wilberforce the flood plain narrows and the hills close in on either side of the river. Further downstream the river, still maintaining its meandering course, flows deeply entrenched through rugged highland which attains a maximum level of about 700 feet. The geological history of the Hawkesbury River and its tributaries is a complex one. About one or two million years ago there began, in the so called Kosciusco Epoch a general uplifting and warping of the coastal areas of Eastern Australia. This process, which brought into being the Great Dividing Range, profoundly affected the streams which had been flowing over the peneplain preceding this epoch. A description of this process and its effects on the Hawkesbury River and its tributaries is given in Reference 2. In addition there have been considerable fluctuations in mean sea level associated with climatic changes (3). According to Figs. 8 and 12 in this reference, (see also

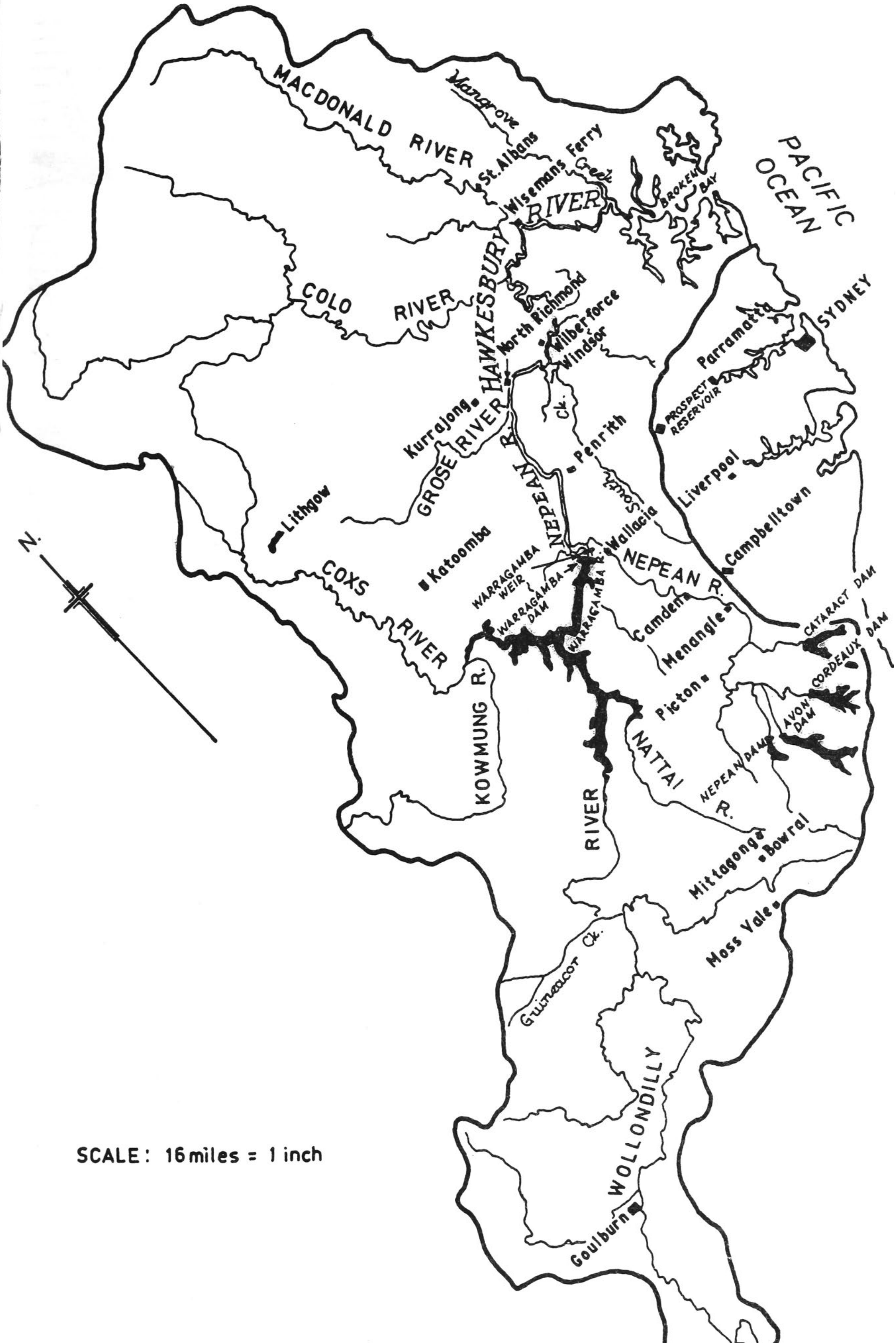


FIGURE 1·1: HAWKESBURY-NEPEAN VALLEY

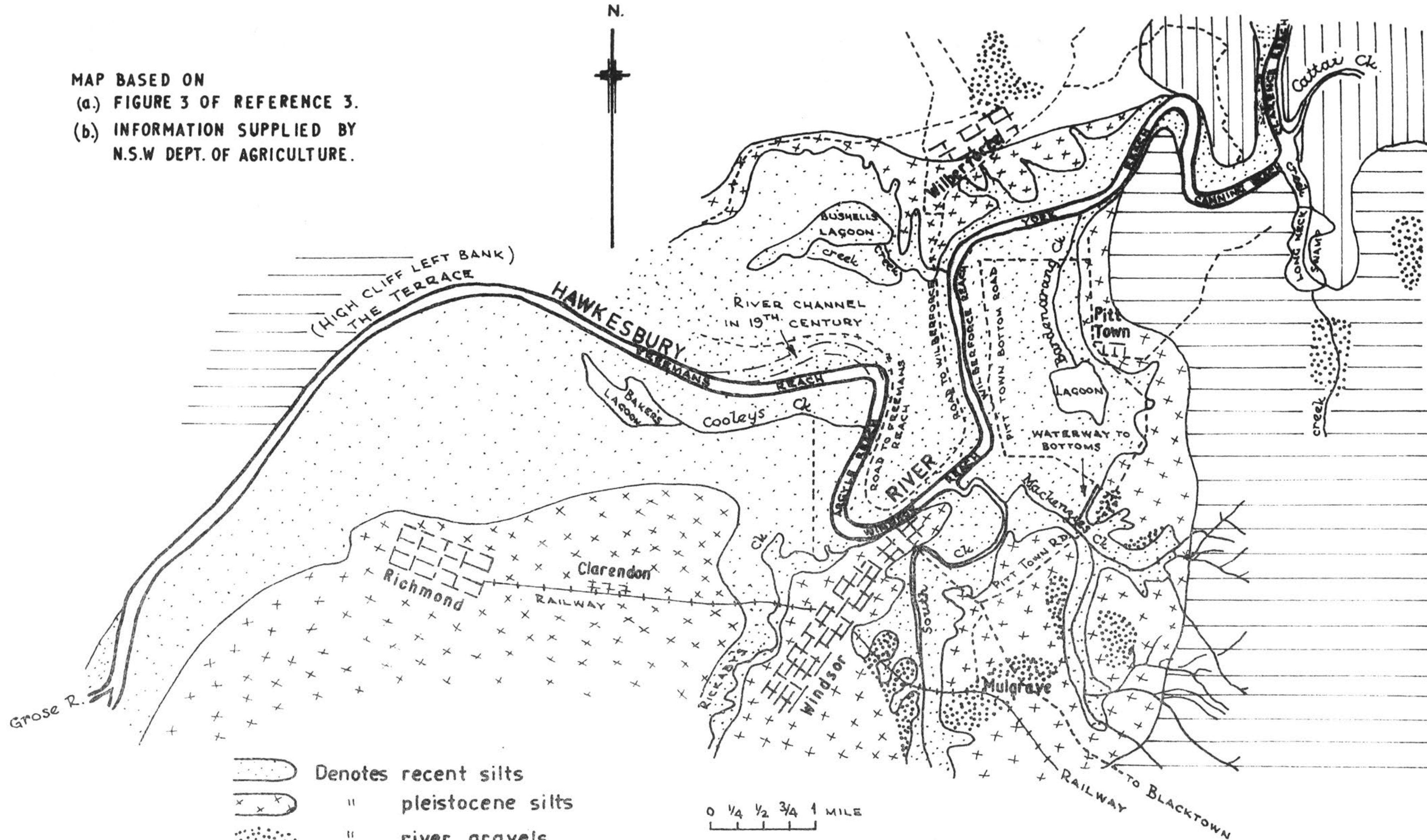
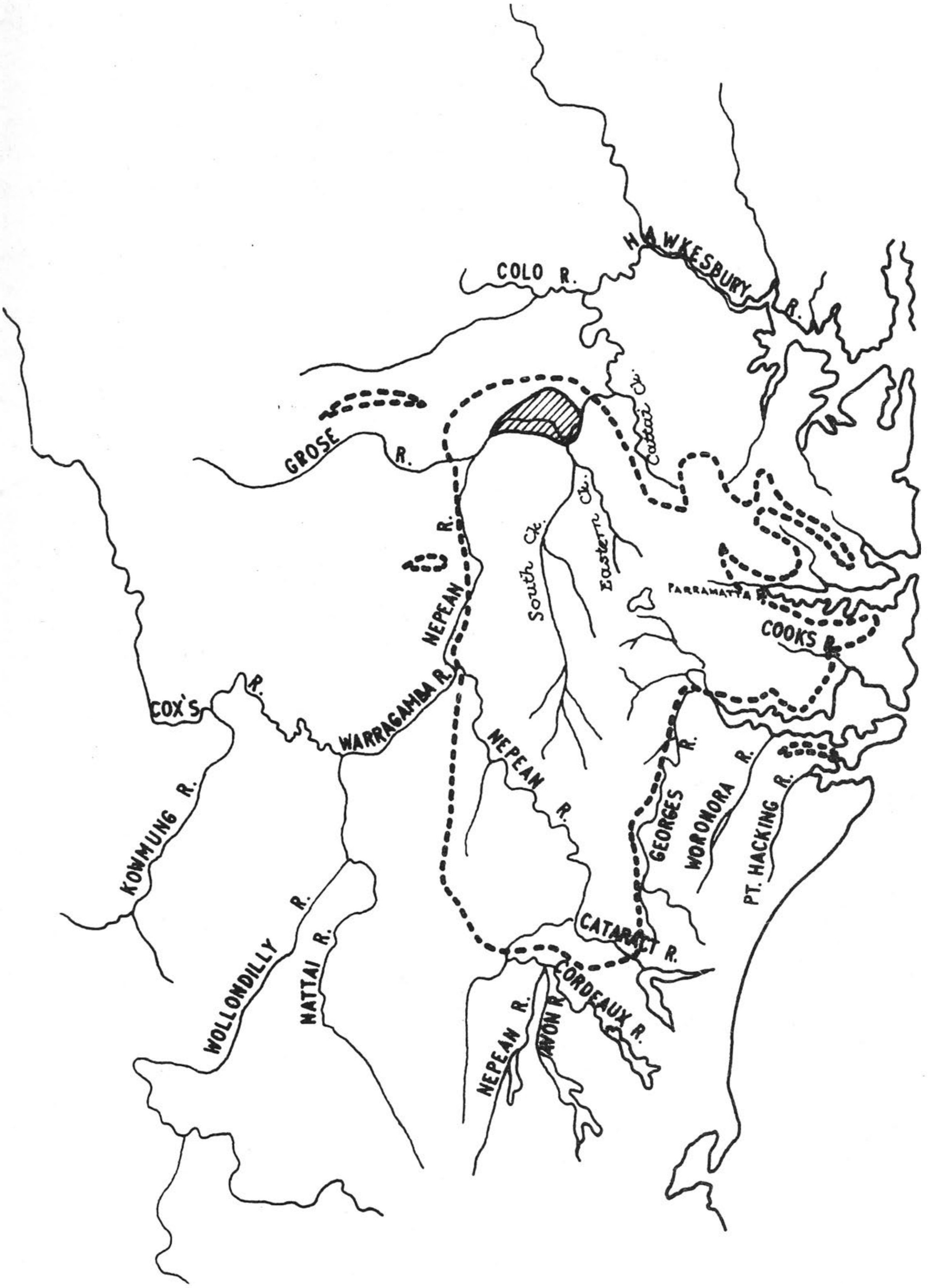


FIGURE 1·2: FLOOD PLAIN OF HAWKESBURY RIVER BETWEEN THE GROSE RIVER JUNCTION AND WILBERFORCE



FROM "THE WIANAMATTA SHALE WATERS" BY A.N. OLD DEPARTMENT OF AGRICULTURE N.S.W.

Boundary of Wianamatta Shale Terrain

Flood plain between Grose Junction & Wilberforce

FIGURE 1·3: SKETCH MAP SHOWING WIANAMATTA SHALE AREA.

Figs. 2.1 and 2.2 in Chapter 2 of this report) mean sea level was 150 feet lower than present level 12,000 years ago, more than 300 feet lower than present level 22,000 years ago and more than 300 feet higher than present level 250,000 years ago, with large upward and downward fluctuations in level occurring between the last two dates. Accordingly, the sedimentation behaviour of the lower river has varied between that of a large drowned estuary and that of a fast flowing upland river; in the latter case the thalweg of the river, when sea levels were minimal, would have approached the longitudinal profile indicated by the rock surfaces shown in Fig. 2.3, Chapter 2. Bores giving these rock surfaces are included in the list of bores given in Appendix 1.I hereunder.

Uplift having occurred so recently on the geological time scale, large quantities of sediment are being brought down the river, the product of active down cutting by the headwaters of the river and its tributaries and the transport of sediment down the steep slopes of the catchment. The sediment load, the bulk of which is transported down the river in times of flood, is brought into the estuarine reaches of the river where the floodwaters are ponded and levee banks are formed. The levees which extend along the lower flood plain reaches of the recently rejuvenated rivers on the east coast of Australia are among the highest in the world.

Near Richmond the levee crests are about 25 feet above the lowest area in the flood plain behind them. The soil on the crests of the levees is a friable loam with a relatively high sand content. Further down, on the land side of the levees, the soil texture becomes finer and the silt content increases. Proceeding down further into the flats the soil becomes finer, denser and heavily charged with silt, clay and organic matter. The finer materials here have been deposited from floodwaters spreading over the flats at reduced velocities. The levees prevent the inundation of the flood plain behind them by freshes and minor floods.

The levee and flood plain areas have fertile soils and are extensively used for a variety of agricultural purposes, including the growing of vegetables, citrus fruits and fodder and dairying on natural and improved pastures. Thus the flood plain between the Grose River junction and Wilberforce has considerable economic significance because of its proximity to the metropolis (the town of Windsor is 34 miles from Sydney by rail and approximately the same distance by road). With the exception of a few small areas, e.g. Liverpool and Canley Vale, where there are local alluvial deposits, the above region with its 25 square miles of rich river flats, is unique in the County of Cumberland. For a general description of the geographic features of the Hawkesbury Valley below Richmond reference should be made to the paper by L.D. Hall (4).

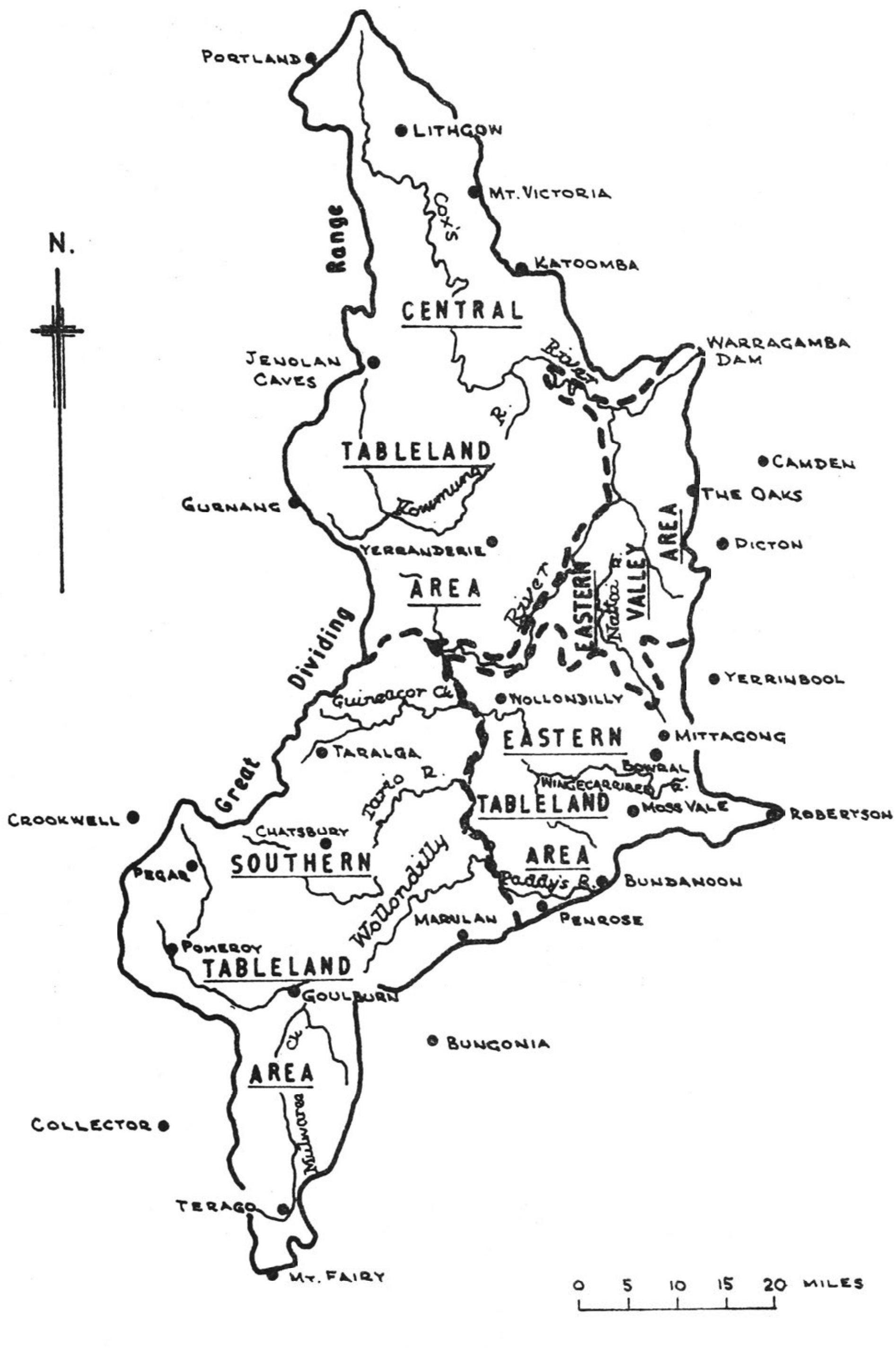
Figure 1.3 shows the extent of the Wianamatta Shale area. Apart from the recent alluvials the Wianamatta soils are of indifferent quality. Outside the Wianamatta shale area, the greater part of the Hawkesbury Valley is barren sandstone. These shales have a high salt content originally derived from their formation in a marine environment. Seepage through the shales dissolves some of these salts and carries them into adjacent alluvial material with a resulting increase in the salinity of groundwaters which may render them unfit for irrigation. The Hawkesbury sandstones have little or no salt content, being of fresh water origin, and hence have negligible effect on the quality of groundwater. Map 3 in Reference 5 shows the salt distribution in Wianamatta Shale sub-surface waters. As indicated on this map, the salinities of the sub-surface waters in the vicinity of the river upstream from Penrith can exceed half that of sea water; downstream from Penrith the salinities can approach half that of sea water.

The section of the river flats between Penrith and Castlereagh is an important area of primary production, principally dairying and the growing of lucerne and pasture in association with same. Fruit and vegetables are also grown in the area. Over a large portion of the flats wells are the major source of water supply. These wells are recharged, in the main, from the river, the weir at Penrith facilitating this process. A benefit from Warragamba dam is discharge in dry weather which assists in keeping water flowing over Penrith Weir, thus allowing continual recharge. Away from these areas of replenishment by the river and in areas adjacent to the Wianamatta Shales, well salinities tend to rise to levels which make the waters unfit for stock or irrigation. Groundwater conditions and valuable geological information on the terrain associated with the upper Hawkesbury River is given in Reference 6. In this reference certain adverse effects of extractive industries on groundwater supplies are described.

Unstable Portions of the River

Unstable portions of the river inspected by the writer are the portion of the river at the junction with the Grose River, the lower end of Freemans Reach and the upper and lower ends of Argyle Reach. The positions of the Hawkesbury River channel and the Grose River channel at the junction of these two channels changed sometime in the 19th century (7) and heavy local bank damage at the junction is said to have occurred in the November 1969 flood. At the lower end of Freemans Reach, the river channel has moved south about $\frac{1}{4}$ mile in a little over a century (8, 9), the greater part of this movement having occurred suddenly (according to Lands Department records and advice from local people) in one of the big floods in the period 1864 to 1867. The upper and lower ends of Argyle Reach have also moved, respectively eastwards and westwards some hundreds of feet in a little over a century (9, 10). It is precisely in these unstable portions of the river where the channel has been shifting that the most extensive bank damage has been occurring; the banks on the side of the river which oppose the channel shift suffering the damage. These are the banks of the river which are being given special attention in the programme of flood mitigation works described in the report of Ref. 11.

Extensive erosion has been occurring to the banks of the river downstream from Glenbrook Creek. This is particularly marked downstream from Penrith Weir. To quote from Ref. 11: "The alignment and waterway area of the Hawkesbury River below Penrith Weir has been



CATCHMENT AREA - APPROX. AREA: 3,530 SQ. MILES

FIGURE 1·4: WARRAGAMBA CATCHMENT AREA

adversely affected by gravel mining operations." The effects of the removal of sand and gravel by extractive industries are dealt with in Chapter 4. Upstream from Glenbrook Creek, between Wallacia Weir and Menangle, the river has been blocked by snags and vegetation which have increased the severity of floods in areas adjoining this portion of the river.

Causes of Bank Failure

Bank failure on the Hawkesbury consists of two processes occurring singly or in combination, namely direct erosion by fast flowing water or bank sloughings induced by the loss of stability of waterlogged banks during flood recessions and the leaching of bank material by tunnelling (also called "piping"). These sloughings may, or may not be initiated by direct river current erosion at the toes of the banks. Bank sloughings can be made less frequent if the flood height recession rates are diminished and if accumulations of water in local depressions behind the banks are eliminated. The gates of the Warragamba Dam are so operated in the falling stages of floods as to minimise the flood height recession rates.

The leaching of bank material by tunnelling is a process that can increase with time (see pages 509, 510 of Ref. 12), and, if allowed to go on, the material behind the eroding bank may become so deteriorated as to require the provision of an elaborate subsurface drainage system such as that required to stabilise a badly eroding section of bank at the upper end of Argyle Reach. About 2000 feet of bank were involved at this location, and the total cost of the work, including rock for toe protection was about $150,000 (the work was carried out in 1957). Tunnelling is described in papers published in the Journal of the Soil Conservation Service (13, 14, 15, 16 and 17). Tests to ascertain the susceptibility to tunnelling (the "dispersability" index) of soils are described in Ref. 13. Chemical treatments are described in Refs. 17 and 18.

Sedimentation of the River and Tributaries

The catchment above the Warragamba is shown in Fig. 1.4. This catchment has, in the past, been extensively settled and erosion of the soil in various degrees has followed (19). However, since 1959, the date of publication of this reference, an extensive programme of remedial soil conservation works has been commenced in the areas which have been affected by settlement (most of the areas requiring soil conservation works have been alienated lands under arable use and grazing). Erosion due to natural agencies will continue and it has been estimated (20) that this will result in dam siltation at the rate of 250 tons per square mile per annum. The steep streams (the Cox's, Kowmung and Nattai Rivers and Guineacor Creek) carry large coarse bed loads and debris. The streams with relatively small gradients (the upper Wollondilly River and Mulwaree Creek) carry large suspended loads. The Wingecarribee River and Paddys River flow through swamps and do not transport large quantities of material (21).

The Warragamba Dam was completed in 1959. Earlier in 1952 the dam works began to hold back large quantities of sediment. Plots of concentrations of suspended sediment vs. discharges in the Warragamba River have been made by the Metropolitan Water Sewerage and Drainage Board. The suspended sediment is wash load and the concentration vs. discharge relationship before the construction of the dam does not differ significantly from the relationship after the construction of the dam. From the plotted points (22) and the flow duration curve (23) it is estimated that the Hawkesbury River received annually 600,000 tons of sediment from the Warragamba catchment, in the form of wash load, before the construction of the dam. On the basis of flood information supplied by Mr. B. Greiss of the M.W.S.& D.B. (personal communication) and the abovementioned suspended sediment vs. discharge rating curve it is estimated that wash load now passes the dam at the average rate of 400,000 tons per annum. This implies that sediment at the rate of 114 tons per sq mile per annum of the catchment above the dam now passes the dam. Adding this rate to the abovementioned dam siltation rate of 250 tons per sq. mile per annum a total sediment supply rate of 364 tons per sq. mile per annum a total sediment supply rate of 364 tons per sq. mile per annum is obtained for the dam catchment. In other words, before the construction of the dam the Hawkesbury River received annually 3500 x 364 = 1,275,000 tons of sediment. Now the river receives annually 3500 x 114 = 400,000 tons of sediment and sediment at the rate of 875,000 tons per annum is accumulating behind the dam. The significance of these figures is given in Chapter 4.

There are heavy sand deposits in the lower Macdonald River and, to a lesser extent in the Colo River and Webbs Creek. These deposits have resulted from erosion of the steep sandy slopes associated with these streams. Erosion is caused by bushfires and over-frequent burn-offs, timber getting, unstable fire trails and other access tracks and poor farming and grazing practises (11). A report on an inspection made in 1969 of deposits in the Macdonald River and Webb's Creek is given in Appendix II. The sanding up of the Macdonald River has been going on over a long period; in 1926 (4) the river bed was entirely filled with sand at St. Albans, the only water present being a chain of ponds.

In November 1971 the Public Works Department of N.S.W. organised a hydrographic survey of part of the river for this project. Drawings were prepared showing cross sections of the river channel, extending from the junction with the Grose River to Wiseman's Ferry (24).

In April 1971 an echo sounding run of the river was made, commencing at Pumpkin Point, 17.5 miles from the ocean entrance and finishing at Pitt Town Wharf, 73.7 miles from the ocean. From this run it was evident that between these two locations there had been no significant alteration in channel depths since the survey of the river in 1872 by Lieutenant Gowlland (25).

Composition of the River Bed and Banks

Samples of river bed and bank materials were taken along the river in 1971. Sampling commenced at a point just below Wiseman's

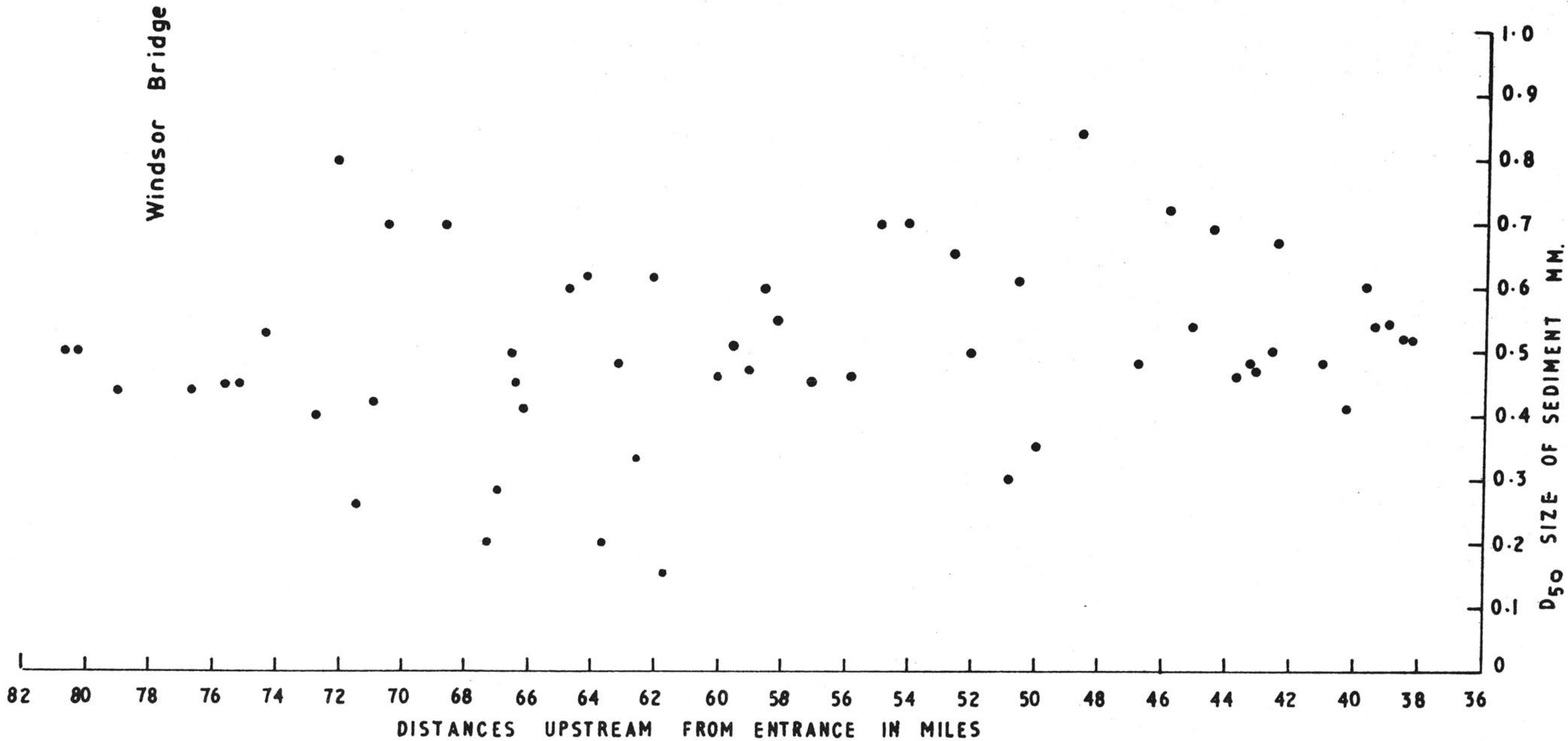


FIGURE 1·5: PLOT OF D_{50} SIZES OF SEDIMENTS SAMPLED FROM BED OF HAWKESBURY RIVER IN APRIL 1971.

Ferry, 38.2 miles from the ocean, and finished at a point in Freemans Reach, 80.8 miles from the ocean. A description of these samples and figures showing their location are given in Appendix 1.III. Average grading curves of samples from the river bed and banks are given in this appendix, included is the average grading curve of samples from the river bed between Richmond Bridge and Windsor Bridge taken in 1970. Also included are the results of the sampling of the deposits between Richmond and Wilberforce of the November 1969 flood. These samples were taken by teachers and pupils of Richmond High School.

Fig. 1.5 is a plot of the D_{50} sizes (i.e. median grain sizes) of river bed material sampled in April 1971. The bed of the river between Richmond Bridge and Wiseman's Ferry is mainly sand, the average percentage of material less than 0.074 mm being 3.7%. Most of this finer material was found in the deeper (generally bends) portions of the river downstream from Windsor Bridge. The following table is based on Fig. 1.5 and the grading curves in Appendix 1.III.

Table 1

Material Sampled	D_{50}	Percentage of Material $\leq$.074 mm
River bed between Richmond Bridge and Wiseman's Ferry	0.45mm-0.5mm	3.7%
River bed between Richmond Bridge and Windsor Bridge	0.45 mm	0
River bed between Windsor Reach and Portland Reach (from shallower and generally straight portions of reaches	0.45 mm	0
River bed between Portland Reach and Wiseman's Ferry (from shallower and generally straight portions of reaches)	0.55mm	0
River bed between Canning Reach and Portland Reach (from deeper portions of reaches, generally in bends)	0.37mm	11%

Table 1 (cont'd.)

Material Sampled	D_{50}	Percentage of Material $\leq .074$ mm
River bed between Sackville Reach and Lower Half Moon Reach (from deeper portions of reaches, generally in bends)	0.53 mm	8%
River levee banks Free-mans Reach to Canning Reach	0.13 mm	34%

Table 2 gives the D_{50} sizes of bed material in other rivers:-

Table 2

Material Sampled	D_{50}
Bed of Moruya River (26)	
Average for bed between 4 miles and 13 miles upstream from entrance (limit of tidal influence about 12 miles from entrance)	0.45 mm
Average for entrance reaches	0.20 mm
Bed of Clarence River (27)	
Average for bed between 27 miles and 42 miles upstream from entrance (limit of tidal influence about 67 miles from entrance)	0.38 mm
Average for entrance reaches	0.2mm
Bed of Tweed River (28)	
Average for bed between 11 miles and 17 miles upstream from entrance (limit of tidal influence about 19 miles from entrance.	0.45mm
Average for entrance reaches.	0.2 mm
Bed of Hunter River (R. Nittim Uni. N.S.W. personal communication)	
Average for bed between 36 miles and 38 miles upstream from entrance)	0.55 mm
Sizes of bed material decrease with distance downstream.	

Comparing the two tables, it appears that D_{50} = 0.45 mm is the size that is probably representative of the middle and upper tidal reaches of N.S.W. coastal rivers. The smaller D_{50} sizes in the entrance reaches of the rivers given in Table 1 are consistent with the general tendency, due to processes of abrasion, of the median grain size of river bed materials to diminish with distance downstream (29). Little is known, however, about the processes of sorting and the contributions of sediments from tributaries which

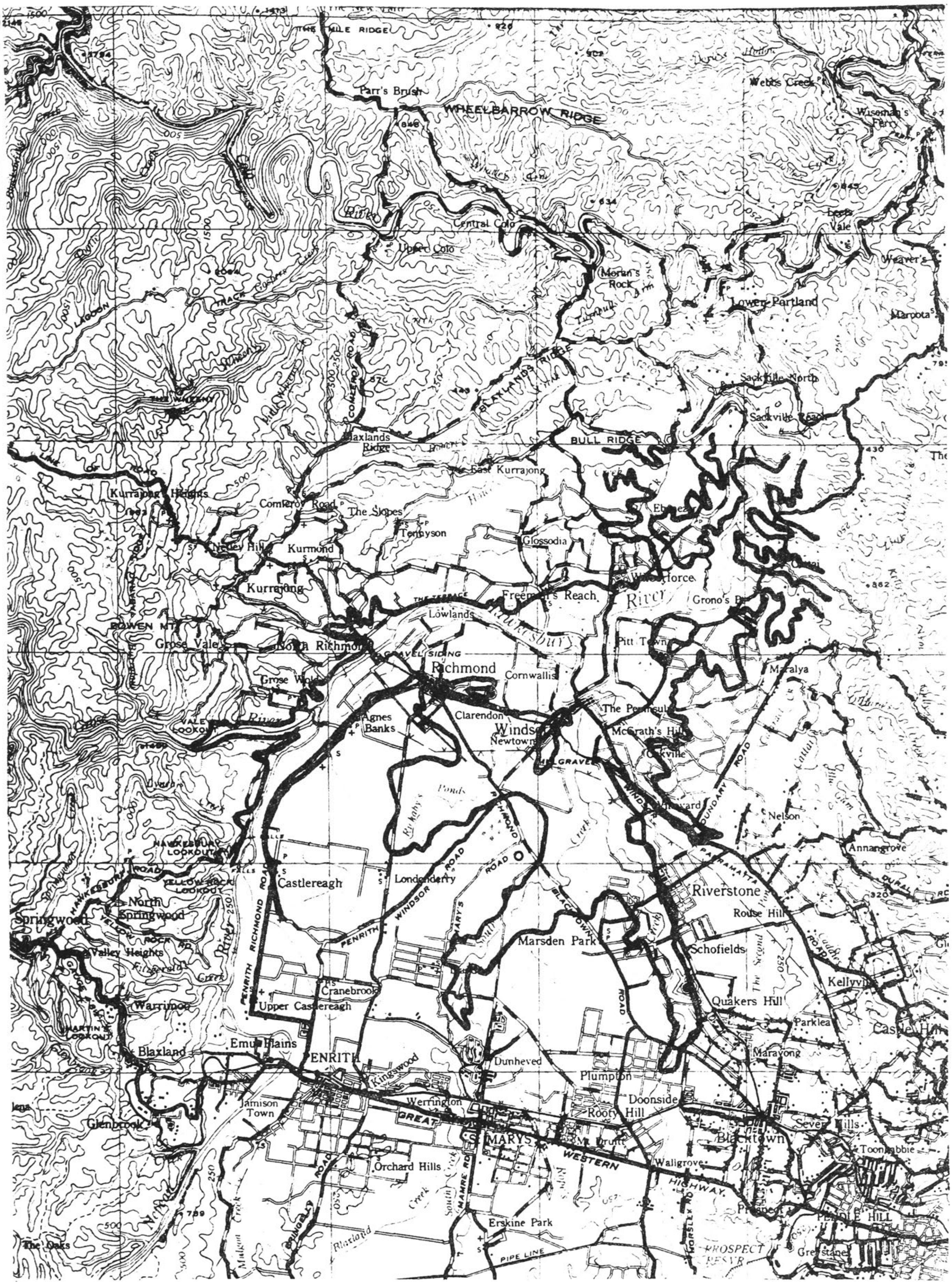


FIGURE 1·6: AREAS BETWEEN CASTLEREAGH & SACKVILLE INUNDATED BY THE FLOOD OF 1867. (Peak Height at Windsor 63·7 Standard Datum.) Charted from the map in "History of Floods in the Hawkesbury River" 1886, by J. P. Josephson.

can provide exceptions to this tendency. Fig. 1.5 shows the tendency for the D_{50} size of bed material in the Hawkesbury River to increase in size from about 0.45 mm to 0.55 mm in about 45 miles, proceeding downstream. This anomaly might be due to an oustanding feature of this river, namely that in the portion under consideration, the river is flowing from a region of low relief (the region associated with Richmond, Windsor and Wilberforce) into highlands through which it has cut its way to the sea. In the latter incised region the river is receiving debris from sandstone cliffs and material from tributary rivers and creeks with eroding sandstone catchments.

The median grain size of the material (D_{50} = 0.13mm) in the levee banks is much finer than that of the bed material. The percentage of material $<$0.74mm is much higher than that of the bed material. The significance of this percentage, which can be regarded as an indicator of the stability of the levee banks, is discussed in Chapters 4 and 7.

Figure 1.III.13Appendix III shows the average grading curves of samples of sediments deposited by the November 1969 flood. The samples were taken just after the flood and their grading curves were distributed about one or the other of the two average grading curves shown. These bimodal distributions reflect two depositional regimes; deposition of sandy material from the faster flowing phases of the flood and deposition of silts from the slower flowing phases. This bimodality was not evident in samples of bank material taken in 1971, the 1969 flood deposits having been homogeneized by rainfall, runoff and biotic activity in a little over a year.

Appendix IV gives information disclosed by the dredging undertaking of W. Davidson Pty. Ltd. in the Windsor Reach of the river. Noteworthy is the fact that the composition of the river bed material over the dredging site did not vary with depth down to 35 feet below low water. This encourages the belief that the surface and near surface samples of river bed material taken in April 1971 are representative of bed material in the same category at lower levels.

River Flooding and Flow Behaviour

Figure 1.6 shows areas between Castlereagh and Sackville which were inundated by the flood of 1867 which reached a peak height at Windsor Bridge of 63.7 feet Standard Datum. This has been charted from a map made by J.P. Josephson (30). From the historical information available in the Mitchell library it is considered that this was the highest flood (with reference to the peak at Windsor bridge) since the earliest days of settlement. The flood behaviour of the river before and after the construction of the Warragamba Dam is given in References 11, 31 and 32. Until the science of short term weather forecasting has advanced to the stage that it will enable the gates of the Warragamba Dam to be operated predictively for purposes of flood mitigation, it would be prudent to restrict land occupation and land use to limits imposed by the 1867 flood.

A study of streamflow records at Penrith for the period since 1891 discloses that for a given peak discharge at Penrith, the peak flood height at Windsor Bridge may vary over a considerable range (31). The flood discharges in the Grose River are partly responsible, but the backwater effects of floods in the Colo and Macdonald Rivers are the principal causes of this variation. Additional evidence on these effects was obtained by the writer in 1973 (33).

From personal observations, the maximum flood velocities of the river between Richmond and Pitt Town are generally less than 10 ft. per second. Violent eddies can, however, develop in sharp bends in floods. Such eddies occur in the bend between Freemans Reach and Argyle Reach where banks have suffered considerable damage. Big eddies can be seen in the bends of the river in photos of the 1964 flood in the possession of Colo Shire Council. Huge eddies are said to be formed in the sharp bend at Gunderman (Co-ordinate point 080670 on military map "Gosford and Norahville") in major floods (34). In the echo sounding run that was made in April 1971, it was noted that on the inside of some of the bends the sounder trace took the form of a jagged "fuzz" that could have been indicative of an irregular bottom composed of fallen rocks. Indeed at these locations there were cliff scars and masses of perched rocks which attested to past and future falls. At these bends it was clear, from the appearance of the water and the "shuddering" of the boat, that there was pronounced eddying even under conditions of dry weather flow which obtained at the time of this survey. In floods it is clear that this eddying becomes violent in these bends, developing sufficient energy to break up and abrade the fallen rocks and facilitate the transport of this material downstream. In fact this appears to be the mechanism whereby the river clears away the fallen rock debris (and thus prevents the damming up of the river) and maintains the deep pools at the bends. A discussion of this type of turbulence is given in Ref. 35.

Oblique photographs of the river, from the Warragamba Dam to Castlereagh, were taken by Richmond R.A.A.F. for this study. The negatives and a set of prints have been lodged with the Library of N.S.W.

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APPENDIX I TO CHAPTER 1.

Bores associated with the Hawkesbury-Nepean River and its tributaries

The locations of these bores are shown in Figures 1.I.1, 1.I.2 and 1.I.3. A longitudinal section showing the depths to rock disclosed by bores 10a, 10, 22, 6, 9, 17a, 17, 18 and 11 is given in Figure 2.3 Chapter 2.

The following list gives information on the bores; the numbers assigned to the bores are those in Figures 1.I.1, 1.I.2 and 1.I.3.

1. & 2. Bridges at 7.7 miles and 9.7 miles from Webb's Creek on M.R. 181. Refer to Rankine and Hill, Consulting Engineers.

3. Bridge over Little Wheeney Creek, Old Bells Line Road, Kurrajong. Refer to Willing, English & Devin, Consulting Engineers.

4. Colo Valley Bridge, Upper Colo Road. Refer to Willing, English & Devin, Consulting Engineers.

5. Bridge Grose River Road. Refer to Willing, English & Devin, Consulting Engineers.

6. Colo River Bridge, Lower Portland, Public Works Department of N.S.W. Plan Cat. No.1-228 65/66.

7. Webb's Creek Bridge near Webb's Creek Ferry. Department of Main Roads.

8. Bridge Turnbull's Arm. Refer to Rankine and Hill, Consulting Engineers.

9. Bridge Addy Creek. Refer to Rankine and Hill, Consulting Engineers.

10. Bridge over Hawkesbury River at Mooney Mooney. Department of Main Roads.

10a. Railway bridge over Hawkesbury River at Brooklyn. Railways Dept. Plan Cat. 968-31838.

11. Bridge over Nepean River at Regentville Department of Main Roads. Plan Cat. X4B101.

12. Bridge over Mulgoa Road, Department of Main Roads. Plan Cat. X4B103.

13. Ropes Creek Bridge. Department of Main Roads. Plan Cat. 5B226.

14. South Creek Bridge. Department of Main Roads. Plan Cat. X4B106.

15. Eastern Creek Bridge. State Highway No. 5 Department of Main Roads.

APPENDIX I to CHAPTER 1 (cont'd.)

16. High Level Bridge over Nepean River at Camden. State Highway No. 2. Department of Main Roads. Sketch No. 4.

17. Bridge over Hawkesbury River at Windsor Public Works Department of N.S.W. Plan dated 1891.

17a. Bardenarang Creek, Pitt Town Bottoms. Public Works Department of N.S.W. Plan Cat. 222/65.

18. Bridge over Hawkesbury River near Richmond. Public Works Department of N.S.W. Plan dated 1891.

19. Railway Bridge at Penrith. Railways Department. Plan dated 1862. Ground surface and rock surface only.

20. Windsor Water Supply Pumping Station. Public Works Department of N.S.W. Micro Film No. 16049.

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22. Proposed bridge over Hawkesbury River at Wiseman's Ferry. Department of Main Roads. Coffey and Hollingsworth Consulting Engineers. Drawing No. 1868/1.

23 to 32. Sites for proposed weirs on the Nepean River. Water Conservation and Irrigation Commission. Plan Cat. No. 45/19.

33. Camden Line. Proposed railway bridge over the Nepean River, Railways Dept. Plan Cat. No. 605/213.

FIGURE 1·I·1: LOCATION OF BORES

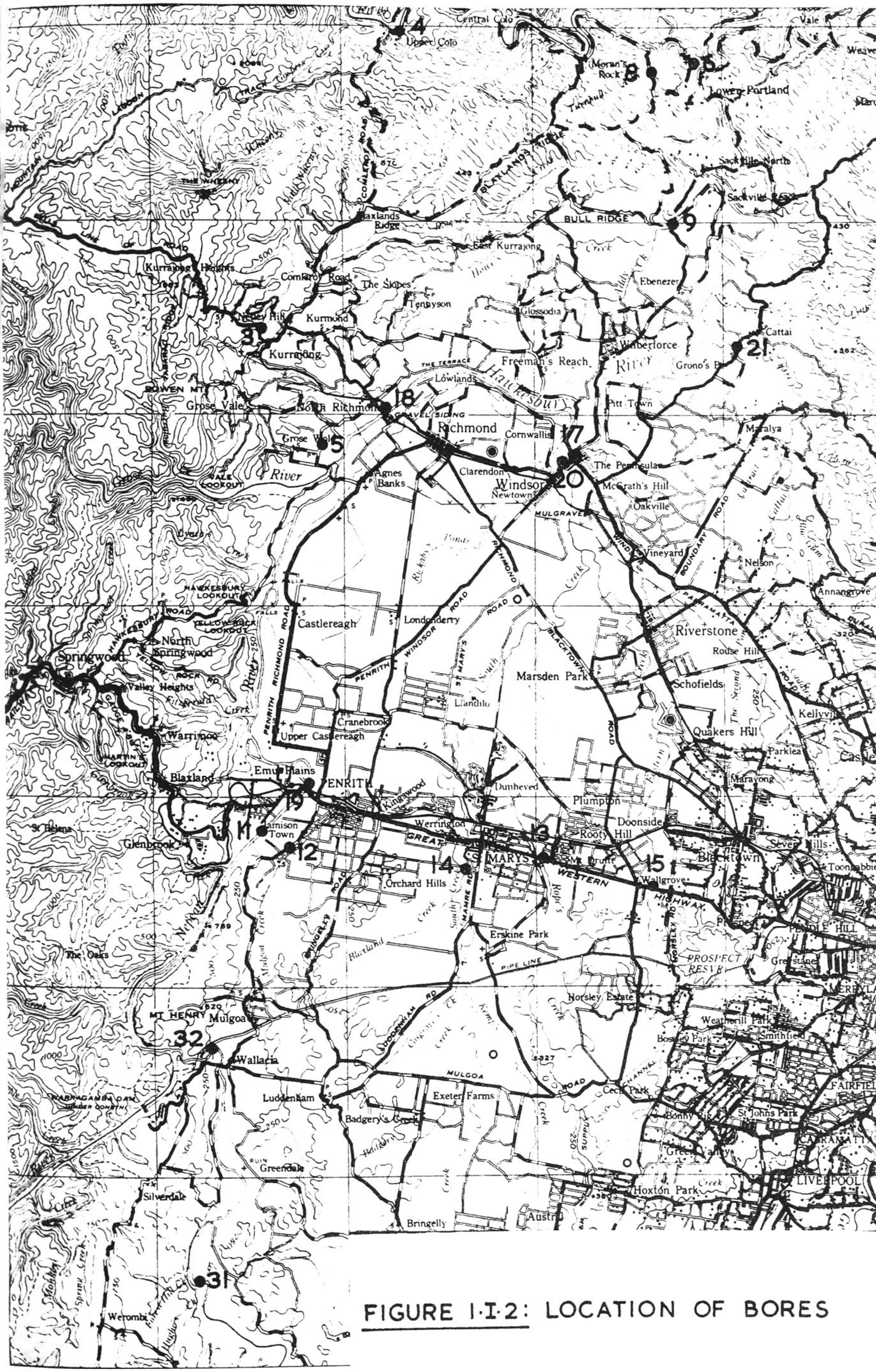


FIGURE 1·I·2: LOCATION OF BORES

FIGURE I·I·3 : LOCATION OF BORES

APPENDIX II to CHAPTER 1.

Inspection of Sand Deposits in the Macdonald River and Webbs Creek on 30.10.69.

On 30.10.69 an inspection of sand deposits in the Macdonald River and Webbs Creek was made by representatives of the Colo Shire Council, the State Planning Authority, the Mines Department, the Lands Department and the Public Works Department of N.S.W. The representatives were as follows:-

Mr. Bailey,	President of Colo Shire Council
Mr. McSullea,	Shire Clerk " " "
Mr. Cranston,	Shire Engineer" " "
Mr. Shearman,	State Planning Authority
Mr. Probert,	Mines Department
Mr. Cremer,	" "
Mr. Simmons,	" "
Mr. Fenton,	Lands Department
Mr. Williams,	" "
Mr. Scholer,	Public Works Department

The inspection disclosed extensive deposits of sand, as regards areas of coverage, in the Macdonald River. The extent of the deposits in Webbs Creek appeared to be much smaller.

The depths of the sand in the Macdonald River deposits, and hence the quantities of sand available, could not be estimated with any accuracy. Mr. Bailey said that large areas had been covered to depths of 8 to 9 ft. by sand brought down by floods in the last twenty years.* Mr. Probert said that the depths of sand would be more accurately known after a geophysical survey to be made in the future by his department.

From the point of view of extractive industries most promising areas of deposits in the Macdonald River appear to be located between the junction with the river of Wright's Creek and the junction with the river, about five miles north, of Wallambine Creek (also referred to as Mago Creek). Downstream from the Wright's Creek junction, Mr. Probert thought there were also considerable deposits of sand, but these were probably admixed with higher proportions of silt than are the deposits upstream from the junction. In any location, in the regions inspected, the extracted material would require washing to rid the sand of silt and organic matter. However, it appeared that the proportion of these contaminants in the deposits were no higher, and are probably less than the proportions in the deposits which were being worked in the Hawkesbury River upstream from Pitt Town and in the Georges River at Chipping Norton.

* See addendum at the end of this report.

Mr. Fenton said that, apart possibly from the bed of the river below the limit of tidal influence, the above deposits were on private property. The limit of tidal influence is at St. Albans, about halfway, measured along the river, between the junctions of Wright's Creek and Wallambine Creek. However, as Mr. Fenton pointed out, downstream from the limit of tidal influence the position as regards titles to the river bed required investigation. Access from the road adjoining the deposits would be no physical problem; however, rights of access would have to be negotiated with private landowners.

Mr. Cranston gave rough estimates of the costs of roadwork required to accommodate trucks hauling material from these deposits. As regards trucks hauling sand to Sydney, the Windsor and Richmond region and the Parramatta region, Main Road 181 on the southern of the Hawkesbury River, and roads nearer these centres, were adequate. The ferry at Wiseman's and, consequently, the road leading to it on the eastern side of the Macdonald River, were to be preferred to the ferry at Webbs Creek and the road leading to it on the western side of the river.

The ferry available at Wiseman's had a bigger capacity and would run more continuously than the Webbs Creek ferry. Mr. Cranston considered that the ferry at Wiseman's could take four 20 ton trucks per trip and could make four trips per hour - in other words the ferry could accommodate about 300 tons of sand per hour. This capacity was ample, in view of Mr. Probert's estimate that an output of 3000 tons of sand per week for an indefinite period would be an attractive proposition for an extractive firm.

Mr. Cranston estimated that it would cost about $250,000 to recondition the road between Wright's Creek and Wiseman's Ferry and about $45,000 per mile for the five miles of road running alongside the deposits between Wright's Creek and Wallambine Creek. The total cost of the road works for the Macdonald River deposits would be, therefore, $250,000 + 5 x $4,500 = $475,000, <u>say</u> $500,000.

According to Mr. McSullea, Davidson Wash Sands Pty. Ltd. was getting $1.40 per ton of sand at its bin at Windsor. According to Mr. Cranston, the cost of haulage of sand was about 7 cents per ton-mile. Hence, since the deposits in the Macdonald River were about twenty miles further away from Windsor, Parramatta and Sydney than the Davidson Wash Sands Pty. Ltd. bin, the extra cost of sand to builders in these centres would be about be about 7 x 20 cents = $1.40. Again, assuming that the haulage distance between Windsor and Sydney was forty miles, the cost of Windsor Sand delivered to Sydney would be about $1.40 + 7 x 40 cents = $4.20 per ton as against $1.40 + 7 x 60 cents = $5.60 per ton (assuming that the cost per ton at a McDonald River bin would be the same as the abovementioned cost per ton at the Windsor bin and that the Macdonald River deposits are 60 miles from Sydney). On the other hand, as Mr. Williams pointed out might be the case with Gosford, urban development in the coastal region east of the Macdonald River might favour the deposits in this river as regards the cost of supply of sand. In these estimates neither the costs of the road works nor the costs of road maintenance associated with these deposits had been taken into account.

It was considered that controlled extraction of sand from these deposits would not result in any harmful effects on the Macdonald River, the Hawkesbury River or the adjoining farmlands. Indeed controlled extraction could be beneficial insofar as the diminution of the large deposits upstream from Wrights Creek might prevent farmlands downstream being covered with sand as a result of future floods. (The extensive stands of young poplar trees downstream from Wrights Creek are particularly vulnerable in this regard). Controlled excavation implied that the location of, and quantities of material removed should be in accordance with conditions established by the appropriate authority after an adequate investigation of river regime had been made. The conditions would be designed to ensure that no damage to banks, farmlands or wildlife areas would result from extractive activities. In the matter of wildlife areas Mr. Shearman expressed concern for the preservation of lagoons as bird sanctuaries.

As pointed out previously, the extent of the deposits in Webbs Creek appeared to be much smaller than those in the Macdonald River Moreover the terrain such that road access would be difficult even if a sum comparable to that estimated for the Macdonald River were to be spent on roadworks. The Webbs Creek deposits were not, therefore, considered to be an economic proposition for extractive industries in the foreseeable future. The deposits in the Colo River, which were not inspected, were not considered to be suitable in quantity or quality for extractive industries interested in sand.

Tentative Conclusion

The deposits in the Macdonald River appeared to be promising sources of supply of sand for the building industry. An estimate of quantities of sand available would be made as a result of a geophysical survey which was to be made by the Mines Department in the near future. The deposits in Webbs Creek and the Colo River were not considered to be economically feasible sources of supply of sand for the building industry.

About half a million dollars would have to be spent on road works for access to the Macdonald River deposits. All, or nearly all of these deposits were on land which was privately owned. Disregarding the expenditure on road works and maintenance, the cost to the building industry in Sydney of sand from the Macdonald River would be about 33-1/3% in excess of that of sand from the Windsor and Richmond region ($5.60 per ton as against $4.20 per ton, these figures being comparative only). With urban development in the coastal region east of the Macdonald River these deposits would become more economically attractive. It was considered that controlled excavation would not result in any harmful effects on the river or adjacent farmlands provided that the controls were based on an adequate physical investigation of the regime of the river.

Offsetting the extra cost of sand from the Macdonald River was the fact that controlled extraction from these deposits would probably not have the harmful effects which, very likely, would be the result of large scale extractive activities in the vulnerable Windsor and Richmond areas of the Hawkesbury River.

Addendum

For the causes of the erosion responsible for the sanding up of the Macdonald and Colo Rivers and Webb's Creek,reference should be made to the report by the Soil Conservation Service which is Appendix 3 in the publication entitled "Interim Report on Short Term Flood Mitigation Works and Measures in the Nepean - Hawkesbury Valley, February 1968". Available from the Department of Conservation N.S.W."

APPENDIX III TO CHAPTER 1.

Bed and Bank Materials

This appendix contains a description of the samples of river bed and bank material taken in April 1971, figures giving the location of the samples and the average grading curves of same. An average grading curve of samples of the river bed between Richmond Bridge and Windsor Bridge is included.

Also included is a description of the samples of deposits of the November 1969 flood taken by teachers and pupils of Richmond High School, figures giving the location of the samples, the average grading curves of the samples and the stage-height curves of the November 1969 flood.

Samples of the river bed material taken in 1970 and 1971 were taken with grab and tube samplers. Samples taken by grab and tube from the same site were tested. It was found that the composition of the samples did not differ appreciably. Samples were usually taken with the grab - however tube samples were taken in locations where the nature of the bed precluded the use of the grab.

Each sample of bank material was taken by coring the bank, the core penetrating to a depth of $2\frac{1}{2}$ inches beneath the surface.

Hawkesbury River

Samples of River Bed and Bank Material taken by H.A. Scholer over period 5.4.71 to 8.4.71.

Sample	Description and Location ("P" is percentage of material < .074mm)
1A	From river bank on Richmond side. A composite of 3 samples of approx. the same size (all such samples were taken just above high water, halfway up the bank and near the top of the bank). About a mile upstream from the bend at the lower end of Freeman's Reach. Clayey, silty, fine and medium sand, P = 22%, D_{50} = 0.22 mm.
2A	Composite of 4 samples (all such samples equally spaced across the channel) taken from the river channel bed. Adjacent to 1A. Coarse and medium sand. P = 0. D_{50} = 0.5 mm.
3A	From river bank on Wilberforce side. A composite of 3 samples of approx. the same size (all such samples were taken just above high water, halfway up the bank and near the top of the bank). Low bank of river flat where levee corresponding to that on the Richmond side has not yet been formed. Here river has moved about $\frac{1}{4}$ mile south in a little over a century. Adjacent to 1A. Coarse, fine and medium sand, little silt. P = 8%, D_{50} = 0.4 mm.
1B	From river bank on Richmond side. A composite of 3 samples. About half a mile upstream from the bend at the lower end of Freeman's Reach. Clayey, very silty, medium and fine sand. P = 39% D_{50} = 0.11 mm.
2B	Composite of 4 samples taken from the river channel bed. Adjacent to 1B coarse and medium sand. P = 0 D_{50}=0.47 mm.
3B	From river bank on Wilberforce side. A composite of 3 samples. Adjacent to 1B. Low bank of river flat where levee corresponding to that on the Richmond side has not yet been formed. Here river has moved $\frac{1}{4}$ mile south in a little over a century. P = 10%, D_{50} = 0. 23 mm.
1C	From river bank on Richmond side. A composite of 3 samples. About halfway along Argyle reach. Clayey, very silty, medium and fine sand. P = 40%, D_{50} = 0.12 mm.
2C	Composite of 4 samples taken from the river channel bed. Adjacent to 1C. Coarse and medium sand. P = 0, D_{50}=0.44mm.
3C	From river bank on Wilberforce side. A composite of 3

	samples. Adjacent to 1C. Clayey, silty, medium and fine sand. P = 36.5%. D_{50} = 0.12 mm
1D	From Pitt Town bank of river. A composite of 3 samples. About 120 yards from bend at the lower end of Windsor Reach. Clayey silt and fine sand, some medium sand. P = 62% D_{50} = 0.047 mm.
2D	A composite of 4 samples taken from the river channel bed. Adjacent to 1D. Coarse and medium sand. P = 0, D_{50} = 0.44 mm.
3D	From the Wilberforce bank of river. A composite of 3 samples. Medium and fine sand and clayey silt. P = 56%, D_{50} = 0.057 mm.
1E	From Pitt Town bank of river. A composite of 3 samples. About halfway along Wilberforce Reach. Clayey, very silty, medium and fine sand P = 40%, D_{50} = 0.096 mm.
2E	A composite of 4 samples taken from the river channel bed. Adjacent to 1E. Coarse and medium sand, some fine sand and silt. P = 6%, D_{50} = 0.45 mm.
3E	From the Wilberforce bank of river. A composite of 3 samples. Adjacent to 1E. Medium and find sand, some clayey silt. P = 13%. D_{50} = 0.15 mm.
1F	From Pitt Town bank of river. A composite of 3 samples. At lower end of Wilberforce Reach about 600 yards up-stream from the entrance to Buttsworth Creek. Clayey, very silty, fine and medium sand. P = 31%, D_{50}=0.16mm.
2F	A composite of 4 samples taken from the river channel bed. Adjacent to 1F. Coarse and medium sand. P = 1.5% D_{50} = 0.45 mm.
3F	From Wilberforce bank of river. A composite of 3 samples. Adjacent to 1F. Clayey silty, medium and fine sand. P = 21% D_{50} = 0.14 mm.
1G	From Pitt Town bank of river. A composite of 3 samples. About halfway along York Reach. Clayey, silty, medium and fine sand. P = 28% D_{50} = 0.15 mm.
2G	A composite of 4 samples taken from the river channel bed Adjacent to 1G. Coarse and medium sand. P = 0, D_{50} = 0.53 mm.
3G	From Wilberforce bank of river. A composite of 3 samples. Adjacent to 1G. Clayey, silty, medium to fine sand. P = 34% D_{50} = 0.13 mm.

1H	From Pitt Town bank of river. A composite of 3 samples. At the lower end of York Reach. Clayey, very silty, medium and fine sand, P = 32%, D_{50} = 0.12 mm.
2H	A composite of 4 samples taken from the river channel bed. Adjacent to 1H. Medium sand, some coarse, little fine sand. P = 0, D_{50} = 0.4mm.
3H	From Wilberforce bank of river. A composite of 3 samples. Adjacent to 1H. Clayey, silty, medium and fine sand. P = 19%, D_{50} = 0.15 mm.
I	From deep area between York Reach and Canning Reach. Depth approx. 60'. Clayey, silty, gravelly sand P = 10.5%, D_{50} = 0.8 mm.
J	From depth of 60' in Canning Reach. Clayey, silty sand, little gravel. P = 21%, D_{50} = 0.26 mm.
1K	From right (facing downstream) bank of river. A composite of 3 samples. Halfway along Canning Reach. Clayey very silty, fine sand, some medium sand. P = 33%. D_{50} = 0.135 mm.
2K	A composite of 4 samples taken from the river channel bed. Adjacent to 1K. Coarse and medium sand, some fine sand P = 1.5%, D_{50} = 0.42 mm.
3K	From left bank of river. A composite of 3 samples. Adjacent to 1K. Clayey, silty, fine and medium sand. P = 18%, D_{50} = 0.15mm.
L	In deep area at the meet of Canning and Clarence reaches. Depth 53 ft. Coarse sand. P = 0, D_{50} = 0.7 mm.
M	Depth 60 ft. Lower end of Clarence Reach - in bend at upper end of Swallow Rock Reach (near Ebenezer Church). Silty, clayey, medium sand, some fine, medium and coarse sand. P = 13%, D_{50} = 0.4 mm.
N	In 18 ft. of water near lower end of Swallow Rock Reach. Clayey, silty fine and medium sand. P = 13%. D_{50} = 0.2 mm.
O	In 50 ft. of water. Sand overlain by layer of mud (thickness of mud layer $\frac{1}{4}$"). In bend at end of Swallow Rock Reach. Silty, medium and fine sand, little clay. P = 12.7%, D_{50} = 0.28 mm.
P	In 15 feet of water. Midway along straight portion of channel between the reaches labelled "Swallow Rock Reach" and "Upper Crescent Reach". Coarse and medium sand. P = 0, D_{50} = 0.46 mm.

Q	In 18 feet of water at the end of the abovementioned reach - near the left bank (looking D/s) and at the commencement of the bend at the upper end of "Upper Crescent Reach". Coarse and medium sand. $P = 0$, $D_{50} = 0.42$ mm.
R	Depth of 60 feet in the abovementioned bend. Clayey, coarse, fine and medium sand. $P = 13\%$, $D_{50} = 0.41$ mm.
T	In 38 feet of water. Thin film of mud overlying sand in tube sample. In bend at upper end of Lower Crescent Reach. Medium and coarse sand, little clay. $P = 4\%$, $D_{50} = 0.6$ mm.
U	In 12 feet of water about halfway along Lower Crescent Reach. Medium and coarse sand. $P = 0$, $D_{50} = 0.62$ mm.
V	This is a composite of a tube sample at a depth of 50 ft. and another tube sample at a depth of 70 ft. Nothing was obtained from two other tubes which were used to sample at a depth of about 50 ft. At the bend at the end of Lower Crescent Reach. Silty, clayey, fine and medium sand. $P = 18\%$, $D_{50} = 0.2$ mm.
W	From a depth of 15 feet. Halfway along the straight portion of Portland Reach which is immediately downstream from the locale of sample W. Coarse and medium sand. $P = 0$, $D_{50} = 0.48$ mm.
X	From a depth of 52 ft. in Portland Reach, near Portland Head. Medium and some coarse and fine sand. $P = 0.5\%$, $D_{50} = 0.36$ mm.
Y	From a depth of 8 ft. towards the lower end of Portland Reach. Coarse and medium sand. $P = 0.6\%$, $D_{50}=0.62$mm.
Z	From a depth of 65 ft. near the lower end of Portland Reach. Sand overlain by what appeared to be $\frac{1}{4}''$ of mud. Medium and fine sand, some silty clay. $P = 12\%$, $D_{50}=0.15$ mm.
AA	From a depth of about 10 feet halfway along the straight portion of Sackville Reach. Coarse and /medium sand. $P = 0$, $D_{50} = 0.46$ mm.
BB	In first bend of the hairpin bend between Sackville Reach and Kent Reach. Coarse and medium sand. $P = 1\%$. $D_{50} = 0.52$mm.
CC	From 50 feet of water in the second bend of the hairpin bend between Sackville Reach and Kent Reach. Fine coarse and medium sand, some silty clay $P = 10.5\%$, $D_{50} = 0.47$mm.

DD	From a depth of 10 feet towards the top end of Kent Reach. Coarse and medium sand. P = 0, D_{50} = 0.6mm.
EE	From 40 ft. depth in Kent Reach. Coarse and medium sand P = 1%. D_{50} = 0.56 mm.
FF	From 50 ft. in bend between Kent Reach and Cumberland Reach. Clayey, coarse and medium sand, little silt. P = 11.4%, D_{50} = 0.45 mm.
GG	From 25 ft. Bend between Cumberland and Cambridge Reaches. Coarse and medium sand. P = 0. D_{50}=0.46mm.
HH	From 42 ft. Bend between Cumberland and Cambridge Reaches. Coarse and medium sand. P = 0. D_{50} = 0.7mm.
II	From 12 ft. halfway along Cambridge Reach. Medium and coarse sand. P = 0. D_{50} = 0.7mm.
KK	From 15 ft. halfway along Sussex Reach. Coarse and medium sand. P = 0. D_{50} = 0.66 mm.
LL	From 65 ft. in bend between Sussex Reach and Gloucester Reach. Coarse and medium sand. P = 0. D_{50} = 0.5 mm.
MM_1	From 30 ft. In Gloucester Reach about 700 ft. upstream from Portland ferry which itself is just upstream from the mouth of the Colo River. Fine and medium sand, some clayey silt. P = 10%. D_{50} = 0.3mm.
MM_3	From 20 ft. in the Hawkesbury - at about the same distance below the junction with the Colo as MM_1 is above it. Medium and coarse sand, little gravel. P = 0, D_{50} = 0.6mm.
NN	From 30 ft. In mid channel and in middle of hairpin bend between Gloucester Reach and Liverpool Reach. Medium sand, some fine sand P = 0, D_{50} = 0.35 mm.
PP	At 15 ft. in Liverpool Reach. Medium and coarse sand. P = 0, D_{50} = 0.85.
QQ	From 69 ft. in bend at lower end of Liverpool Reach. Not plotted.Coarse sand and gravel P = 0, D50 = 2.0mm.
RR	From about 20 ft. depth at top end of upper half Moon Reach, coarse and medium sand. P = 6% D_{50} = 0.48mm.
SS	Label almost indecipherable. Assumed to be SS. At 65 ft. in Upper Half Moon Reach. Medium and coarse sand P = 2%, D_{50} = 0.74 mm.
TT	From 18 ft. in Upper half Moon Reach Coarse and Medium Sand P = 0.6%, D_{50} = 0.55 mm.

UU	From 48 ft. at the upper end of Lower Half Moon Reach. Silty, clayey, medium and coarse sand. P=16%, D_{50}=0.69mm.
VV	From 26 ft. in Lower Half Moon Reach. Coarse and medium sand. P = 0, D_{50} = 0.46mm.
WW	From 56 ft. in Lower Half Moon Reach. Coarse and medium sand. P = 0, D_{50} = 0.48 mm.
XX	From 38 ft. in Lower Half Moon Reach. Coarse and medium sand P = 0.5%, D_{50} = 0.47 mm.
ZZ	From 25 ft. in mid channel in Lower Half Moon Reach. Coarse and medium sand, some silty clayey fine sand. P = 6%, D_{50} = 0.5 mm.
AAA	Adjacent to ZZ but close in to the right bank. Depth of water 52 ft. Coarse sand P = 0, D_{50} = 0.68 mm.
BBB_1	Composite of 4 samples taken from the channel bed (12 ft., 14 ft., 14 ft., 35 ft.). In Milkmaid Reach (or Bathurst Reach) in straight portion of reach immediately downstream from the bend at the end of Lower Half Moon Reach. Coarse and medium sand P = 0, D_{50} = 0.48 mm.
BBB_2	Composite of 3 samples taken from left bank (looking downstream). Adjacent to BBB_1. Right bank of the river is steep and rocky. The left bank is bordering alluvials. Clayey, silty, fine and medium sand. P = 26%, D_{50} = 0.15mm.
CCC_1	Composite of 4 samples taken from the channel bed (15 ft., 15 ft., 21 ft., 18 ft.) in Bathurst Reach about 3/4 mile downstream from BBB_1. Medium coarse sand, some silty clayey fine sand. P = 10%, D_{50} = 0.42 mm.
CCC_2	Composite of 3 samples taken from right bank (looking downstream) as for BBB_2. Adjacent to CCC_1. Left bank of the river is steep and rocky. The right bank borders alluvials. Clayey silt and sand. P = 61%, D_{50} = 0.04 mm.
DDD	Depth 18 ft., about 800 ft. above Webbs Creek junction. Coarse and medium sand. P = 2%, D_{50} = 0.6 mm.
EEE	Depth 13 ft. about 800 ft. below Webbs Creek junction. Coarse and medium sand. P = 0, D_{50} =0.55 mm.
FFF	Depth 18 ft. about 800 yards d/s EEE. Coarse and medium sand. P = 0, D_{50} = 0.55 mm.

JJJ In centre of Hawkesbury River channel nearly opposite the ferry at Wiseman's Ferry. Depth 32 ft. (N. B. no sample III was taken). Coarse and medium sand. $P = 0$, $D_{50} = 0.53$mm.

KKK Depth 20 feet, channel centreline of Hawkesbury River about 100 yards downstream from JJJ. Coarse and medium sand. $P = 0$, $D_{50} = 0.52$ mm.

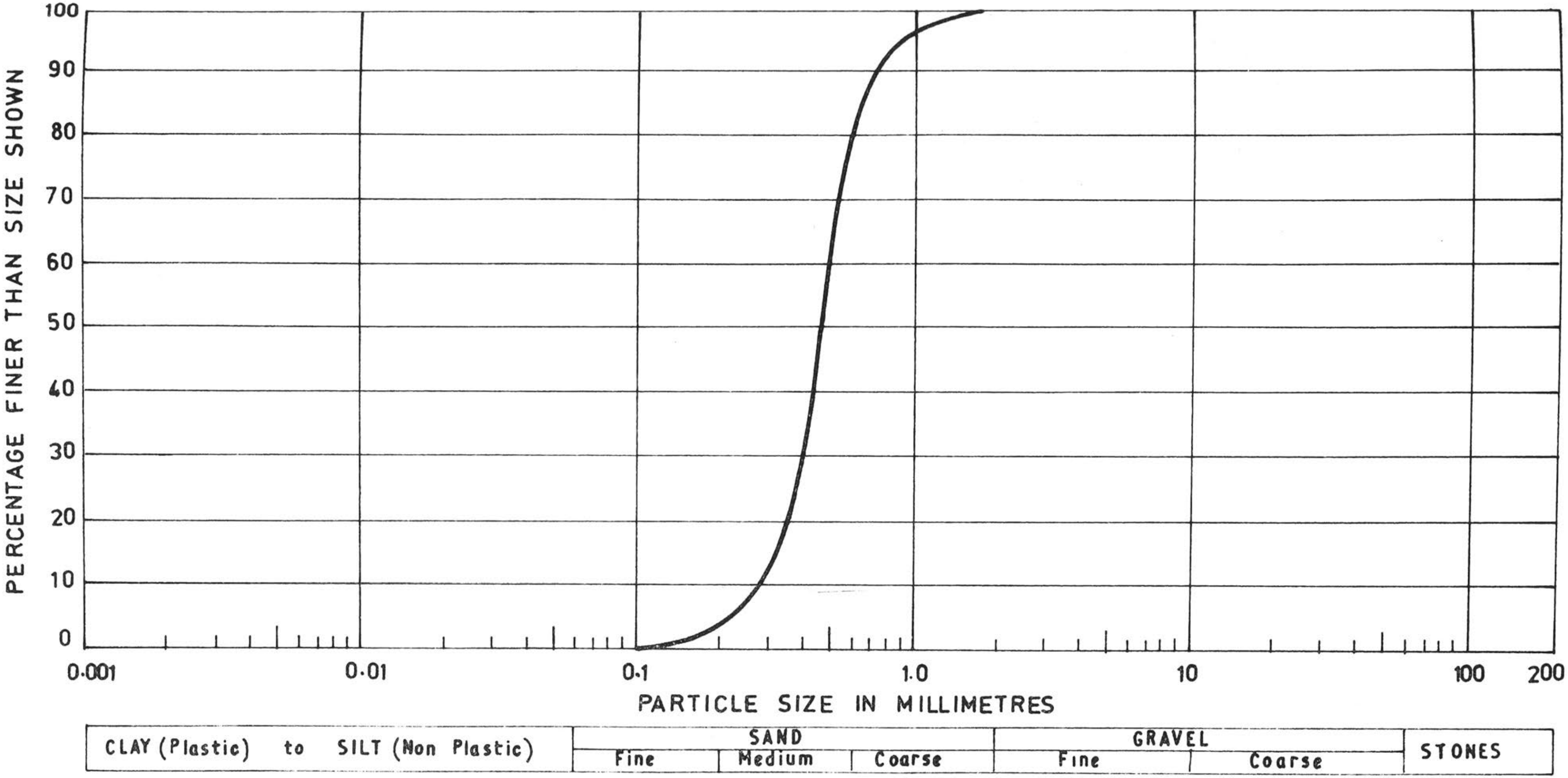


FIGURE I·III·I : AVERAGE GRADING CURVE OF 15 SAMPLES OF RIVER BED BETWEEN RICHMOND BRIDGE AND WINDSOR BRIDGE. SAMPLES TAKEN IN 1970.

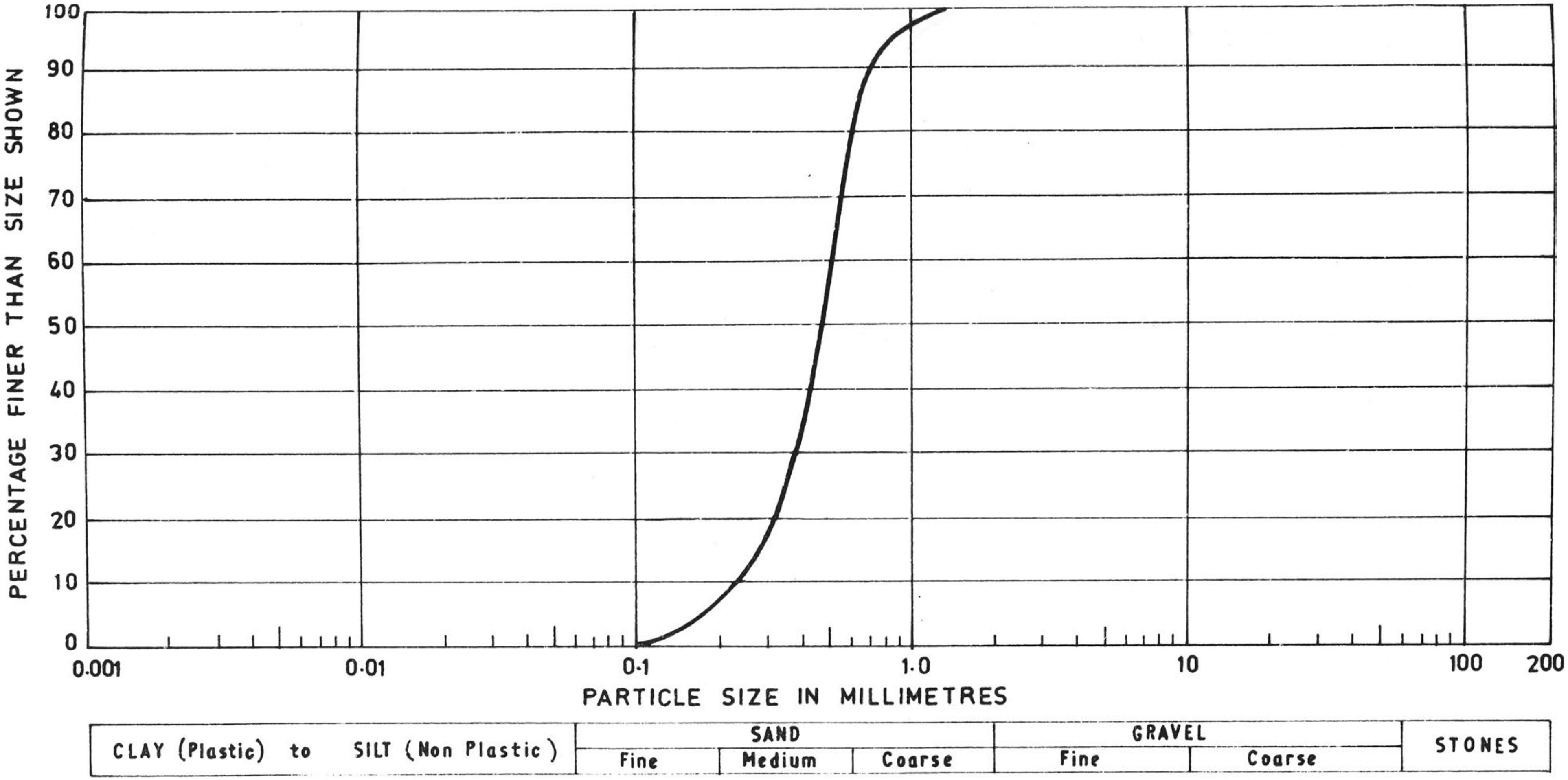


FIGURE I·III·2: AVERAGE GRADING CURVE OF BED SAMPLES TAKEN FROM SHALLOWER (AND GENERALLY STRAIGHT) PORTIONS OF REACHES BETWEEN WINDSOR REACH AND PORTLAND REACH. SAMPLES TAKEN IN APRIL 1971.

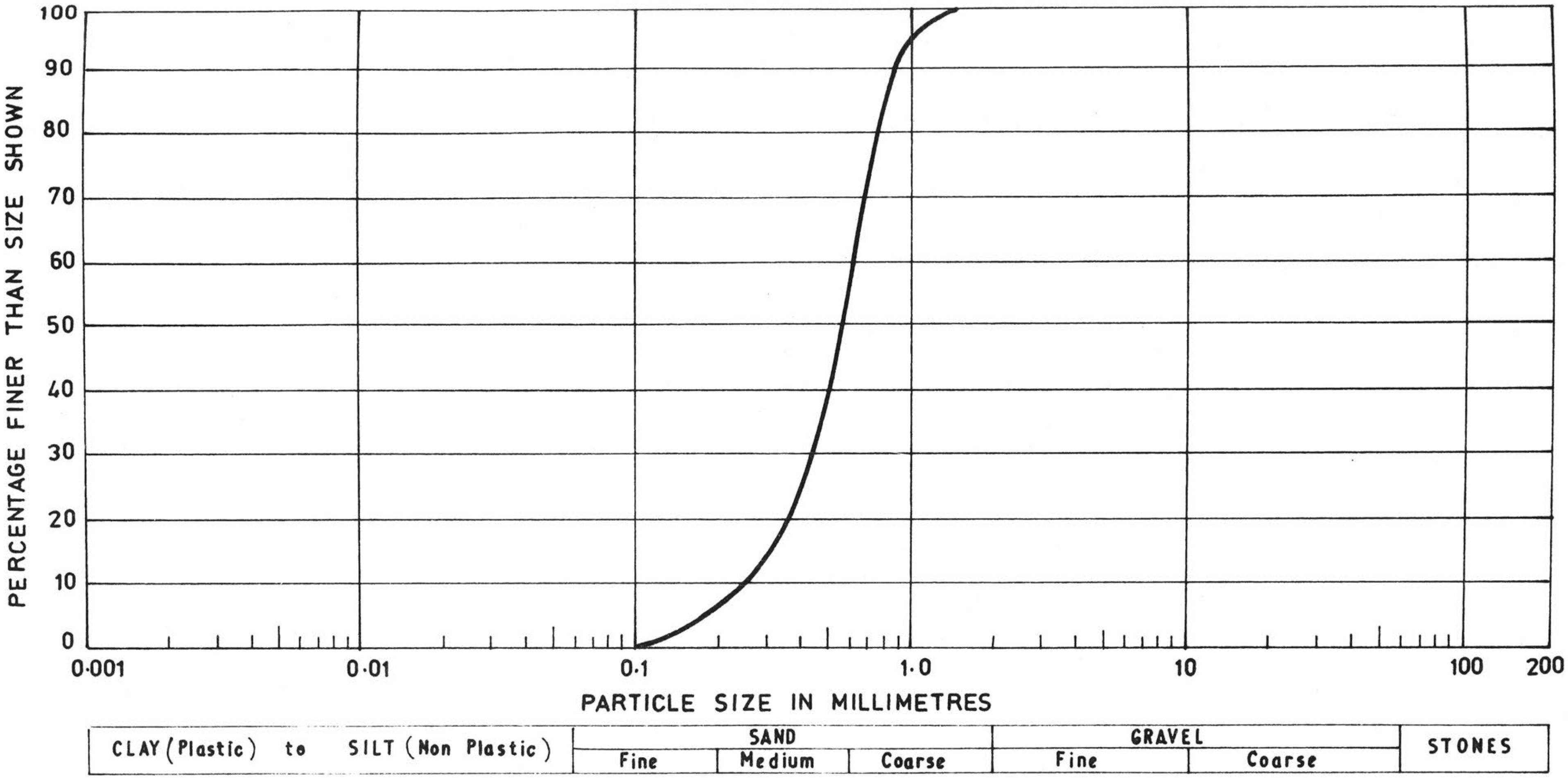


FIGURE I·III·3: AVERAGE GRADING CURVE OF BED SAMPLES TAKEN FROM SHALLOWER (AND GENERALLY STRAIGHT) PORTIONS OF REACHES BETWEEN PORTLAND REACH AND WISEMAN'S FERRY. SAMPLES TAKEN APRIL 1971.

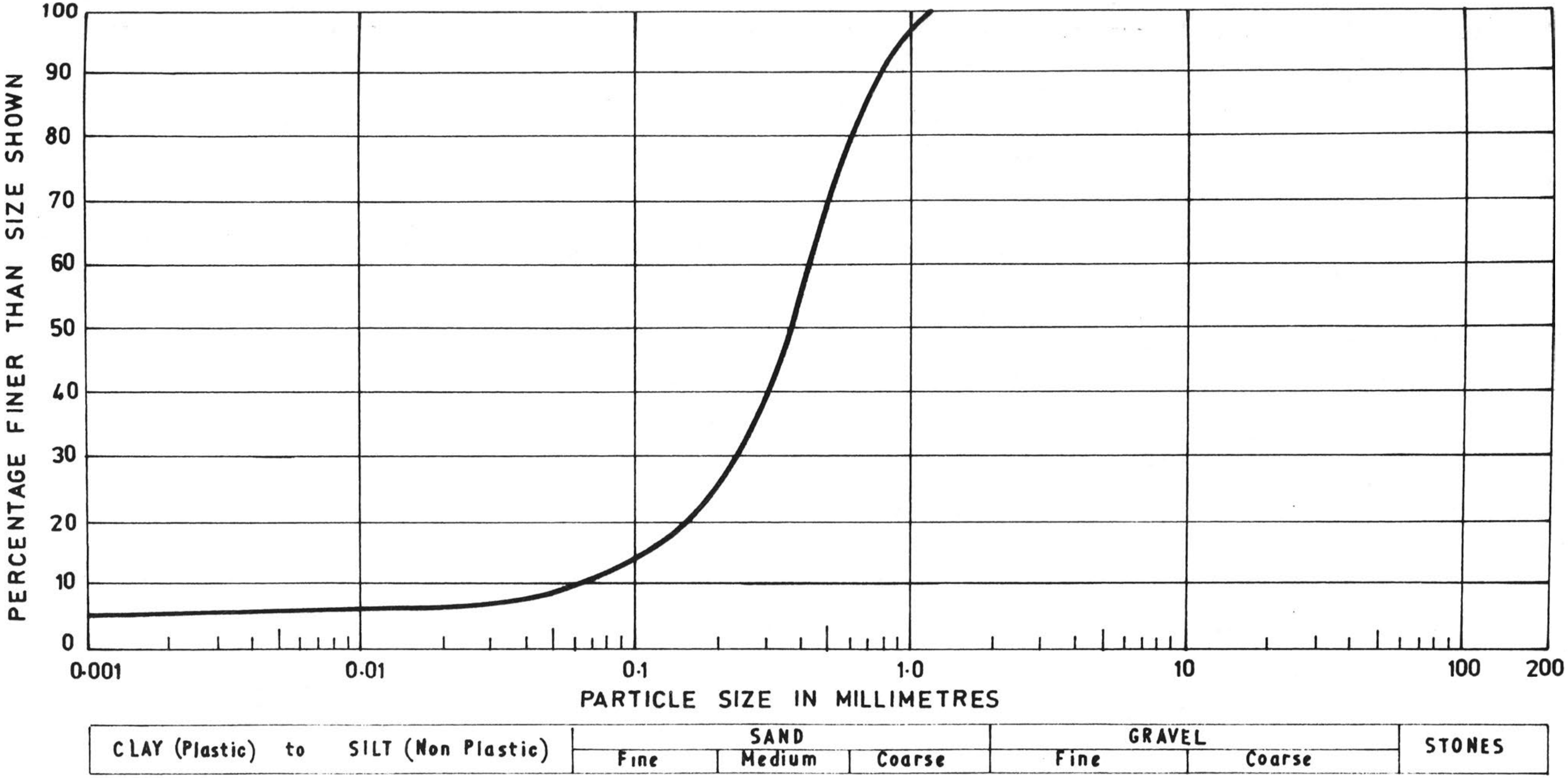


FIGURE I·III·4: AVERAGE GRADING CURVE OF BED SAMPLES TAKEN FROM DEEPER (GENERALLY IN BENDS) PORTIONS OF REACHES BETWEEN CANNING REACH AND PORTLAND REACH. SAMPLES TAKEN IN APRIL 1971.

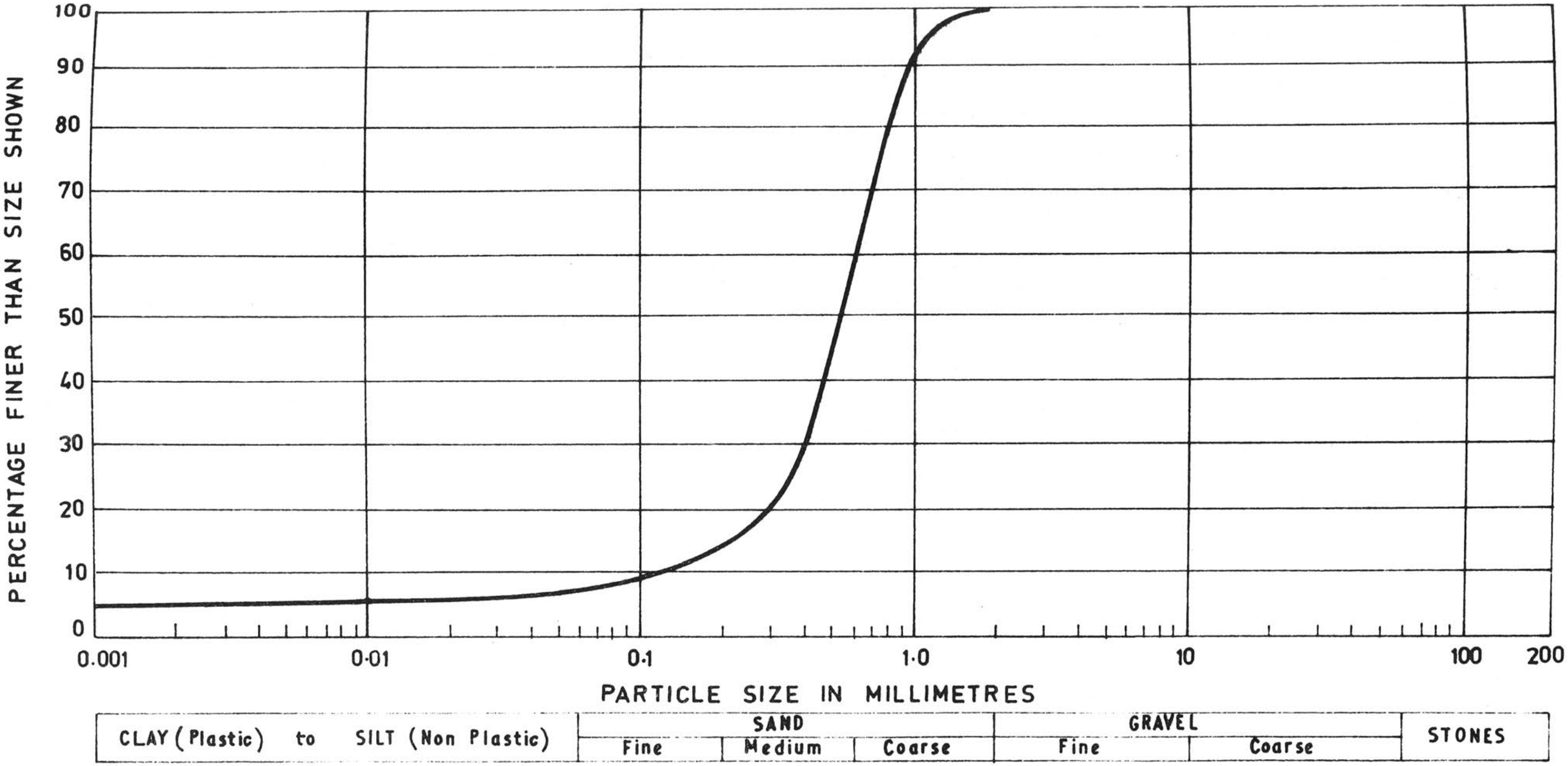


FIGURE I·III·5: AVERAGE GRADING CURVE OF BED SAMPLES TAKEN FROM DEEPER (GENERALLY IN BENDS) PORTIONS OF REACHES BETWEEN SACKVILLE REACH AND LOWER HALF MOON REACH. SAMPLES TAKEN IN APRIL 1971.

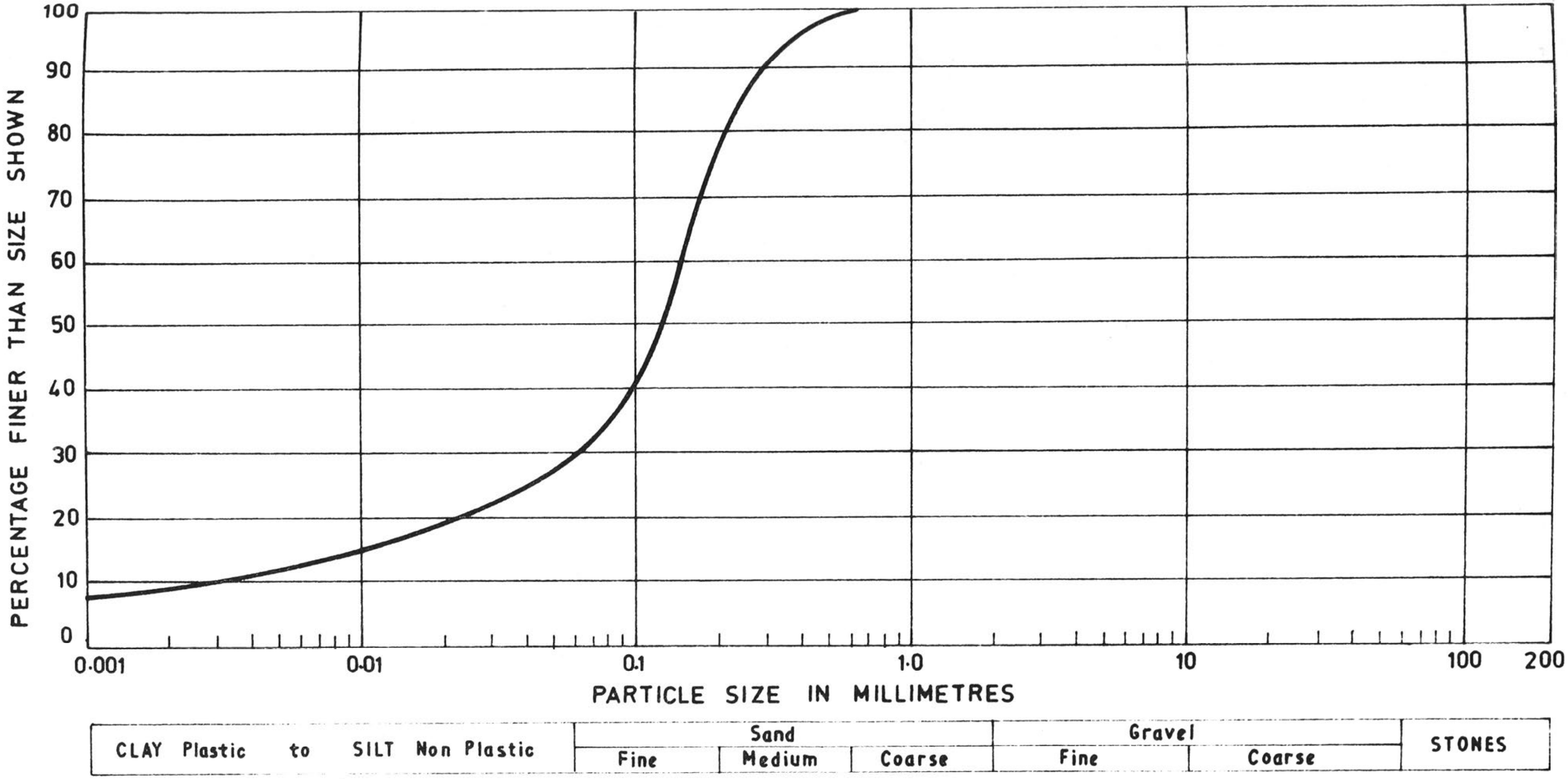


FIGURE I·III·6: MEAN GRADING CURVE OF SEDIMENTS IN BANKS OF HAWKESBURY RIVER FROM FREEMAN'S REACH TO CANNING REACH. BASED ON GRADING CURVES FOR SAMPLES 1A, 1B, 1C, 3C, 1D, 3D, 1E, 3E, 1F, 3F, 1G, 3G, 1H, 3H, 1K, 3K. SAMPLES TAKEN IN APRIL 1971.

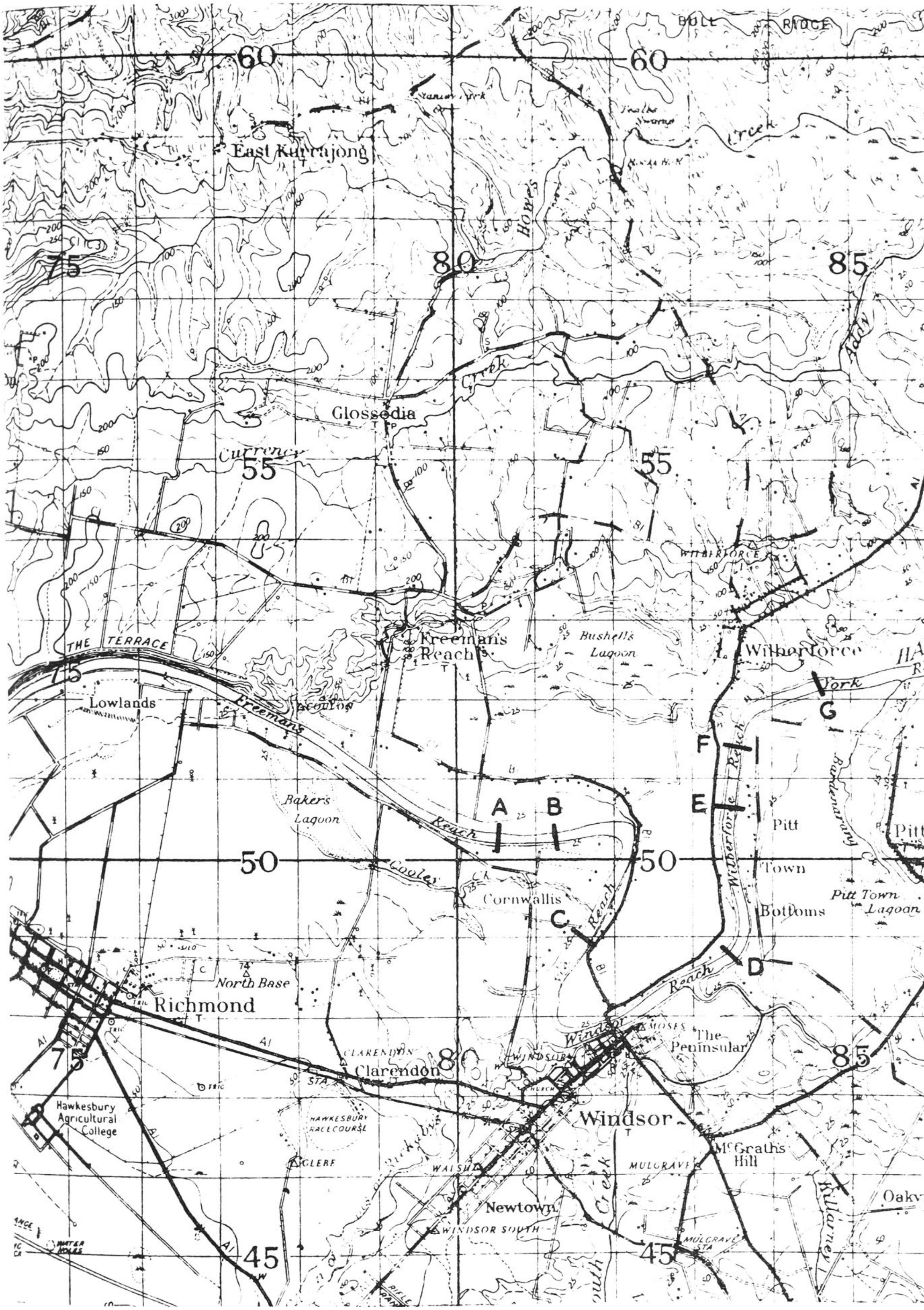


FIGURE I·III·7: LOCATION OF RIVER BED AND BANK SAMPLES TAKEN IN APRIL 1971

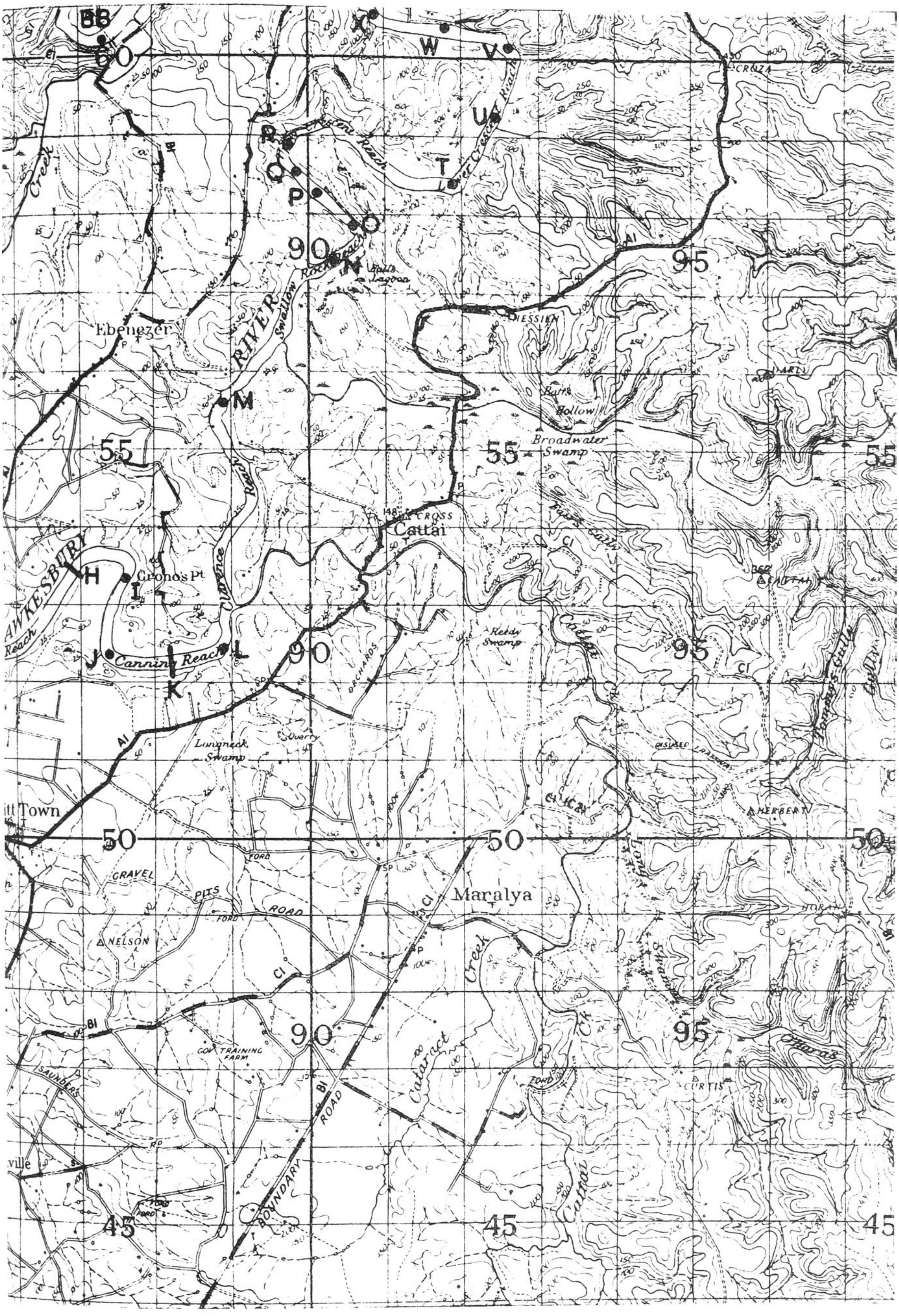


FIGURE I·III·8: LOCATION OF RIVER BED AND BANK SAMPLES TAKEN IN APRIL 1971

FIGURE I·III·9: LOCATION OF RIVER BED AND BANK SAMPLES TAKEN IN APRIL 1971

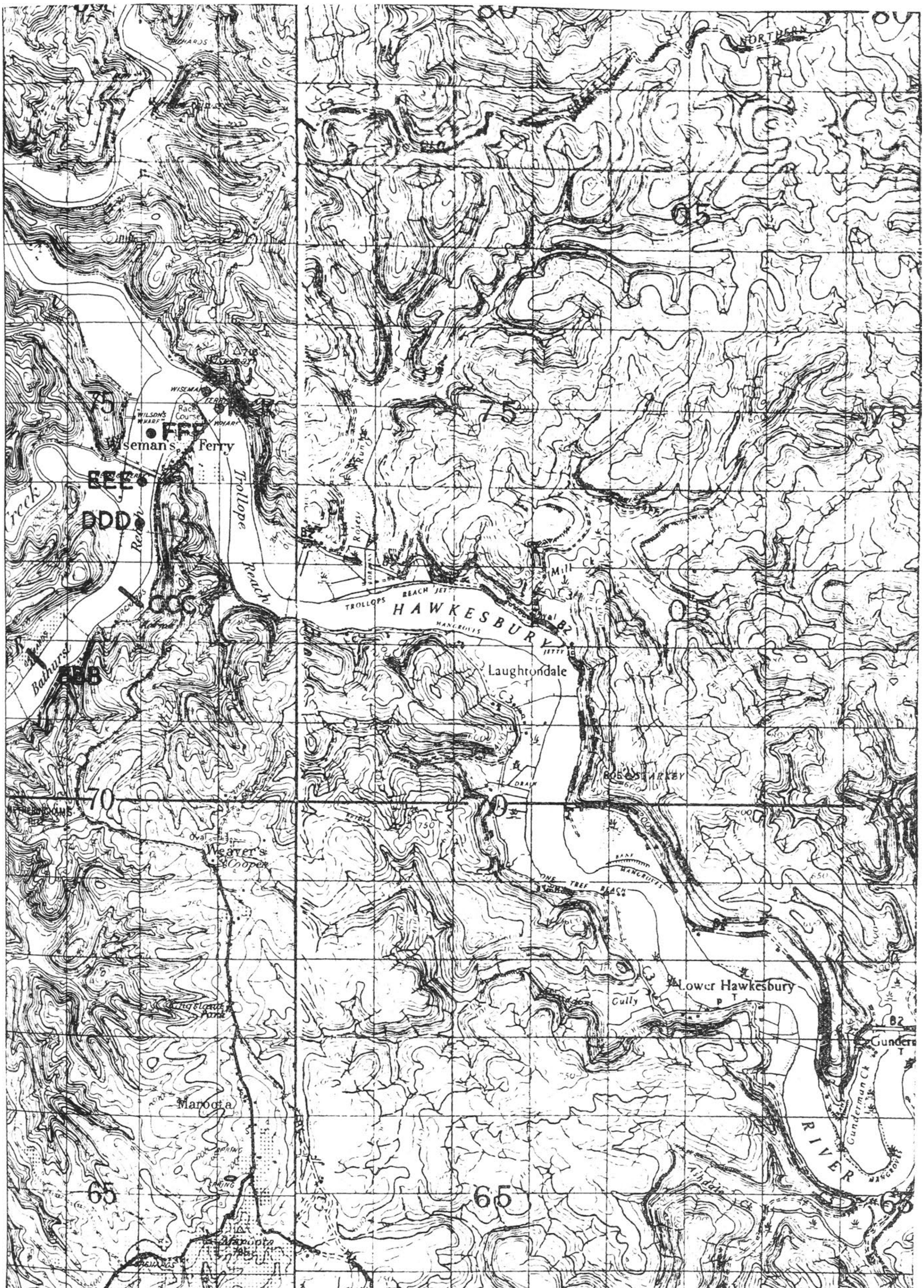


FIGURE I·III·10: LOCATION OF RIVER BED AND BANK SAMPLES TAKEN IN APRIL 1971

Samples of deposits of November 1969 flood. Samples taken by teachers and pupils of Richmond High School on 18.11.69 and 19.11.69 and analysed by the University of N.S.W. Note that the wording in the column "Location of sample and description of deposits" is that of the pupils.

Location of sampling site	Number of sample	Location of sample and description of deposits	Representative sizes of particles (mm)			% by wt. $<$ .074 mm	Inferred height (above Standard Datum) of sampled deposit above normal water level of river
			D65	D50	D35		
About 1 m downstream from Nth. Richmond Bridge abt. 7-7/8 m. up-stream from Windsor Bridge	1A	"Opposite Redbank Ck. entrance; 4 ft. above water level. Dark mud deposits, thin coatings of sand ranging from $\frac{1}{2}$ inch to 6 inches in places".	.06	.04	.02	78	22 ft.
	1B	"Top levee 12'. Deposit of new sand about 4" deep thin film of mud"	.27	.25	.22	3	33 ft.
	1C	"Other side of levee. Thin film of sand 2" very thin mixture of mud and sand".	.20	.18	.15	8	
About $1\frac{1}{4}$ m. downstream from Nth. Richmond Bridge abt. 7-5/8 m. upstream from Windsor Bridge	2A	"1 yard from water level. Film on top of the grass and sand film about $\frac{1}{4}$" thick."	.25	.18	.11	29	19 ft.
	2B	"Film on sand and grass 1/8" thick"	.19	.08	.03	49	24 ft.
	2C	"50 yards from water. Film 1/8" deep, the water did not go over the bank of the levee"	.08	-	-	60	40 ft.

About 2-1/8 m. downstream from Nth. Richmond Bridge about 6-3/4 m. upstream from Windsor Bridge	3A	"$5\frac{1}{2}$ to 6 feet from water's edge. 1" deep deposited. Dead plant matter leaves, sticks etc.	.14	.08	.04	49	20 ft.	
	3B	"12 feet from water's edge. $2\frac{1}{2}$" deposited fine dry clay sand"	.20	.16	.13	14	25 ft.	
	3C	"30-35 feet from water's edge. $1\frac{1}{2}$" deposited fine clay-sand soil".	.07	.03	.01	66	30 ft.	
About 3m downstream from Nth. Richmond Bridge about 5-7/8m upstream from Windsor Bridge	4A	"2 yards from water's edge. Deposit of sand found over grass on bank depth 1"-$1\frac{1}{2}$".	.27	.24	.20	3	24 ft.	
	4B	"About 1/8" to 1/4" thick film of caked silt over grass"	.15	-	-			
	4C	"6 yards from water. Silt deposit film found on grasses $\frac{1}{2}$" deep"	.10	.04	.02	61		
About 3-5/8 m. downstream from Nth. Richmond Bridge about 5-1/4 m. upstream from Windsor Bridge	5A	"5 feet above water level. Sand deposits thin layers of mud (scattered about)"	.24	.21	.18	7	22 ft.	
	5B	"7 feet from river. Sand 2-3 ins. thick mixture of mud and sand topping"	.29	.27	.24	6	24 ft.	
	5C	"13 feet from water. 20' from top levee. Sand, mud and small portions of soils with mixture of leaves and sticks	.17	.14	.11	16	30 ft.	

About 4-5/8 m. downstream from Nth. Richmond Bridge, about $4\frac{1}{4}$m. upstream from Windsor Bridge	6A	"1 yard from water's edge. Sand deposited in bars about 1" thick and 6" across was deposited as water went down"	.11	.09	.08	34	18 ft.
	6B	"Minute pieces of silt 1/16" deep if anything 1% vegetation"	.07	.05	.02	66	20 ft.
	6C	"Water didn't go over levee. Sample taken about 20 yards from the top of the levee. Thin film on all the grass with deposits about $\frac{1}{4}$" thick behind the tall grass"	.07	-	-		35 ft.
About $5\frac{1}{2}$ m. downstream from Nth. Richmond Bridge, about 3-3/8 m. upstream from Windsor Bridge.	7A	"4 feet from water's edge. $\frac{1}{2}$" deposit of fine sand"	.26	.24	.20	6	18 ft.
	7B	"16 feet from water's edge. $\frac{1}{4}$" film of clay over sand; very fine clay deposits" 10% vegetation.	.15	.09	-	45	21 ft.
	7C	"32' from water's edge. 3" deposited $1\frac{1}{2}$" sandy humus, $\frac{1}{2}$" clay 1" clay sand"	.15	.12	.09	28	30 ft.

About $6\frac{1}{2}$ m. downstream from Nth. Richmond Bridge, about 2-3/8 m. upstream from Windsor Bridge	8A	"about 2 yards from water's edge, thin film of silt over grass"	.12	.03	.01	61	17 ft.
	8B	"10 yds. from water's edge, sand deposit 6"-8" deep found on grassed slope"	.23	.20	.16	4	19 ft.
	8C	"30 yds. from water, silty loam sand film. Found on grasses and old sand deposits. Depth $\frac{1}{4}$" "	.07	.03	.02	66	20 ft.
About 7-3/8m downstream from Nth. Richmond Bridge, about $1\frac{1}{2}$ m upstream from Windsor Bridge.	9A	"2' from water level, cake of sediment 1/8" to $\frac{1}{4}$" thick.	.09	.04	.01	62	18 ft.
	9B	"6 ft. vertical 20 ft. from water's edge. Fine sand replaces caked layer, marked contrast"	.22	.18	.14	7	23 ft.
	9C	"25' vertical. Film of material on grass". 2% vegetation.	.09	.06	.02	57	35 ft.
About $8\frac{1}{4}$ m. downstream from Nth. Richmond Bridge, about 5/8m. upstream from Windsor Bridge.	10A	"3ft. above water level. homogeneous layer of newly deposited sand"	.27	.24	.18	5	19 ft.
	10B	"8ft. vertical. Fine silt caked layer about 1/8" thick new deposits underneath".	.25	.20	.16	9	24ft.
	10C	"25-30 ft. vertical, large deposits of debris stacked up to 5 ft. high silt".	.23	.20	.16	9	

About 1/8 m. downstream from Windsor Bridge.	11A	"At water's edge, homogeneous layer of ruffled sand depth about 1"	.29	.27	.24	1	17 ft.
	11B	"12 ft. vertical, sand silt organic matter extensive ½" to 1" deep."	.26	.22	.18	7	29 ft.
	11C	"20' vertical, horizontal terrace, compact layer of damp silt"	.11	.08	.04	48	35 ft.
About 1/8m downstream from Windsor Bridge.	12A	"2 ft. above water level, compact layer of sand heavy erosion of bank"	.23	.20	.16	5	19 ft.
	12B	"7 ft. vertical, deposits of sand 1/8" caked fine silt"	.16	.13	.09	26	24 ft.
	12C	"25ft. vertical, cakes of silt amongst (kikuyu?) grass up to 1" still very damp" 10=15% veg.	.08	-	-	65	41 ft.
About 3/4 m. downstream from Windsor Bridge, opposite entrance of South Creek.	13A	"3ft. vertical 2 ft. from water, clean sand layer about 8".	.27	.25	.22	1	19 ft.
	13B	"10 ft. vertical, clean sand ½" layer"	.26	.24	.21	2	26 ft.
	13C	"25-30ft. vertical terrace. Fine layer of silt among (kikuyu?) 1/8" to 1/4" in depth"	.04	.02	.01	87	35 ft.

About 7/8 m. downstream from Windsor Bridge	14A	"4ft. above (see 14B) $\frac{1}{2}$" layer of fine silt caking"	.15	.12	.10	20	20 ft.
	14B	"active path of flood evidence of considerable current. Same height as "A" horizontal 40 ft. Layers of fine silt shallow film 1/16". Material retained on sieves 14, 25, 36, 52 mainly vegetation.	.12	.10	.08	30	20 ft.
	14C	"50 yds. from water 20 ft. vertical. Layer of silt loam about 3/4" to 1" deep".	.15	.11	.08	31	35 ft.
About 1-3/4 m. downstream from Windsor Bridge.	15A	"Alternating layers of sand and organic matter leaves, grasses and twigs. Massive deposition several feet deep". Material retained on sieves 14 & 25 mostly vegetation.	.11	.10	.09	4	
	15B	"6ft. vertical, 5 yds. horizontal"	.24	.22	.21	1	21 ft.
	15C	"Crest of levee. 1" deep silt sand fine not consolidated".	.19	.17	.09	33	32 ft.

About2-3/4 m. downstream from Windsor Bridge.	16A	"Massive deposition clean sand 4 ft. in depth built up of a point bar by this flood. Active undercutting and bank collapse on other side".	.30	.26	.24	0	
	16B	"8 ft. vertical; 10 yds. horizontal. Fine silt sand".	.20	.17	.15	3	23 ft.
	16C	"Fine silt with some sand about ½ inch"	.14	.10	.08	34	
Location is an area adjoining eastern side of Cupitt's Lane about 1000 ft. from the junction of that lane with the road skirting the aerodrome. Area about 24' above normal level of river.	AA	"1/16" - 1/8" deposit"				95	24 ft.

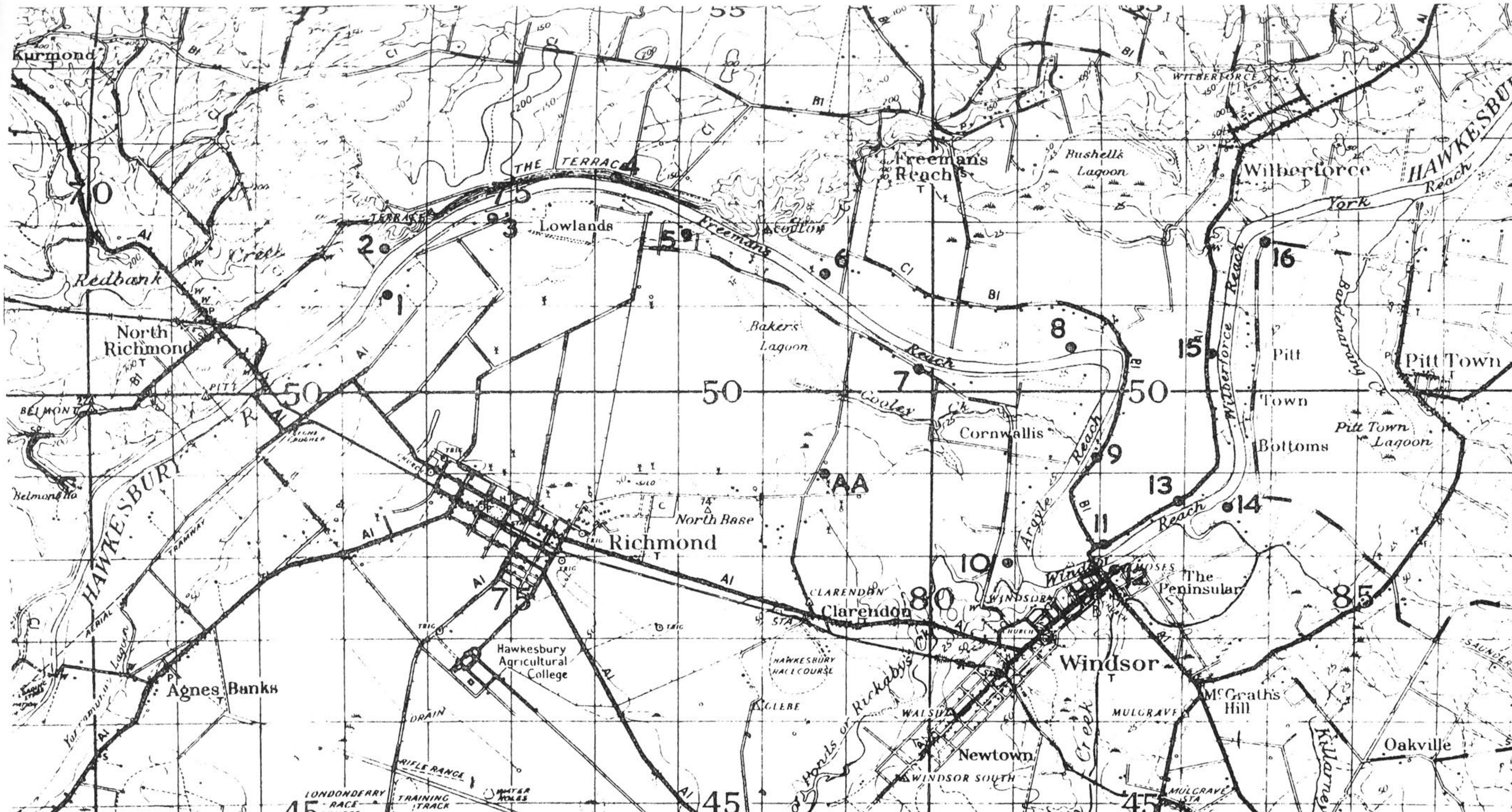


FIGURE I·III·11: LOCATION OF SITES WHERE SAMPLES OF SEDIMENTS DEPOSITED BY THE NOVEMBER 1969 FLOOD WERE TAKEN BY RICHMOND HIGH SCHOOL STUDENTS AND TEACHERS

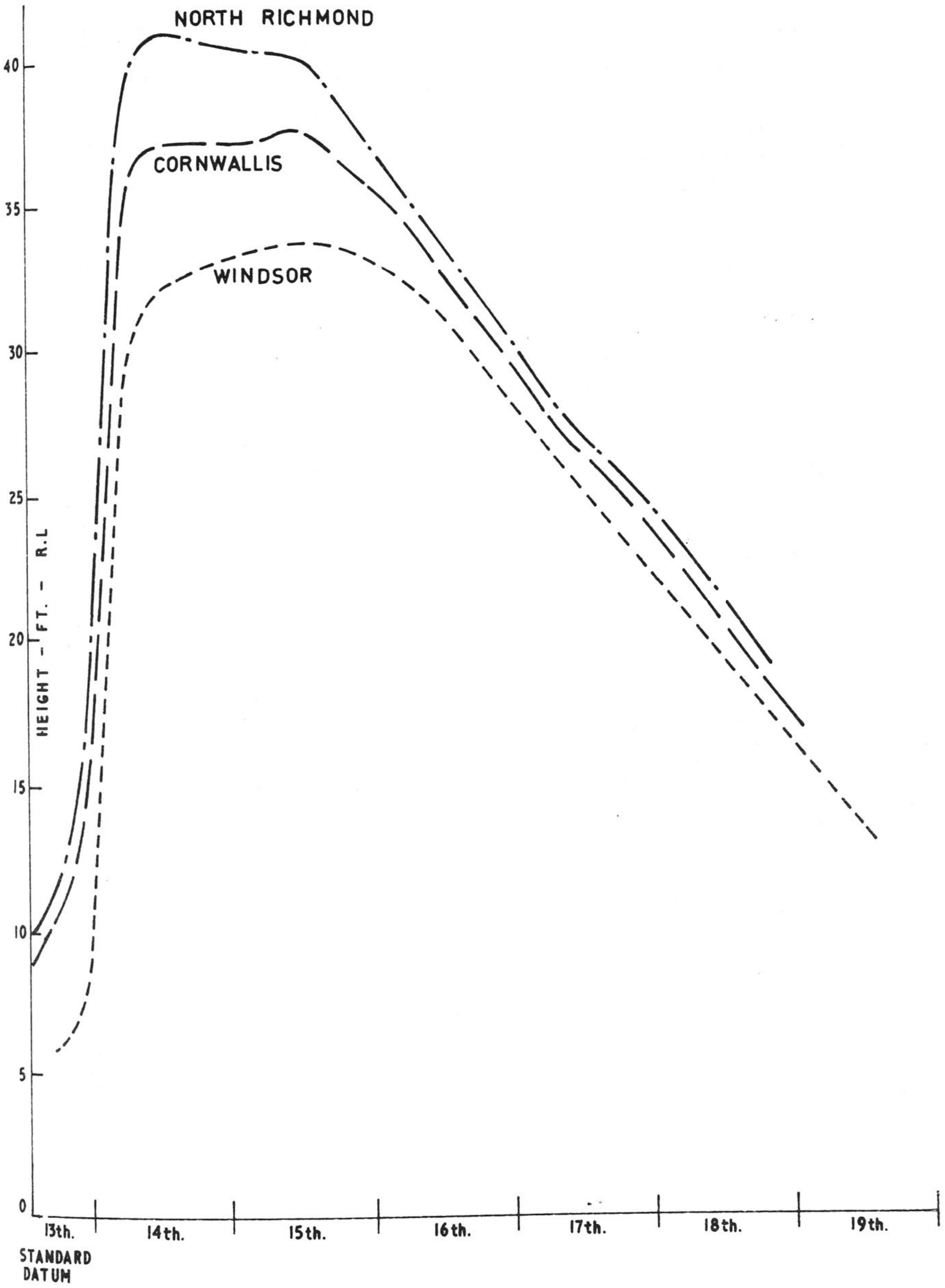


FIGURE I·III·12: NOVEMBER 1969 FLOOD

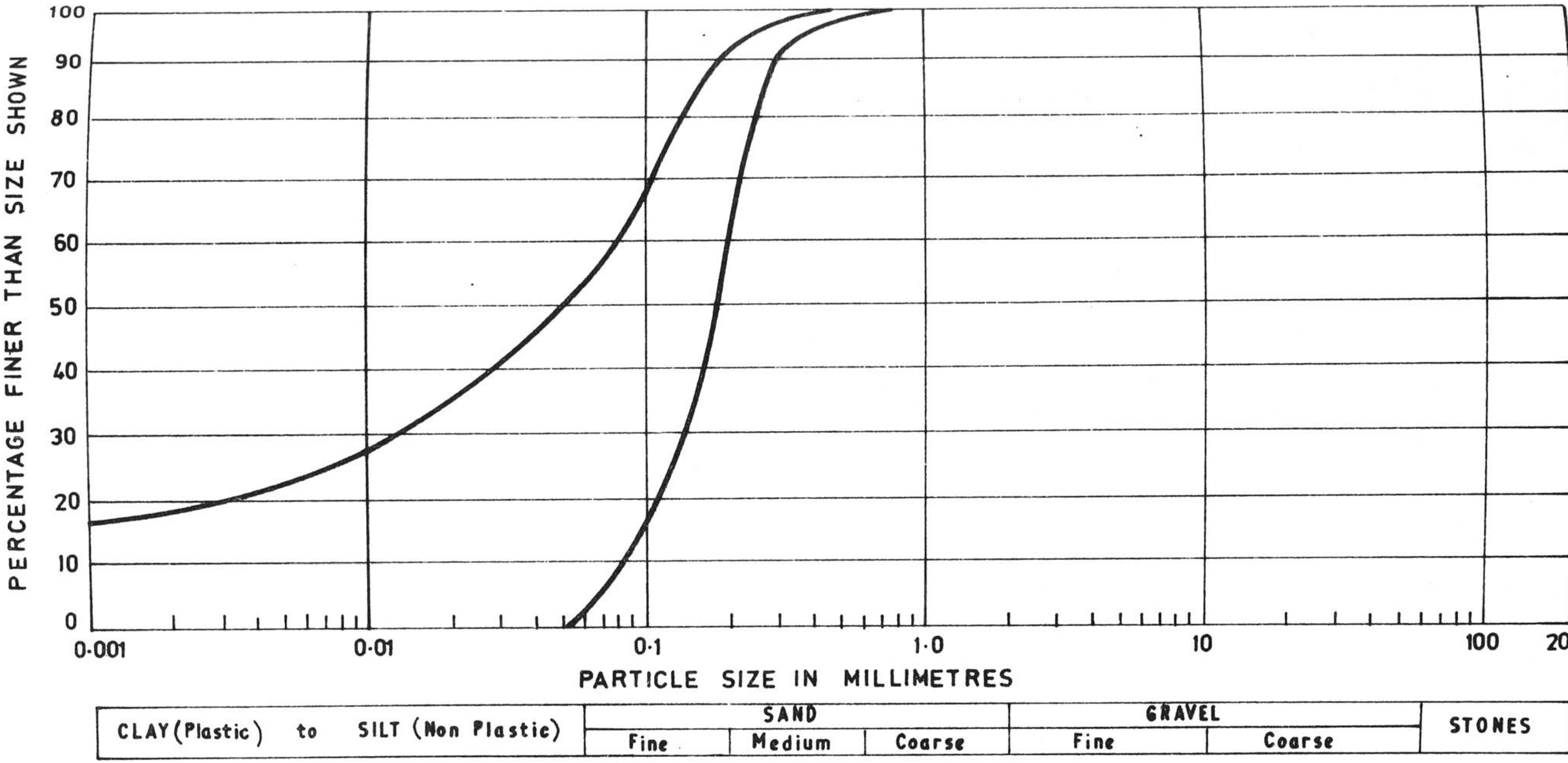


FIGURE I·III·13: AVERAGE GRADING CURVES OF SAMPLES OF SEDIMENTS DEPOSITED BY NOVEMBER 1969 FLOOD. SAMPLES OBTAINED BY RICHMOND HIGH SCHOOL STUDENTS AND TEACHERS.

APPENDIX IV TO CHAPTER 1.

Information Disclosed by the Dredging Undertaking of W. Davidson Pty. Ltd. in the Windsor Reach of the Hawkesbury River.

The undertaking, which is the subject to Permissive Occupancy 66/24, is located below Windsor Bridge and extends for about a mile along the river.

The company has been dredging in this area for about ten years. Mr. Davidson is of the opinion that this area has not been dredged before and, in fact, considers that if it has been previously dredged, this dredging would have been restricted to the sandy gravel-free region which would then have extended down to about 12 feet below low water.

The following description is now given of the river bed material and its composition as it was supposed to have been ten years ago before dredging commenced. This is based on observations by Messrs. Davidson and Croucher (Mr. Croucher is the site superintendent) of material brought up by dredging "the first time around" and thus excludes material deposited in dredged areas by the floods which have occurred in the past ten years (specific cases of flood deposition are dealt with later).

Ten years ago, before dredging commenced, the average depth of water at low water, over Mr. Davidson's lease was approximately 5 feet (which is about the present average depth at low water at Windsor Bridge). At any location in the area dredged, the material in the first 6 feet to 8 feet depth of bed was found to be sand only. Below this band of sand the material brought up was a mixture of sand, gravel and organic material (charcoal, twigs, wood fragments etc.). See Figure 1.IV.1. However, plastic material which "might have been clay or silty clay" was encountered at about 20 feet below low water. This clay-like material did not seem to constitute a definite stratum but rather seemed to be located in patches in a zone whose width ranged from 6" to 9". The nature of this claylike material and its average depth and distribution over the dredged area was consistent with the findings of Mr. Bruce Morgan, who said that he had found the same material at about the same depth in an area of the river near the old Pitt Town Wharf, where he had been excavating with dragline some years ago. Indeed Mr. Morgan had told Mr. Davidson that he might expect to find this material in the river bed. Mr. Davidson thought that the conditions of deposition of this material must have been very unusual and in marked contrast to the conditions of deposition of the bed material above and below it. When I spoke to Mr. Morgan (on 6.3.70) about this clayey material he was also of the opinion that it was an unusual deposit which he would not have expected to find in the river bed. Mr. Ray Wells, who is operating a suction dredge in the river for the Metropolitan Sand Company, this lease being located between Windsor Bridge and the old Pitt Town Wharf, said that he had brought up lumps of a plastic clay-like material from a depth of about 15 feet below low water, which is the limit of his dredging. He said that this material could at times block the intake of the dredge suction pipe despite the fact that the inlet had jets of high pressure water disposed around it to keep it clear.

Also, on the Windsor side of the river in a zone located between 25 feet to 30 feet below low water, Mr. Davidson said that he had encountered patches of conglomerated material consisting of sand, gravel and some shells. This zone ranged in width from 3" to 12". Mr. Morgan said that he had found patches of the same material at about the same depth when he had been excavating near the old Pitt Town Wharf. Note that the level of the bedrock surface beneath the river channel is, in this dredging area, about 45-50 feet below mean sea level. This is inferred from borings listed in Appendix 1.I.

Apart from the bands of clayey material and conglomerated material, the composition of the river bed material located below the abovementioned band of sand, did not vary with depth down to 35 feet. That is to say, the proportions of gravel and organic material intermixed with the sand, and the sizes of sand, gravel and organic material did not vary with depth down to 35 feet (35 feet was the maximum occasional departure from the target depth of 30' - which is consistent with legitimate dredging practise).

The composition of the river bed material beneath the band of sand did, however, vary from one side of the river to the other, the sand being coarser and then being a higher proportion of gravel on the Windsor side than on the Richmond side.

Mr. Croucher said that one cubic yard of gravel weighed about 1-1/4 tons and that $1\frac{1}{2}$ cubic yards of organic material (wet) weighed about 1 ton. He said that near the bank on the Windsor side of the river the proportions of sand, gravel and organic material were: 50 tons of sand to 8 tons of gravel to $\frac{1}{2}$ cubic yard of organic material. Near the Richmond side the proportions were 50 tons to 2 tons of gravel to 5 cubic yards of organic material. These figures imply that the average composition (over the dredging lease area) of the river bed material beneath the abovementioned bed of sand was, at the commencement of dredging, 88% sand, 9% gravel and 3% organic material (percentages by weight).

A description is now given of deposits by two floods in 1969 over a dredged area, which is the upstream portion of Mr. Davidson's dredging lease:-

Mr. Croucher said that soundings taken over the dredged area (approximately 550 ft. x 350 ft. - see below) before and after a small flood, which occurred in February or March 1969, showed that about 5 feet of bed material had been deposited by this flood. The average bed level over the dredged area before this flood was 30 feet below low water and the average bed level over this area after the flood was 25 feet below low water. He estimated that the big flood in November 1969 had deposited bed material of an average thickness of 15 feet over the dredged area, this area being about 550 feet long (i.e. the length of a strip extending 550 feet upstream from the dredging bins) and about 350 feet wide (i.e. the width of the strip whose edges are about 50 feet from the low water marks on the banks of the river, the width of the river being about 450 feet). See the cross section on Figure 1.IV.2. He said that over this area the average bed level before the flood was 25 feet below low water and that after the flood the average bed level was 10 feet below low water. This is

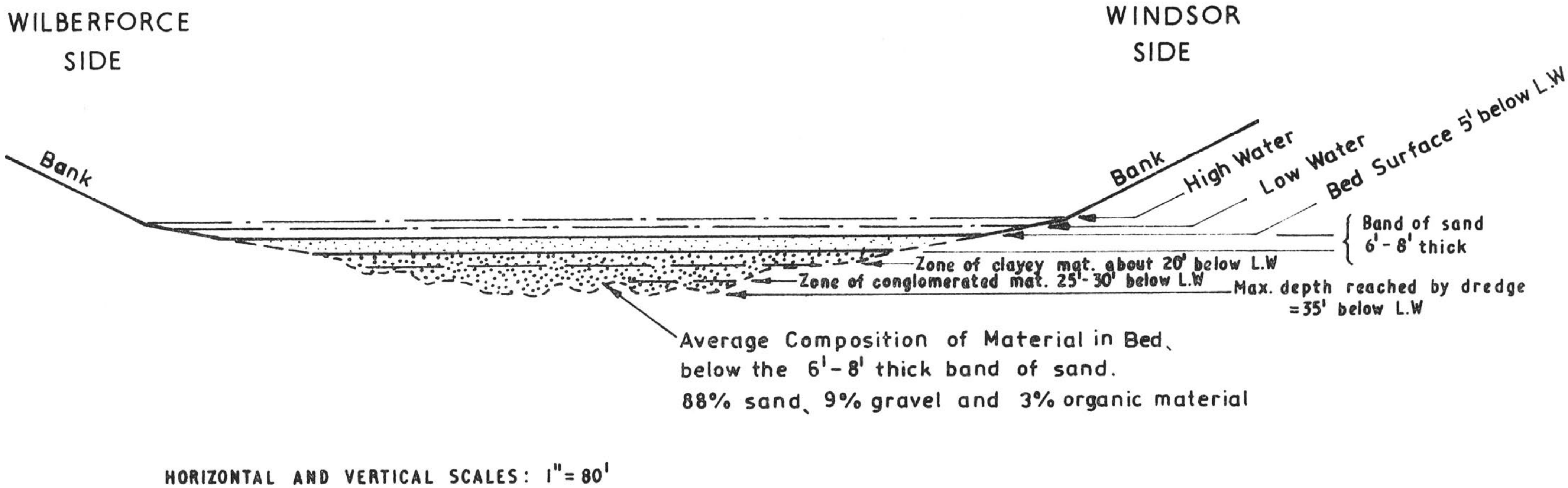


FIGURE I·IV·I: CROSS SECTION LOOKING DOWNSTREAM FROM WINDSOR BRIDGE, SHOWING AVERAGE COMPOSITION OF RIVER BED OVER MR. DAVIDSON'S LEASE, BEFORE DREDGING COMMENCED.

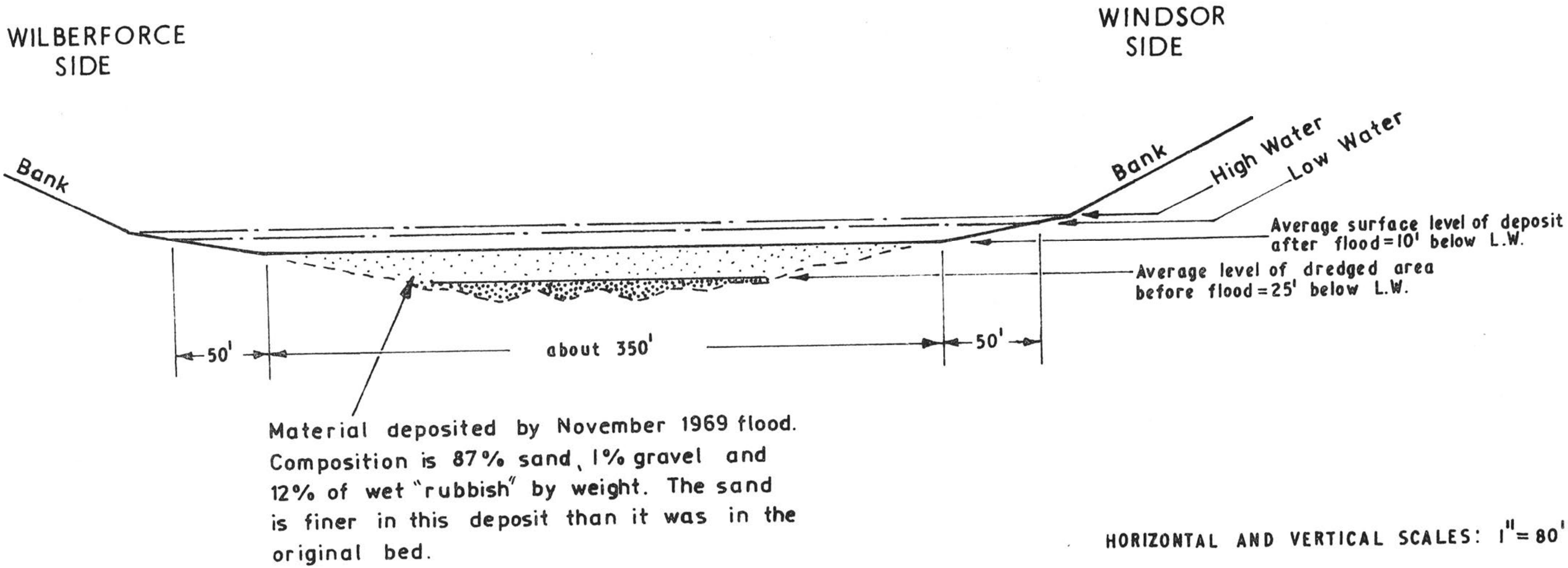


FIGURE 1·IV·2: CROSS SECTION SHOWING MATERIAL DEPOSITED BY THE NOVEMBER 1969 FLOOD OVER THE 550' × 350' DREDGED AREA AT THE UPSTREAM END OF MR. DAVIDSON'S LEASE.

equivalent to 100,000 tons of sand deposited and hence this dredged area absorbed 1/5 of the total quantity of sand passing Windsor Bridge in the November 1969 flood (estimated to be approximately 500,000 tons). Mr. Croucher said that the sand in the material deposited by the November flood over the abovementioned dredging area had a smaller percentage of coarse grains than the original sand in the river bed. There was practically no gravel in the deposit but a higher proportion of organic material than there had been in the original bed material.

The average size of the gravel in this flood deposit was about 2" (my estimates after inspecting piles of gravel near the bins on 27.2.70). The organic material as delivered from the dredge was 90 pc. charcoal in the form of granules intermixed with fine particles, the average size of the granules being about 3/16". The remaining 10 pc. of the organic material consisted of twigs and timber fragments, some carbonized, others unburnt, in various lengths up to about 5". It was noted that the sizes of the granules in the "rubbish" dredged from the river were larger than the "strikes" of charcoal grains embedded in a nearby exposed portion of the river bank. It was also noted that mixtures of fine material and water oozing from the wet heaps of "rubbish" had the appearance of black ink.

Mr. Croucher said that the composition of this November 1969 flood deposit and the proportions of sand, gravel and "rubbish" in it did not vary throughout the 15 feet thickness of the deposit, nor did it vary from one side of the river to the other over the 550 ft. x 350 ft. dredging area. He said that the proportions of sand, gravel and organic material in the deposit were:- 50 tons of sand to ½ ton of gravel to 10 cubic yards of organic material. These figures imply that the composition of this November 1969 deposit was 87% sand, 1% gravel and 12% organic material (by weight).

Mr. Croucher said that after each flood since he has been on the project there have been deposits of material on the river banks on Mr. Frank Johnson's farm which adjoins the dredging bins. He said that the November 1969 flood had deposited about 3 feet of sand on the river side of the bank in the vicinity of Mr. Johnson's pump house.

CHAPTER 2: SOME LAND FORMS AND SOIL STRATIGRAPHY ASSOCIATED WITH BANKS AND FLOOD PLAIN OF THE HAWKESBURY RIVER.

by A.M.H.Riddler and H.A.Scholer

INTRODUCTION:

In this chapter the alluvial sediments of the Hawkesbury River between Richmond and Sackville are examined in an attempt to distinguish and characterise the several strata of which they are composed and the soils, or remnants thereof, on each.

This study of land forms and their soils is intended to assist surveys of the alluvial lands associated with the Hawkesbury-Nepean river and in the assessment of their uses. These uses include their suitability for various agricultural operations, including drainage, irrigation and the growing of specific crops. This study could also be of assistance in engineering investigations such as site explorations for foundations and bank stabilisation works, the identification of soils which are susceptible to tunnelling being an important feature of the latter explorations. The assessment of sites for waste disposal or for the creation of artificial lakes require a knowledge of the physical and chemical properties of the soil strata and their distribution in the affected areas, the latter being the principal object of this study.

Also, by identifying sequences of flood plain sediments, described in this chapter, it becomes possible to interpret the history of floodplain and levee bank growth and to identify unstable reaches where the river might be tending to change its course. The Hawkesbury River and its tributaries have undergone great changes in the late Tertiary and Quaternary Periods. In addition to the uplift and warping of the coastal peneplain there have been considerable fluctuations in mean sea level associated with global climatic changes (1). These fluctuations are shown in Figures 2.1 and 2.2. From these figures and Figure 2.3 showing the longitudinal profile of the rock surface underlying the Hawkesbury River, it is evident that the flow behaviour of the river has fluctuated greatly also (the effects of regional climatic changes as regards rainfall would have to be taken into account in assessing past flow behaviour). Accordingly, the sedimentation behaviour of the river has been subject to radical changes and the history of the alluvial deposits is a complex one. The chronological placement of some of the soil strata associated with the river in any particular locality is a task fraught with difficulty, while the inter-regional correlation of ground surfaces is even more uncertain. Nevertheless headway has been made with this problem and in Part A an attempt has been made to set down and apply to the Hawkesbury deposits the criteria developed by workers in Eastern Australia (11, 23).

Pedological patterns associated with the ground surfaces identified are shown in Figs. 2.15 to 2.24, Part B. A description is given of each pattern.

Notes and a glossary of technical terms are given at the end of Part B.

Previous publications on land forms and soils associated with the ... the end of the chapter.

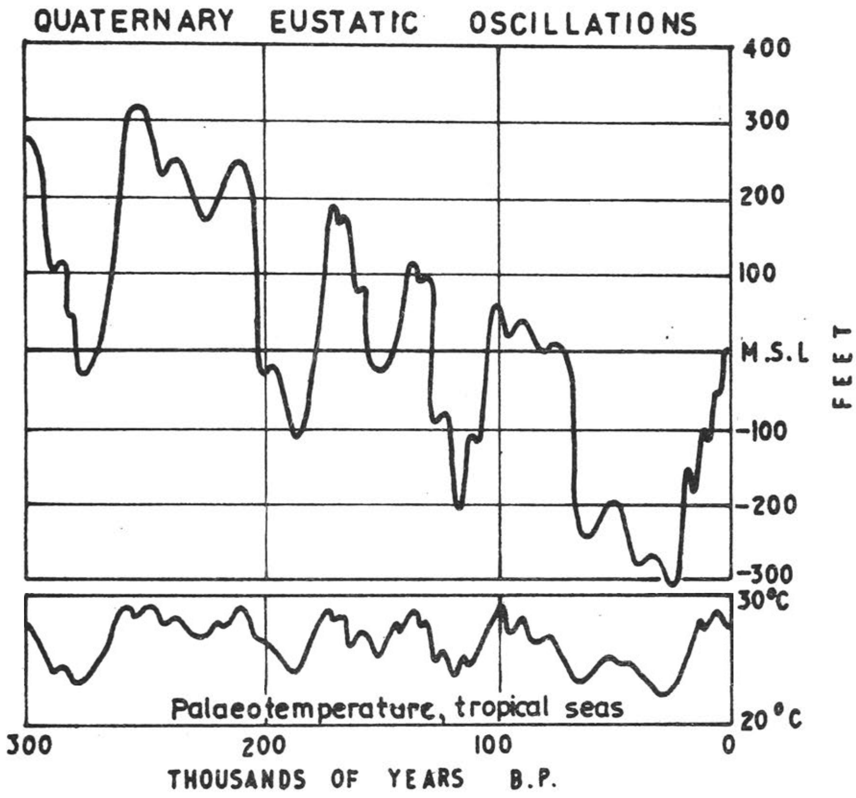


FIGURE 2·1: EUSTATIC OSCILLATIONS OF SEA LEVEL DURING QUATERNARY TIMES.
(after E.C.F. Bird, 1964.)

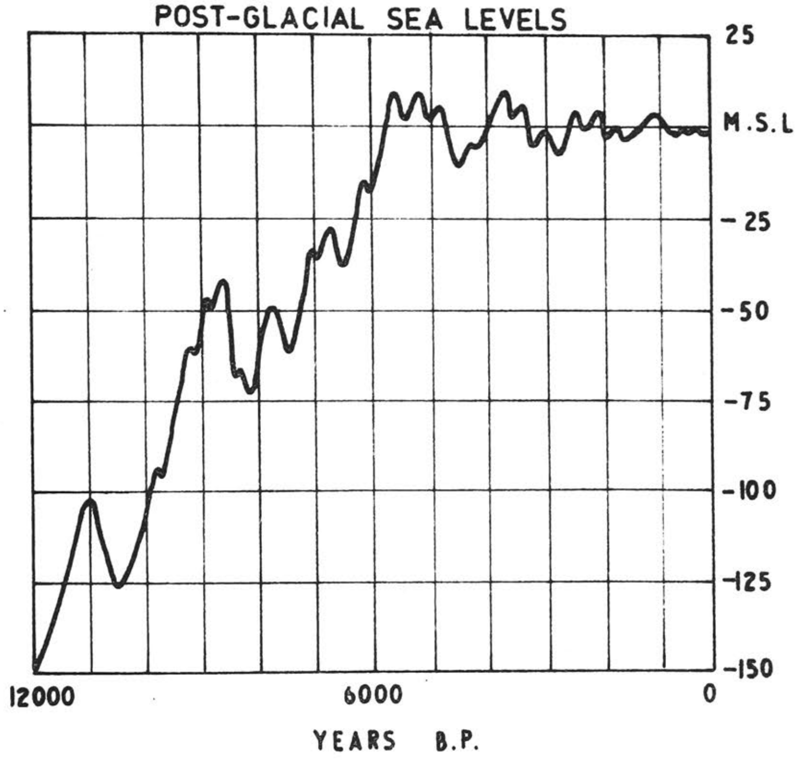
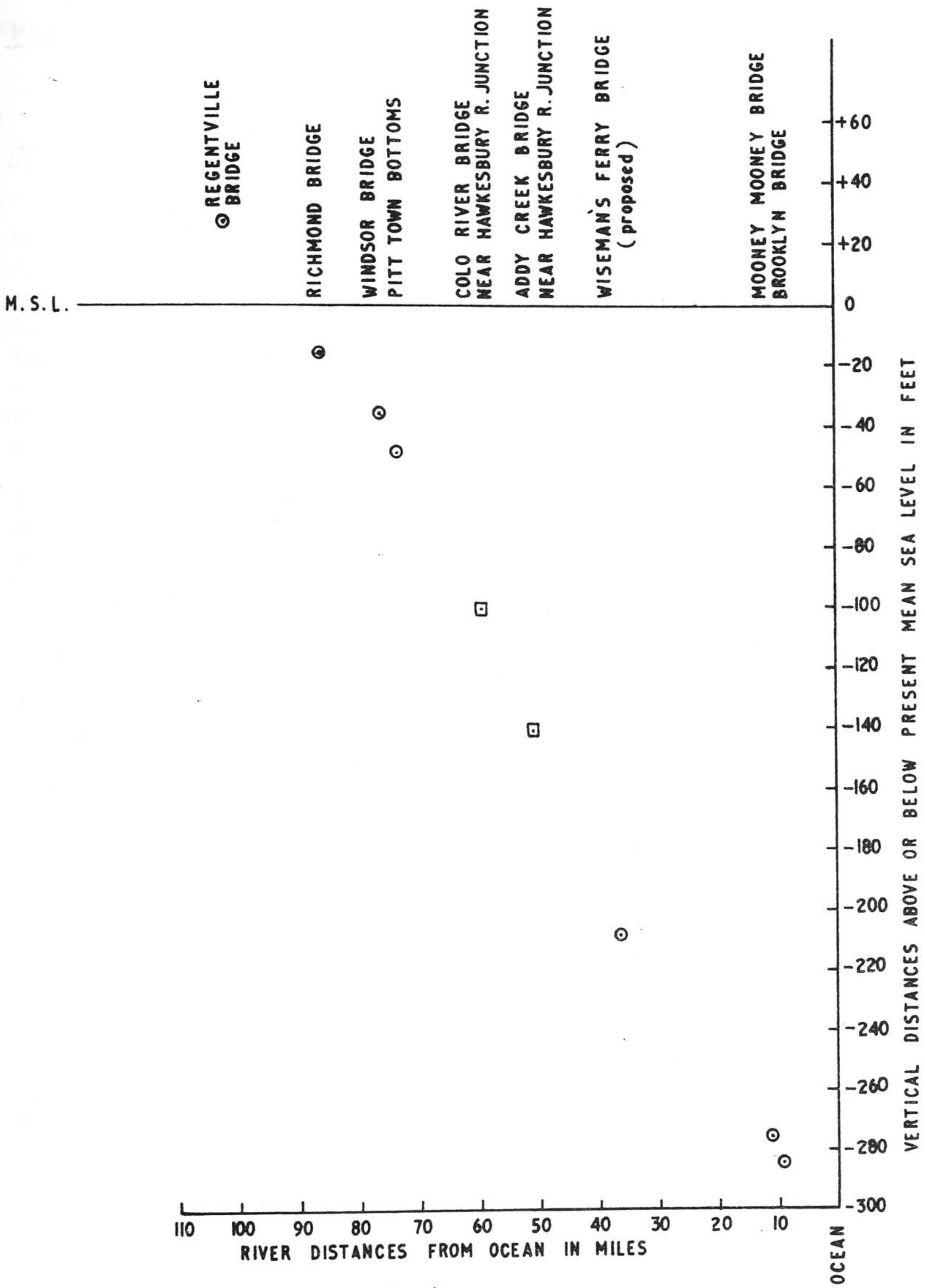


FIGURE 2·2: SEA LEVEL OSCILLATIONS DURING THE PAST 12,000 YEARS.
(after E.C.F. Bird, 1964.)



⊙ Rock surface at this level

⊡ Rock surface below this level

Levels obtained from bore data supplied by the Department of Main Roads, the Railways Department, Colo Shire Council and the N.S.W Department of Public Works. These bores are included in the list given in Appendix I, Chapter I.

FIGURE 2·3: ROCK LEVELS ALONG THE HAWKESBURY RIVER.

PART A: SOIL STRATIGRAPHY AND LAND FORMS

SOIL STRATIGRAPHY

Introduction

In any attempt to unravel the complexities of occurrence of soils in a coastal flood plain, a number of assumptions must be made. Some of the more important of these are set out below.

1. A soil is a product of the interaction of parent material, climate, time, organisms, rainfall and topography. Hence, similar combinations of these factors will give rise to similar soils, while alteration in any one of the factors will give rise to a different soil. Once formed a soil tends to retain evidence of its past pedogenic history.

2. Soil formation is relatively slow and requires much time for the development of separate soil horizons and deep weathering of sub soil material.

3. There have been large fluctuations in sea level in geologically recent times resulting in several erosive and depositional phases in the lower reaches of coastal rivers and in areas associated with these lower reaches (see Figs. 2.1 and 2.2).

4. These fluctuations of sea level, being associated with the growth and retreat of the Polar ice caps were accompanied by climatic fluctuations involving not only changes in average temperatures and precipitations but also changes in the modes of occurrence of these variables.

5. The major alterations to the landscape may have occurred during periods of rapid rise or fall of sea level, i.e. periods of rapid climatic change.

6. In the periods of relatively stable sea level, new soils were formed and these soils differed from their predecessors in degree of profile development and in the degree and depth to which mineral weathering took place.

7. The older soils are more strongly differentiated and mineral weathering in the subsolum has proceeded to a greater depth and is more complete.

8. Where not truncated, deposits of the older terrace material are often elevated with respect to more recent deposits (see Figure 2.6).

9. Recurrent erosional and depositional phases have largely truncated and buried older terrace materials and their associated soils (see Figure 2.7).

Criteria used in the Separation of Ground Surfaces

The separation of the various materials into ground surface pedomorpholiths (for this and other terms used below, see glossary in Part B) associated with specific terraces requires extensive investigations along the river and its tributaries both in the estuarine reaches and in the upland catchment area. It is only by detailed examination of terrace exposures laterally along the river and its tributaries and by tracing the separate ground surfaces so identified over watersheds to adjacent basins that a regional model of the occurrence of a specific pedomorpholith can be reached with any degree of confidence - and hence predictions as to its mode of occurrence, properties and characteristics over the basin being studied (9, 23).

Some of the characteristics and properties which should be examined in detail in each deposit are:-

1. Elevation of present surface in relation to the adjoining mean river level.

2. Elevation of base deposit above the thalweg of the stream.

3. Variation in thickness of the deposit along the stream.

4. Relation of the present surface of the deposit to present day peak flood level.

5. Nature and character of the solum.

6. Nature and characteristics of the subsolum materials.

7. Vertical and lateral uniformity or otherwise of deposits.

8. Presence or absence of bedding.

9. The nature, thickness, extent and uniformity of the bedding (sic) or deposit.

10. Pedopetrogenetic differentiation and deep seated gleying associated with variations within the deposit.

11. Presence or absence of depositional and pedogenic unconformities within the deposit (in both solum and subsolum).

12. Evidence of disruption of pedogenic processes such as pedogenic anomalies, fossil soils, traces of past climatic and/or hydrologic conditions (which differ from the present).

13. In examining fabric patterns and pseudogleying, care must be taken not to confuse fabric patterns such as gleying, fills etc. which occur as a direct result of, and concomitantly with biotic agents (either vegetable or animal), with patterns which occur as a result of the following:-

(a) Processes taking place some time after the biotic agent ceased to be active.

(b) Changes in climate with or without soil-hydrologic and attendant biotic changes.

(c) Effects of replacing the disruptive biotic agents which were constituents of a climax community. These effects include:-

(i) Gleying resulting from the activities of a new family of biotic agents which were not disruptive, but occupied zones of weakness and areas of activity of the former biotic agents (because of changes in conditions of the air-soil moisture complex which favoured the new family of biotic agents).

(ii) Pedogenetic subsolum gleying processes in anaerobic conditions.

In the above comments no distinction has been made between endogenesis by direct action "in situ" of the bio agents or exogenetic action through movement of secreted organic products, and the concentration of these products in certain sub solum layers giving rise to differential weathering and/or pseudo gleying (see text below). Particular note must be taken of the part played by macro faunal and floral agents in the pattern forming process by burrowing, removal of soil material and compressive shear; as opposed to the differential chemical weathering processes brought about by both aerobic and anerobic micro fauna and flora. Where possible, a distinction ought to be made between the effects of local organisms and the effects of organic compounds secreted by organisms elsewhere in the profile. It is emphasised that a distinction must be made between patterns resulting from biological agents and those patterns of segregation and differential weathering arising from differences in structure, fabric and texture of the parent material and associated fluctuations of perched or permanent water tables.

From an examination and analysis of such characteristics, the character of each separate terrace deposit and pedomorpholith is evolved for a number of parent materials subject to differing hydrologic conditions in different parts of the basin (i.e. differing physiographically). The relation of each present day surface solum to that of the subsolum is worked out and a composite dynamic model of the physiography of the basin is compiled for each ground surface. From these models predictions can be made as to the location and nature of the deposits throughout the present day basin. The pattern of deposits so obtained can be extrapolated into adjacent basins and thence to a whole region.

From the correlations involved in determining the patterns and characteristics of these mantles, the pedomorpholiths are identified and physical and visual (13, 24) features associated with them are established. These features become an aid to the identification of like pedomorpholiths in other catchments.

Some of the easily identified characteristics are elevations of the surface of the terrace and its base/relative to the present day mean river level and to the thalweg respectively; the relation of the surface to the height and spread of average floods, the suite of soils one can expect and the visual characteristics of deep weathering of the subsolum material (see pedological patterns in Part B (Figures 2.15 to 2.24). These few features cannot replace those listed previously in any serious attempt at the establishment of a soil stratigraphy for a basin, but merely act as pointers to the most probable chronological sequence of deposits and to the nature of the several pedogenic phases that have taken place since the locally oldest deposit was laid down.

An examination of the terrace deposits on the Hawkesbury River between Richmond and Sackville resulted in the finding of a wide array of soil types resting on a variety of substrates.

The present examination was by no means exhaustive and much reliance was placed on comparison of both solum and subsolum materials with those found and characterised elsewhere in N.S.W. (11, 23).

Many surface soils have been variously truncated and altered by past erosive phases and by present river action during floods. Most of the present day back slope and swamp soils are affected to some degree by the deposition of recent material during floods.

Soil mantles of the various groundsurfaces were derived in large part from highly pre-weathered and leached soil materials and highly weathered rock, i.e. only resistant materials remain; most of the nutrient minerals having been leached out and simple colloids and "low-energy" clay minerals predominating. Mass movement and pluvial subaerial erosion only partially remove the former mantle from a region; rather they bring about a major redistribution of the surface horizons. So deep is the weathering that the incorporation of fresh rock material into the succeeding ground surface mantle would take place only in zones of massive slope failure of the prior mantle and deep incision into the exposed but partially weathered rock surface. Thus the same highly weathered and leached material, with only minor additions of relatively fresh rock material form the successive terraces and associated upland ground surfaces. Recent river deposits, resulting from erosion, contain a greater proportion of coarse grained, relatively unweathered rock and organic material producing a fertile soil associated with the levee banks.

LAND FORMS

River Terraces at Windsor

The river banks vary both laterally and vertically in composition, age and properties including susceptibility to erosion, undercutting, tunnelling and attrition. The descriptions, given below of river bank and terrace materials are illustrated by Figures 2.5, 2.6, 2.7 and 2.8 which attempt to show the stratigraphic sequence of materials as displayed on the sloping river banks in the vicinity of Windsor. Insufficient time was available to obtain the surface elevation and relief of the deposits,

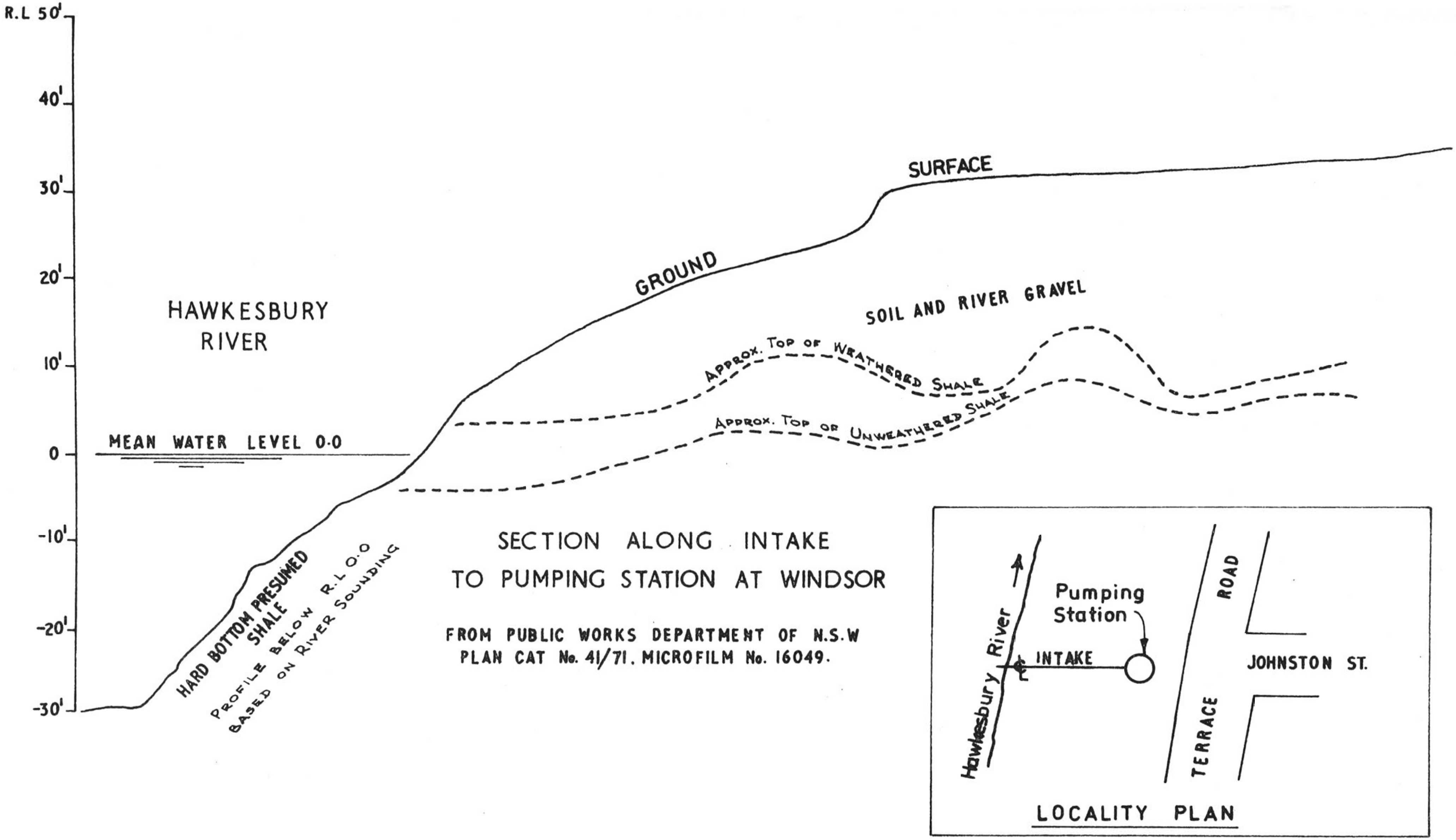
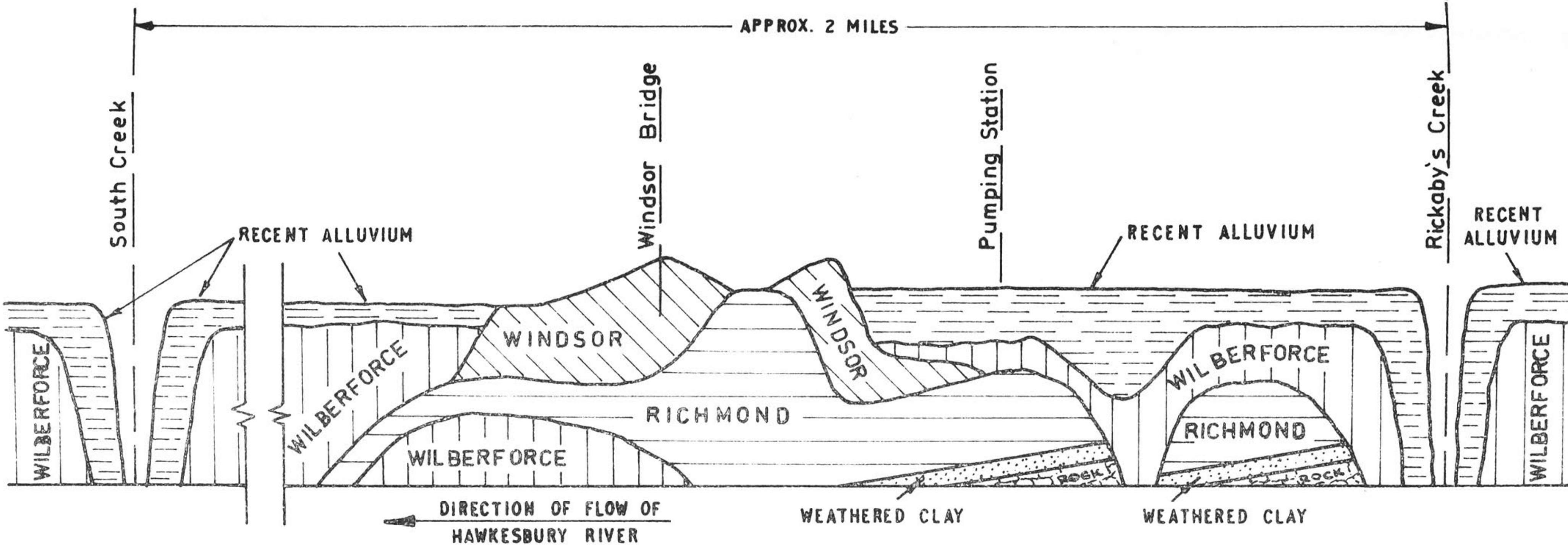
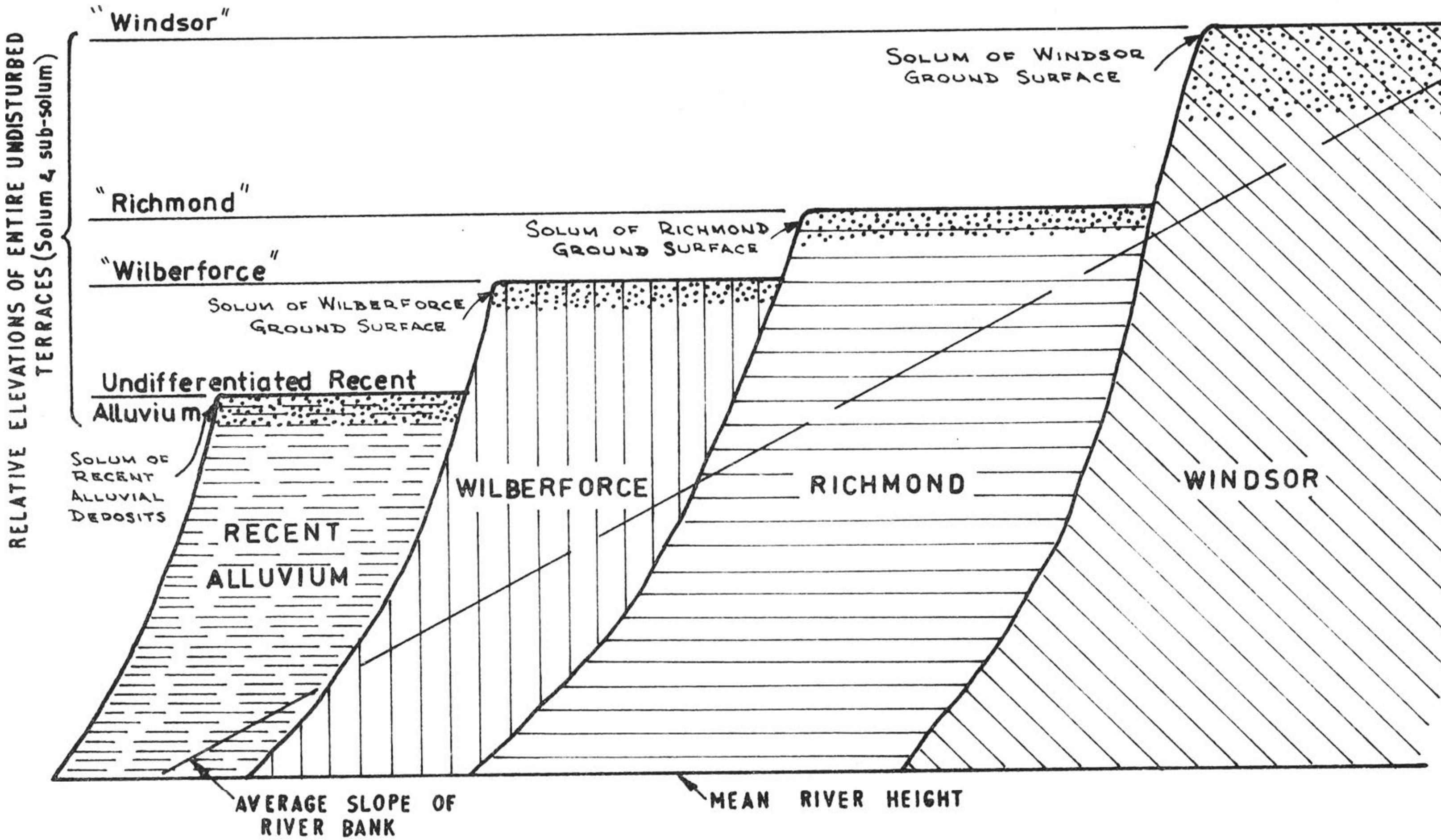


FIGURE 2·4: SHALE BED IN VICINITY OF THE TOWN OF WINDSOR.



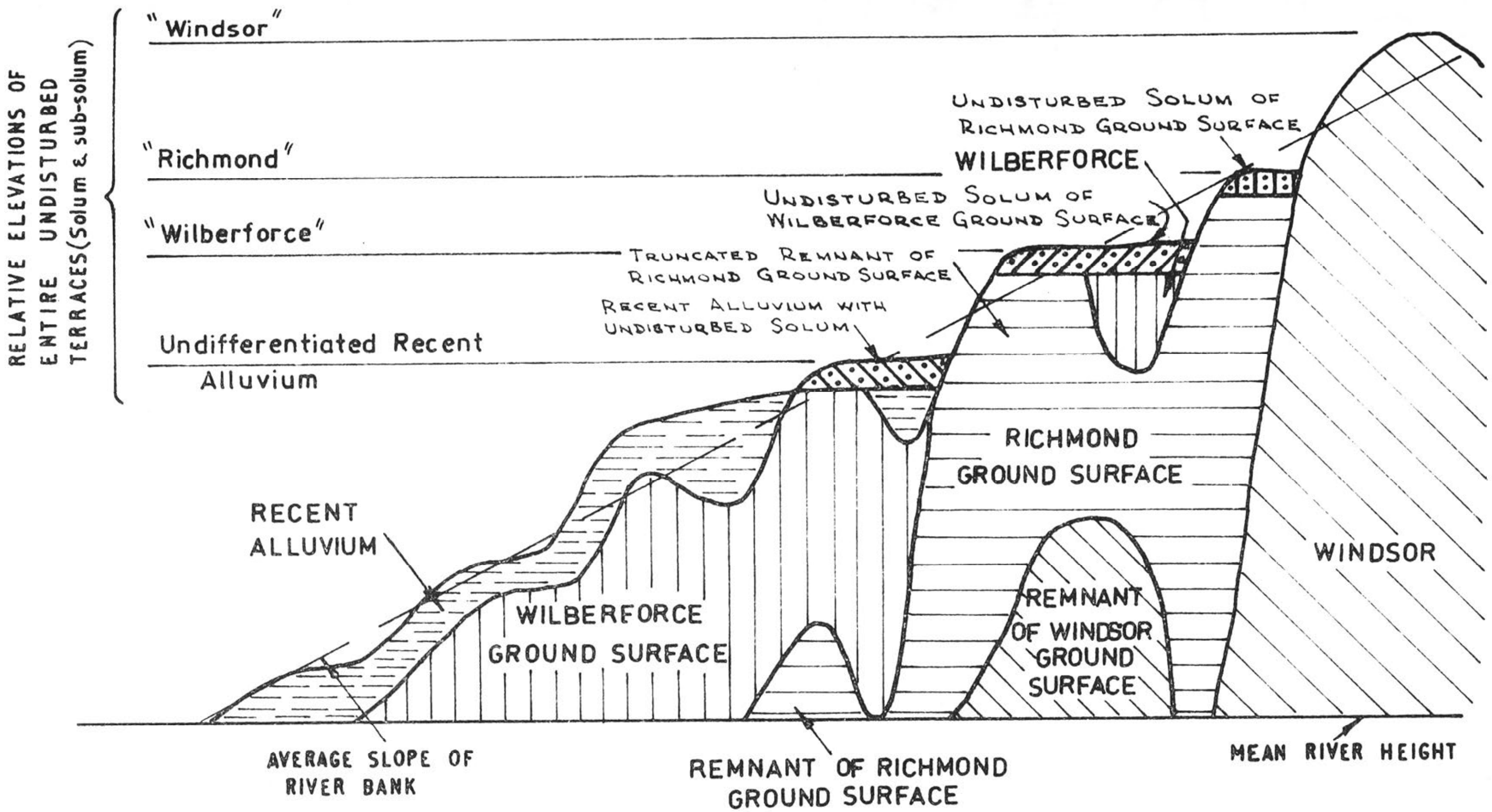
The diagram does not represent a vertical section, but rather the impression given by the sloping bank when viewed from the river — hence the exposures of ground surface materials may at first sight seem anomalous. Thus the Wilberforce ground surface appears above and below the Richmond ground surface — the lower member in this instance representing material on the "toe" of the bank which is in front of the Richmond "plug." It is not, however, below it vertically in section. For an understanding of these exposures see Figures 2·6 & 2·7. See also Section A (which embraces locations numbered 1 & 2) in Figure 2·14

FIGURE 2·5: SLOPING EXPOSURE OF RIGHT BANK OF HAWKESBURY RIVER AT WINDSOR, SHOWING GROUND SURFACES.



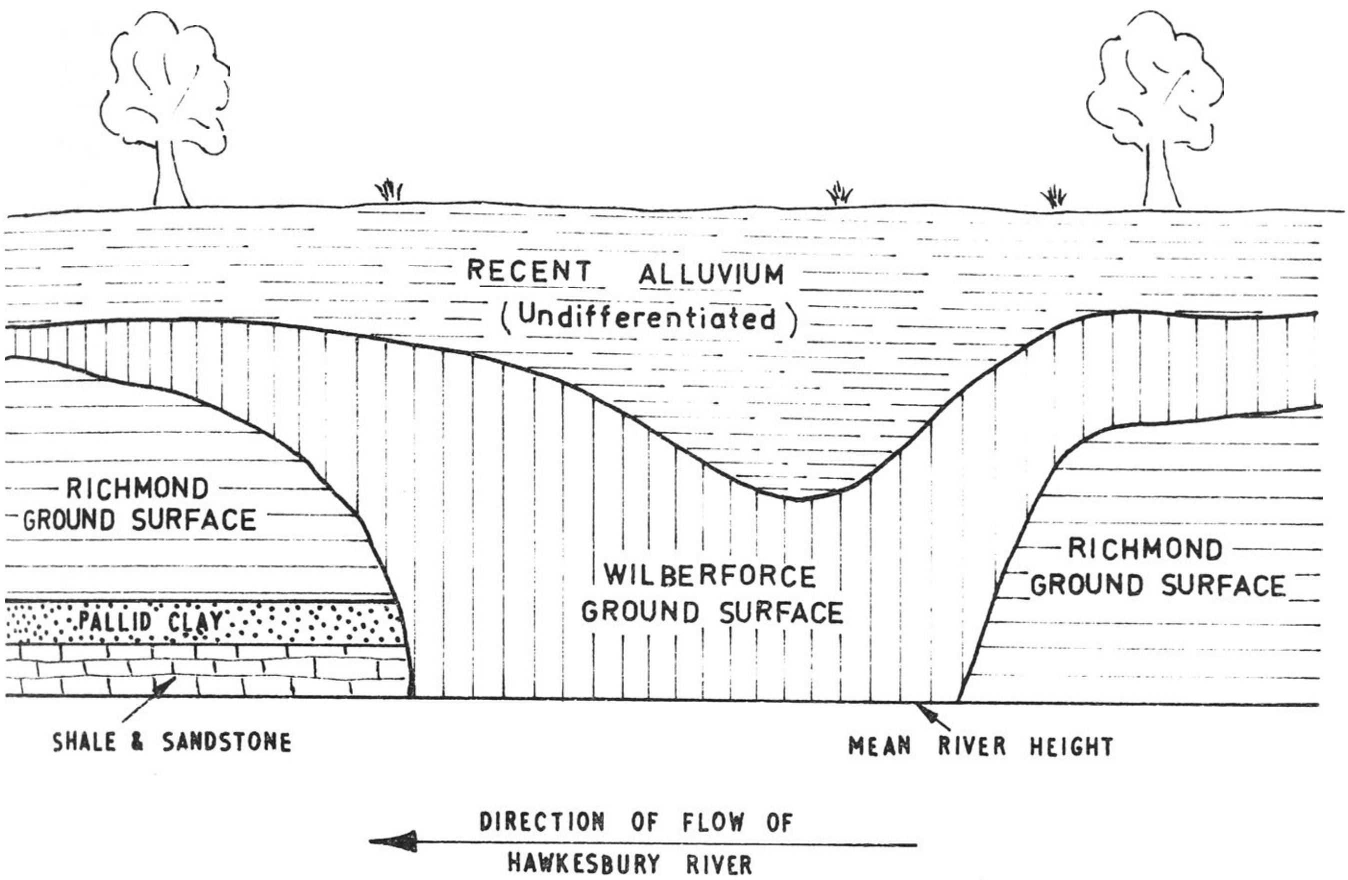
Schematic Cross Section of Terrace Sequences showing relative elevations of the terraces and their respective "in-situ" sola. (An idealised distribution practically never encountered in major streams.)

FIGURE 2·6: SCHEMATIC CROSS SECTION OF RIGHT BANK NEAR WINDSOR BRIDGE.



Schematic Cross Section showing the typical distribution of the various ground surface terrace materials after truncation and subsequent deposition of successively younger material. (Older deposits exposed by removal of younger sediments.) This is the most usual type of distribution of materials encountered.

FIGURE 2·7: SCHEMATIC CROSS SECTION OF RIGHT BANK NEAR WINDSOR BRIDGE.



Schematic diagram (not to scale) of a "cut and fill" feature - about 7 chains upstream of the pumping station at Windsor - South bank of river. Height of feature about 25 ft. - length about 3 chains.

FIGURE 2·8: RIGHT BANK UPSTREAM FROM WINDSOR BRIDGE their thicknesses, their lateral extent and configuration over the flood plain. The locations of the sites in these figures are numbered 1 and 2 in Fig. 2.14. (Note that Figs. 2.13 and 2.14 are in Part B).

A bed of shale runs under the town of Windsor, as shown in Figure 2.4, the surface of firm rock being about a foot above high tide level. The exposures of this shale bed are also shown in Figures 2.5 and 2.8. The shale constitutes a barrier to the shift of the river southwards in this locality, thus making more certain the identification and placement in a chronological sequence of the soil strata below the town of Windsor.

Windsor itself (at the highest elevations) appears to have a substratum of dense, laterised, resistant red sandy clay which displays tubules of pallid clay material surrounded by aureoles of yellowish material. The tubules have generally a vertical orientation, but bifurcate and intertwine in places and are presumably biotic in origin. (See Figs. 2.19, 2.20 and 2.21). This material has been termed the "Windsor" ground surface and is similar to the "Kremnos" ground surface (see table). It appears to have a thickness of at least fifty feet at the highest point of the town. In exposures at lower elevations on the river bank younger terrace materials are seen (see Figures 2.6 and 2.7). Three such strata have tentatively been separated. The youngest consists of recent sands, silts and clay loams which generally cover, and give the surface configuration of the river banks. This material extends over the present day flood plain, being sandy and coarse on the levee banks and becoming gradually finer in texture with increasing distance from the river, and texture approaching that of loams and light clays. The soils from this material are mainly alluvial regosols, although deeper subsoils may be similar in characteristic to prairie soils. Nowhere are these soils very deep at any distance from the river. Their substrata consist of remnants, benches and plugs of prior terrace formations and remnants of old levee banks where the river has changed its course - e.g. at the lower end of Freemans Reach.

At the respective confluences of Rickaby's Creek and South Creek with the Hawkesbury River, large areas of this recent sandy regosol occur, as back-filled levee formations from the main river on the flood plain beyond. Near South Creek this material has been extensively mined by an extractive industry.

In areas where trees are absent evidence of large bank slumping is seen. In these "unstable" areas, evidence is seen of tunnelling the source or point of entry of the leaching water being some distance back from the levee bank in the flood plain, often in "ponded" areas. In some locations there is evidence of scour by flood currents.

The next prior terrace remnant identified, is a material termed "Wilberforce" consisting of drab grey brown, massive, vesicular material. The vesicles and crescentic, randomly oriented vughs may represent shrinkage cracks, giving what is known as a "rimulate" pattern (see Fig. 2.24) and are frequently lined with cutanic material which may consist of dark brown clay, gleyed clay or iron-enriched colloids. The vesicles and vughs do not appear to be interconnected, and the type of cutans would appear to depend on the type of material present in the soil-water locally during the process of pedo-petrogenetic* differentiation. No evidence of

* For this and other special terms see glossary of technical terms in Part B.

individual bedding planes was seen in the alluvial body. However, broad zones of either clay-iron enrichment or gleying are evident and are possibly due to varied soil-water regimes and pseudo-gleying caused by variation of texture and permeability in the parent material. Frequently, long, vertical tubes of gleyed material are seen penetrating the mass. The tubes, varying from about 2" to 6" in diameter, proceed for almost the entire thickness of the deposit, being constricted and changing direction on encountering resistant horizons. These vertical tubes have aureoles of leached material, and, at depth, clay may be deposited in and around the tubes. This vertical "gammate" pattern (see Figures 2.10 and 2.11) is thought to represent pedopetrogenetic differentiation caused by locally increased infiltration in zones of weakness caused perhaps by deep rooted tree species i.e. leaching (± subsequent deposition) of the tube and of the fractured zone caused by the penetration of a root which has subsequently decomposed. This process is described in Figs. 2.12 and 2.24. These columns and their aureoles are frequently more resistant to weathering (slaking and attrition by flowing water) than the matrix of the alluvial body, and on exposure adopt a "buttressed" configuration, the columns standing "away" from the retreating face of the exposure. This coarse, columnar buttressing is not to be confused with adventitious, consequent rilling (i.e. buttressing is a secondary weathering phenomenon). This material, termed "Wilberforce", is similar to terraces which have been identified as "Gundaroo". It forms the substratum under the present day flood plain, varying in depth below the surface from about 2 ft. to 6 ft. and is less permeable than the recent regional alluvial deposits in this region. The surface of the "Wilberforce" terrace as shown in Figure 2.7 is quite irregular, being in the form of a series of ridges and depressions, believed to represent former scour-flood channels. The recent material is deposited over these ridges and depressions, often thinner on the ridge crests and troughs than on the flanks of the prior ridges.

The next oldest terrace is termed the "Richmond" terrace. In this terrace, and occurring as plugs, are grey and yellowish grey well structured clays. The clays are plastic and somewhat unstable, sloughing off in 1" thick, 4" diameter sticky cusps or spalls. Some evidence of slickensides is seen in darker members of this clay series, the result of internal movements which are associated with instability of the soil body (the darker coloured clayey zones may represent hydromorphic members of a catenary sequence). These clays often display a fine rectangular gley pattern corresponding to former bedding planes and major vertical structural units (see Fig. 2.22). The clay is deeply weathered and slakes easily and is susceptible to tunnelling. This is especially serious as an erosion hazard when clays of this prior terrace formation are exposed on the river bank and in ponded areas of the flood plain. If two such exposures are contiguous, water seepage will cause tunnelling and eventually bank failure and collapse.

This terrace material is similar to terraces elsewhere identified as belonging to the Tarago ground surface (see table and Figure 2.6). Observations on Tarago groundsurface soils indicate that the solum would be solodic (greater than 5% exchangeable sodium in the B horizon) and they are known for their tendency to slaking and tunnelling. Tunnelling and slaking were seen in some exposures of this ground surface and from evidence elsewhere it is inferred that this subsoil may be saline and the solum probably solodic (no undisturbed surface soils were observed).

Some rock outcrops are evident also near to the pumping station upstream from Windsor which give stability to the course of the river at these locations.

Immediately superimposed on these finely stratified shale and sandstone beds is a zone of structureless, pallid, plastic clay, possibly lateritic in origin and derived from a shaly parent material (see Figures 2.5 and 2.8). Very occasionally, irregular tubular red mottles are seen in this exposure, due possibly to some biotic activity during the formation of the laterite. In some exposures evidence of the bedding planes of the shale are observed. The age of this weathering is quite uncertain and most probably predates the highly laterized "Seeland" gravels (Pitt Town, McGraths Hill, Riverstone etc.). This weathering zone probably represents the true parent material of the various ground surface soils of Eastern Australia (see footnote at the end of this part).

Upstream from the pumping station at Windsor there occurs a "cut-and-fill" form which displays varying quantities of the several materials described above: recent alluvium, and terrace materials of Wilberforce and Richmond age, overlying pallid weathered clays, possibly derived from a shaly bed, which in turn immediately overlies the sandstone exposures. This "cut and fill" feature is shown in Figure 2.8. Figures 2.5, 2.6 and 2.7, showing the general relationships of bank and terrace materials, because of insufficient detailed field observations, are schematic only, are not to scale and do not accurately place boundaries. The locations of the sites in these figures are shown on Figure 14, Part B.

Figure 2.5 is a schematic representation of the major exposures of the various ground surface materials. No attempt has been made to indicate the actual dimensions of individual exposures; it is intended only to indicate some broad relationships between the ground surfaces and to draw attention to the extreme variability of the terrace substrates. The heights indicated in this figure represent an average maximum elevation of the truncated remnant sub-sola of the various ground surfaces and do not represent the elevations of the ground surfaces entire with sola. The figure is simplified also in that the frontal coating of recent alluvium is removed to give a clear impression of these prior remnants. The elevations of the various ground surfaces above river level vary directly with age (for entire units see Figures 2.6 and 2.7). The locations of the sites in these figures are shown on Figure 2.14, part B.

Levee Banks, Terraces and Flood Plain at Pitt Town Bottoms

Areas inspected in detail are numbered 3,4,5 and 6 on Figure 2.14, Part B. The low flats and swamps in this area would appear to be "Wilberforce" (see table) in age, the solum of which has been variously truncated and replaced by younger sediments, mainly during river floods (as opposed to local sub-aerial processes). Very deep channels are infrequent. The surface is undulating and probably shaped by localised flood currents which are frequently seen travelling in courses roughly/

parallel

to the main channel. The currents follow the swales in the flood plain landscape which has an undulating or corrugated ridge and swale surface configuration. The usual surface scour-channel pattern is evident in parts of the flats. The area is quite representative of such situations elsewhere on the Eastern sea board. At the southern end of the Pitt Town bottoms road (Figures 2.17, 2.18, 2.19 and location 3 Figure 2.14 Part B) there is an exposure of laterized gravel in a pallid clay matrix. Occasional large reddish mottles are present, quite irregular in shape and about 1 foot in diameter and having 18" to 24" separation. Much of the gravels have entirely weathered away and are recognised as pseudomorphs in the pallid clay which is believed to be aluminium rich and to represent the pallid zone of a laterite. Gravels of siliceous origin such as quartzites and cherts remain in bedding planes. The gravels are similar to those identified as Bonegilla in Victoria and in the Clarence Valley, N.S.W. and have been called "Pitt Town" gravels. This terrace remnant is quite isolated and is an outlier from the main terrace formation on which is situated the village of Pitt Town.

Bardenarang Creek (see location 4, Figure 14, Part B) to the north of Pitt Town Bottoms is an inlet for river flood waters and a natural drain for the marshy back swamp which (as usual) lies close under the high terrace step. The levee banks of the creek have their greatest elevation near the Hawkesbury River, and decrease in amplitude southwards to the swampy Bottoms.

The high levees along Bardenarang Creek next to the river represent a 'deltaic' system from the Hawkesbury running back towards the 'Bottoms'. Relatively fast flowing, turbulent sediment laden water from the Hawkesbury flows back along the Creek, into the still waters of the 'Bottoms', depositing sediment to form these levees. As the river falls after a flood, these levees confine the drainage flow and thus retard the fall of water level in the Bottoms. Rising from Banderanang Creek to Pitt Town are a number of steps corresponding, in part, to former terrace levels. These steps are not continuous and are variously preserved. The firstterrace encountered (see location 5, Figure 2.14, Part B) displays a deep podzolized profile over red, friable clayey sands, which show thin varves of iron enrichment due to pedopetrogenetic differentiation along bedding planes. This exposure corresponds in topographic position, configuration, pedological features and properties to the terraces at Richmond and Parramatta (earth profile developed from truncation of a podzol profile as seen on the Parramatta River) and are believed to be equivalent to the Tarago ground surface. The next highest exposure is a complex material which has been subjected to polycyclic weathering, truncation and solum development (see location 6, Figure 14, Part B2). The base material appears to consist of a lateritic clay (possibly mottled zone?). It displays coarse irregular red (iron enriched) mottles about 12" across) in a pallid clayey matrix (see Fig. 2.21). This material is called the "Pitt Town" ground surface and is similar to the "Seelands" ground surface (see table).

The upper subsolum horizon of the exposure displays a fine reticulate intermeshed pattern of tubules which bifurcate and intertwine.

Individual tubules have, on occasions, clay fills up to $\frac{1}{4}$" diameter. These tubules occur in a matrix ranging from a yellow-red friable clay to a pallid clay (see Fig. 2.20). Occasionally near the upper boundary of this zone and grading into the Solum above, the tubules are gleyed, and casing or cortex is a yellow red (hydrated iron) clay in a bright red earthy clay matrix of a highly stable nature (see Fig. 2.19). This zone, and the pedal, stable, bright red earthy clays above appear to belong to a younger pedological cycle than Pitt Town - most probably, the pedological characteristics of that ground surface identified as "Windsor" - that is to say, Windsor pedological development merging into the truncated remnant of the Pitt Town material.

The solum presents an extremely complex pedogenic history as there appears to be evidence of both Wilberforce and Richmond sola on this Windsor material. The material appears, at first sight, to consist of an A/B - horizon podzolic configuration developed on a partially truncated Windsor red, pedal, well structured earthy clay. However, there appears to be evidence of stripping and redistribution of the original Richmond A-horizon and a new cycle of leaching developed on this surface mantle, extending into the Richmond B-horizon boundary and a yellowing of the B-horizon for a further 4". In this "yellowed" zone, break up and leaching of the angular blocky Richmond B - horizon units is evident. This is considered to be the true B-horizon of the Wilberforce pedomorpholith and represents the total development and weathering of the Wilberforce solum.

A cursory examination indicates that the village of Pitt Town is built on similar material to the Kremos terraces at Jackadgery on the Mann River near Grafton which display both Tarago and Gundaroo solum development superimposed on the red, friable, stable pedal, well structured clay of the Kremnos solum B-horizon.

Halls Creek at KentReach - A Trough Valley

See Figures 2.9, 2.10, 2.11, 2.12 and locations 7,8 and 9 on Figure 2.14 Part B. The area examined is a "drowned" alluvial filled lateral valley of the Hawkesbury River. It has the typical rocky convex hills plunging into a flat bottomed swampy valley.

The soils vary from grey to very dark grey, seasonally cracking, uniform to gradational texture profiles in the back swamps through minimal podzolic soils to sandy alluvial regosols on the levees.

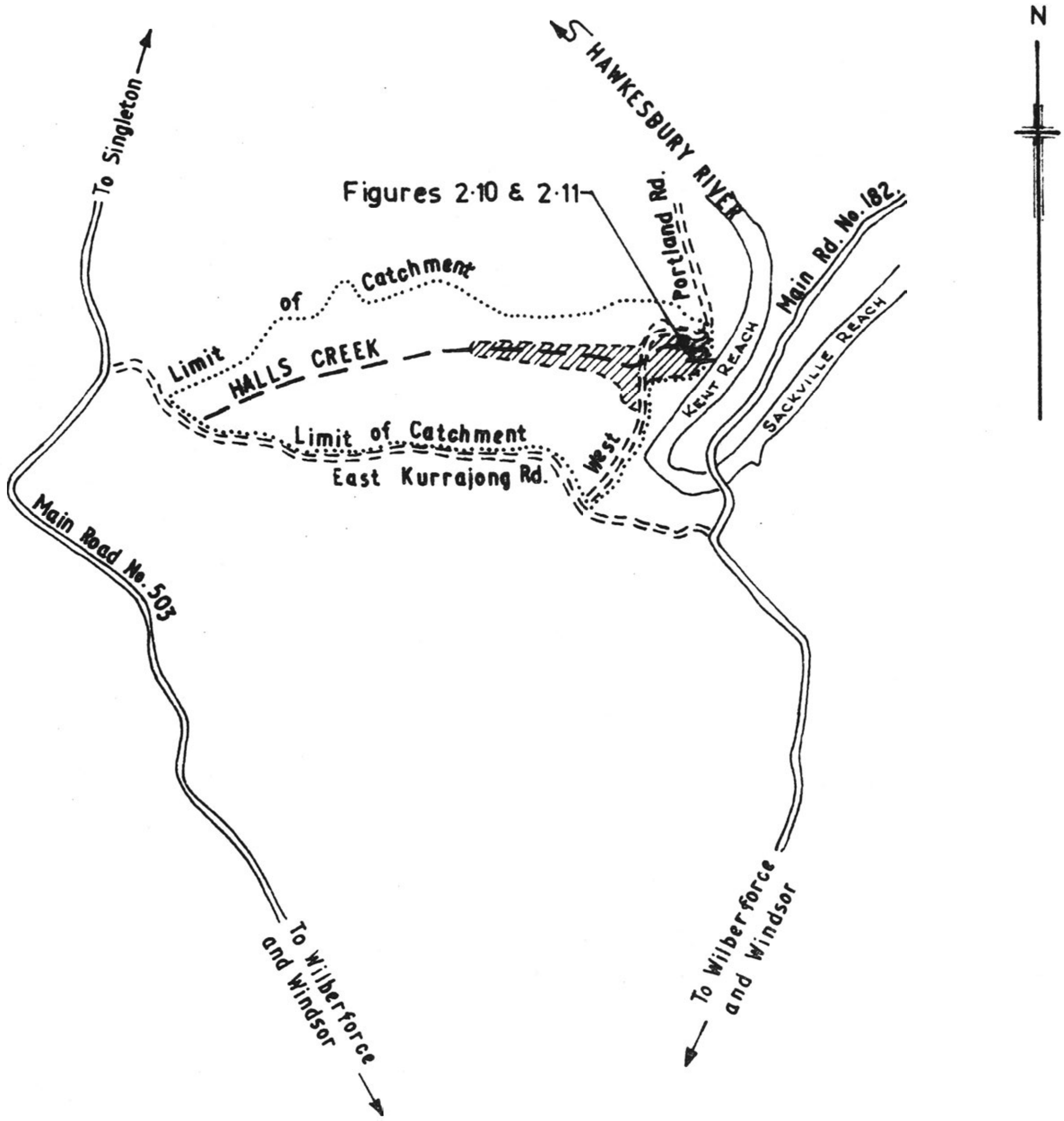
The mouth of the valley is underlain by rock, the surface of which has an elevation of 2-3 ft. above the mean river height at its exposure on the river bank. Levee banks occur, skirting the main river course, and also along the lateral stream channel. The river levee is highest at the upstream side of the valley, sloping down to the creek bank, which suggests a spit-like formation. On the downstream side of the creek the levee bank is lower and has a smoother configuration. At the far downstream end of the valley there is a flood-scour-channel below the bank (on the landward side).

The creek levee banks are lower than the river levee bank. They have a crest height of about 2 ft. in the mid-section of the creek course. The levee banks of the creek are indefinite near the river (possibly due to river scour). Near the back swamp no levee banks are apparent. As is the case with Bardenaring Creek, the creek levees have been formed by back flooding from the Hawkesbury River.

Apart from the recently deposited levee bank soils and a recent surface cover in the area of the floodways or scour channels, the main bulk of the alluvial sediment appears to be similar to terraces elsewhere identified as the "Gundaroo" (see table). Two major soil types are evident (on preliminary reconnaissance) on this formation. The first type is the dark grey, seasonally cracking material, mentioned above, in the back swamps (Location 8, Figure 2.14, Part B) which appears to overlie a pallid clay at depth. The other soil type consists of either a gradational, dense, blocky grey brown clay loam or a minimal podzolic (dependent on hydromorphic conditions and/or admixture with more recent deposits (see Figures 2.9, 2.10, 2.11, 2.12 and location 7 on Figure 2.14, Part B). The subsolum displays a gley zone immediately below the B-horizon of the solum, which may have ironstone concretions at wetter (low-lying) sites. Below this horizon, some evidence of the alluvial depositional beds are evident, mainly as gleyed or iron rich pedopetrogenetically differentiated horizons. Present also are narrow, vertical gleyed tubules. These tubules may represent differential weathering and gleying due to deep penetration of water following some prior root channel (and associated compression zone in the soil). Occasionally secondary deposition has taken place in these vertical tubes (gammate pattern) from material brought down from above by the leaching water. These vertical tubes are affected by locally hardened beds (due to pedopetrogenetic processes) causing apparent discontinuities, presumably, as the precursors of these tubes adventitiously sought weaker zones for further penetration. The general soil matrix displays a 'rimulate' shrinkage pattern effect displaying many vesicles and crescentic narrow vughs. These tubules, vughs etc. are frequently lined with clay, iron or gleyed material.

Vertical pedogenic differentiation causes differential weathering on the exposure of this sub-solum material giving rise to a buttressed effect of vertical columns of soil material which may stand (quite) "proud" of the retreating eroding face (as opposed to rilling by running water). In most instances, the vertical gammate gleyed columns form into one of these "buttresses". However, the differential degree of resistivity to erosion is dependent on the pedogenesis of the materials within the stratum: the degree of leaching of the columns, the quantity and type of secondary deposition within the gleyed part of the columns and diffusion beyond them, differential weathering and deposition along old bedding planes (interrupting the vertical erosion separation of the columns on exposure) and the density and cohesivity of the matrix. ("Cohesivity" is not just a measure of mechanical cohesion but rather its overall ability to resist a complex of disintegrative processes).

Below this "Wilberforce" material (see table) areas of easily dispersed grey and dark grey clay occur. This material is similar to material elsewhere identified as the "Richmond" (see table) ground surface.



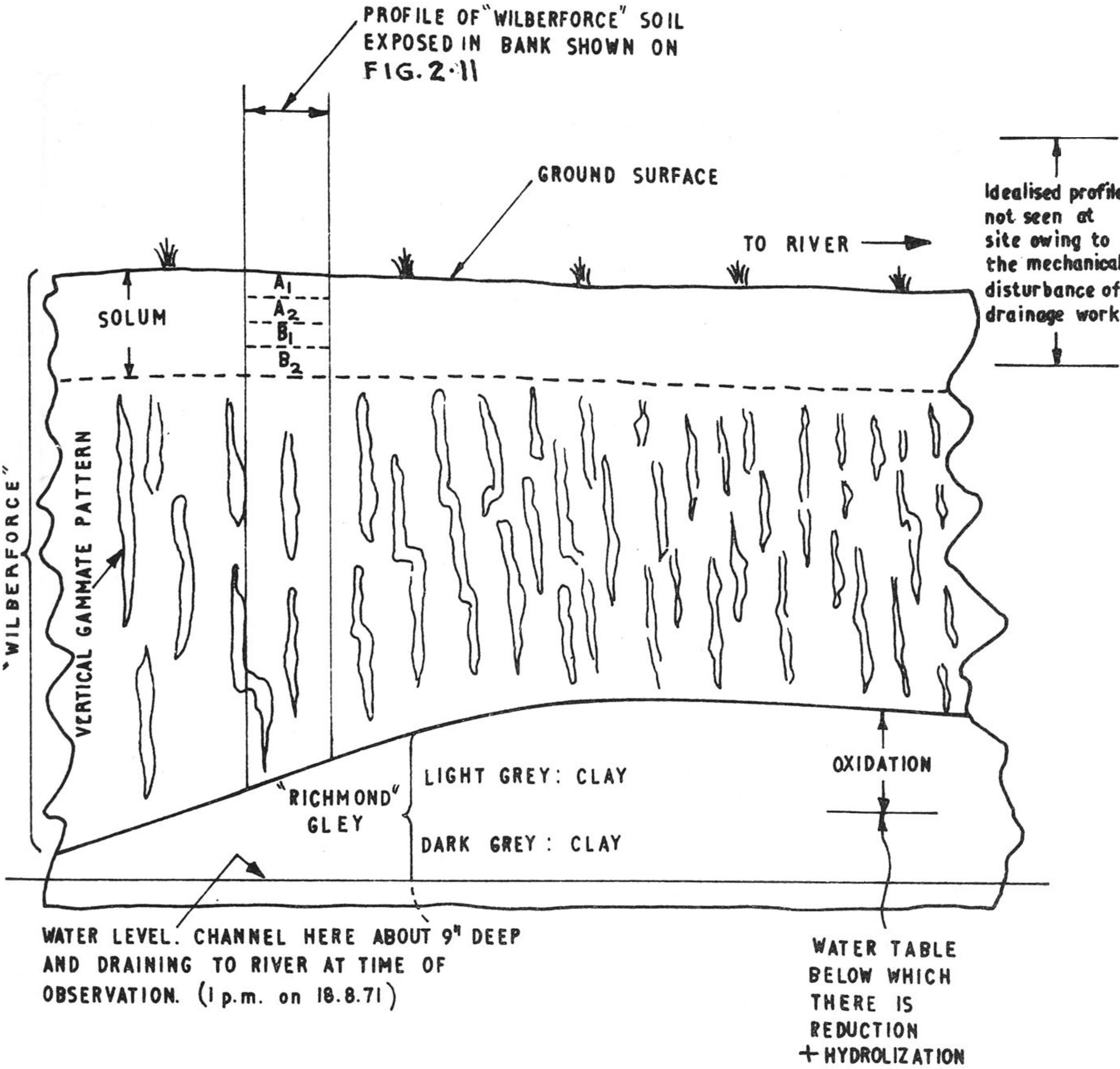
NOTES:

The mouth of Halls Creek Valley is underlain by rock the surface of which has an elevation of 2-3 feet above the mean river height.

The soil features shown in Figures 2·10 and 2·11 are behind the levee bank of the Hawkesbury River at the mouth of Halls Creek.

SCALE: 1 mile to 1 inch

FIGURE 2·9: LOCALITY MAP - HALLS CREEK



NOTES:

The vertical gammate pattern of the "Wilberforce" sub-solum, breaks away to give a buttressed weathering erosion pattern. The "Richmond" clay weathers in skins (spalls) and these slough off giving a "slump" erosion pattern.

The "Richmond" clays are highly weathered, easily slaked, are unstable and hence susceptible to tunnel erosion.

FIGURE 2·10: LONGITUDINAL ELEVATION SHOWING BANK OF CREEK AS EXPOSED BY EXCAVATION.

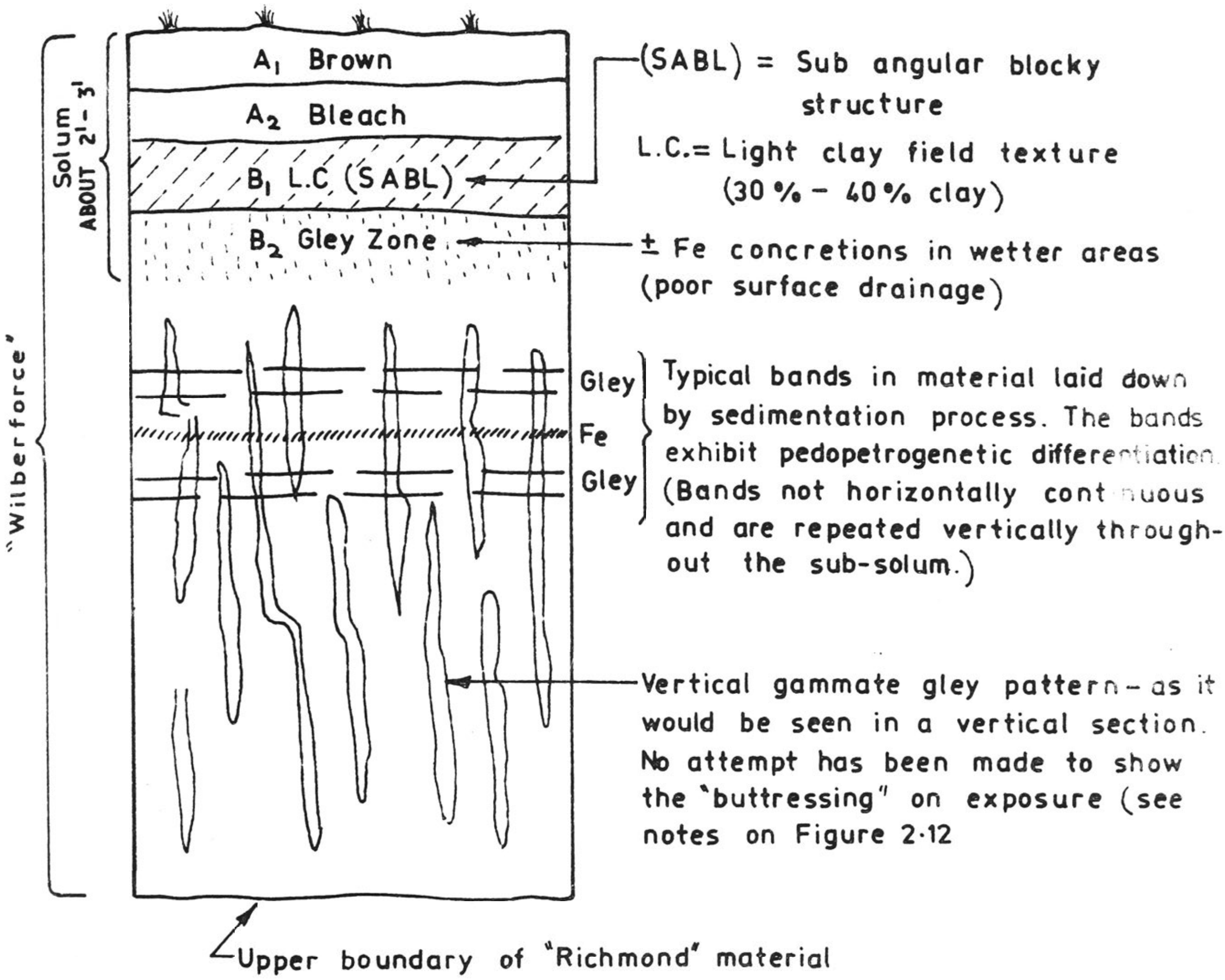
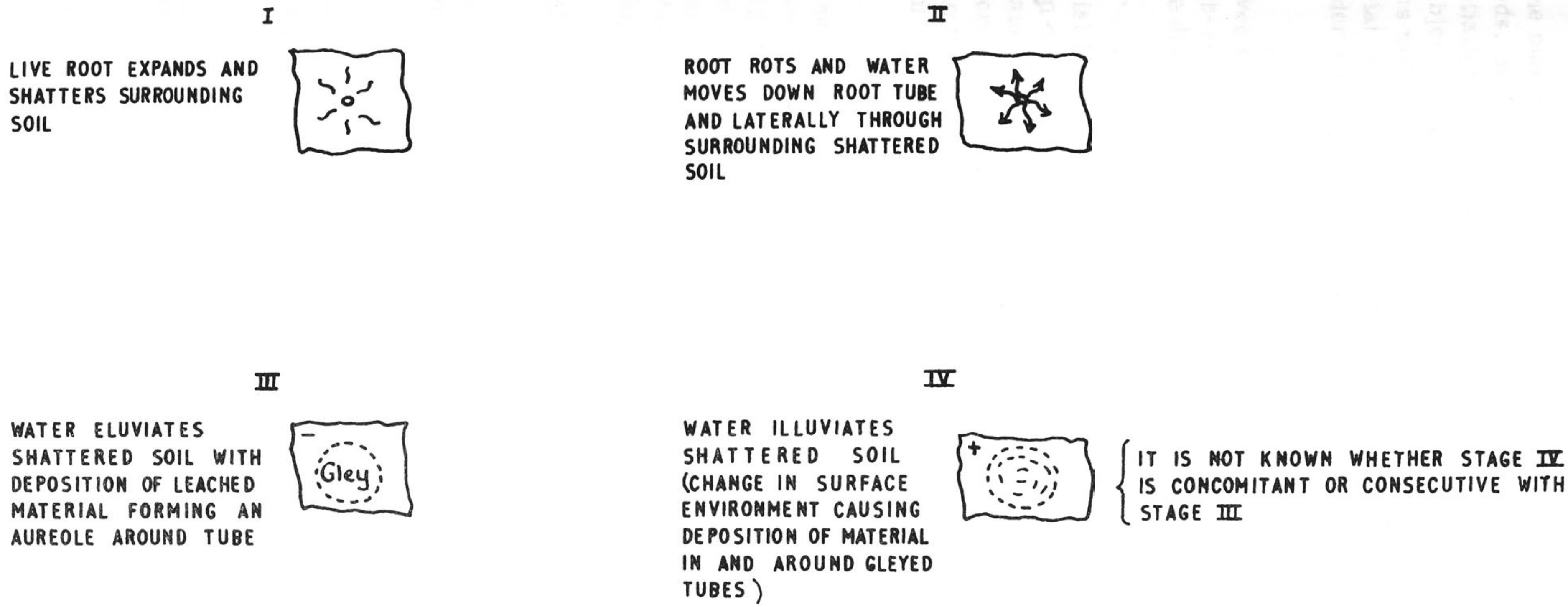


FIGURE 2·11: SOIL PROFILE OF CREEK BANK

(Minimal Podzolic Solum)



NOTES:

Occasionally tubes erode when exposed, leaving surrounding material as buttresses. Usually, being harder, tubes and aureoles form buttresses.

The vertical gammate pattern of the "Wilberforce" sub-solum, breaks away to give a buttressed weathering erosion pattern. The "Richmond" clay weathers in skins (spalls) and these slough off giving a "slump" erosion pattern.

The Richmond clays are highly weathered, easily slaked, are unstable and hence susceptible to tunnel erosion.

FIGURE 2·12: FORMATION OF GAMMATES

The material has an angular blocky structure with thick cutans around the peds, and a fine reticulate gley pattern corresponding to pedogenic differentiation along the depositional bedding planes. This material is unstable, subject to tunnelling and progressively sloughs off on exposure. Plugs of this material are common in the valley. Some evidence of lateritic material is seen along the margins of the valley, representing remnants of an older system.

Figures 2.10, 2.11 and 2.12 show soil features behind the natural levee bank of the Hawkesbury River at the entrance of Hall's Creek, the sub-surface of this bank having been exposed by excavation for increasing the drainage capacity of the creek.

"Tunnel" outlets were noted in the bank indicating that the bank material is erodible by infiltrating waters. This susceptibility to tunnelling can cause bank collapses along the creek. Tunnelling can be inhibited by draining off water that might be ponded in areas adjoining the creek or by chemical treatments of these areas - see the paper entitled "investigations into the Control of Earthwork Tunnelling" in the July 1970 Journal of the Soil Conservation Service (see Chapter 1).

Evidence of deep lateretic weathering was observed in road cuttings in sandstone near Sackville (the same deep lateritic weathering has been observed in shales at Rooty Hill). Almost total destruction of the original bedding units was observed giving rise to bright red earthy clays and pallid plastic clays in coarse mottles, sometimes angular, sometimes gammate. Only the most siliceous sandstones appear little weathered although in these silicate cemented units, translocation of iron enriched compounds was observed.

<u>Table of Ground Surfaces</u>

In the following table the Hawkesbury River ground surfaces, which have been recognised, are presented. These ground surfaces have been tentatively correlated with ground surfaces already named and published by van Dijk et al (8, 11, 23).

Tentative Inter-regional Correlation of Ground Surfaces

Riddler	van Dijk (1959, 1968) (8, 11)	Riddler (1968) (23)	Tentative Placement	Remarks
Hawkesbury	Southern Tablelands	Nth. Cst. Region (Grafton Series)		
Freeman's Reach	-	Grafton	K_{OO}	Recent Industrial
-*	Kambah	Vinegrove	K_O	Regosol
-*	Tharwa	-	K_1	Regosol

Table (cont'd.)

Riddler	van Dijk (1959, 1968) (8, 11)	Riddler (1968) (23)	Tentative Placement	Remarks
Hawkesbury	Southern Tablelands	Nth. Coast Region (Grafton Series)		
-*	Kurrumbene	Tallawudjah	K_2	Prairie
-*	Pialligo	-	K_3	Earth Podzolic
Wilberforce	Gundaroo	Koolkhan	K_4	Minimal Podzolic
Richmond	Tarago	Musk Valley	K_5 ?	Solodic Podzol
Windsor	-	Kremnos	K_6 ?	Weakly Lateritic
Pitt Town	-	Seelands	K_7 ?	Lateritic
-*	Marinna	Cangai	K_8 ?	- ?
-*	-	Coombadjah	K_9 ?	- ?

Notes to Table

1. *No attempt was made to differentiate these materials.

2. Inter-regional correlations were attempted by comparing topographic position, physiographic form and internal characteristics of the solum and sub-solum.

3. There is no general currency in names of the various layers to date. Where evidence of absolute dating is available layers are assigned to a specific K-cycle. Local names ought to be applied to terraces and ground surfaces which have been identified (and to the entire pedomorpholith if sufficient investigation has been carried out) - until a continuous traverse links these features with van Dijk's work in the upper Wollondilly Catchment.

   Since Dr. D.C. van Dijk (7) carried out early work in the Southern Tablelands, those working with him in interregional correlations of local investigations usually try to relate back to his nomenclature as guide to relative age. As indicated in the above table, Riddler in the Clarence Valley has identified a series of older terraces - hence reference must be made to them in this instance (12). It is understood that van Dijk is working on the correlation of the oldest series in S.E Queensland and has constructed a positive sequence. The results of this are not available (joint inspections are required) and so the above "Grafton" series is used for older soil materials outcropping in N.S. Extreme care must be exercised in the choice of a locality and a nam since ideally there should be no confusion at the site in question between the terrace exposure being described and other stratigraphic units in the area. Also this exposure must not be so isolated as to prevent easy comparison of the terrace in question with others (i.e. as regards its specific features and its relation to other terraces and deposits considered regionally and physiographically).

4. In the absence of positive evidence of absolute age, it is necessary to indicate that the assignment of the terraces identified is placed tentatively only in a specific K-cycle. van Dijk's interpretation in the S. Tablelands of N.S.W. has not an absolute dating and is the subject of some controversy. In such cases question marks must be placed next to the K-cycle numbers - or some positive statement made as to the tentativeness of the correlation.

5. Sola in the "Remarks" column of the above table are dominant sola of the respective ground surfaces.

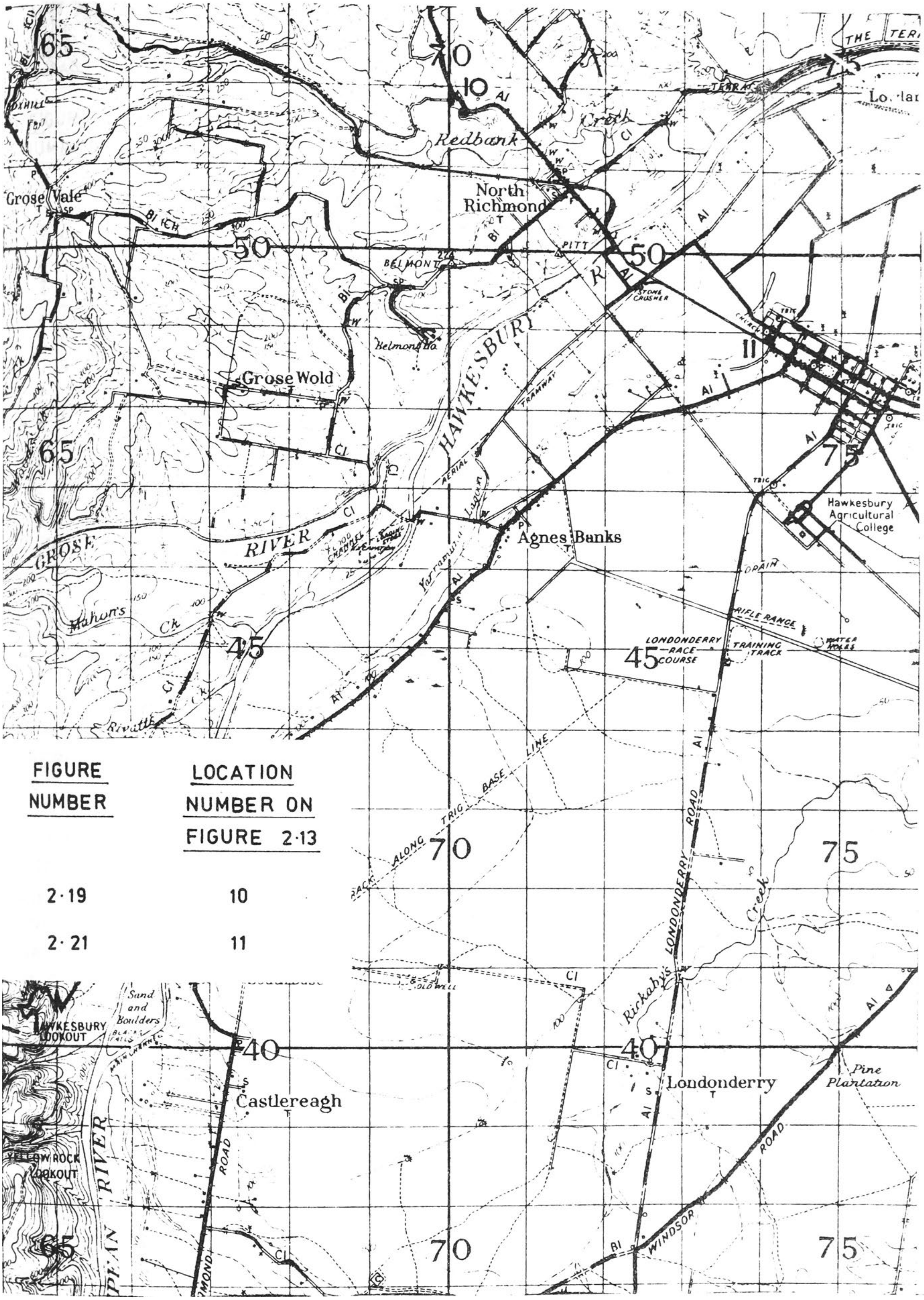


FIGURE NUMBER	LOCATION NUMBER ON FIGURE 2·13
2·19	10
2·21	11

FIGURE 2·13: PORTION OF 1 MILE TO 1 INCH MILITARY MAP "WINDSOR"

FIGURE NUMBER	LOCATION NUMBER ON FIGURE 2·14
2·4	1
2·5	embraces 1,2 (Section A)
2·6	1
2·7	1
2·8	2
2·9	7,8,9
2·10	7
2·11	7
2·12	7
2·15	9
2·16	3
2·17	3
2·18	3
2·20	1
2·22	7
2·23	7
2·24	7

LOCALITIES REFERRED TO IN TEXT	LOCATION NUMBER ON FIGURE 2·14
Pitt Town Bottoms	3, 4, 5, 6
Halls Creek at Kent Reach	7, 8, 9
River Terraces at Windsor Bridge	1, 2

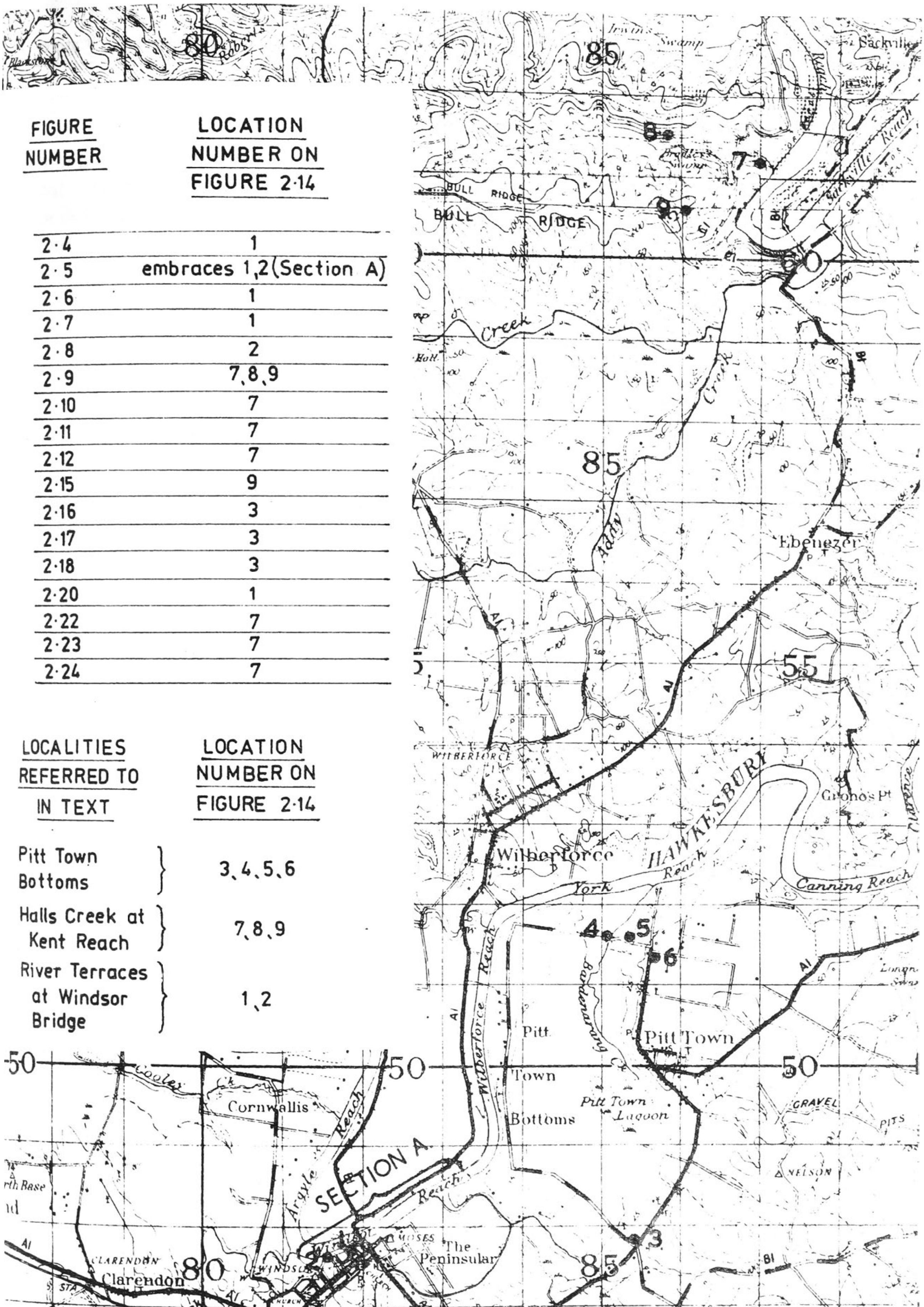


FIGURE 2·14: PORTION OF 1 MILE TO 1 INCH MILITARY MAP "WINDSOR"

PART B: PEDOLOGICAL PATTERNS

As an aid to the identification of materials from different pedomorpholiths Figures 2.15 to 2.24 are given which show some of the visual characteristic features of deep subsoil weathering and gleying. The pedological patterns in these figures refer only to the subsolum materials and not to the surface soils. A description is given of each pattern.

Figures 2.13 and 2.14 show the locations of these patterns.

A glossary of technical terms is given at the end of this Part.

PEDOLOGICAL PATTERN FIG. 2.15

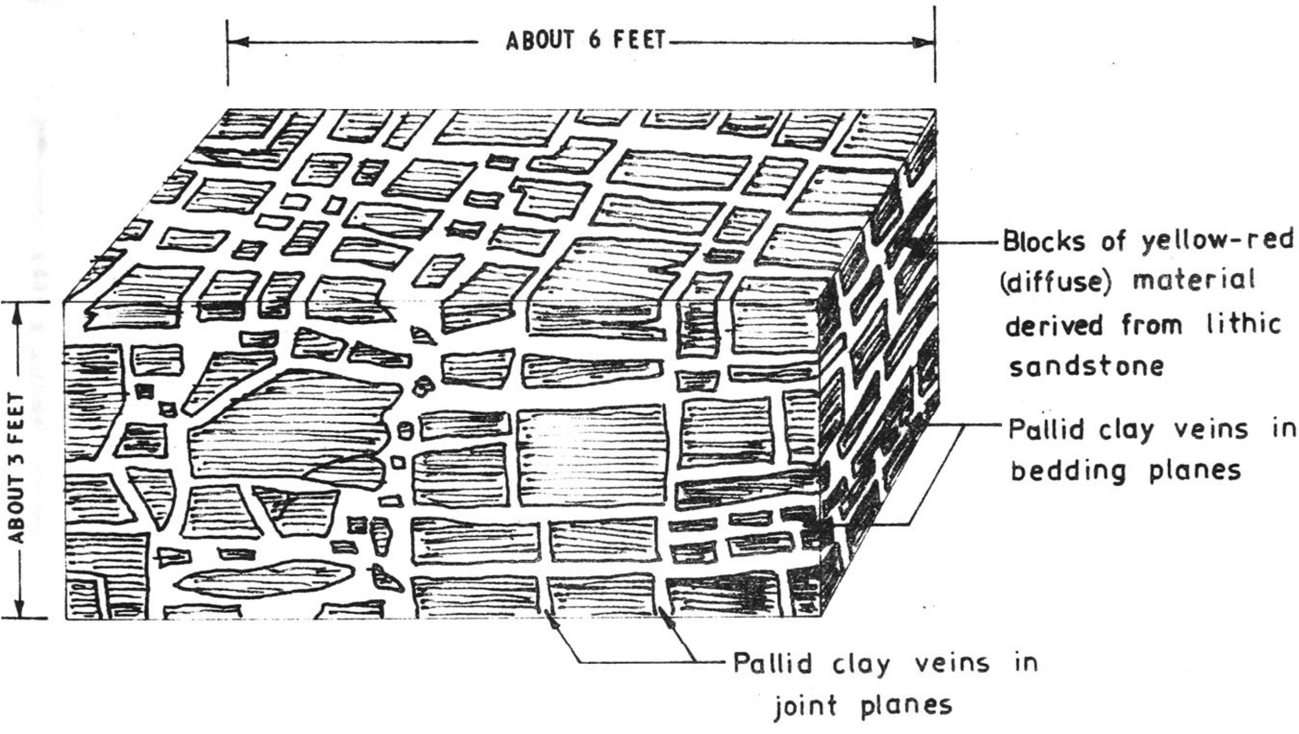
AT LOCATION 9 FIG. 2.14

Reticulate - Tesselated pattern associated with deep weathering of sandstones*

The pattern represents deep weathering of bedded lithic sandstones and siltstones; it consists of diffuse, blocky yellow red iron rich mottled sandstone material separated by pallid clay veins in a reticulate pattern. These veins represent differential weathering along joint and bedding planes of the sandstone. The veins often contain a core of foliated dark grey cutans with a surface pallor. Pale hard porcelainized or siliceous materials occur sporadically in some cases. The cutans of these materials are up to 1.5" thick. The cutanic foliate cores may represent deposition of material along the original joint plane after weathering and leaching of the original mineral constituents and concomitant shrinkage of the block thus formed.

In rock formations with thin beds, the pallid clay zones are wider, the yellow red mottled sandstone material more rounded and irregular in shape and the central foliate cutans thicker and more widespread throughout the pallid clay veins. The yellow red blocks of sandstone material are generally of the order of 6" to 9" across, but may range up to 24" in thicker, more siliceous beds. There is a diffuse yellow boundary between the pallid clay veins and the yellow red iron-enriched blocks of sandstone material.

* Of an undetermined but extreme age



PATTERN AT LOCATION 9 ON FIG. 2·14

FIGURE 2·15

PEDOLOGICAL PATTERN FIG. 2.16

AT LOCATION 3 FIG. 2.14

Reticulate

Polygonal pattern associated with the Pitt Town* groundsurface sub-solum. The matrix consists of pallid clay surrounded by broken, diffuse, iron-rich veins which have an irregular polygonal configuration in the horizontal plane. The thickness of the veins is about 1.5" and the polygons have a diameter ranging from 9" to 12".

Individual groups of polygonal veins may be separated by about 3 ft. on the vertical face. The iron rich veins themselves are slightly more resistant to weathering and form diffuse, irregular ridges about 0.5 inches high, up to 1.5 inches thick and are about 9 to 12 inches apart on horizontal exposures. Their separation is more irregular on vertical exposures.

The pattern reaches its maximum expression in fine textured materials in zones which probably represent former, low lying, wetter areas in the Seelands groundsurface during the stable soil forming phase. The material possibly represents an upper horizon of the pallid zone of the Seelands pedomorpholith.

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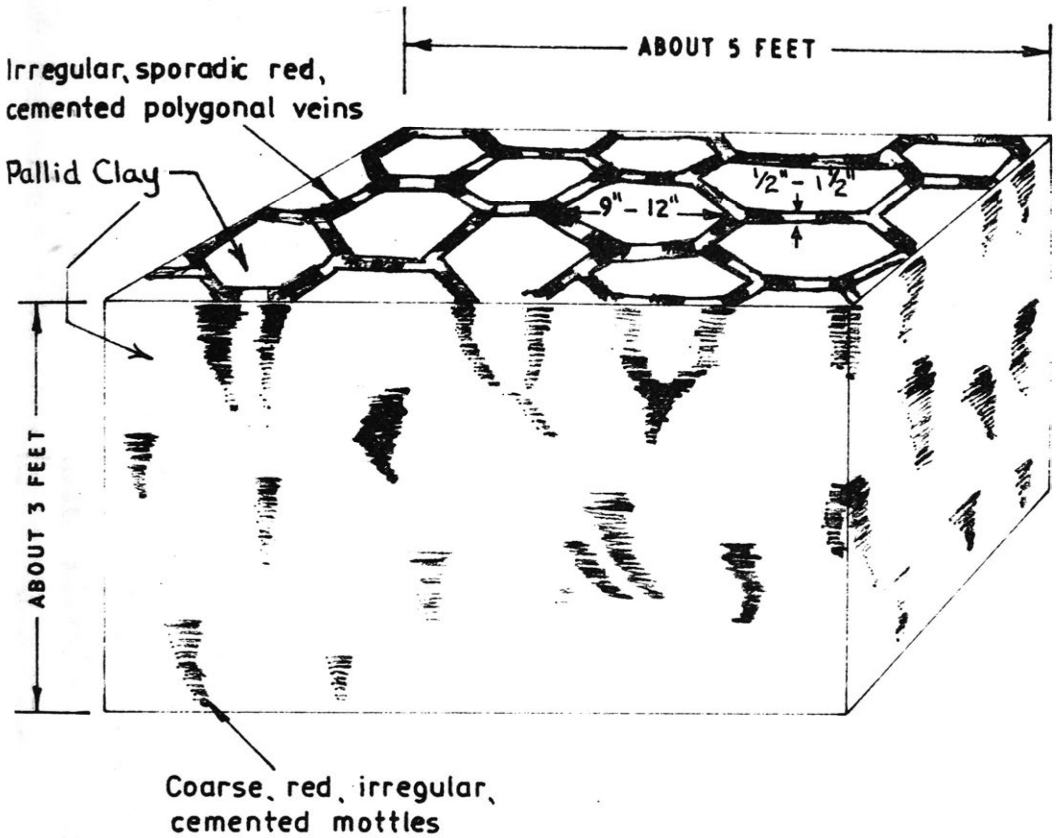
*See table of Ground Surfaces



PATTERN AT LOCATION 3 ON FIG. 2·14

FIGURE 2·16

PEDOLOGICAL PATTERN FIG. 2.17

AT LOCATION 3 FIG. 2.14

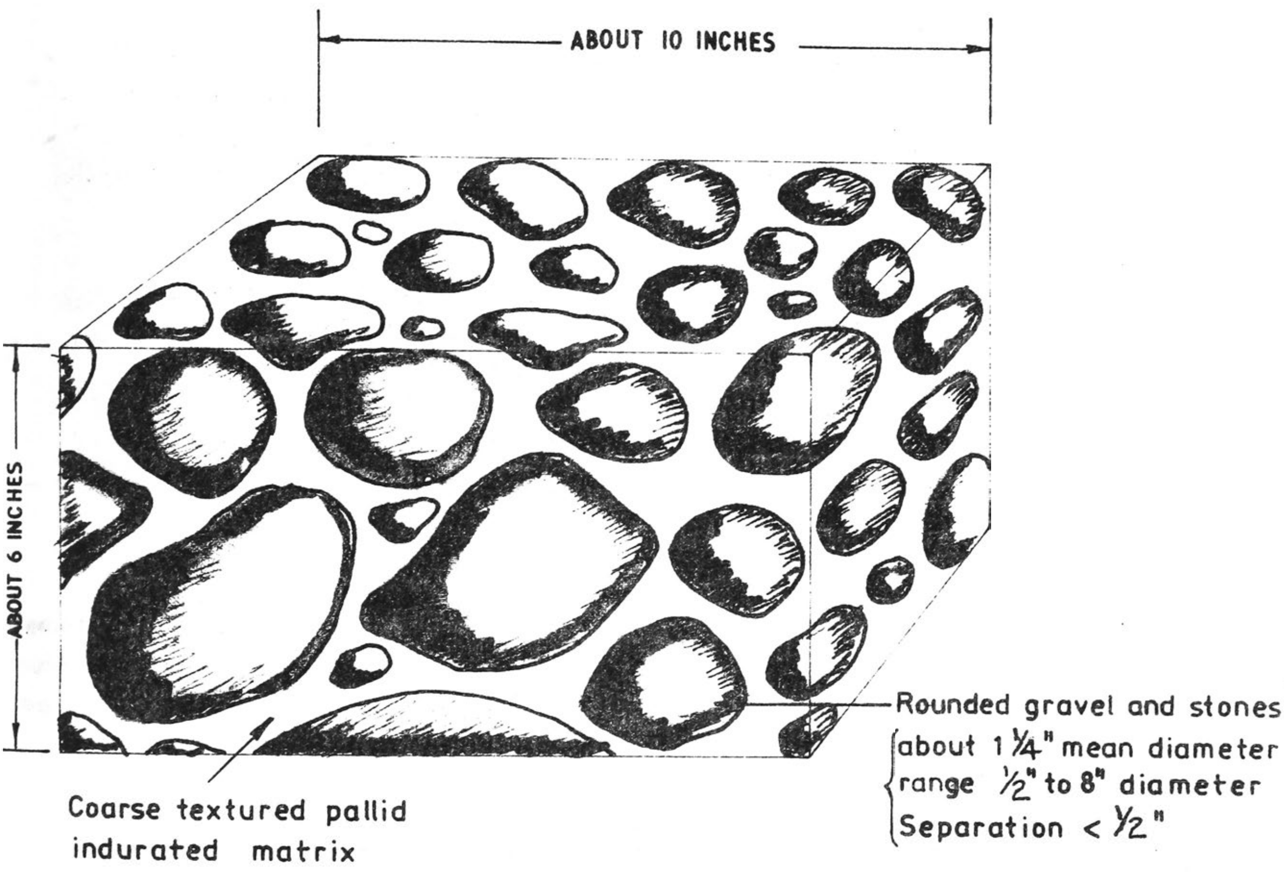
Pallid, indurated horizon associated with the Pitt Town* groundsurface subsolum.

This horizon consists of stones and pebbles which are severely weathered, displaying rinds of discolouration, but are still hard and brittle. Quartzite and chert pebbles are unaltered; coarse grained igneous rocks are the most affected, crumbling on exposure. It is surmised that some pre-weathered stones were incorporated in the terrace during formation and deposition in a mixed colluvial-alluvial environment i.e. certain stones could have been incorporated in the beds by mass movement and subsequent localised alluvial resorting without being broken up.

Stones of slate or shale origin are generally very much less weathered than the underlying bed rock of similar lithology. The induration and strong cementing by silica brings about the preservation as caps of large segments of this terrace along the valley sides. The base of the deposit is about 80 ft. above the present river thalweg; the available relief or elevation of the truncated surface is about 100 ft. (occasionally up to 120 ft.) above the present river thalweg. The elevation above the present mean water surface of the river will decrease as the thalweg runs below sea level in the estuarine reaches.**

* See table of ground surfaces.

** The base level of all prior terraces increases in elevation above the present day river thalweg upstream towards the headwaters of the catchment because of prior incision by the river. Thus care must be taken when correlating base levels of terrace remnants between catchments to ensure that the relevant measurements of level are taken at the same relative positions along the thalwegs of the main streams - that is to say, the difference in elevation between the river bases and the river thalwegs should be adjusted in accordance with the relative positions of the points of measurement along the thalwegs.



PATTERN AT LOCATION 3 ON FIG. 2·14

FIGURE 2·17

PEDOLOGICAL PATTERN FIG. 2.18

AT LOCATION 3 FIG. 2.14

Indurated mottled horizon associated with the Pitt Town* ground surface subsolum. The stones and pebbles are severely weathered displaying weathering rinds. Both the yellow red and red mottles extend into the fabric of the stones. Coarse grained igneous stones are most severely weathered, quartzites and cherts are practically unweathered. The yellow and red mottles are quite diffuse and irregular in shape and occur predominantly in the finer textured zones of the matrix but extend into the adjacent stones.

The red mottles are often associated with pockets and lenses of coarse textured matrix material. Both the fine, silty matrix and the sand sized grains are coloured red. Diffusion takes place also into the surrounding pebbles. Thin dark red cutans are also deposited round pebbles in contact with the red mottled zone.

When viewed as a whole, mottles in the terrace formation tend to adeopt a roughly polygonal format which reaches its maximum development in fine textured sediments. The polygons are not entire, have walls about 1" to 1.5" thick and are about 6" to 9" in diameter. In coarse textured material and gravel beds the pattern is much more random and sporadic, but some traces of polygonal orientation persist.

Sporadic plates of thick, light grey cutans occur. These are generally about 1/8" thick and range from pieces about 3"x 3" in areal extent to coatings on major structural planes. The shape is quite irregular both in outline and surface, which follows the surface configuration of the stones etc. The faces of these cutans display a neutral grey pallor:

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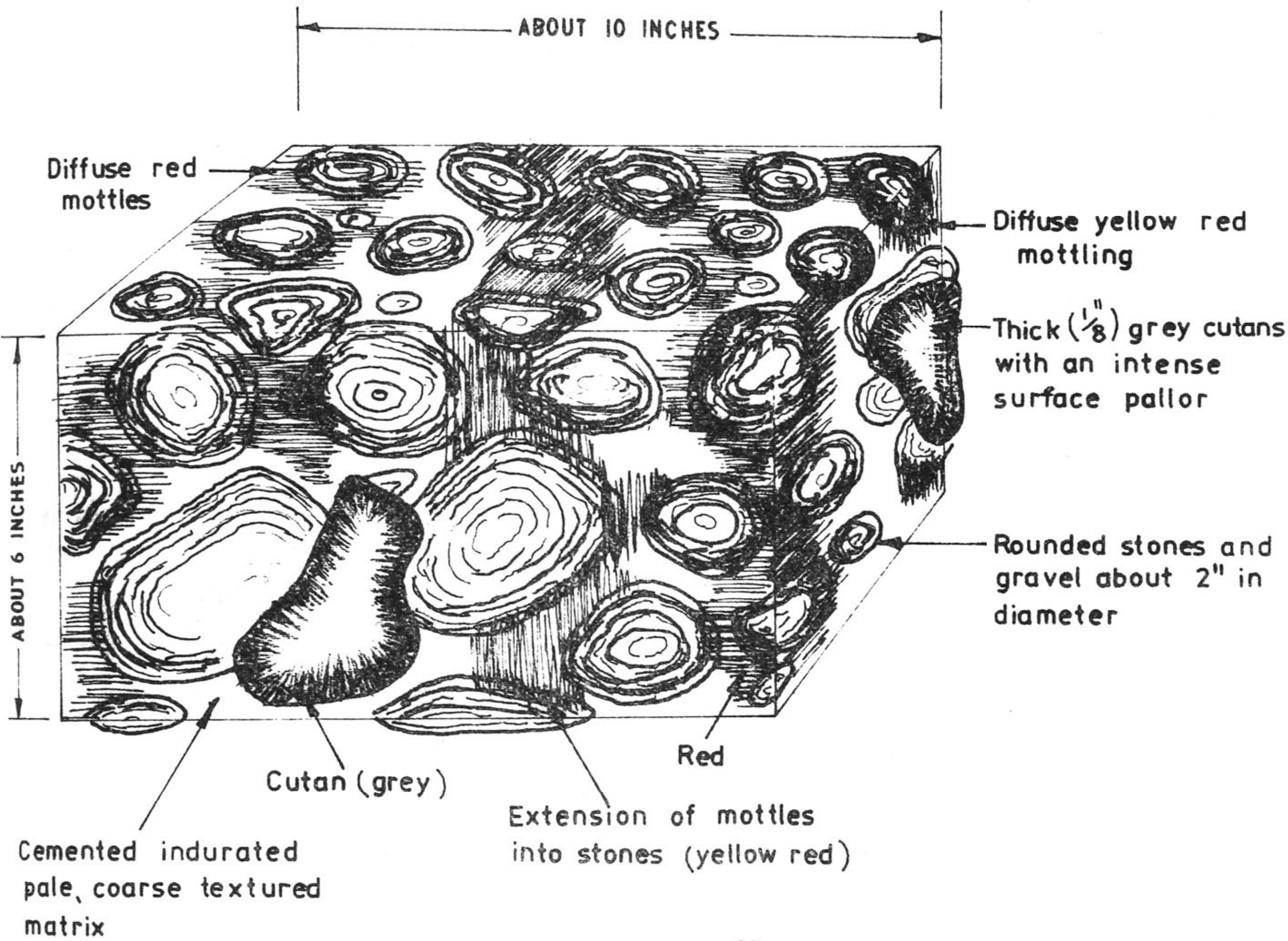
* See table of ground surfaces.



PATTERN AT LOCATION 3 ON FIG. 2·14

FIGURE 2·18

PEDOLOGICAL PATTERN FIG. 2.19

AT LOCATION 10 FIG. 2.13

Dendritic tubules in mottled earthy clays associated with the Windsor* ground surface subsolum.

The material consists of medium to large tubules, frequently gleyed, in a matrix of gleyed and iron-rich separations in clayey sands. The tubules are thought to be the result of some form of biotic activity and frequently contain cutanic concentric rings or other material differing from the surrounding matrix. The tubules run through both the pallid and iron-rich areas and have a predominantly vertical trend with a tendency to form dendritic structures. The tubules are normally more gleyed than either the pallid or red iron-rich matrix. Gleying frequently extends from the well defined tubule into the surrounding matrix. In non-uniform stratified deposits, these large tubules may be confined to certain beds, and their development may be interrupted by the presence of relatively impermeable depositional lenses or beds.

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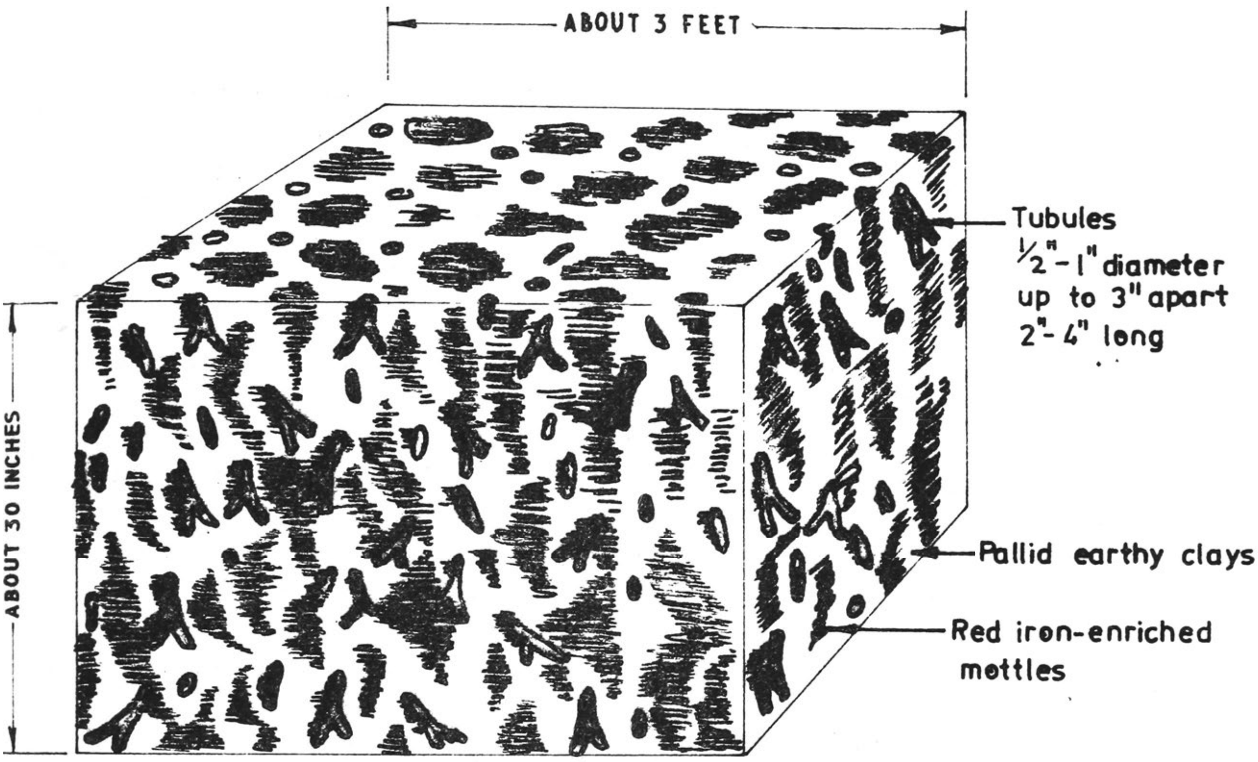
* See table of ground surfaces.



PATTERN AT LOCATION 10 ON FIG. 2·13

FIGURE 2·19

PEDOLOGICAL PATTERN FIG. 2.20

AT LOCATION 1 FIG. 2.14

Fine Biotic pattern associated with the Windsor* ground surface sub-solum (clayey).

The material consists of closely packed tubules in a clay matrix. The vermiform tubules are frequently gleyed and often contain material washed into them from the superposed horizons. This fill can either be relatively unaltered earthy material or grey to pallid clays which display a concentric structure in section. The fills are often coated with red cutans.

Gleyed tubules have a diffuse boundary with the surrounding matrix, the gleying proceeding from the well defined tubule into the matrix (red earthy clays) forming a partially hydrolized, partly hydrated aureole round the tubule proper. Although there is a vertical trend, the material presents a similar appearance in both horizontal and vertical planes. The vermiform, sponge-like fabric is thought to be the result of biotic activity (root channels and animal burrows and termite galleries). The fabric reaches its maximum development just below the red earthy Krasnozemic solum. Tubules filled with red earthy clays or concentric clay deposits are thought to be animal in origin. The more diffuse gleyed tubules are thought to be the result of gleying brought about by water leaching from above and accumulating and diffusing from old root channels and other fine elongated tubules of biotic origin.

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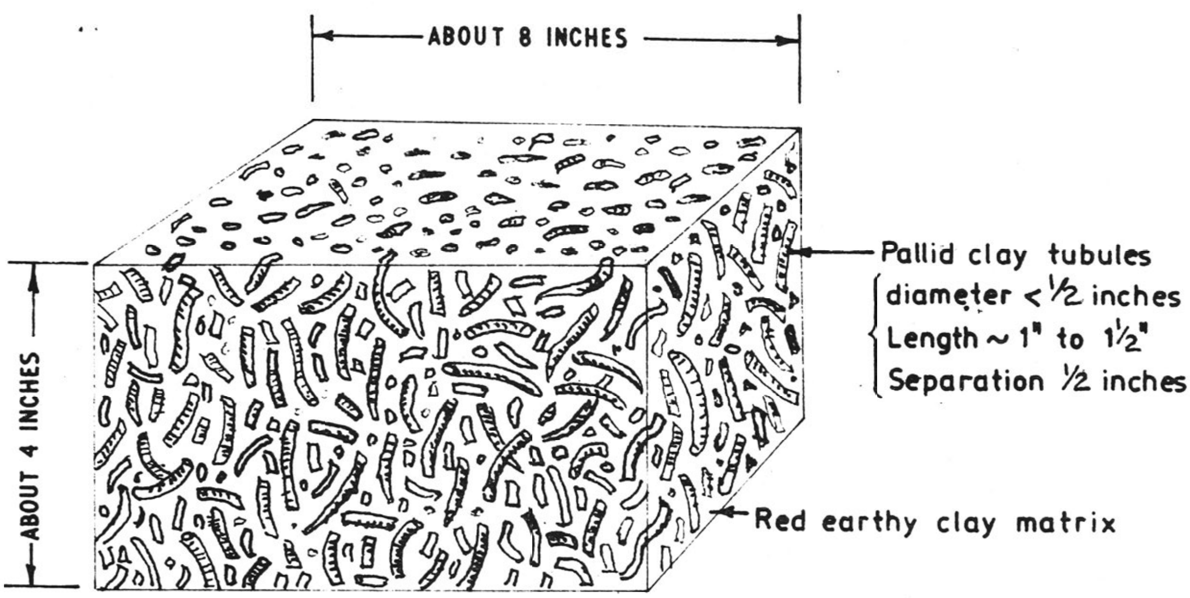
* See table of ground surfaces.



PATTERN AT LOCATION 1 ON FIG. 2·14

FIGURE 2·20

PEDOLOGICAL PATTERN FIG. 2.21

AT LOCATION 11 FIG. 2.13

Biotic pattern associated with the Windsor* groundsurface subsolum. The material consists of red, cemented, iron-enriched separates and pallid aluminium-rich plastic clays in a reticulate to dendritic pattern. Both the red mottles and the pallid clays tend to be elongated in the vertical direction. The dendritic nature of the pattern gives the impression of the pallid clays having had a biotic origin. The gley pattern is discontinuous, however, as are the red, cemented, mottles. This discontinuity may be a function of the relatively coarse texture of the parent material.

The gley pattern is thought to represent differential weathering and leaching of the iron-enriched colloids in a former uniform-iron dominated matrix. The dendritic nature of the gleyed, pallid material gives the impression that some form of biotic organism penetrated the iron-rich horizon allowing water to penetrate from the superposed layers and cause reduction and hydrolization in the vicinity of these biotically disturbed tubules. The iron-colloids removed from the gleyed tubules may have been redeposited in the surrounding matrix causing induration and cementing of the background red clay matrix. A certain degree of diffusion is observed at the interface of the pallid gleyed zone and the surrounding matrix.

Note: On truncation and exposure of this material to subsequent weathering cycles, a break up of the pattern is observed with hydrated yellow iron colloids diffusing back into the pallid clays, and the iron-enriched mottles breaking up into discrete units (shumach pattern) and ultimately forming rounded concretions. Thus varieties of structural alteration will be observed, depending on the degree of post-erosional pedogenesis.

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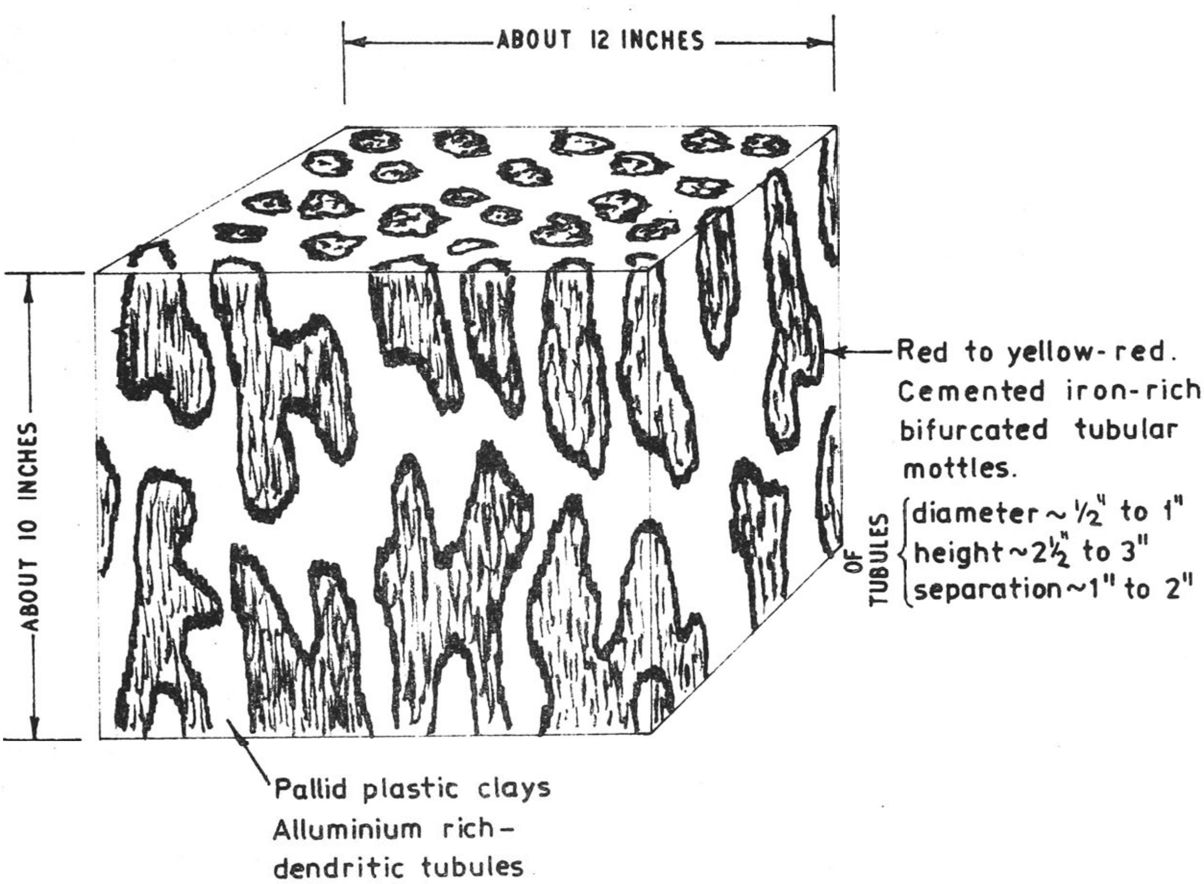
* See table of ground surfaces.



PATTERN AT LOCATION II ON FIG. 2·13

FIGURE 2·21

PEDOLOGICAL PATTERN FIG. 2.22

AT LOCATION 7 FIG. 2.14

Net - Gammate pattern associated with the Richmond* ground surface subsolum. This is representative of the general appearance and structure of the subsolum matrix. Found in deep terrace formations of highly weathered clays, which display uniform bedding and grading.

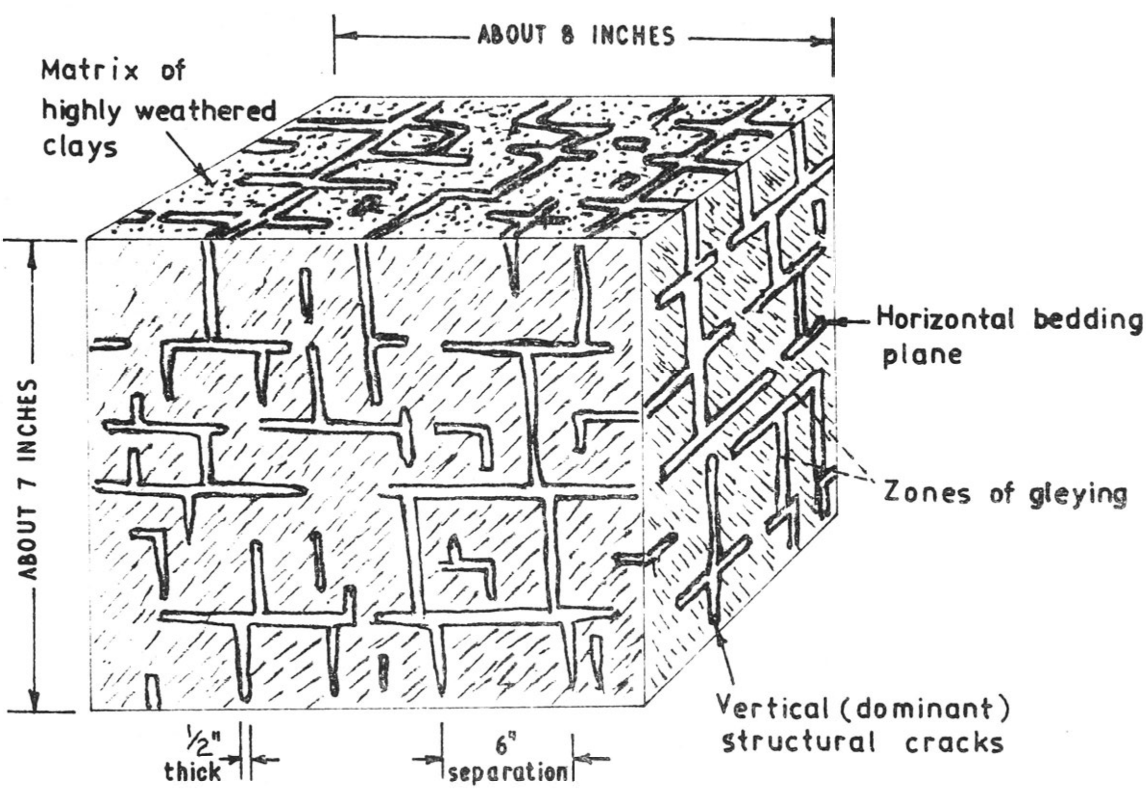
Since the matrix clay is easily dispersed and alters on exposure and weathering by spalling and sloughing off, the net gammate pattern is visible only on freshly exposed faces resulting from bank collapse and slumping associated with this material which is very susceptible to tunnelling and formation of ravines. Normally it is necessary to remove up to 3 ft. of altered clay materials before this pattern is easily identified.

The net gammate pattern of gleying in the weathered clays is due to differential weathering caused by leaching along former bedding planes and major vertical structural cracks between the bedding planes. The differential weathering associated with former depositional beds is an example of pedopetrogenetic differentiation. The pattern has a dominantly vertical trend, the horizontal members are smaller, sporadic and generally less easily distinguishable, and represent horizontal extensions of the gleying process along certain former depositional beds. These lateral extensions are not continuous over any distance. The vertical cracks may proceed through several former bedding planes before interruption and lateral shift on encountering, locally, a relatively impermeable bed. The horizontal gleying appears to be best developed in the coarser textured lower member of the depositional varves**.

---

* See table of ground surfaces.

** In cyclic fluviatile deposition giving rise to varves (a multiply banded pattern - also termed Liesegang bands) each stratigraphic unit consists of a series of fine, medium and coarse textured members representing different flow patterns with their associated transport of sediment; the coarse bed represents the commencement of one depositional cycle.



PATTERN AT LOCATION 7 ON FIG. 2·14

FIGURE 2·22

PEDOLOGICAL PATTERN FIG. 2.23

AT LOCATION 7 FIG. 2.14

Gammate pattern associated with the Wilberforce* groundsurface subsolum.

Representative of the general appearance and structure of the subsolum in vertical section and exposed face, showing vertical (gammate) tubes and pedopetrogenetic differentiated, indurated horizons.

These narrow, vertical, gleyed tubes are thought to represent differential weathering and gleying due to deep, relatively rapid, penetration of water following the path of some prior root channel with its associated zone of compression, shear, and weathering. Water from above would fill these tubes causing reduction and gleying. As the water diffused into the surrounding soil matrix, a gleyed aureole would develop; deposition occurring at the periphery. Occasionally secondary deposition of soil colloids has taken place in the lower portions of these vertical tubes from material leached from the superposed solum.

The tubes are affected locally by hardened (pedopetrogenetically differentiated) horizons causing apparent discontinuity (in vertical section) in the gammate pattern, presumably due to lateral movement of the precursor root as it adventitiously sought weaker zones in the hard bed for further vertical penetration. The gammate vertical differentiation gives rise to differential weathering on exposure of this subsolum material producing the buttressed effect of vertical columns which may stand 'proud' of the retreating erosion face (contrast with rilling).

Normally vertical gleyed columns vary in diameter from about 3" to 6". When uninterrupted by relatively impermeable horizons they proceed to a depth which may be in excess of 15 feet. On exposure these columns form the cores of buttresses about 6" to 9" diameter and, when separate from the main erosion face, are up to 6 ft. in height.

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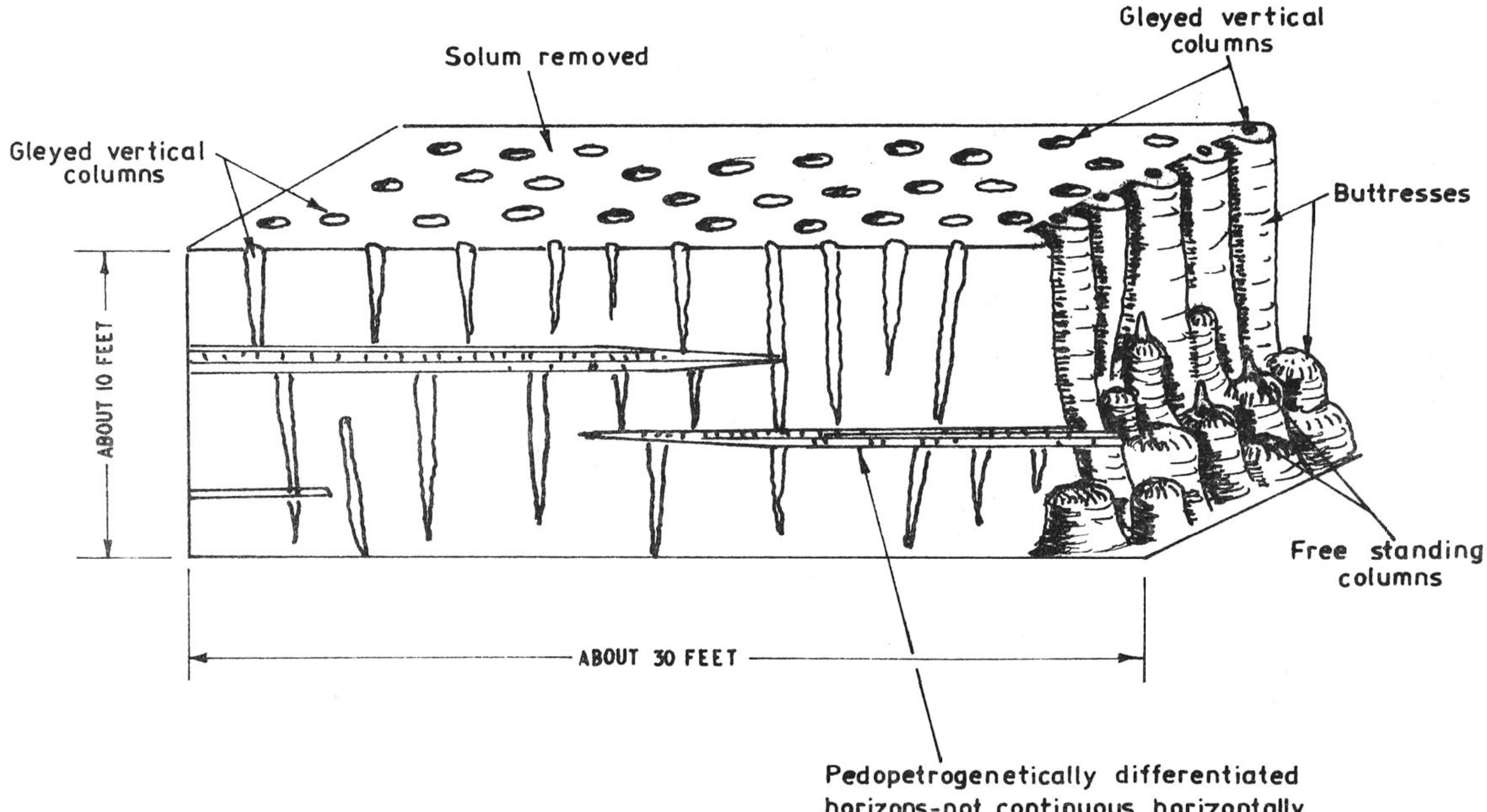
* See table of ground surfaces.



PATTERN AT LOCATION 7 ON FIG. 2·14

FIGURE 2·23

PEDOLOGICAL PATTERN FIG. 2.24

AT LOCATION 7 FIG. 2.14

Rimulate pattern associated with the Wilberforce* groundsurface subsolum

The figure shows the general appearance and structure of the subsolum matrix. The matrix consists of a drab grey brown, fine textured earthy clay. No structural aggregates are present. No peds are evident.

The large pores and vughs are lined with cutanic material which may consist of dull brown clay material, iron enriched material or gleyed material. In vertical section, a reticulate gley pattern may be observed occasionally corresponding to gleying along former depositional bedding planes and vertical cracks associated with specific beds (pedo-petrogenetic differentiation). Both vughs and pores are discrete - nowhere are they continuous. The net-gammate pattern associated with specific beds may be, in part, continuous.

The curved lenticular vughs and larger pores are thought to represent shrinkage cracks etc. brought about after deposition by removal of water entrapped during deposition and subsequent eluviation of colloidal material by weathering and leaching. The various cutans in the vughs attest to differing soil water and aeration conditions:- fluctuating water and aeration will give an iron enriched deposit; permanent water will give gleyed cutans; and "through" movement of soil water will give clay cutans. The cutans are deposited after the formation of the vughs and vesicles.

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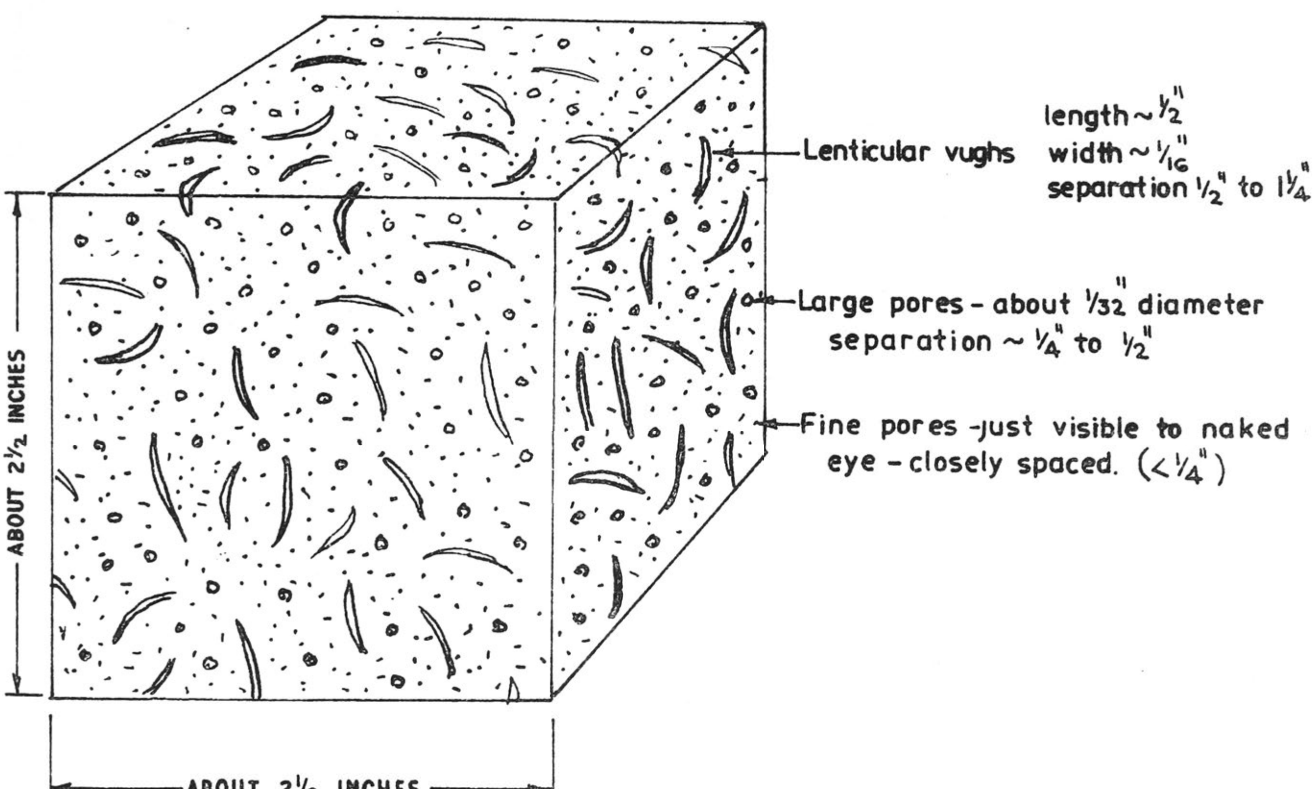
* See table of ground surfaces.



PATTERN AT LOCATION 7 ON FIG. 2·14

FIGURE 2·24

Glossary and Explanation of Technical Terms

Gammate: "Resembling a repetition of the Greek letter " γ " gamma. These are vertical columns of leaching in the subsoil. Taylor, N.H. 1962 N.Z. D.S.I.R. Soil Bureau Bull. 25. "Soil Survey Methods" pages 81 and 82. See also Fig. 2.23.

Deep differentiation: General term referring to features resulting from soil forming processes operating deep in the sub-solum.

Pedogenic Differentiation: Differentiation due to soil forming processes in a uniform material such as sesquioxide and clay segregation and their associated resultant structural and chemical differences.

Pedopetrogenetic Differentiation: Pedogenic differentiation caused by grading in the parent material - that is differences in fabric and texture (e.g. alternate bands of sand and clay giving rise to varying soil environments, hence different expression of the pedogenic processes).

Gleying: Mottling in the soil produced by partial oxidation and reduction of iron caused by intermittent water-logging (from F.A.O. Multilingual Vocabulary of Soil Science). Soils which are permanently water-logged, i.e. under permanently reduced conditions, assume a pallid grey or dark grey colour, the dark grey colour being due to the presence of sulphides. Pale blue and greenish mottles are due to the presence of hydrolyzed ferrous iron compounds. Pale straw yellow mottles are due to the presence of basic ferric sulphides.

Pseudo-gleying: is gleying associated with perched water tables - i.e. local water tables not associated with the main regional water table.

Pedomorpholith: A body of material recognised and mapped by its soil and weathering characteristics, colour, and by the surface form it displays rather than its texture, it may or may not transgress time throughout its extent (12, page 137). The material is said to "transgress time" if the weathering processes extend into and alter prior soil mantles. The pedomorpholith represents the total number of individual pedons (see below) or rather polypedons developed on a ground surface and may include:-

(a) 1. whole profiles of the groundsurfaces on deep materials
2. profiles with alteration zones in antecedent material.

(b) Suites of soils developed with regard to either lithology, parent material or degree of weathering.

(c) The hydrologic catena (see below).

(d) Subsequent truncation and alteration features.

Pedon is a unit of soil one metre square in surface area. U.S. Dept. Ag. Soil Classification 1968, page 2. Also N.Z.D.S.I.R. Soil Survey Method. Soil Bureau Bull. 25, p. 16.

Polypedon is a collection of pedons with some relationship between the pedons. Knox E.G. (1965) Soil Sci.Soc.Amer.Proc. 29 (1): 79-84 Soil Individuals and Soil Layering pp. 82-83.

Ground Surface: General term describing the surface expression of a specific soil stratigraphic unit (c.f. Land surface). Butler, B.E. (1959) Periodic phenomena in landscapes as a basis of soil studies - C.S.I.R.O. Soil Publication No. 14, pp. 8-9, (Ref.4).

Hydrologic Catena: Sequence of soils on similar parent material which occurs with varying relief and drainage conditions down a slope. Milne G. (1935) Soil Research Proc. 3rd Internal Conf. of Soil Science Oxford pp. 345-7: "Composite units for the mapping of complex soil associations".

Also van Dijk D.C. (1961) Soils of the Yass River Valley - Report No.6 Page 55. Regional Research and Extension Study in the Southern Tablelands, N.S.W. Joint Planning Committee N.S.W. Dept. of Agr. and C.S.I.R.O. Division of Soils, p. 55, (Ref. 9).

K-Cycle: This is defined as the interval of time covering the formation by erosion and/or deposition of a new landscape surface, the period of development of the soils on that surface, and ending with the renewal of erosion and/or deposition on that surface.----It is proposed to distinguish one K cycle from another by a numerical subscript and, since the present time seems the most acceptable datum, they are designated as K_1 K_2, K_3 etc. backward in time from the present. The K_1 cycle is the first cycle back from the present, the K_2 the second and so on. The soil features in a locality to be associated with each cycle are determined by stratigraphic principles. The letter "K" designating each cycle refers to the Greek word "Kremnos" = time. Butler, B.E. (1959) Periodic Phenomena in Landscapes as a basis of Soil Studies. C.S.I.R.O. Soil Publication No. 14, p. 7, (Ref. 4).

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CHAPTER 3 : SURVEY OF THE NATURAL VEGETATION OF THE FLOODPLAIN OF THE HAWKESBURY RIVER AND ITS MAJOR TRIBUTARIES

by D. H. Benson

1. Introduction

This survey was carried out by D.H. Benson, Botanist-Plant Ecologist of the National Herbarium of New South Wales. The survey was carried out for H.A. Scholer, who, under the supervision of the School of Civil Engineering, University of New South Wales, has been carrying out research on the geomorphology of N.S.W. coastal rivers for several government departments. The purpose is to provide basic data concerning the original distribution of native vegetation on the river floodplain, together with details of its present extent. The use of vegetation to indicate the presence of old river channels was also examined.

2. Area examined

The area examined and mapped during the survey was the present floodplain of the Nepean-Hawkesbury River System. The area is between latitude 33° 15'S and 34° 10'S, and longitude 150° 35' and 151° 15'E. It is bounded upstream by the railway bridge at Menangle and downstream by the junction with Mangrove Creek. The survey also included the floodplains on the lower reaches of the tributary rivers, MacDonald (upstream to the Common at St. Albans), Colo (upstream to Upper Colo) and Mangrove Creek (upstream to Dubbo Creek). The area is shown in Figure 3.1.

3. Climate

Climatic data were obtained from the Bureau of Meteorology. The monthly average rainfall figures for stations bordering the floodplain are given in Table 1. Temperature data were available only for Richmond and are given in Table 2.

4. Geology

The area is covered by alluvial deposits of gravel, sand, silt and clay of Quaternary age. (N.S.W. Department of Mines, 1966).

5. Soils

Soils in the area belong to the Nepean and Elderslie Soil Association (Walker, 1956) and are mainly dark grey undifferentiated deposits.

6. Physiography

The most important physiographic features of the area studied are firstly, the physiography of the country which borders the floodplain and secondly, the actual physiography of the floodplain itself.

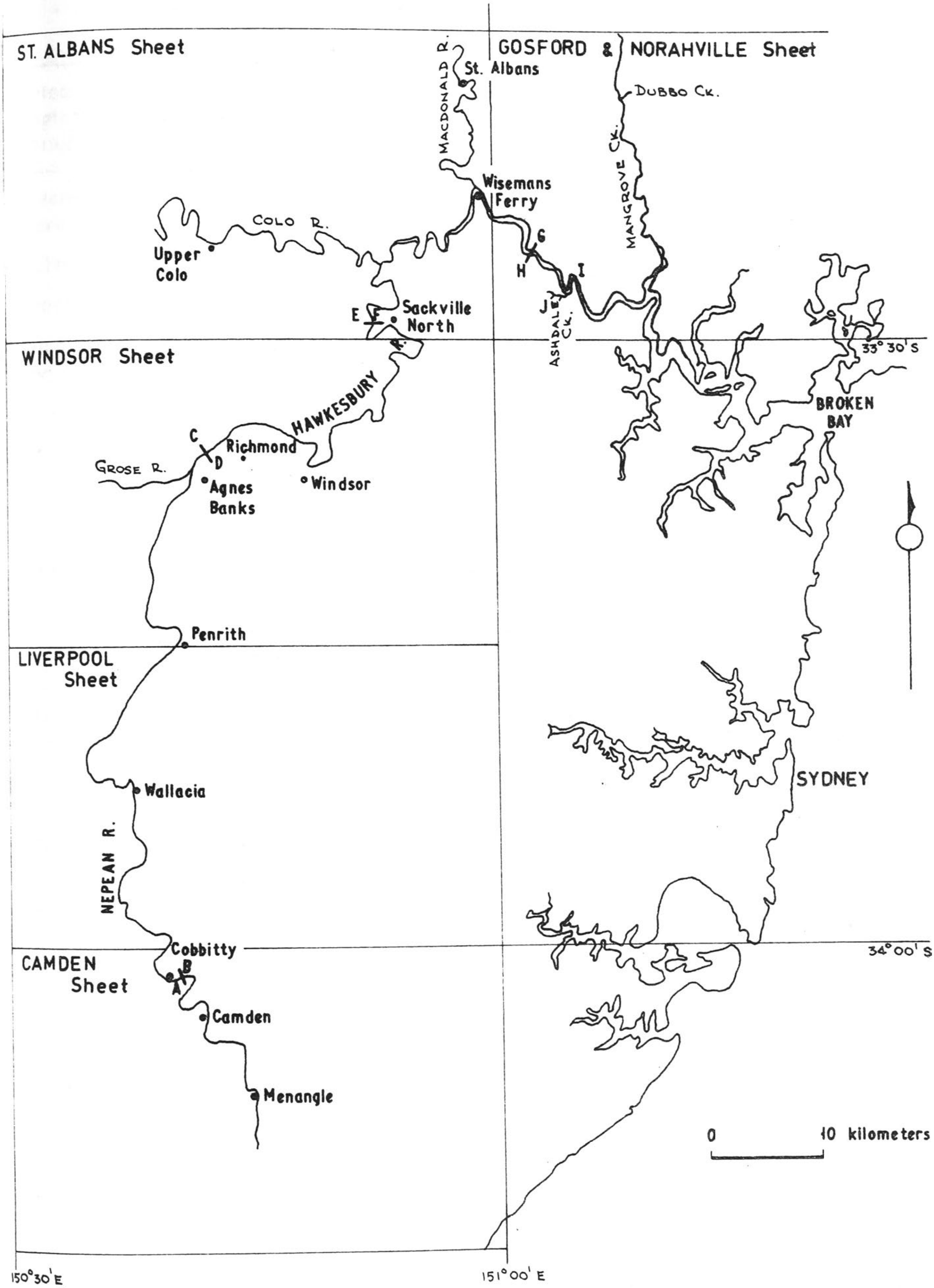


FIGURE 3·1: LOCALITY DIAGRAM SHOWING MAP COVERAGES AND SITES OF CROSS SECTIONS

Table 1
Monthly Average Rainfall in Points (0.01 inch)

Meteorological Station	No. of Years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Wisemans Ferry	25	299	346	322	257	253	267	291	167	171	197	217	274	3061
Richmond	30	330	261	303	301	196	171	212	117	168	185	255	310	2809
Penrith	68	351	334	322	270	231	243	222	159	157	209	269	322	3089
Camden	81	339	297	320	271	237	277	236	169	155	200	247	285	3033

Table 2
Average Daily Maximum and Minimum Temperatures
at Richmond (alt. 22.3m)

	No. of Years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Maximum Temp. ^{o}C	30	29.4	29.5	27.2	23.5	20.2	17.5	17.0	19.0	22.2	25.1	27.3	29.0	23.9
Maximum Temp. ^{o}C	30	16.6	16.7	14.7	11.2	7.2	4.2	3.4	4.3	7.0	10.3	13.1	15.5	10.3

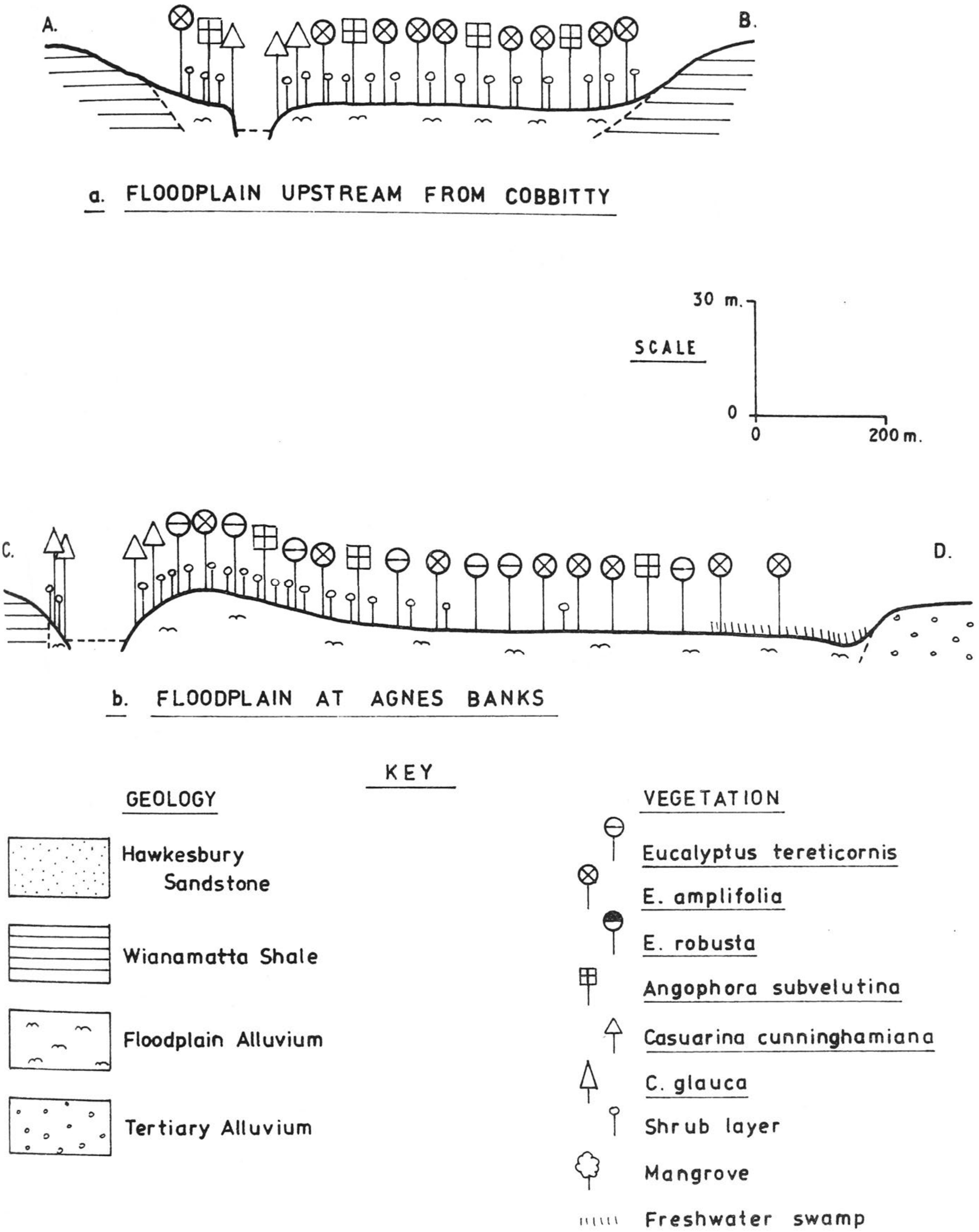
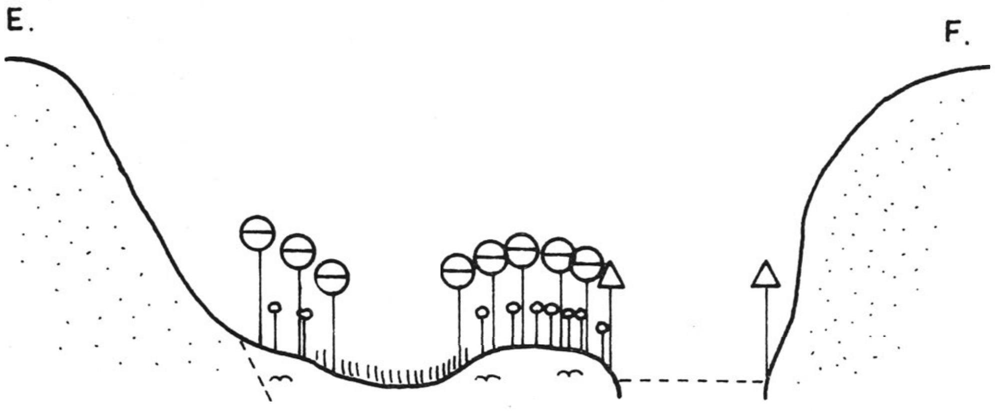
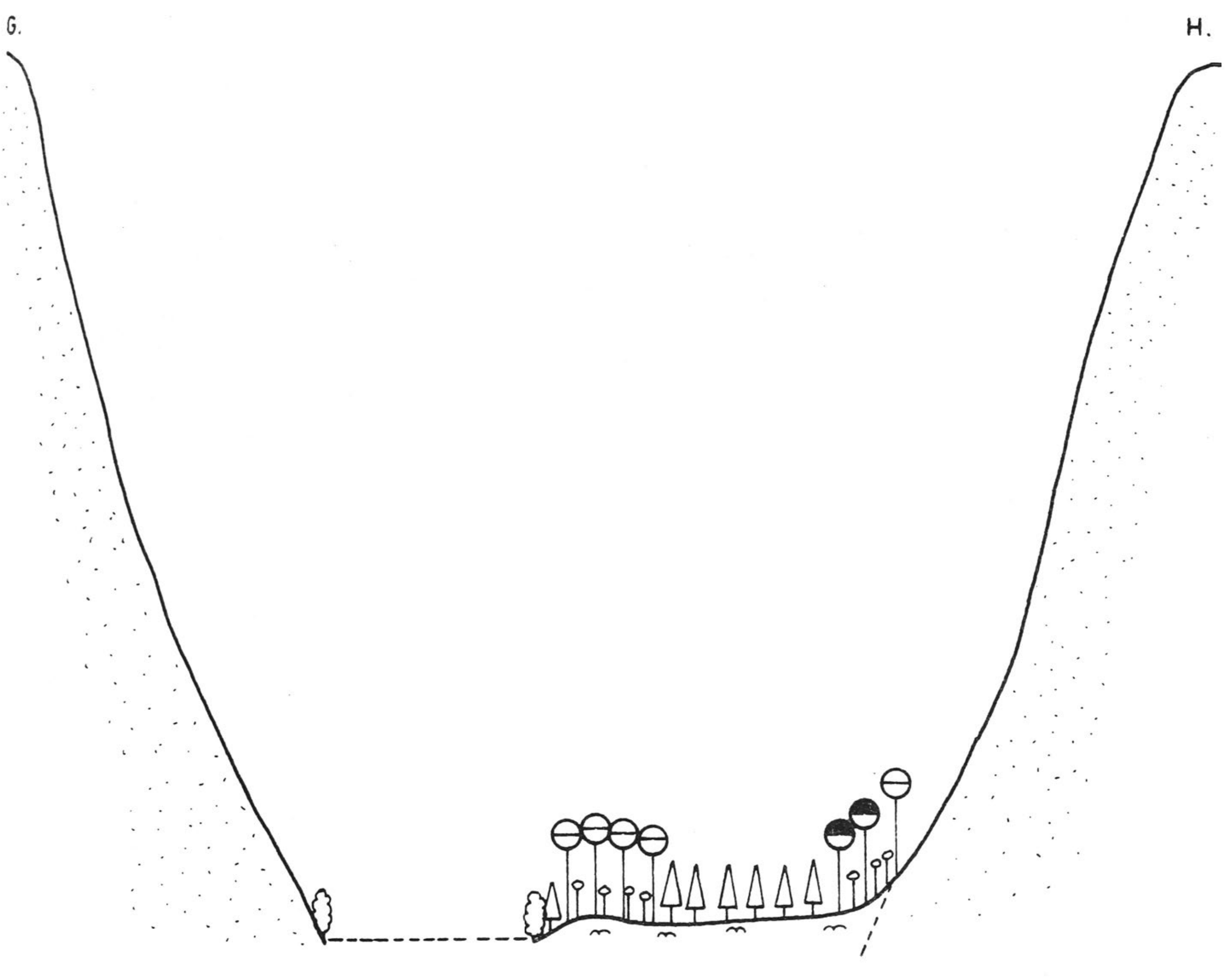


FIGURE 3·2: DIAGRAMMATIC CROSS SECTIONS OF FLOODPLAIN SHOWING PHYSIOGRAPHY, GEOLOGY AND VEGETATION

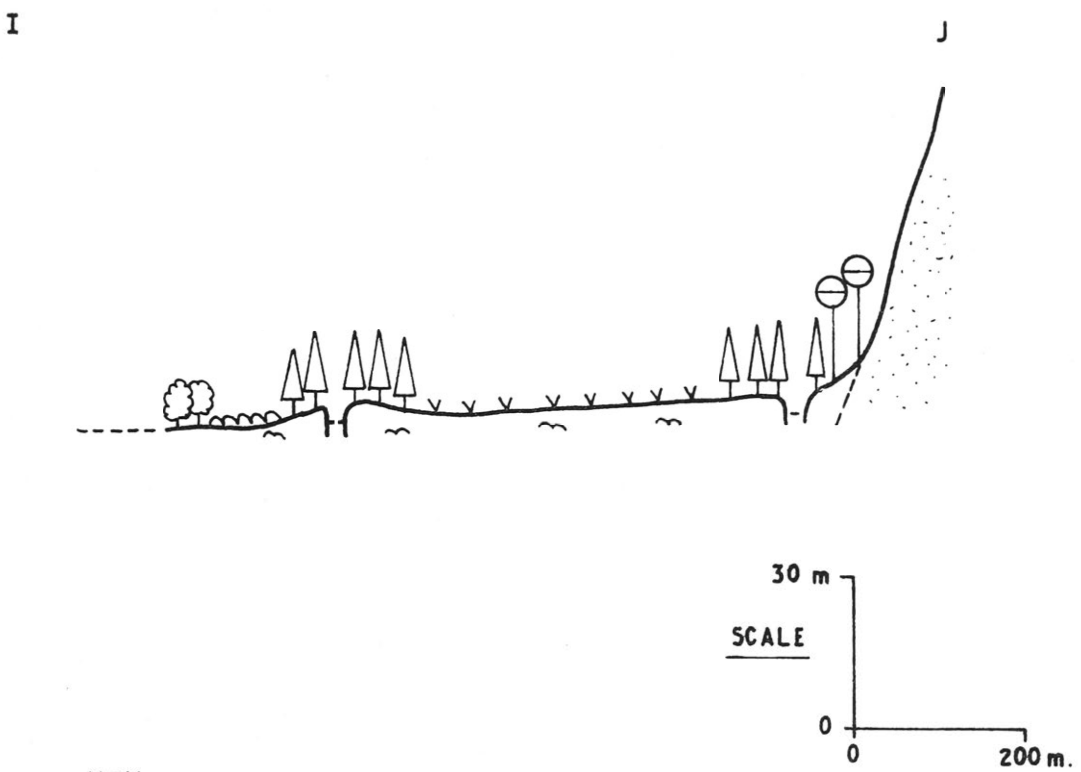


c. FLOODPLAIN NEAR SACKVILLE NORTH



d. FLOODPLAIN DOWNSTREAM FROM WISEMANS FERRY

FIGURE 3·3



KEY.

Saltmarsh

Rushes

Other symbols as in Figs. 2 and 3

FIGURE 3·4: DIAGRAMMATIC CROSS SECTION ACROSS ASHDALE CREEK AND HAWKESBURY RIVER

The floodplain is situated within two distinct physiographic units. North of Wilberforce the river passes through an uplifted sandstone plateau. The edges of this plateau form steep cliffs which have at their base either the river, or a thin strip of floodplain, depending on the curve of the river. This region of uplifted topography has been described by Hall (1926).

The other physiographic unit is south of Wilberforce. Here the river flows through a region of undulating low hills formed from Wianamatta Shales and Tertiary alluvium.

The main physiographic features of the floodplain are the levee banks which occur along the river's edge. The crests of these levee banks are about 7.6 metres (25 feet) above the flood plain behind them in the Windsor-Richmond region. In areas where the edges of the floodplain are bounded by sandstone or in some cases shale cliffs a low lying swampy region often occurs between the levee bank and the base of the cliff. Upstream from the junction with the Grose River the levee banks disappear and few swampy regions occur.

The varying shape of the river valley is shown in Figures 3.2 and 3.3 which shows a series of river cross sections from Cobbity to below Wisemans Ferry.

7. Previous Work

Little work has been done on the vegetation of the river floodplain. Pidgeon (1941) mentioned the important tree species occurring on the floodplain but included the vegetation with that of the adjoining low rainfall Wianamatta Shales. Phillips (1947) described the floodplain vegetation as a separate unit but restricted her study to the area south of Sackville.

8. Survey Methods

The aim of the survey has been to produce a vegetation map of the floodplain as it would probably have been in 1788, before the arrival of European settlers. This was done by means of ground traverses aided by aerial photography together with the searching of historical documents for the reconstruction of cleared areas. Mapping was carried out at a scale of one inch to a mile (1:63, 360) using the military topographic maps No. 410 and 411 Gosford and Norahville, No. 409 St. Albans, No. 416 Windsor, No. 422 Liverpool and No. 428 Camden as bases.

Some difficulties arose in the positioning of the boundaries of the floodplain. In the lower reaches of the Hawkesbury and in the MacDonald and Colo, the boundaries were interpreted from aerial photography. The steep nature of the sandstone cliffs and the clear distinction between floodplain and sandstone enabled these boundaries to be plotted fairly accurately. However, for the rest of the area the determination of floodplain boundaries was more difficult because of the undulating nature of the terrain. Between Sackville and Richmond the boundaries of the Quaternary alluvium on the Windsor 1:50,000 Geological Series Sheet 9630-I were used. For the rest of the area approximate boundaries were drawn using aerial photography in conjunction with the Sydney 1:250,000 Geological Series Sheet SI 56-5 and soil maps from the Soil

Survey of the County of Cumberland (Walker 1956).

Field work was carried out between March and September, 1972.

9. Map Reliability

The accuracy of the mapping has been affected most by the amount of clearing that has occurred. Settlement took place at Windsor as early as 1790, where the rich alluvial flats produced excellent crops. The large expanses of alluvium around Windsor, Richmond, Penrith and Camden were cleared almost completely and used for cultivation or intensive grazing. The scattered alluvial flats downstream from Windsor were also sought out. However, because they were limited in size and separated by rugged sandstone cliffs which made boat access the only practical means, they were not as extensively cleared. As a result it is possible to reconstruct the original vegetation on these from the small remnant patches and to extrapolate from them to the broad alluvial flats which have been thoroughly cleared.

Clearing was generally only directed towards those vegetation types which grew on arable land so that it was mainly the tall open forests that were removed. In addition some of the less swampy areas were drained and grazed, but areas which had large permanent swamps, Casuarina forest, saltmarsh and mangroves were in general little damaged and have remained essentially in their original condition.

Because the vegetation units differ in the degree of disturbance and frequently occupy narrow zones it is not possible to give a reliability diagram. Instead, the following reliability scale has been applied to the vegetation units mapped.

Vegetation Map Reliability Scale

I. Relatively undisturbed vegetation. Description and vegetation boundaries accurate.

II. Slightly disturbed vegetation resulting from logging, light grazing, some clearing or draining. Original species present and vegetation structure essentially undisturbed. Description and most boundaries accurate.

III. Badly disturbed vegetation with only scattered pockets remaining. Original species and some indication of vegetation structure remain. Description fairly accurate, boundaries approximate.

IV. Completely disturbed vegetation with only scattered examples of original species remaining. Description and boundaries approximate.

10. Vegetation Classification

Vegetation has been classified using the structural formations of Specht (1970) (see Table 3). Where possible these formations have been further divided and mapped as vegetation units. These units are further

Life Form and Height of Tallest Stratum	Projective Foliage Cover of Tallest Stratum			
	Dense (70-100%)	Mid Dense (30-70%)	Sparse (10-30%)	Very Sparse (10%)
Trees * 30 m	-	Tall open-forest	-	-
Trees 10 - 30 m	-	Open forest	-	-
Trees 5 - 10 m	Low closed-forest	-	-	-
Shrubs * 2 - 8 m	closed scrub	-	Tall shrubland	-
Shrubs 0 - 2 m	-	-	-	-
Hummock grasses 0-2m	-	-	-	-
Herbs	-	Herbland Sedgeland	-	-

* A tree is defined as a woody plant more than 5 m tall, usually with a single stem. A shrub is a woody plant less than 8 m tall, frequently with many stems arising at or near the base.

Structural Formation of Vegetation in the Flood plain (modified from Specht (1970) divided into subunits which are below the scale of mapping but which are recognizable in the field and may be conveniently discussed in the text. The mapped units may in some cases be equivalent to the association of Beadle and Costin (1952), "a climax community of which the dominant stratum has a qualitatively uniform floristic composition, and which exhibits a uniform structure as a whole". However, in other cases the unit may contain subunits from different formations, some of which may be seral (e.g. Casuarina glauca unit) so that it fails to satisfy the conditions of this definition.

A small departure from Specht's classification has been made with regard to tree height. His tall open forest formation is composed of trees greater than 30 m high. Very few trees of this height occur on the floodplain and it is doubtful whether many were originally of this height. However, because of the similarity of the structure of many of the forests on the floodplain to tall open forest formation, they have been placed in this formation rather than in the open forest formation.

Although the vegetation has been mapped in discrete units this is generally a simplification of the true state. In most cases vegetation is continuous, the vegetation units grading into one another and forming an intergrade or ecotone of varying width. In this ecotone, components of both units may occur making the position of a dividing line between two units rather subjective. An ecotone between two tall open-forest units at Agnes Banks has been shown on the map by intertongued bars. This area has been extensively cleared so that a definite boundary between the two units, if it ever existed as such, is impossible to place.

11. Distribution of Vegetation

The distribution of vegetation units could in general be related to floodplain topography. The levee bank-swamp system resulted in vegetation catenas with tall open forest on the well drained soil at the top and sides of the levee bank, sedge and rush swamps on the lower sides and reed swamps in the hollows between the levee bank and the cliffs at the edge of the alluvium. To the south of this area, where the topography is generally flat, large expanses of tall open forest occurred. The relationships of important vegetation units with the topography is shown in Figure 3.2.

The distribution of vegetation units that occurred in the estuarine region of the river was influenced by tidal inundation.

12. The Vegetation*

(Numbers denote units shown on Vegetation Maps - See Figure 3.5).

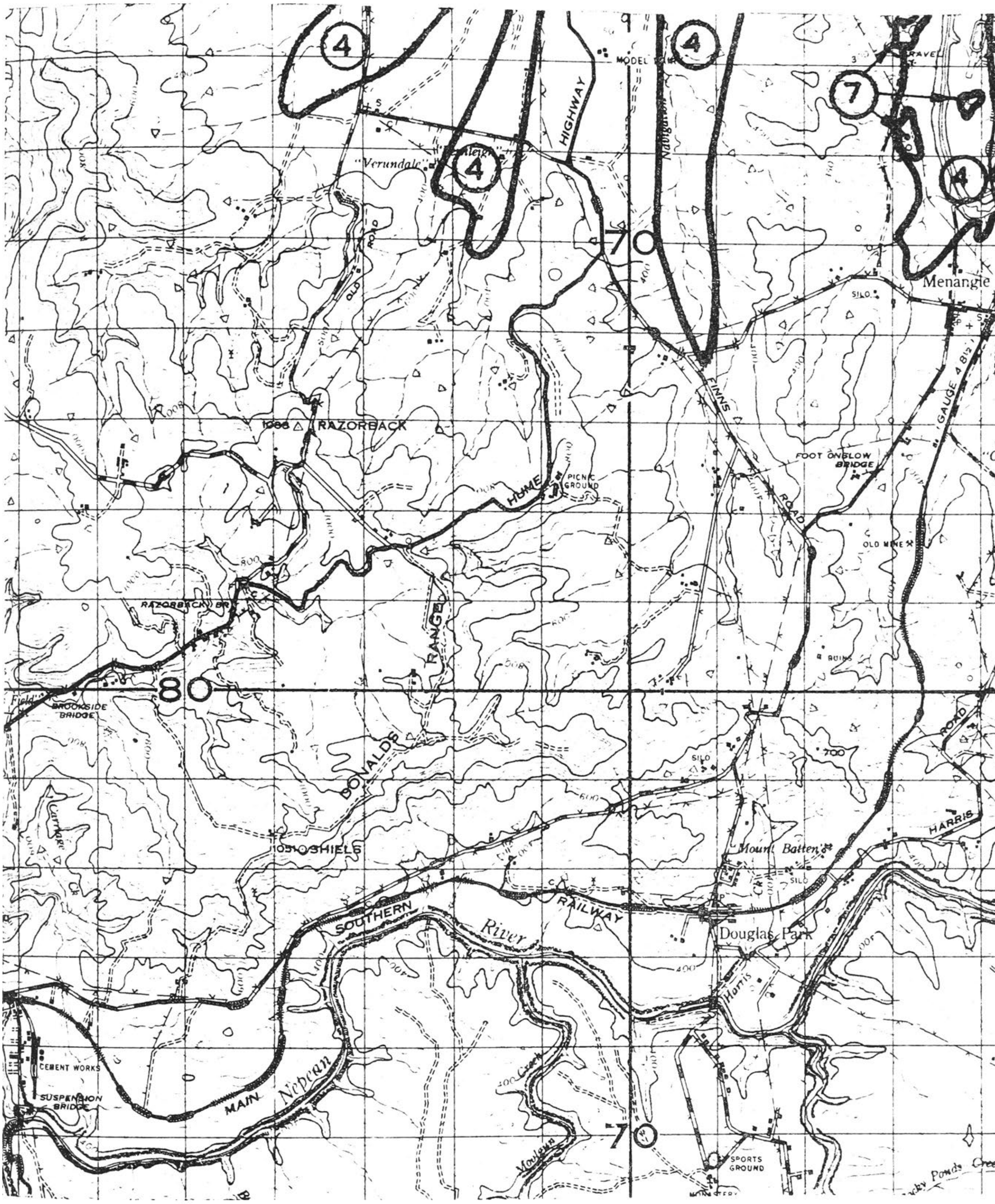
(a) Tall Open-Forest

1. Eucalyptus deanei - E. saligna - E. elata unit.
   This unit occurred on the levee banks and in the more sheltered gullies of the Colo River. It was probably

*Authorities for botanical names are given in Beadle, Evans and Carolin, 1972.

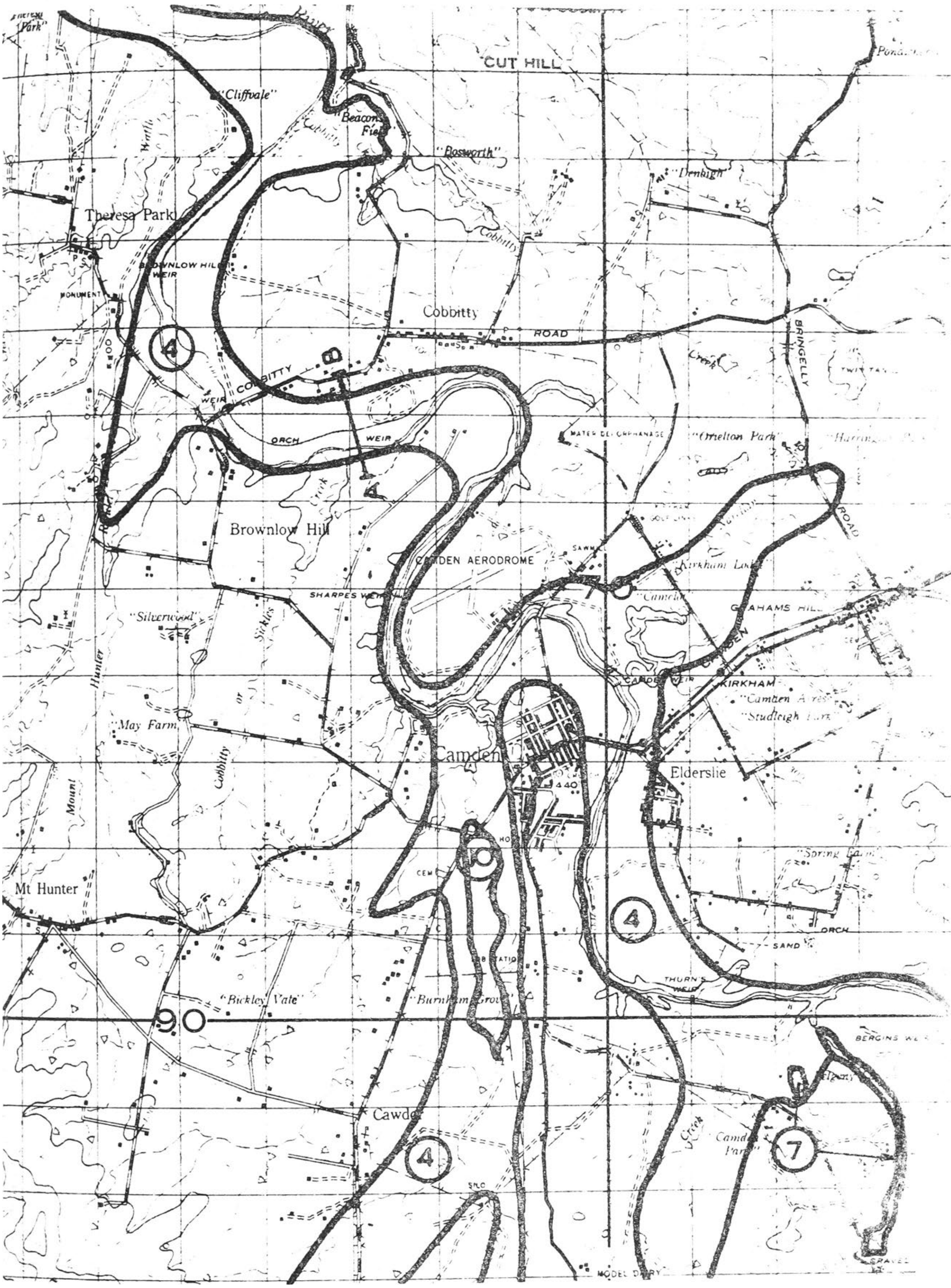
Numbers Denoting Units.	Vegetation Units
	a.) TALL OPEN-FOREST
1	i. *Eucalyptus saligna*, *E. deanei*, *E. elata* unit
2	ii. *Eucalyptus deanei*, *Angophora floribunda* unit
3	iii *Eucalyptus tereticornis* unit
4	iv *Eucalyptus amplifolia*, *Angophora subvelutina* unit
5	v. *Eucalyptus benthamii* unit
	b.) TALL SHRUBLAND
6	*Melaleuca linariifolia* unit
	c.) SEDGELAND
7	Freshwater swamp unit
	d.) CLOSED SHRUB
8	Mangrove unit
	e.) HERBLAND
9	Saltmarsh unit
	f.) LOW CLOSED-FOREST
10	*Casuarina glauca* unit
	g.) OPEN-FOREST
11	i. *Eucalyptus robusta* unit
12	ii *Casuarina cunninghamiana* unit
Not mapped.	h.) RIVER FRINGING VEGETATION
- - - - -	Indication of old river channel

FIGURE 3·5: VEGETATION MAP OF THE FLOODPLAIN OF THE HAWKESBURY RIVER AND ITS MAJOR TRIBUTARIES. KEY TO FIGS. 3·6 TO 3·23



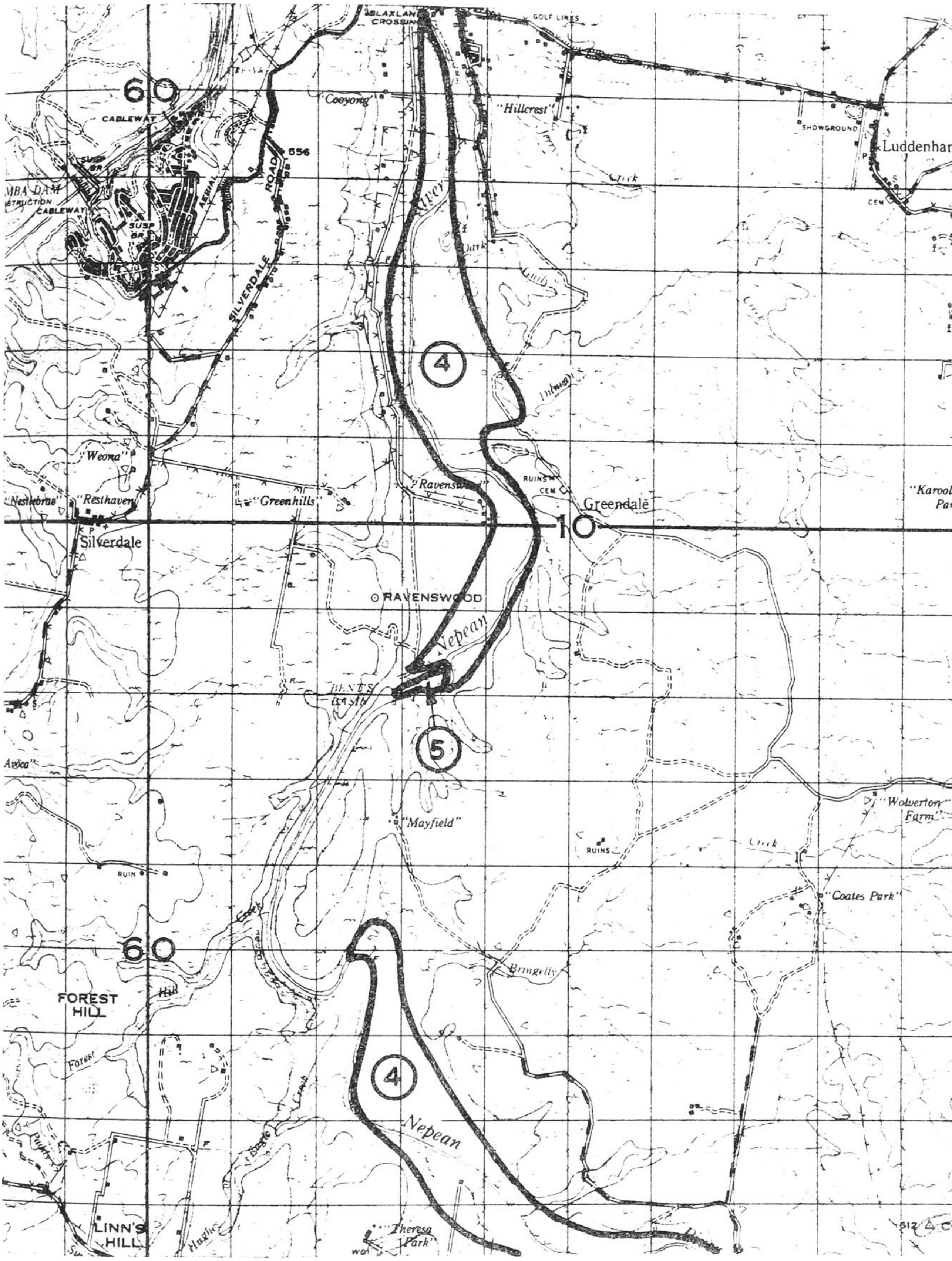
MILITARY MAP - CAMDEN

FIGURE 3·6



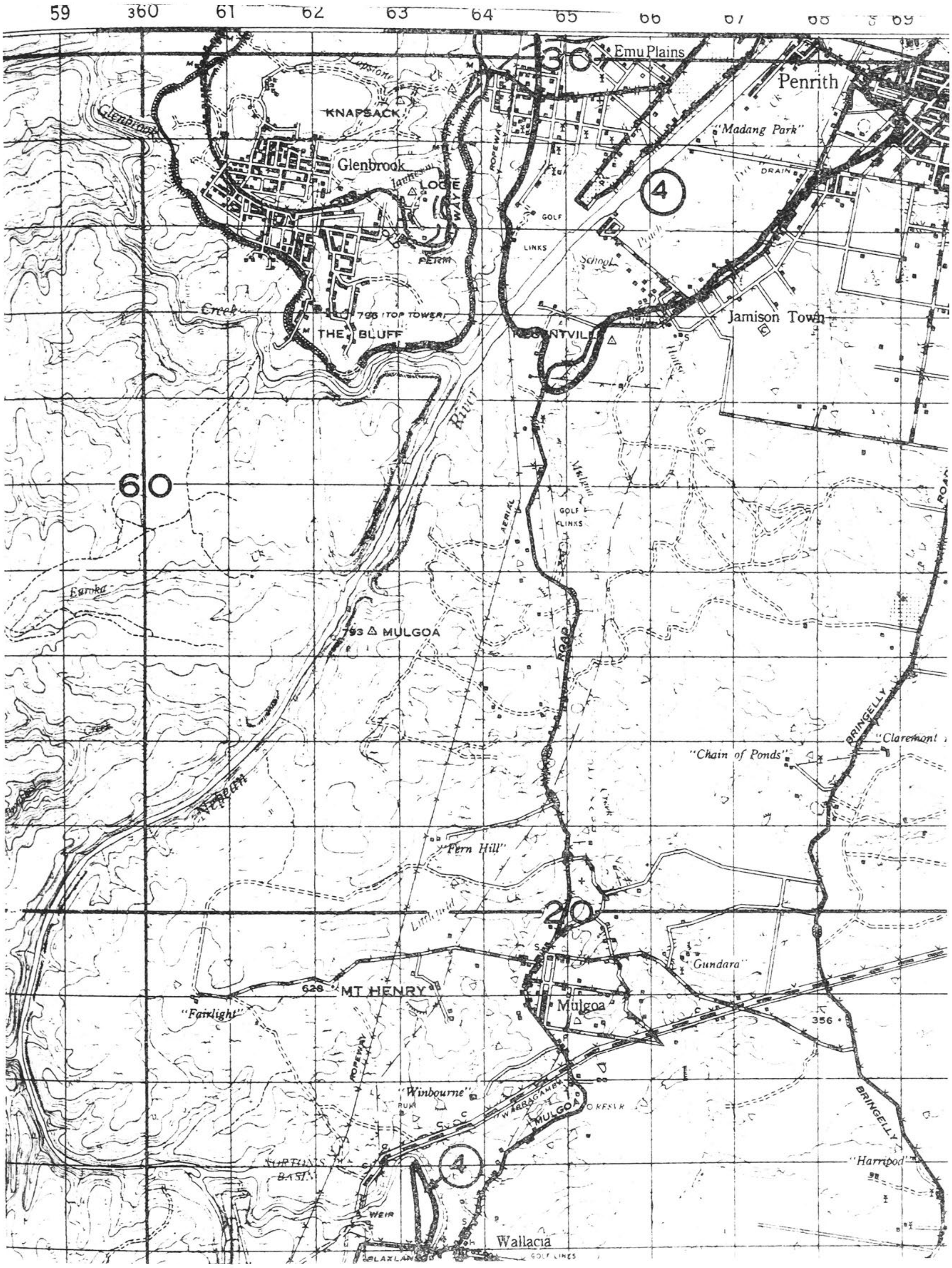
MILITARY MAP - CAMDEN

FIGURE 3.7



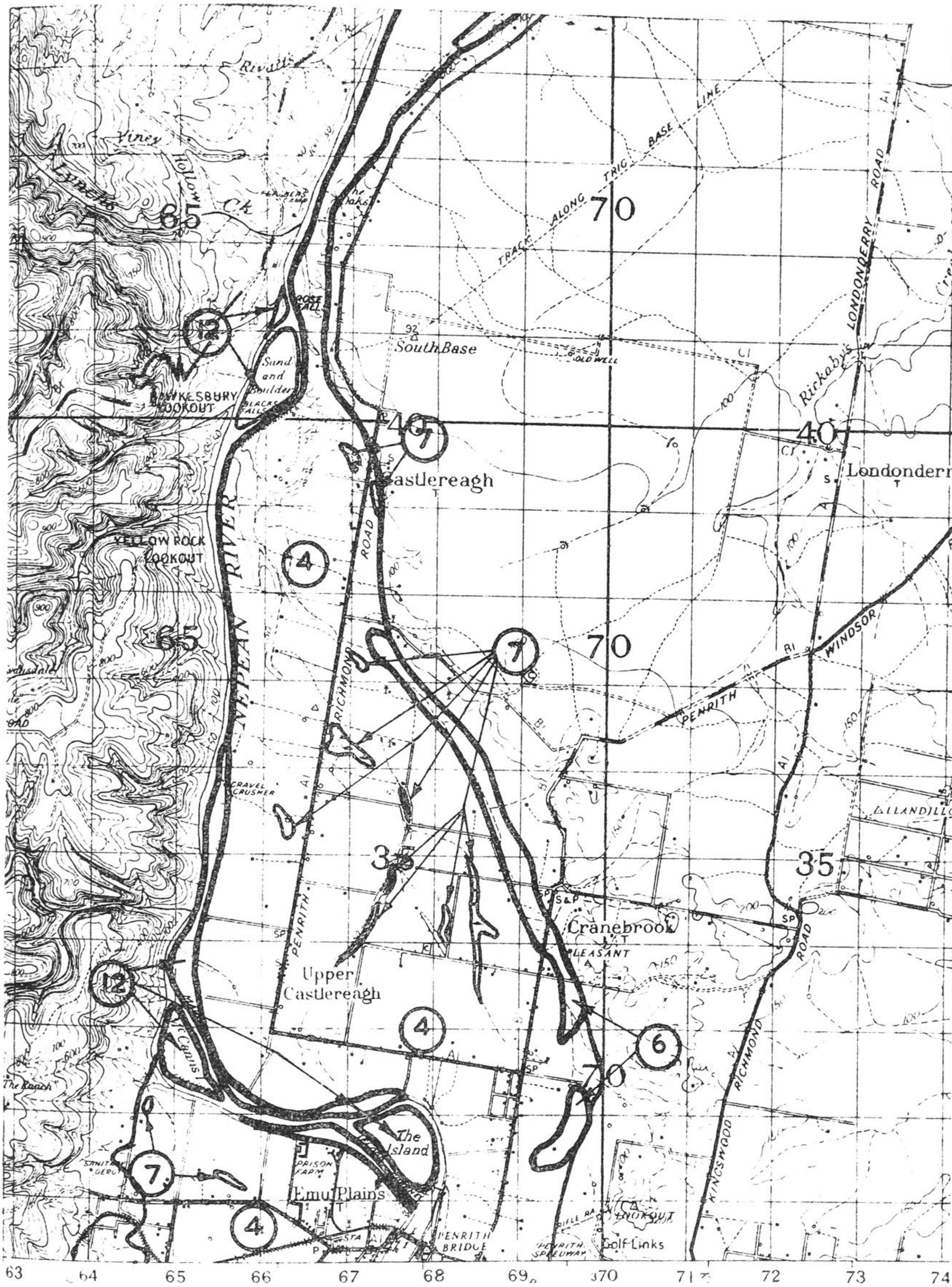
MILITARY MAP - LIVERPOOL

FIGURE 3·8



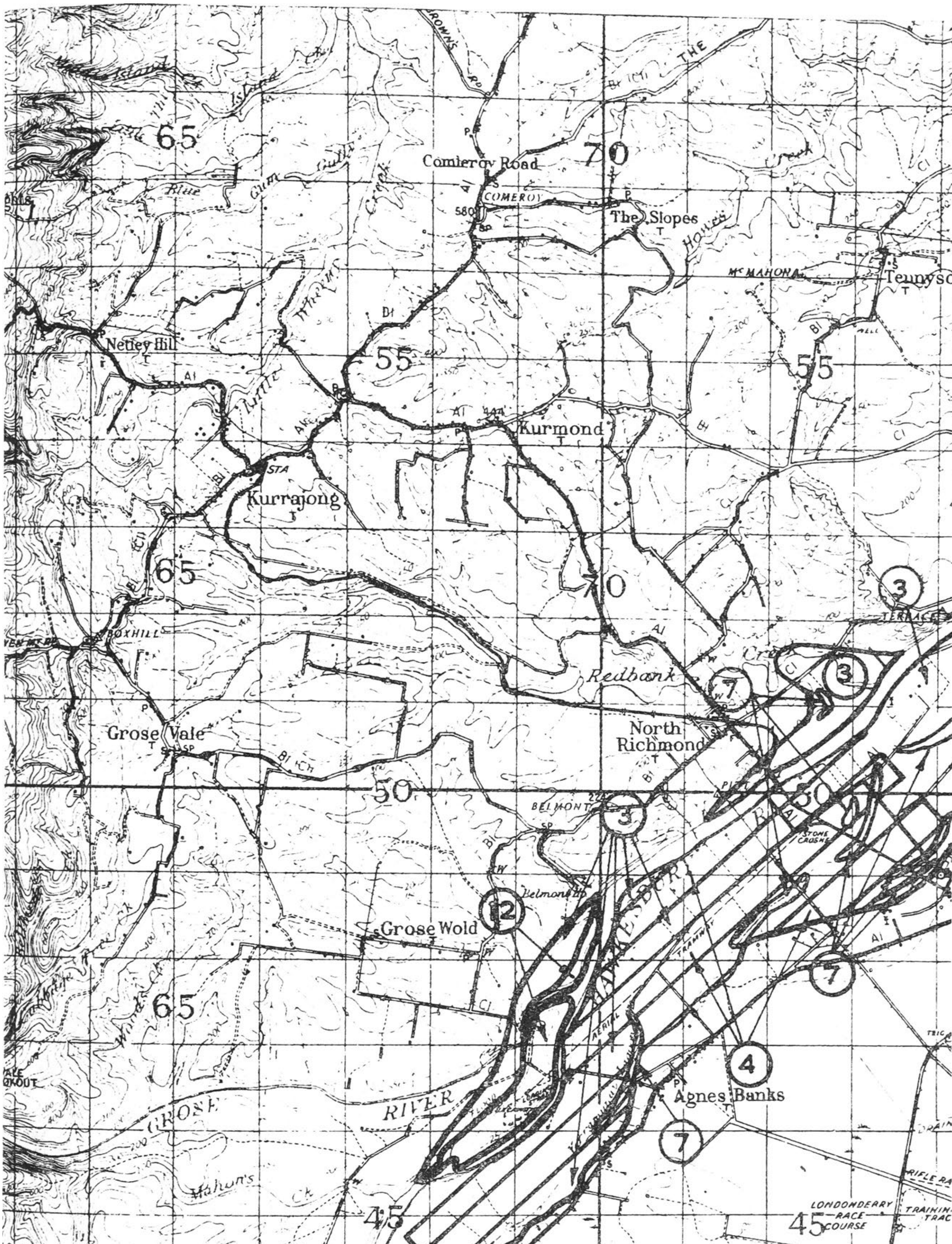
MILITARY MAP - LIVERPOOL

FIGURE 3.9



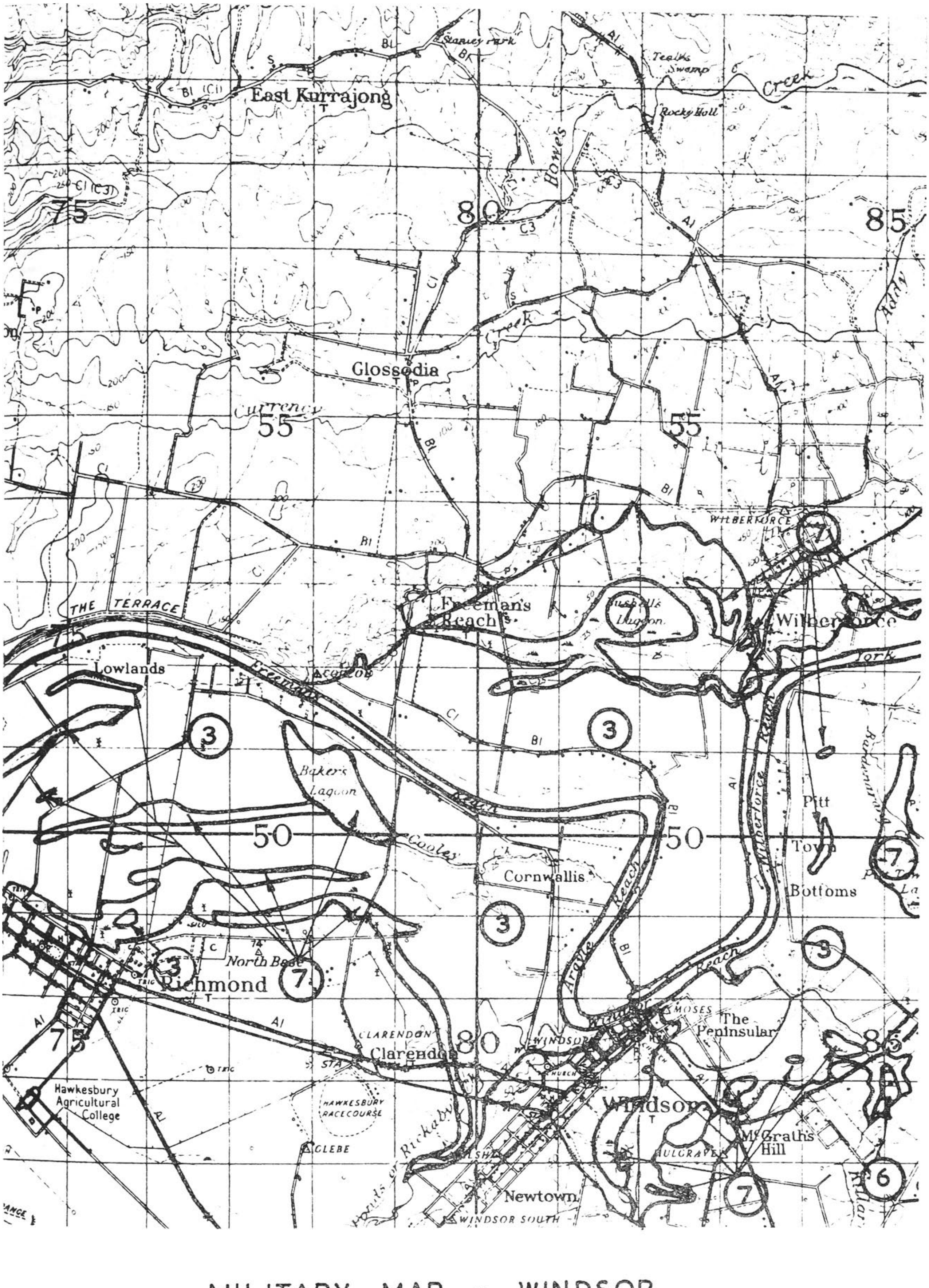
MILITARY MAP - WINDSOR

FIGURE 3.10



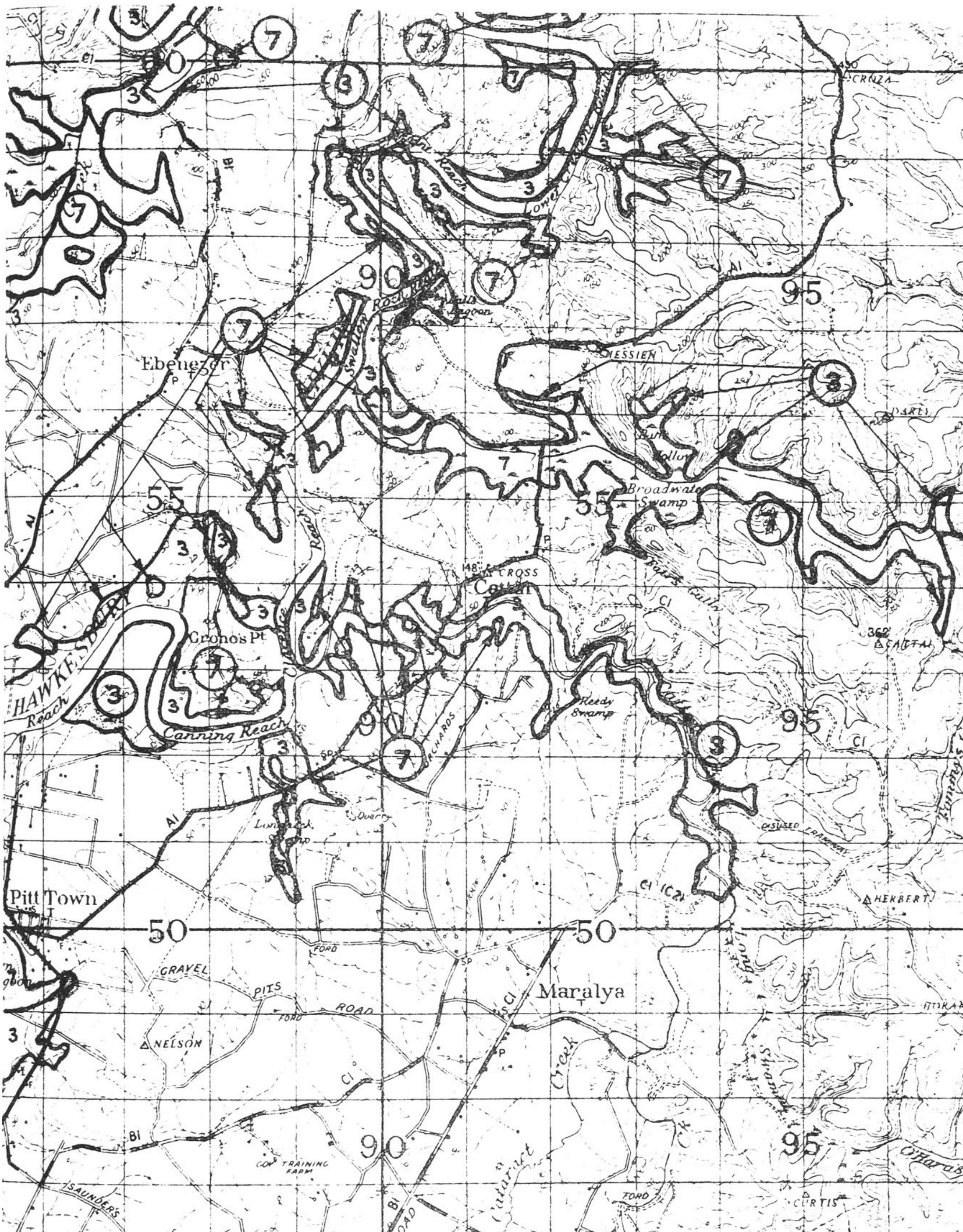
MILITARY MAP - WINDSOR

FIGURE 3.11



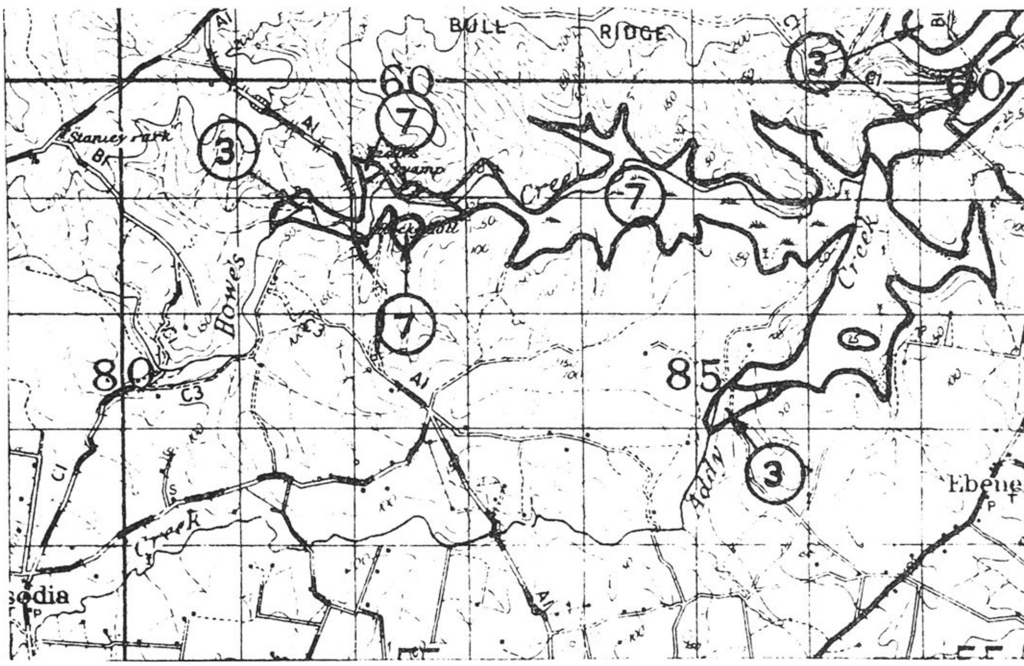
MILITARY MAP - WINDSOR

FIGURE 3.12



MILITARY MAP - WINDSOR

FIGURE 3·13

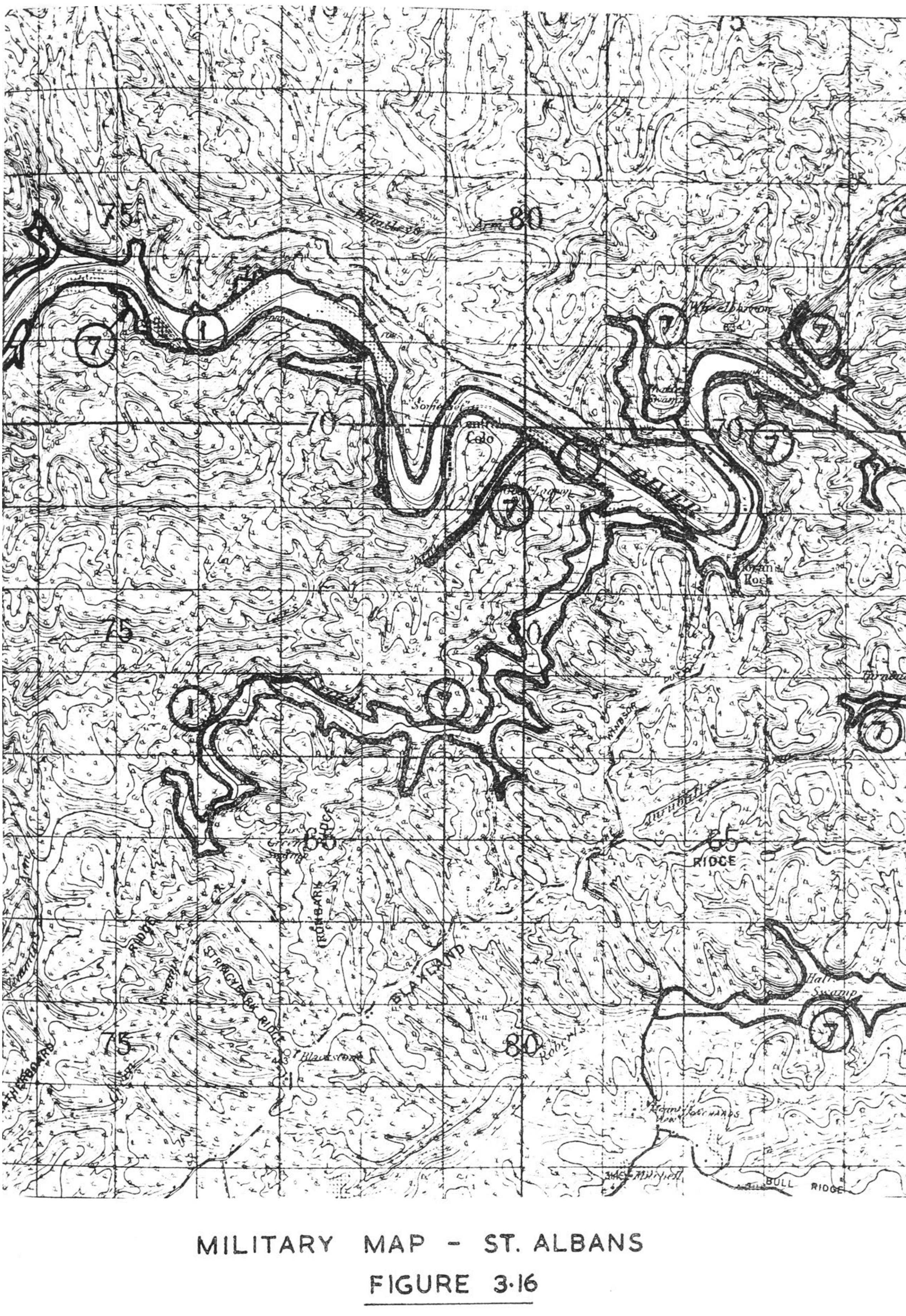


MILITARY MAP - WINDSOR

FIGURE 3·14

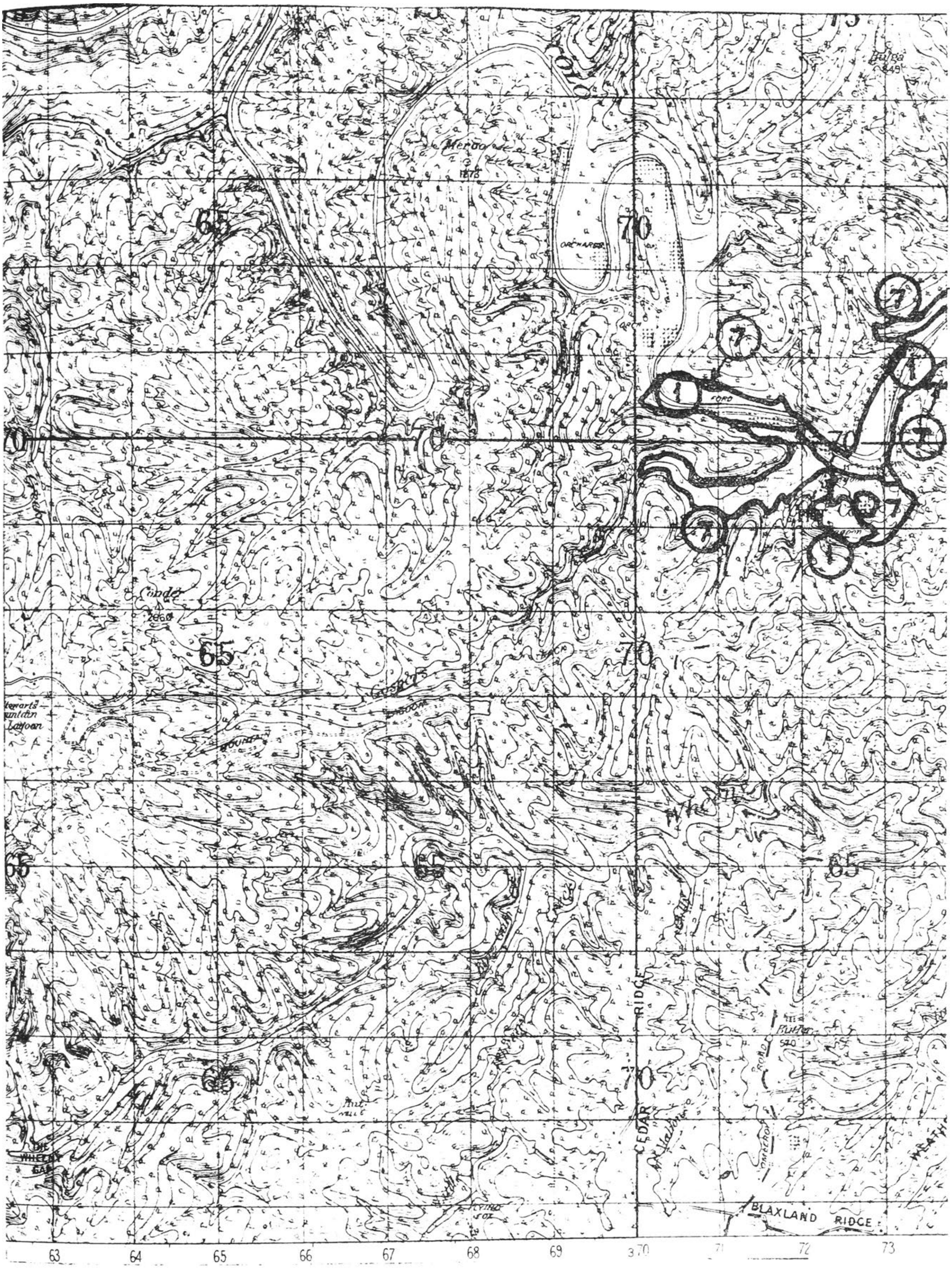
MILITARY MAP - ST. ALBANS

FIGURE 3·15



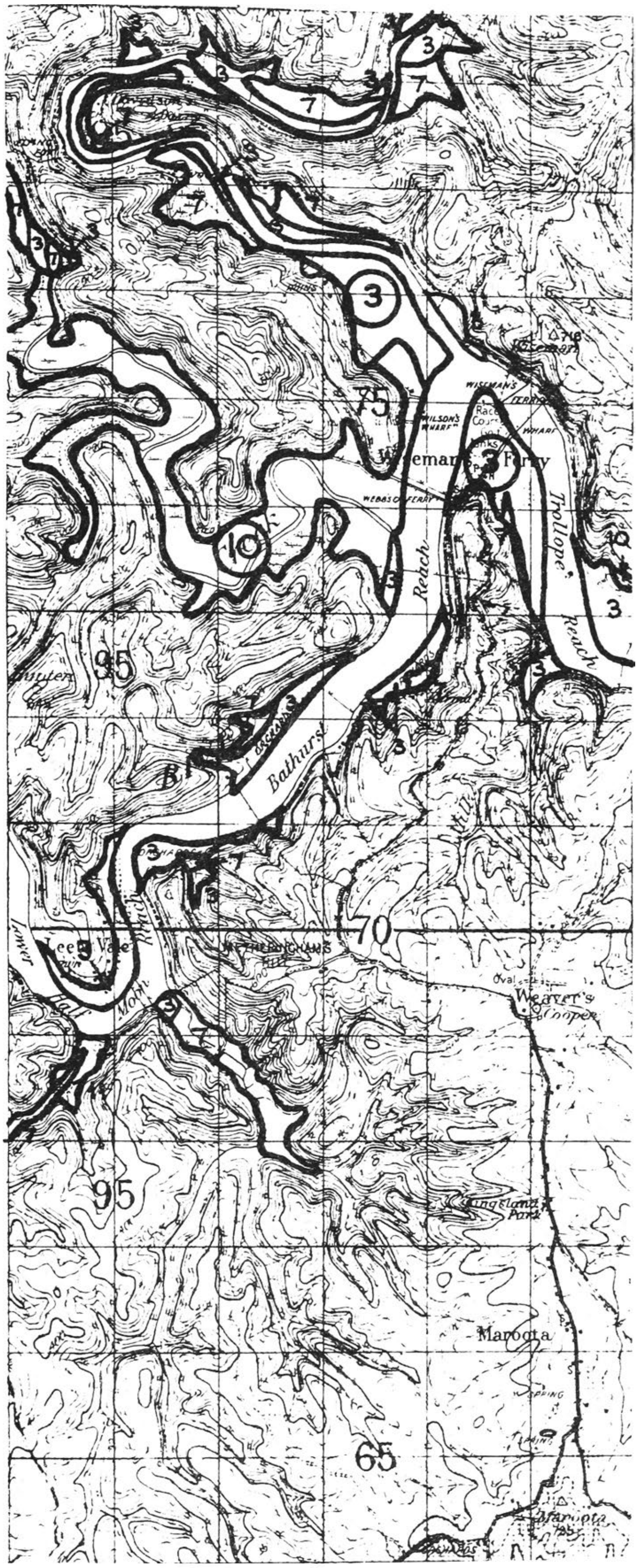
MILITARY MAP - ST. ALBANS

FIGURE 3·16



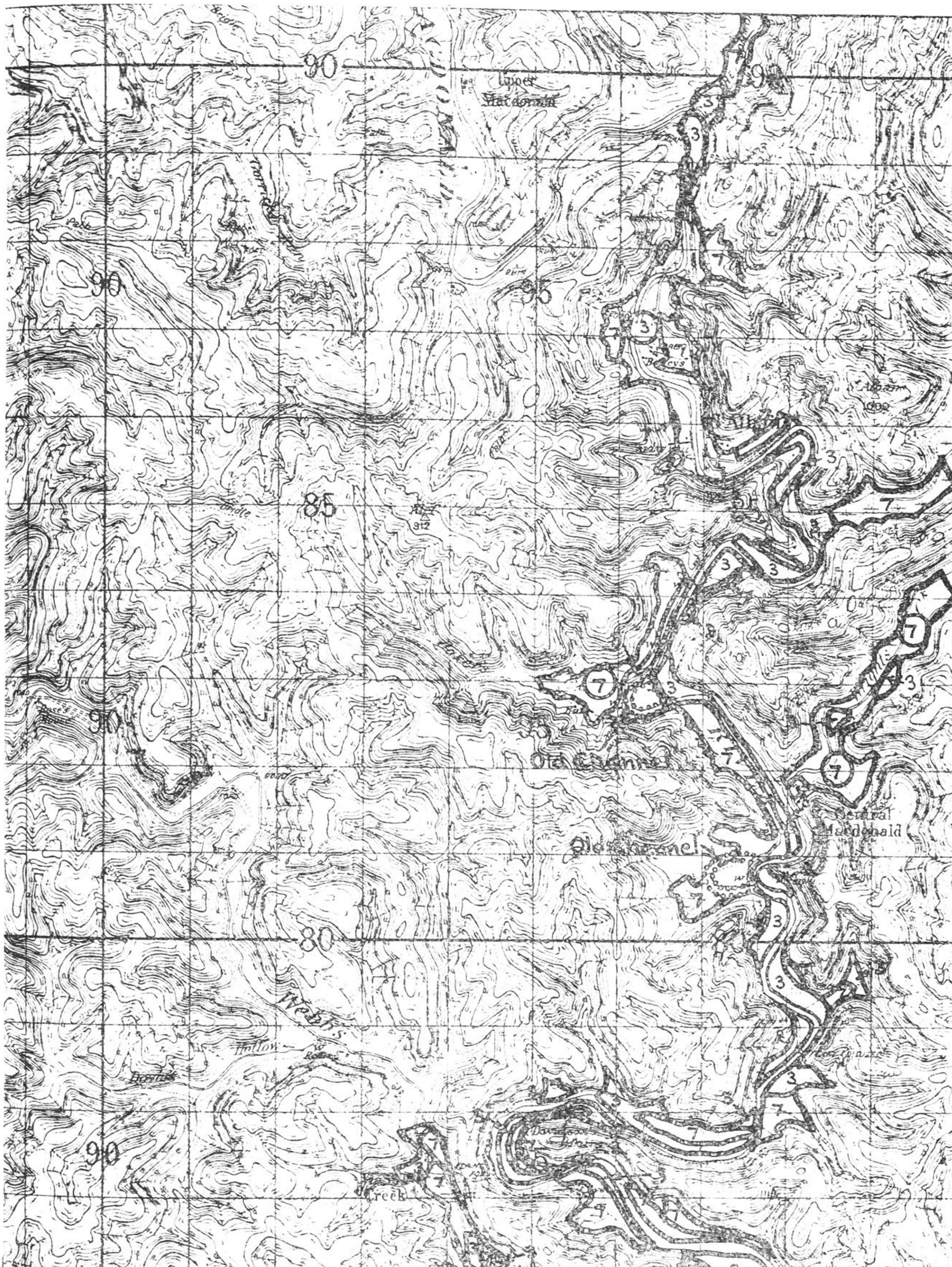
MILITARY MAP - ST. ALBANS

FIGURE 3·17



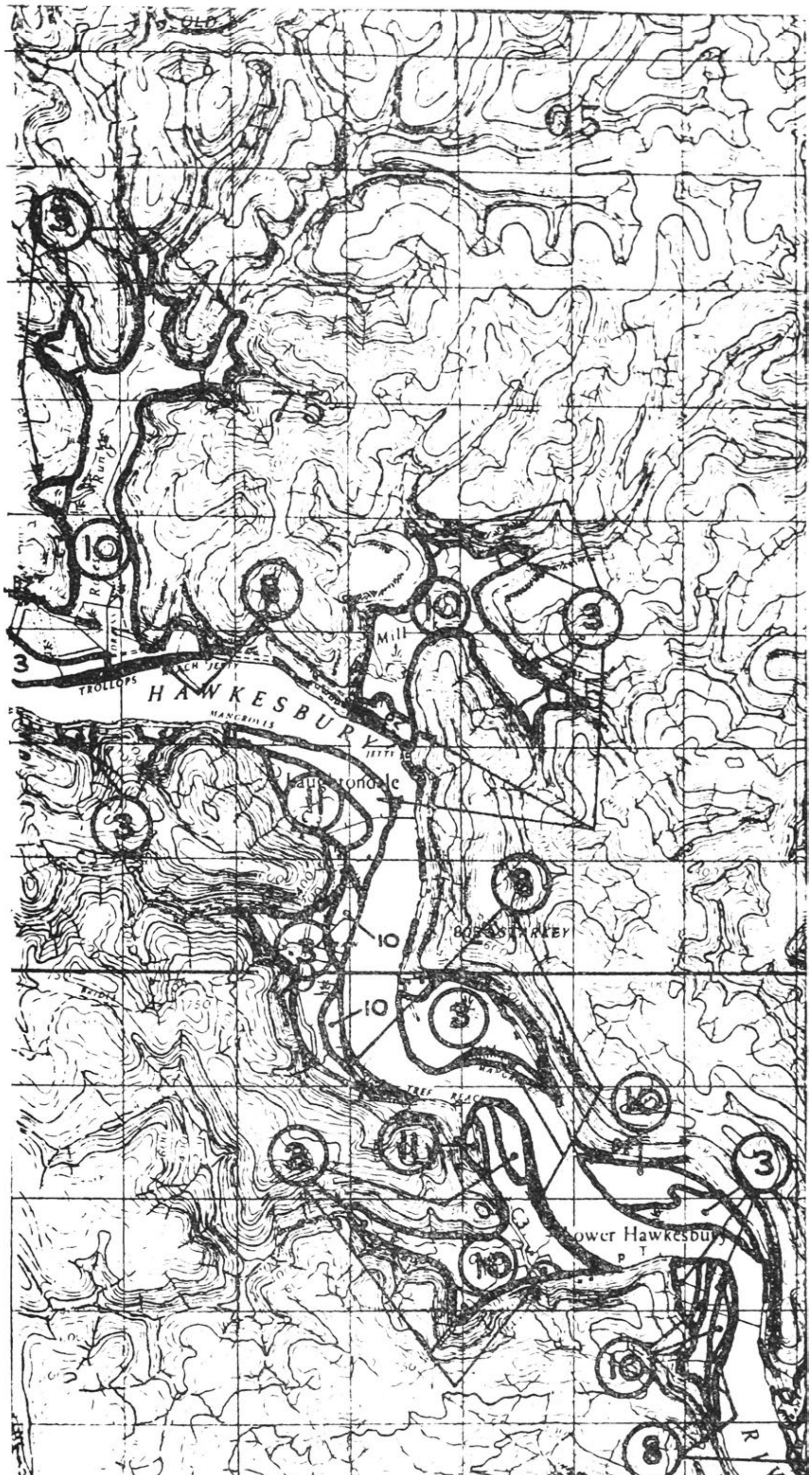
MILITARY MAP - ST. ALBANS

FIGURE 3.18



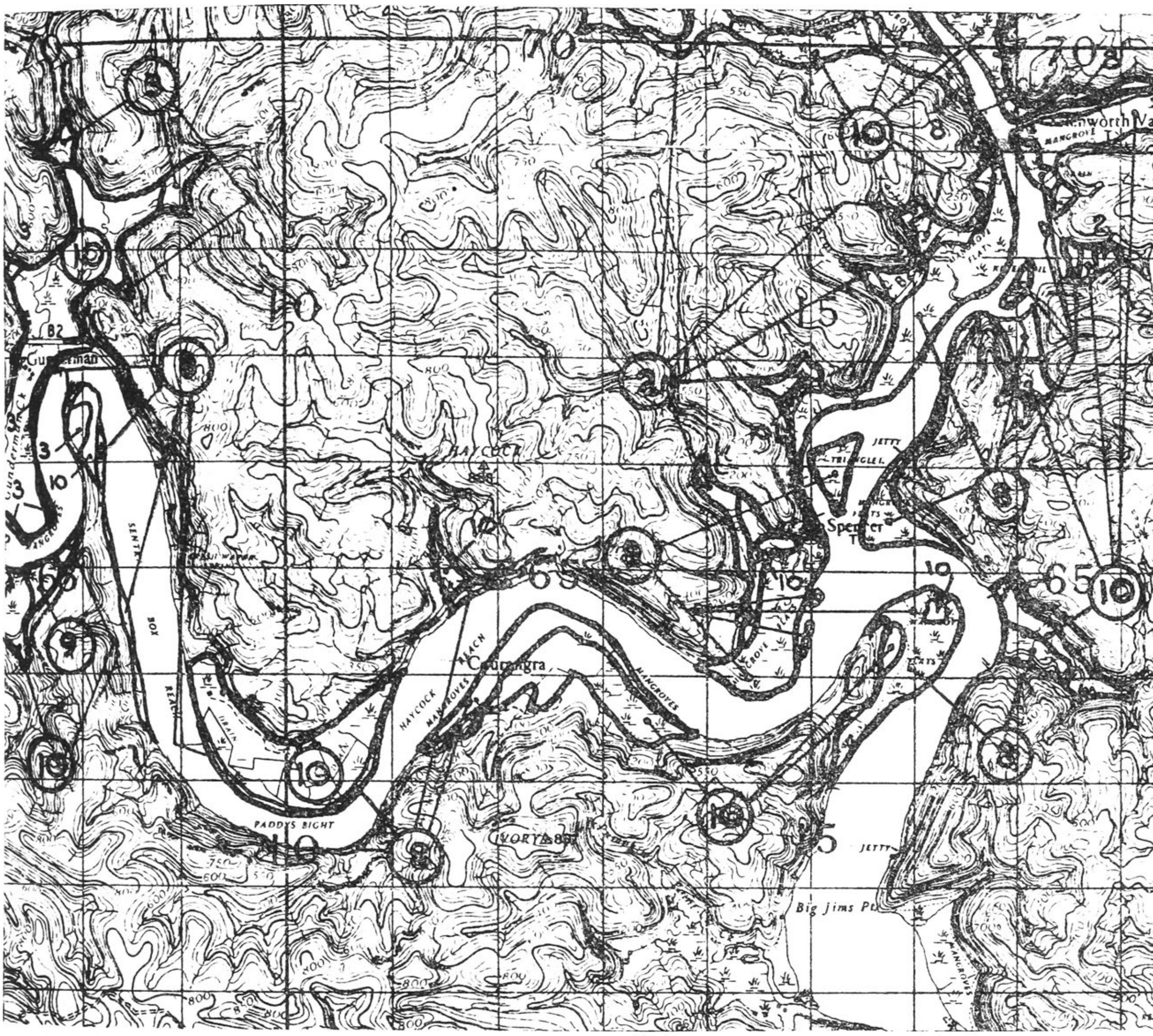
MILITARY MAP - ST. ALBANS

FIGURE 3-19



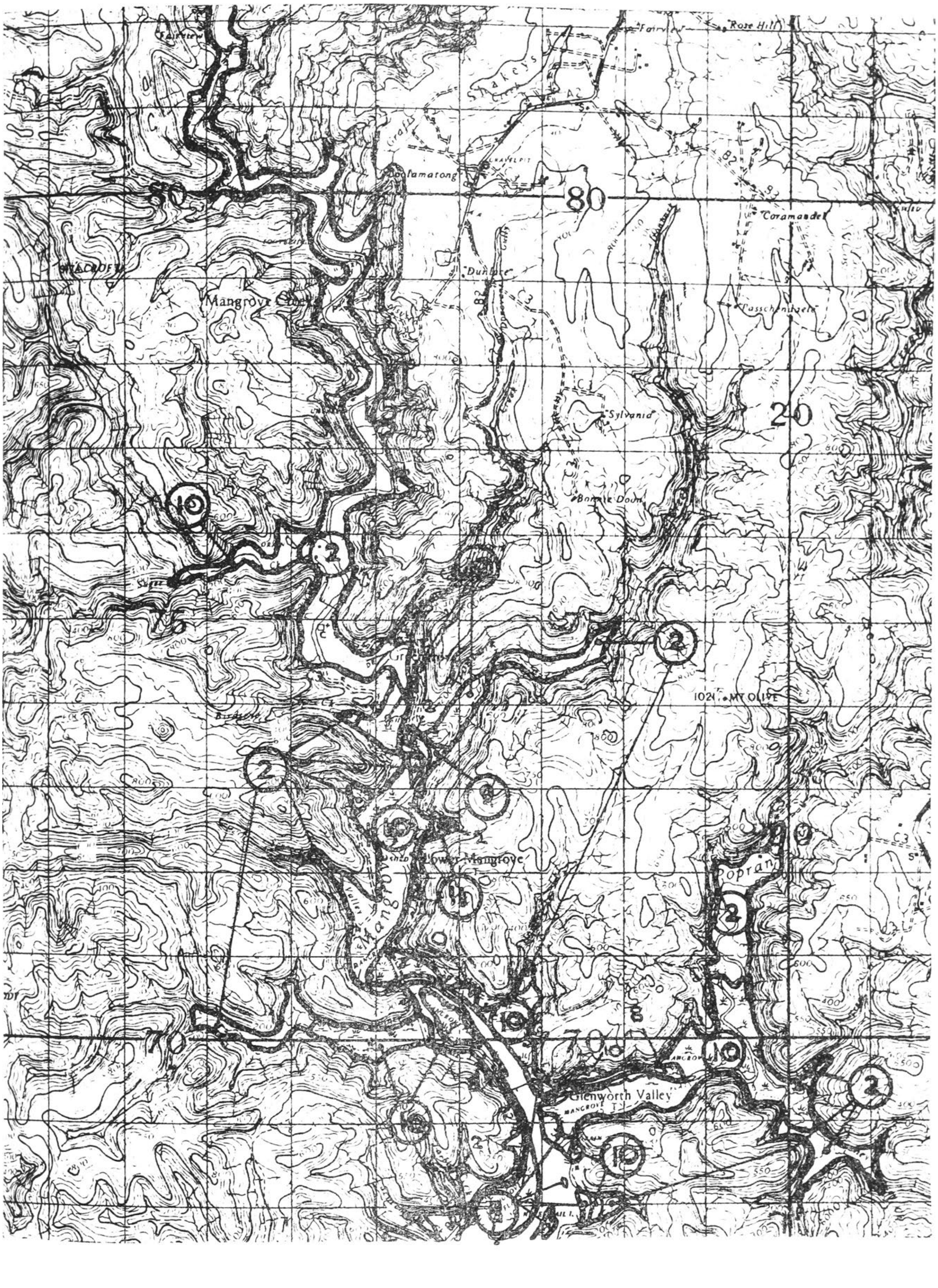
MILITARY MAP – GOSFORD & NORAHVILLE

FIGURE 3·20



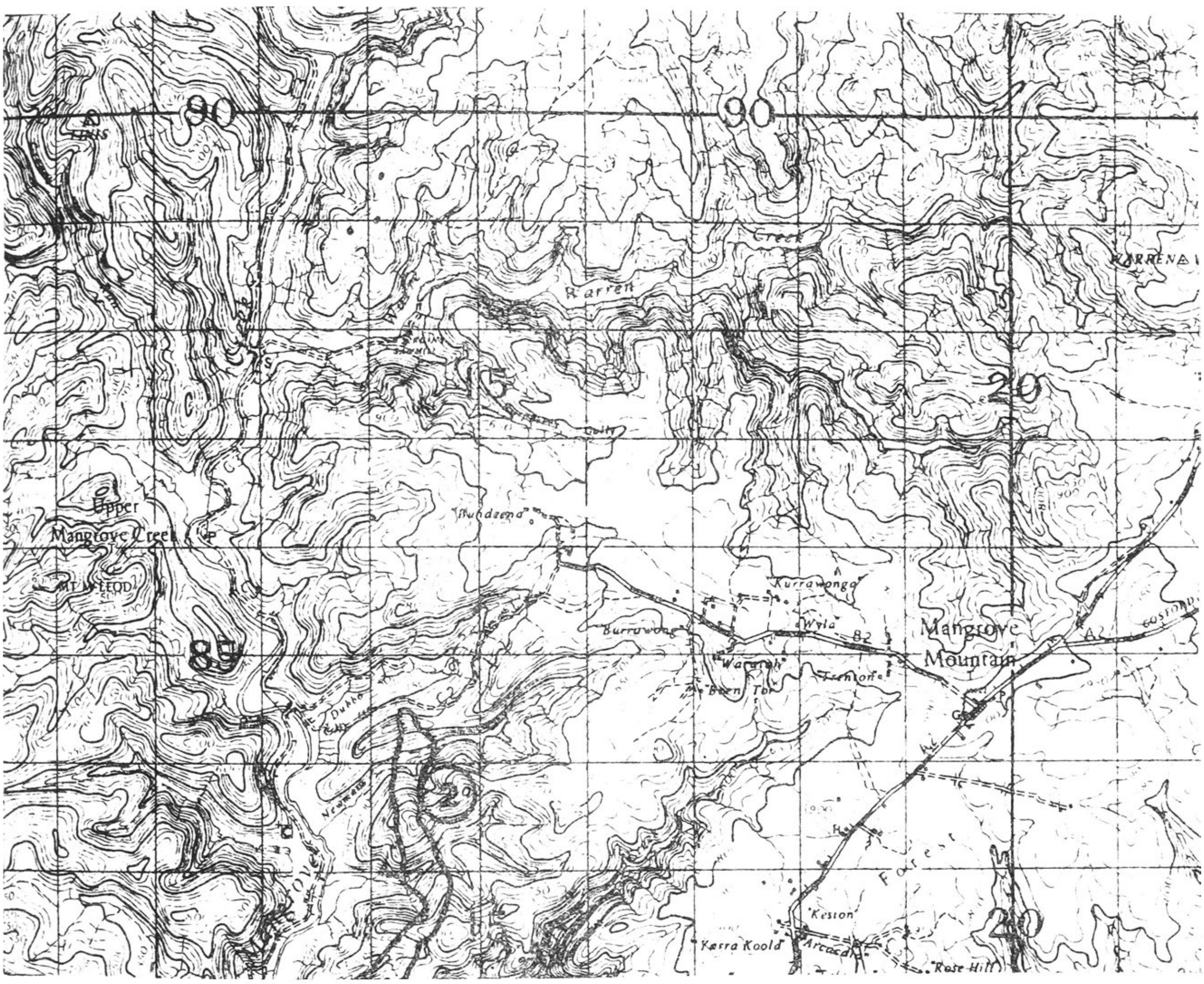
MILITARY MAP - GOSFORD & NORAHVILLE

FIGURE 3·21



MILITARY MAP - GOSFORD & NORAHVILLE

FIGURE 3·22



MILITARY MAP - GOSFORD & NORAHVILLE

FIGURE 3·23

the best developed forest unit that occurred on the floodplain. The dominant trees *Eucalyptus deanei*, *E. saligna* and *E. elata* attained a height of over 30 m, their crowns probably touching each other. Other tree species which occurred were *Casuarina cunninghamiana* which was generally restricted to the banks of the river and *Angophora floribunda*.

In the most sheltered positions such as in gullies and at the bases of sandstone cliffs where soil moisture conditions and drainage were good, a closed understorey of small trees and shrubs developed. Species often found in rainforest communities such as *Acmena smithii*, *Trema aspera*, *Ficus coronata*, *Duboisia myoporoides* and *Omalanthus populifolius* occurred in this understorey, together with some xeromorphic shrubs such as *Tristania laurina*. Vines such as *Eustrephus latifolius*, *Geitonoplesium cymosum* and *Pandorea pandorana* were usually present. Ground cover consisted of a litter layer about 2 - 4 cm deep with scattered ferns such as *Doodia aspera* and *Adiantum aethiopicum*.

Where moisture and shelter conditions were less favourable as on broader and more open flats, a more open shrub layer with *Acacia filicifolia* and *Leptospermum flavescens*, probably occurred together with a ground layer of *Pteridium esculentum* and native grasses. However, *Acacia filicifolia* and *Pteridium esculentum* are often colonizers of disturbed ground so that their current presence may have been the result of fire or grazing and they may not have been as important a part of the original vegetation as is suggested.

The reliability mapping scale for this unit is III. As it occurred on the most fertile areas it has been cleared extensively for orchards and grazing. However, patches remain in more inaccessible gullies which although damaged by logging, still give a reasonable indication of the original forest. The composition of the unit in the more open areas has been almost completely destroyed by clearing.

2. *Eucalyptus deanei* - *Angophora floribunda* unit

This unit was very closely related to the preceding one and may possibly be a logging artefact. It has been separated from the *Eucalyptus deanei* - *E. saligna* - *E. elata* unit by the absence of *E. elata* and the low frequency of *E. saligna*. The understorey shrubs in both units were very similar.

The two units occurred under different topographic conditions. On the Colo there was a distinct pattern of high levee banks which supported *E. deanei* - *E. saligna* - *E. elata* tall open-forest whereas Mangrove Creek had an almost flat floodplain. In the latter area the floodplain was occupied by *E. deanei* - *Angophora floribunda* tall open-forest. The unit has been extensively cleared and allocated map reliability scale III.

3. *Eucalyptus tereticornis* unit

This unit was the most widespread and important unit in the lower reaches of the river system. *Eucalyptus tereticornis* was the dominant tree species, though other tree species did occur and may sometimes have been co-dominant. These species were *E. amplifolia*, *E. pilularis*, *E. deanei*, *E. punctata*, *Angophora floribunda* and *A. subvelutina*. The general height of the unit was between 15 and 25 m. In moister areas a closed shrub layer similar to those of the preceding units was present. This was often accompanied by the presence of Eucalyptus pilularis and E. deanei and generally occurred where sandstone cliffs provided increased shelter.

In less sheltered areas and on broad open flats there was a more open forest of E. tereticornis with some E. amplifolia. Almost all of these areas have been cleared for cultivation or heavily grazed, with the result that the original structure and understorey is very difficult to determine. In addition many areas probably had a higher water table originally, but have been drained for pasture improvement.

The original understorey of most of these areas was probably of rushes and sedges, the most important species now being Juncus usitatus. These areas probably had standing water for part of the year. A scattered shrub layer of Melaleuca linariifolia up to 5 m high occurred in some areas. On higher and better drained areas the rushes were replaced by grasses, ferns and clumps of Lomandra longifolia, together with a discontinuous shrub layer with Melaleuca styphelioides, Bursaria spinosa, Acacia parramattensis and Acacia floribunda. Eucalyptus crebra, normally found on the Wianamatta shale also occurred occasionally.

This unit has been extensively cleared for farming and grazing. Some patches of the unit with dense shrub layer occur in gullies in the Lower Hawkesbury area. However, these are being rapidly invaded by introduced weeds particularly Tradescantia albiflora. Map Reliability Scale - III and IV.

The unit grades into the closely related Eucalyptus amplifolia - Angophora subvelutina tall open forest in the Agnes Banks region.

4. Eucalyptus amplifolia - Angophora subvelutina unit.
This unit covered the largest part of the alluvial area, being the dominant type on practically all the alluvium, south of Agnes Banks. It has been described by Phillips (1947) who regarded it as being dominant on the alluvium as far downstream as Sackville. However, during the present survey no evidence was found that it was widespread so far downstream.

The original forest was probably about 20 to 25 m high and composed mainly of Eucalyptus amplifolia with some Angophora subvelutina. Other trees occurring in the unit were Eucalyptus bauerana, E. tereticornis and Casuarina cunninghamiana. The shrub layer was probably discontinuous with Melaleuca styphelioides, M. Linariifolia and Bursaria spinosa being most common. The vine Clematis glycinoides also occurred. Ground cover was probably grass on the drier areas and sedges and rushes in moister hollows.

The alluvial soils on which this unit occurred are relatively flat and have a high nutrient status. As a result they have been cleared and farmed for many years. In fact the presence of Angophora subvelutina (apple-tree) was used by early settlers as an indication of good soil (Cunningham 1827). The unit is allocated to Map Reliability Scale IV.

5. Eucalyptus benthamii unit.

This unit was restricted to only one locality in the area, Bents Basin, 10 km south of Wallacia. Here Eucalyptus benthamii dominated the upper stratum, growing to about 30 m high on a recent alluvium sandbank in the centre of the river channel. Other trees which also occurred were Casuarina cunninghamiana, Eucalyptus elata, E. amplifolia and Angophora subvelutina. These, however, appeared to be restricted to the alluvium banks of the river and did not occur on the sandbank.

Under the Eucalyptus benthamii was a tall closed shrub layer made up almost entirely of Acacia glaucescens and A. floribunda with a few smaller shrubs such as Breynia oblongifolia and Hymenanthera dentata. The ground layer was bare sand with some Lomandra longifolia and Pteridium esculentum.

The unit has been little disturbed and given Map Reliability Scale I. However, introduced weeds such as Ligustrum and Asparagus have invaded part of the stand.

Scattered individuals of Eucalyptus benthamii also occurred in the fringing forest along the river as far downstream as the junction with the Grose.

(b) 6. Tall Shrubland

Melaleuca linariifolia unit.

This unit was dominated by Melaleuca linariifolia which formed a tall shrubland about 5 m high with an understorey of rushes and sedges. It occurred in low lying areas, as a fringe around freshwater swamps.

(c) 7. Sedgeland

Freshwater Swamp Unit.

This is a composite unit including all fresh swamp areas and areas of permanent open water, together with some areas of Melaleuca linariifolia tall shrubland. The different subunits recognizable have not been classified and described separately as the swamp vegetation is seasonal and field work was mainly during the winter months when most of the swamp species were dead or dormant.

Coastal swamps in New South Wales have been classified by Goodrick (1970) and the unit mapped here includes the following of his types.

(d) Fresh meadows
(e) Seasonal fresh swamps
(f) Semi-permanent fresh swamps
(g) Open fresh waters

Freshwater swamps generally occurred in the depression formed between the levee bank and the edge of the alluvium, particularly where the alluvium ended abruptly at the edge of a sandstone cliff. The swamps generally consisted of a series of zones related to the depth and time for which they were inundated. This ranged from permanent standing water to a few inches of water remaining after rain.

Permanent standing water with no emergent vegetation generally occupied the lowest and most poorly drained areas of the large swamps. Around the open standing water was shallower water with a zone of emergent vegetation usually with Eleocharis sphacelata, Typha orientalis, Philydrum lanuginosum and Triglochin procera. Outside this zone was a zone of rushes (Juncaceae) and sedges (Cyperaceae). This zone did not have any standing water, except after rain, but the soil was usually water-logged or very moist. Common species were Juncus usitatus and Polygonum spp. This zone often had scattered shrubs of Melaleuca linariifolia and M. styphelioides and may in some places have had patches of M. linariifolia shrubland.

Much of the freshwater swamp unit mapped has been drained for improved pasture. However, very rarely are all indications of the original swamp removed as Juncus spp. are not palatable to cattle and often remain as indicators. In addition in some areas the swamps remain relatively untouched. The Map Reliability Scale for the unit is II.

The following four units occurred in the estuarine regions of the Hawkesbury River and Mangrove Creek, their distributions being related to tidal influence and activity. Estuarine communities in the Sydney district have been described by Pidgeon (1940) and studied in detail by Clarke and Hannon (1967, 1969, 1970, 1971).

The units occurred in a zonation related to degree of tidal inundation. This zonation is shown in Figure 3.4 which shows a cross section of the junction of Ashdale Creek with the Hawkesbury River 13 km downstream from Wisemans Ferry.

(d) 8. Closed Scrub

Mangrove Unit.

This unit occurred in the lower reaches of the Hawkesbury River and the Mangrove Creek on mud banks between tide levels. The main species was Avicennia marina var australasica which formed a dense scrub about 7-8 m high. Another species Aegiceras corniculatum occurred as an understorey about 4 m high often with individuals occurring on the seaward side of the Avicennia. However it usually occurred as a pure band on the landward side of the Avicennia. This banding was particularly obvious where the shore was steep and rocky and the mangrove unit was limited to a line of Avicennia, one or two trees wide with a similar line of Aegiceras on the inside. Aegiceras appeared to have a greater tolerance range than Avicennia and occurred as scattered individuals as far up the Hawkesbury as the Webbs Creek ferry. Avicennia individuals were recorded about 3 km upstream from Laughtondale.

This unit has remained relatively undisturbed and is given a Map Reliability Scale of 1.

9. Herbland

Saltmarsh unit.

On the landward side of the Mangrove zone a zone of saltmarsh often occurred, particularly where a tributary creek joined the main river. This was a low dense community dominated by succulent herbs about 30 cm high, the most important being Salicornia quinqueflora. Other species associated with saltmarsh included Suaeda australis, Sporobolus virginicus and Triglochin striata.

The unit was classified as herbland instead of low shrubland as suggested by Specht (1970) for two reasons. Firstly the community was denser than low shrubland and secondly the dominants were regarded as succulent herbs, not small shrubs.

The unit has only been mapped in a few localities as it covered only small areas and was easily confused with parts of the Casuarina glauca unit during photo interpretation. Moreover much of it has been drained so that boundaries with the normally adjoining Casuarina unit have been lost. These areas have been generally mapped as part of the Casuarina unit.

Map Reliability Scale II has been allocated to the unit.

10. Low Closed-Forest

Casuarina glauca unit

This unit includes a series of vegetation types which because of their limited size or because of disturbance resulting from clearing and fire, have been included in the same unit for mapping purposes.

The following distinct subunits can be recognised.

10A. Saltmarsh sub unit.

10B. Juncus rushland sub unit.

10C. Casuarina glauca low closed - forest sub unit

10D. Melaleuca ericifolia closed scrub sub unit.

0A. Saltmarsh sub unit

Known occurrences of saltmarsh have been mapped in a separate unit. However, areas probably exist that were originally saltmarsh but have since been cleared and all trace of the original vegetation lost. The original vegetation on these areas may equally have been Juncus rushland or Phragmites closed grassland with the result that because of the difficulty in determining the original composition these cleared areas have been included within the Casuarina glauca unit.

.0B. Juncus rushland sub unit

This sub unit was dominated by rushes (Juncus spp.) which formed a herbland on areas usually either waterlogged or subject to tidal inundation. In estuarine conditions the subunit made up a zone on the landward side of the saltmarsh zone. In these situations it was dominated by Juncus kraussii Hochst together with Sporobolus virginicus and Baumea juncea.

In swampy areas away from the direct influence of salt water the dominant species was Juncus usitatus. In these areas it formed a similar community to the Juncus zone in the freshwater swamp unit.

10C. Casuarina glauca sub unit

This was the most important vegetation type in the unit. The dominant species was Casuarina glauca which formed a closed forest usually about 10 to 15 m high. In estuarine situations, it occurred as a zone behind the Juncus zone or where the river flat was very narrow it occurred directly behind the mangrove band. The understorey was generally Juncus kraussii.

Casuarina glauca was not confined to estuarine situations. Along brackish and sluggish fresh streams it usually formed a fringing forest two or three trees wide with dense understorey of Phragmites communis. Together with Melaleuca linariifolia it occurred in and around brackish and fresh swamps, again with an understorey of Phragmites or in better drained areas, Juncus usitatus. Casuarina glauca also occurred on better drained areas, where it became codominant with Melaleuca styphelioides and M. ericifolia with an understorey of sedges (Cladium procerum, Gahnia spp.)

10D. Melaleuca ericifolia sub unit

In some areas Melaleuca ericifolia formed pure dense thicket-like stands about 6 m high. These were often adjacent to pure stands of Casuarina glauca and may have been due to slightly different drainage conditions.

Melaleuca ericifolia appears to sucker readily and the presence of the unit may be due to frequent burning either naturally or as a result of white settlement.

Because of the swampy and often saline conditions under which this unit occurs, some large areas have remained in essentially original condition. However, other areas, particularly and extensive occurrence near Camden, have been cleared and drained. Further clearing in the lower Hawkesbury River is being carried out at present. Map Reliability Scale II.

(g) Open Forest

11. Eucalyptus robusta unit

Eucalyptus robusta formed a forest about 12-15m high in the lower reaches of the Hawkesbury River occurring as part of the estuarine zonation on higher ground between the Casuarina glauca zone, and Eucalyptus tereticornis tall open forest. A dense understorey of Melaleuca ericifolia, M. styphelioides and Phragmites australis occurred on the Casuarina side and graded into a dense, mainly mesomorphic shrub understorey on the Eucalyptus tereticornis side.

This unit was probably fairly common originally, but clearing has removed most traces of it. The unit has been mapped only where remnant trees occur. Areas in which all traces of natural vegetation have been removed but which may have had E. robusta have been included in the Eucalyptus tereticornis unit. Map reliability Scale IV.

12. Casuarina cunninghamiana unit

This unit occurred on the islands of sand and gravel in the Nepean River near Penrith. These deposits now have stands of young Casuarina cunninghamiana suggesting that the higher parts of the deposit were originally forested with this species. The edges were probably unstable and subject to change during flood periods. At present the deposits are also being colonised by a number of Acacia species notably A. floribunda A. elata, A. glaucescens, A. ulicifolia, A. obtusifolia and A. parvipinnula, together with Bossiaea rhombifolia, Pultenaea flexilis and Kennedia rubicunda. These species do not occur under large trees of Casuarina cunninghamiana nearby and may only be transitory inhabitants to be swept away by the next flood.

The islands have been intensively mined and the original vegetation severely damaged. Map Reliability Scale IV.

(h) River Fringing Vegetation

The vegetation along the immediate edges of the rivers was generally different from that of the surrounding areas because of the better moisture conditions. As a result, a series of river fringing vegetation types could be recognised but, because of their occurrence in very narrow belts could not be readily mapped.

In the lower reaches of the Hawkesbury River the fringing vegetation was the Mangrove unit, which formed stands broad enough to be mapped in the lower estuarine reaches of the river but gradually upstream became reduced to a band several plants wide and finally to scattered individuals at Wisemans Ferry. As the mangroves decreased, their place was taken by a band of Casuarina glauca with an understorey of Phragmites australis. Often the Phragmites formed a pure band on the outside of the Casuarina. Casuarina extended up the MacDonald River about 3 km past Wrights Creek where its place was taken by dense shrubs of Leptosperum flavescens, Tristania laurina and Acadia parramattensis.

In the Hawkesbury the Casuarina glauca gave way to a fringing forest of Casuarina cunninghamiana and Melia azedarach near Leets Vale. In sheltered positions this forest was overtopped by large eucalypts such as Eucalyptus elata E. tereticornis, E. amplifolia, E. benthamii and had a dense understorey of mesomorphic shrubs such as Trema aspera, Acmena smithii and Duboisia myoporoides.

In drier sections the understorey was probably Leptospermum flavescens, Tristania laurina and Acadia parramattensis with some Acadia floribunda and the vine Clematis glycinoides. Ground cover was probably grasses together with tussocks of Lomandra longifolia and Juncus usitatus in moist hollows. This drier forest probably extended continuously from Cattai Creek to Menangle.

In the Colo River both wet and dry types of forest occurred, the wet being most important as the floodplain here was much more sheltered by cliffs than the floodplain in most of the other rivers.

In Mangrove Creek the fringing vegetation was mangrove in the lower reaches, changing to Casuarina glauca then moist dense shrubs and finally to a line of Leptospermum flavescens.

Species mentioned above as being associated with vegetation units (a) to (g) are listed in the appendix. The popular names of most of these species are included.

13. Old River Channels

During the survey, attempts were made to determine the positions of old river channels using vegetation as an indicator. However, this proved difficult because of the destruction of most of the original vegetation. An exception was the use of some occurrences of Casuarina cunninghamiana. This tree normally grows along the banks of permanently flowing rivers and creeks. A line of trees some distance from the present river channel and not associated with flowing water may therefore indicate the position of an earlier channel. The best example is about 3 km north of Windsor where a line of old C. cunninghamiana indicates the old course of the Hawkesbury River. That this was the old river channel is confirmed from other sources. (H.A. Scholer, pers. comm.)

Another old channel indicated by C. cunninghamiana occurs in the Colo River about 5 km upstream from Central Colo.

Two old channels have been shown in the MacDonald River. These have been determined from aerial photography.

14. The Vegetation Maps

The original distribution of vegetation denoted by units 1 to 12 (see Section 12 above) is shown on Figures 3.5 to 3.23.

15. Present State of the Natural Vegetation

The present state of the vegetation units mapped has been briefly covered in the discussion on individual units and by reference to the Map reliability scale. In general almost all tall open-forest on the floodplain except that in the more inaccessible gullies, the Eucalyptus benthamii stand on a sand bank at Bents Basin and a thin line of trees along some river banks, has been removed and the land used for cultivation or grazing. Those patches that remain have almost all been logged at some time and are now being invaded by numerous exotic weed species.

Much of the area covered by freshwater swamp has been completely or partially drained. Most undrained areas have been subjected to grazing and the introduction of weed species.

The estuarine units have been least affected by man's activities so far. Undisturbed examples of mangrove, saltmarsh and Casuarina glauca units still occur in the Mangrove Creek valley. However, in the Hawkesbury River valley clearing of Casuarina glauca and draining of saltmarsh is now being carried out.

The degree to which clearing of the native vegetation has been carried out particularly in the vicinity of Richmond or Windsor is not immediately perceived by the non-botanist who sees a dense mass of vegetation along the river banks. However, this vegetation is almost all introduced and subsequently naturalised trees such as willows (Salix spp.) together with an understorey of exotic weeds. With the exception of Casuarina cunninghamiana it is very difficult to find a native species.

Acknowledgements

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Appendix

A list of some of the Native species occurring in the vegetation map units. Numbers denote units shown on vegetation maps - see Figure 3.5
x = present

Vegetation Map Units

	1. E. saligna, E. deanei, E. elata	2. E. deanei, A. floribunda	3. E. tereticornis	4. E. amplifolia, A. subvelutina	5. E. benthamii	6. M. linariifolia	7. Freshwater swamp	8. Mangrove	9. Saltmarsh	10. Casuarina glauca	11. E. robusta	12. Casuarina cunninghamiana
Pteridophyta	(a)					(b)	(c)	(d)	(e)			
Dennstaedtiaceae												
Hypolepis muelleri			x		x							
Pteridium esculentum "Bracken"		x	x		x							
Adiantaceae												
Adiantum aethiopicum "Common Maidenhair Fern"	x	x	x							x		
Pellaea falcata var falcata			x									
Blechnaceae												
Doodia aspera "Rasp Fern"	x		x									
Angiospermae												
Ranunculaceae												
Clematis glycinoides				x								
Ranunculus inundatus							x					
Menispermaceae												
Stephania japonica		x	x									
Violacaeae												
Hymenanthera dentata					x							
Viola hederacea "Ivy-leaved violet"										x		
Polygonaceae												
Polygonum strigosum "Spotted Knotweed"							x					
P. hydropiper "Water Smartweed"							x					
Chenopodiaceae												
Salicornia quinqueflora "Samphire"									x			
Suaeda australis "Seablite"									x			
Pittosporaceae												
Bursaria spinosa "Blackthorn"			x	x								
Euphorbiaceae												
Breynia oblongifolia		x			x							
Glochidion ferdinandi "Cheese Tree"		x	x									
Omalanthus populifolius	x		x									

Appendix

A list of some of the Native species occurring in the vegetation map units. Numbers denote units shown on vegetation maps - see Figure 3.5
x = present

Vegetation Map Units

	(a) 1. E. saligna, E. deanei, E. elata	2. E. deanei, A. floribunda	3. E. tereticornis	4. E. amplifolia, A. subvelutina	5. E. benthamii	(b) 6. M. linariifolia	(c) 7. Freshwater swamp	(d) 8. Mangrove	(e) 9. Saltmarsh	(f) 10. Casuarina glauca	(g) 11. E. robusta	12. Casuarina cunninghamiana
Mimosaceae												
Acacia filicifolia "Fern-leaf Wattle"	x	x	x									
A. floribunda			x		x							
A. glaucescens "Coast Myall"					x							
A. parramattensis			x	x								
Myrtaceae												
Acmena smithii "Lillypilly"												
Angophora floribunda "Rough-barked Apple"	x	x	x									
A. subvelutina "Broad-leaved Apple"			x	x								
Backhousia myrtifolia		x	x									
Eucalyptus amplifolia "Cabbage Gum"			x	x								
E. bauerana "Blue Box"				x								
E. benthamii "Nepean River Gum"					x							
E. crebra "Narrow-leaved Ironbark"		x										
E. deanei "Deane's Gum"	x	x	x									
E. elata "River Peppermint"	x											
E. eugenioides "Thin-leaved Stringybark"				x								
E. pilularis "Blackbutt"			x									
E. punctata "Grey Gum"			x									
E. robusta "Swamp Mahogany"												x
E. saligna "Sydney Blue Gum"	x											
E. tereticornis "Forest Red Gum"	x		x	x								
Leptospermum flavescens "Yellow Tea-tree"	x	x	x							x		
Melaleuca ericifolia										x	x	
M. linariifolia			x			x				x		
M. styphelioides "Prickly-leaved Tea-tree"			x							x		

Appendix

A list of some of the Native species occurring in the vegetation map units. Numbers denote units shown on vegetation maps - see Figure 3.5
x = present

Vegetation Map Units

Species	(a) 1. E. saligna, E. deanei, E. elata	2. E. deanei, A. floribunda	3. E. tereticornis	4. E. amplifolia, A. subvelutina	5. E. benthamii	(b) 6. M. linariifolia	(c) 7. Freshwater swamp	(d) 8. Mangrove	(e) 9. Saltmarsh	(f) 10. Casuarina glauca	(g) 11. E. robusta	12 Casuarina cunninghamiana
Tristania laurina "Water Gum"	x	x	x									
Casuarinaceae												
Casuarina cunninghamiana "River Oak"	x		x	x	x							
C. glauca "Swamp Oak"												x
C. torulosa "Forest Oak"	x											
Ulmaceae												
Trema aspera "Native Peach"	x	x	x									
Moraceae												
Ficus coronata "Sandpaper Fig"	x											
Rhamnaceae												
Alphitonia excelsa		x	x									
Vitaceae												
Cissus hypoglauca		x										
Meliaceae												
Melia azedarach var australasica "white cedar"	x											
Epacridaceae												
Leucopogon juniperinus			x									
Myrsinaceae												
Aegiceras corniculatum "River Mangrove"								x				
Compositae												
Cassinia aculeata			x									
Cotula coronopifolia "Water buttons"										x		
Solanaceae												
Duboisia myoporoides "Corkwood"	x	x	x									
Bignoniaceae												
Pandorea pandorana "Wonga Wonga Vine"	x											
Acanthaceae												
Pseuderanthemum variable			x									
Myoporaceae												
Myoporum acuminatum "Boobialla"										x		

Appendix

A list of some of the Native species occurring in the vegetation map units. Numbers denote units shown on vegetation maps - see Figure 3.5
x = present

Vegetation Map Units

	(a) 1. E. saligna, E. deanei, E. elata	2. E. deanei, A. floribunda	3. E. tereticornis	4. E. amplifolia, A. subvelutina	5. E. benthamii	(b) 6. M. linariifolia	(c) 7. Freshwater swamp	(d) 8. Mangrove	(e) 9. Saltmarsh	(f) 10. Casuarina glauca	(g) 11. E. robusta	12 Casuarina cunninghamiana
Verbenaceae												
Avicennia marina var australasica "Grey Mangrove"								x				
Alismataceae												
Alisma plantago-aquatica "Water Plantain"							x					
Juncagin aceae												
Triglochin procera							x					
T. striata									x			
Commelinaceae												
Commelina cyanea			x									
Liliaceae												
Dianella caerulea			x									
Philesiaceae												
Eustrephus latifolius	x		x									
Geitonoplesium cymosum	x											
Xanthorrhoeaceae												
Lomandra longifolia			x	x	x							
Philydraceae												
Philydrum lanuginosum							x					
Typhaceae												
Typha orientalis "Bull-rush"							x					
Juncaceae												
Juncus kraussii Hochst									x	x		
J. prismatocarpus							x					
J. usitatus						x	x					
Cyperaceae												
Baumea juncea										x		
Cyperus polystachyos									x			
Eleocharis sphacelata "Tall Spike Rush"							x					
Fimbristylis ferruginea									x			
Scirpus cernuus									x			
S. maritimus sens. lat.									x	x		
S. prolifer							x					

Appendix

A list of some of the Native species occurring in the vegetation map units. Numbers denote units shown on vegetation maps - see Figure 3.5
x = present

Vegetation Map Units

	1. E. saligna, E. deanei, E. elata	2. E. deanei, A. floribunda	3. E. tereticornis	4. E. amplifolia, A. subvelutina	5. E. benthamii	6. M. linariifolia	7. Freshwater swamp	8. Mangrove	9. Saltmarsh	10. Casuarina glauca	11. E. robusta	12. Casuarina cunninghamiana
Gramineae	(a)					(b)	(c)	(d)	(e)	(f)	(g)	
Imperata cylindrica "Blady Grass"			x									
Oplismenus imbecillis			x									
Phragmites australis "Common Reed"										x		
Sporobolus virginicus "Sand Couch"									x			
Stipa ramosissima "Stout Bamboo Grass"	x											

CHAPTER 4: EFFECTS OF THE WARRAGAMBA DAM AND EXTRACTIVE INDUSTRIES ON THE HAWKESBURY-NEPEAN RIVER.

History

As regards sedimentation, the history of the Hawkesbury-Nepean River can be divided into three periods:-

The first period, which might be taken as the first fifty years of the Colony (Ref. 1), was one in which the increased sediment yield from the catchments resulting from the activities of the early settlers had not appreciably affected the river channel. As early as 1822 Governor Macquarie reported that a wooden wharf was built at Windsor at which vessels of 100 tons could berth. This wharf was on the same site as the present small wharf near Windsor Bridge (Ref. 2).

An intermediate period of a little over one hundred years ending in 1952: The year 1952 was chosen because this was the year when the Warragamba Dam works began to hold back large quantities of sediment (Ref. 3). Also from 1952 onwards the rate of extraction of sand and gravel from the river bed and banks was greatly increased. Prior to 1952 the total quantities of sand and gravel which had been extracted from these areas were comparatively small (see below). In this period the increased yields of sediment resulting from timber getting, burning off and clearing had caused shoaling in the river as far down as the old punt at Pitt Town (Ref. 1). As disclosed by a comparison of an 1890 hydrographic survey of the N.S.W. Public Works Department (Ref. 4) with a survey made by that department in 1971, the shoaling of the river downstream from Richmond Bridge has persisted to the present time. An echo sounding run made by the writer in 1971 indicated that between the entrance to Broken Bay and the old punt at Pitt Town Wharf the channel depths had not altered significantly since Lieutenant Gowlland's survey of 1872. L.D. Hall (Ref. 5) wrote in 1926 that the river was heavily shoaled near Windsor. Consequently the belief, widely held by local people, that there has been recent shoaling in the tidal reaches of the river, has little foundation. On the other hand, there can be local shoaling resulting from bank collapses further upstream.

The present period from 1952 onwards:- Leaving aside the gravel and sand dredged from the river and other local extractive activities downstream from Richmond Bridge, the following figures are for sand and gravel removed from the river and adjacent flood plain between Penrith Weir and Richmond Bridge. These figures were obtained from a Mines Department publication (Ref. 6) and the writer's own investigations at the Mines Department and the Lands Department. The locations of the leases (as at 1972) of the industries extracting sand and gravel from the river between Penrith Weir and Richmond Bridge are shown on the accompanying figure. In addition there are dredging leases below Richmond Bridge.

In 1952 the average annual rate of gravel removal was about 400,000 tons (330,000 cu.yds). In 1972 the average annual rate of gravel removal had risen to about 1,300,000 tons (1,100,000 cu.yds). The corresponding rates of sand removalwere respectively 200,000 tons (180,000 cu. yds) per annum and 650,000 tons (600,000 cu.yds.) per annum. Between 1952 and

1972 the total quantities of gravel and sand removed from the river and adjacent floodways (areas covered by, and subject to the sedimentary processes of the river in flood) are estimated to be, respectively, 20,000,000 tons (17,000,000 cu.yds) and 10,000,000 tons (9,000,000 cu.yds). Prior to the operations of the Metropolitan Water, Sewerage and Drainage Board there were no large scale non-commercial extractive activities in this region (page 6 Ref. 6). It can reasonably be assumed that the quantities of gravel and sand removed from this region over the years 1952 to 1972 are far in excess of the total quantities removed up to 1952.

To form an idea of the impact of the extractive industries on the supply of sand to the river below Richmond Bridge, consider the flood of July 1952. This flood, which attained a peak height of 38.6 ft. Standard Datum at Windsor Bridge, has been equalled or exceeded 10 times this century. It has been estimated by the writer using curves given in Ref. 7 that the quantity of sand passing Richmond Bridge in this flood was 700,000 tons (640,000 cu.yds). Comparing this figure with the figure of 9,000,000 tons for sand removed by extractive industries in the period 1952-1972 from the river and floodways upstream from Richmond Bridge, it can be seen that, even if only a fraction, say a quarter of the sand removed was accessible to river flows, this must constitute a major disturbance to the sedimentation regime of the river.

In the same period as sand was being extracted from the river bed and floodways on an unprecedented scale, the principal source of supply of sand to the upper river was excluded. The completion of the Warragamba Dam in 1959, whereby all the sand and a large proportion of the finer sedimentswere excluded from the Hawkesbury River, completed the process which had begun in 1952 with the retention of substantial quantities of silt, mainly sand, in the coffer dam area at the dam site. Now the only supplies of sand for the Hawkesbury River above Richmond Bridge are in the sediments from the catchments of the Nepean and Grose Rivers.

The Effects of the Warragamba Dam and Extractive Industries

In Chapter 1 figures for the supply of sediments from the Warragamba Dam catchment are given:- Before the construction of the dam the Hawkesbury River received 1,275,000 tons of sediment annually from this source. After the construction of the dam this quantity has been reduced to 400,000 tons per annum. The former sediment was a mixture of bed material and suspended material, the latter sediment is suspended sediment in the form of wash load.

The area of the Nepean catchment, less the catchment area of the dams on the headwaters = 860 - 347 = 513 sq. miles (we shall ignore the wash load passing these dams). From Ref. 8 it is inferred that the sediment yield rates from the catchments of the Grose and Nepean rivers are, respectively twice and 1.7 times that of the Warragamba Dam catchment. The sediment yield rate of the latter catchment is 364 tons per sq. mile per annum (see Chapter 1) and so the sediment yield rates from the Grose and Nepean catchments are 728 tons per sq. mile per annum and 618 tons per sq. mile per annum. The sediment yields from these two catchments are, respectively 183,000 tons per annum and 317,000 tons per annum, a total of 500,000 tons per annum. On the assumption that

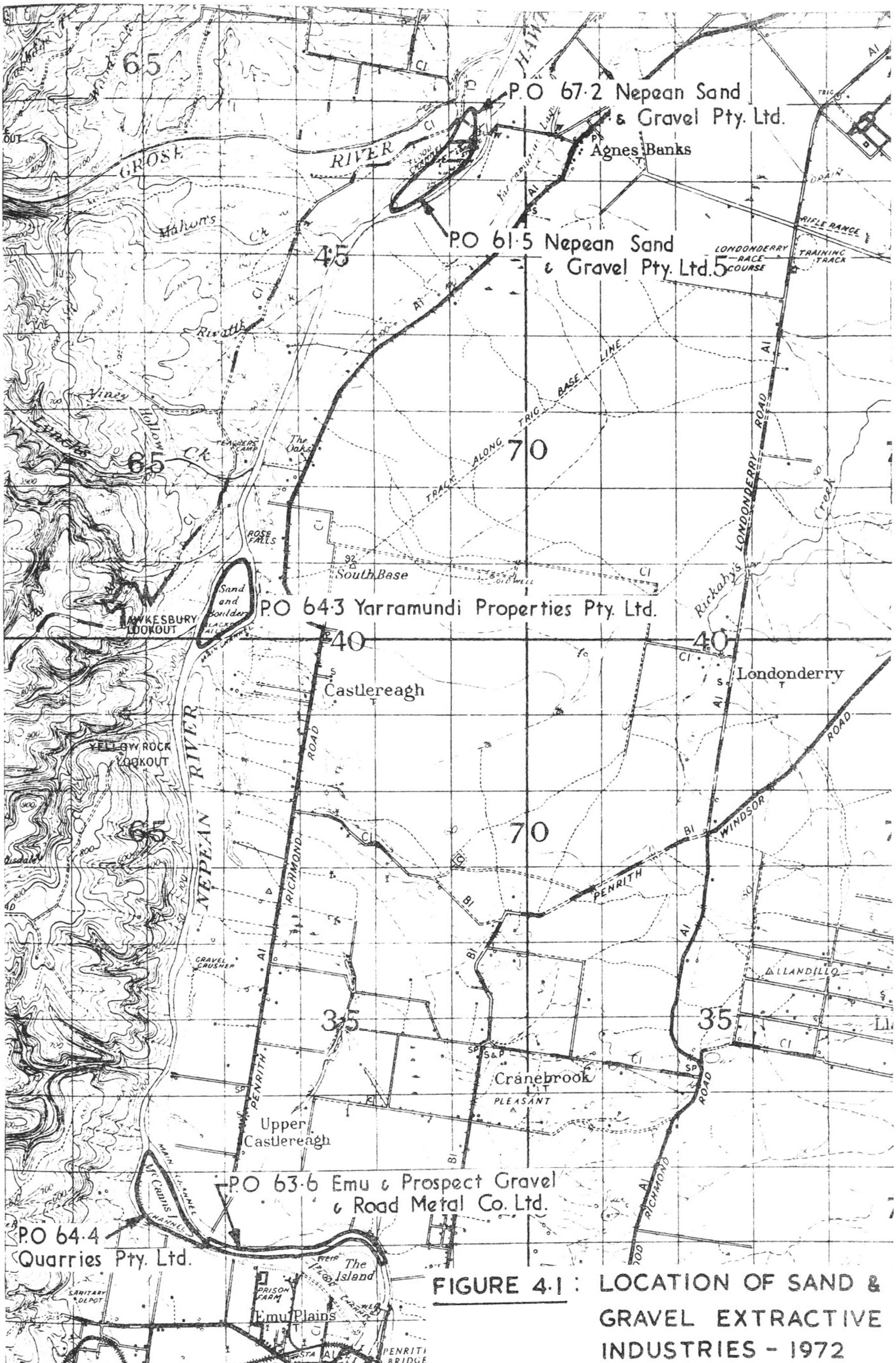

FIGURE 4·1 : LOCATION OF SAND & GRAVEL EXTRACTIVE INDUSTRIES - 1972

the composition, determined in 1970-71, of the material in the river bed and banks is due to the sedimentation regime that existed before the construction of the Warragamba Dam, the following statistics have been computed in the Appendix. In these statistics, following Schumm's usage (9), the terms 'bed material' and 'suspended sediment' are applied, respectively, to sediments with grain sizes $\geq$ 0.074 mm and sediments with grain sizes $<$ 0.074 mm.

(a) Sedimentation Statistics before the Construction of Warragamba Dam

Sediment discharge received by the Hawkesbury-Nepean River from the catchment above the Warragamba Dam = 1,275,000 tons per annum = 206,000 tons per annum of bed material + 1,069,000 tons per annum of suspended sediment.

Sediment discharge from the Nepean catchment = 317,000 tons per annum = 51,000 tons per annum of bed material + 266,000 tons per annum of suspended sediment.

Sediment discharge received by the river between Penrith and the Grose River junction = 1,275,000 + 317,000 = 1,592,000 tons per annum = 257,000 tons per annum of bed material + 1,335,000 tons per annum of suspended sediment.

Sediment discharge from upstream received by the river below the Grose River junction = 1,275,000 + 317,000 + 183,000 = 1,775,000 tons per annum = 287,000 tons per annum of bed material + 1,488,000 tons per annum of suspended sediment.

Percentage "M" of material with grain size $<$ 0.074 mm in the perimeter of the river channel between Penrith and the Grose River junction = percentage of sediment with grain size $<$0.074 mm in the perimeter of river channel in the Richmond-Wilberforce floodplain below the Grose River junction.

(b) Sedimentation Statistics after the Construction of the Warragamba Dam

Sediment discharge received by the Hawkesbury-Nepean River from the catchment above the Warragamba Dam = 400,000 tons per annum (all wash load).

Rate of accumulation of sediment behind the Warragamba Dam = 1,275,000-400,000 = 875,000 tons per annum.

Sediment discharge received by river between Penrith and the Grose River junction = 400,000 - 317,000 = 717,000 tons per annum = 51,000 tons per annum of bed material + 666,000 tons per annum of suspended sediment.

Sediment discharge from upstream received by the river below the Grose River junction = 400,000 + 317,000 + 183,000 = 900,000 tons per annum = 81,000 tons per annum of bed material + 719,000 tons per annum of suspended sediment.

The percentage "M" of material with grain size$<$ 0.074 mm in the perimeter of the river channel between Penrith and the Grose River junction will be, eventually, approximately 7.7.

The percentage "M" of material with grain size $<$0.074 mm in the perimeter of the river channel in the Richmond-Wilberforce floodplain below the Grose River junction will be, eventually, approximately 6.1.

The significance of these alterations in the values of "M" is given

Effects - General

Broadly speaking, the situation in the Hawkesbury-Nepean River is now the reverse of the situation in the lower Hunter River, which is overcharged with sediment resulting from catchment erosion on a much larger scale than was the case of the former river in the past. The situation in the lower Hunter is discussed in Chapter 7. A good general account of the effect of dams on rivers downstream from the dams is given in the book in Reference 10. As regards the Nepean River between, it is noteworthy (11) that over a reach $1\frac{1}{2}$ miles in length, spanned by the new bridge at Regentville, the channel bed has been lowered by about 3 feet in the period 1938-1964 (the survey was made a month after the big flood of June 1964). Downstream from Penrith the position as regards the supply of bed material to reaches of the river further downstream, has been aggravated by the extractive industries. To quote from a report (Ref. 12): "This section (between Penrith Weir and Richmond Bridge) is adversely affected to various degrees by the existence of extensive excavations for the removal of river gravel from the stream bed and banks". Excavations (for sand as well as gravel) have produced large depressions in areas accessible to river flow and these depressions collect bed material from upstream at the expense of downstream reaches. The removal of gravel from these reaches promotes erosion by removing armouring material.

Local effects of extractive industries include the collapse of banks due to waterlogging caused by the accumulation of water in excavation pits behind the banks, dredging too close to banks and the removal of gravel in the vicinity of the toes of the banks. Also extractive operations can have adverse effects on supplies of groundwater for irrigation (13).

The general effect of the extractive operations is the acceleration of the processes which will eventually alter the regime of the river below Penrith as a result of the dimunition in the supply of bed material from the Warragamba catchment.

In considering the effects of altered sedimentation conditions, the river below Penrith is regarded as being made up of three sections:-

(a) The unleveed reaches of the river extending down to the vicinity of the junction with the Grose River. The longitudinal slope of the river bed in this section is about 1.7 ft. per mile.

(b) The leveed reaches of the river in the Richmond-Windsor-Wilberforce-Pitt Town flood plain. The slope of the river bed in this section is about 0.7 ft. per mile.

(c) The estuarine reaches of the river downstream from Pitt Town where the river flows through highlands of sandstone, incised by the river, to Broken Bay.

(a) The River between Penrith and the Grose Junction

Between Penrith and the Grose River junction the response of the river to a very big reduction in the average annual supply of bed material will be a tendency to reduce its slope. A general reduction in slope by incision, however, being prevented by the presence of rock (13) and gravel near the surface of the bed, the river will tend to achieve this reduction by increasing its sinuosity. The calculations on which this prediction is based are given in the Appendix. This prediction also follows from the regime relation between "M" and the sinuosity which is referred to in the Appendix; the prediction is also supported by the author in Ref. 8. The tendency to increased sinuosity implies large scale bank damage, if unchecked.

(b) The Leveed Reaches in the Richmond-Wilberforce Flood Plain

The response in these reaches to altered sediment supply will be a tendency for the levels of the levee crests and the channel bed to be lowered. The width of the channel will tend to narrow. These predictions are based on regime relationships developed in Chapter 7, and calculations given in the Appendix to this chapter. The lowering of levee crest levels implies not only the loss of fertile land but also increased flooding of low lying areas behind the levees by river floodwaters.

(c) The Estuarine Reaches of the River downstream from Pitt Town

The reduction in the upstream supply of sediments will eventually affect the channel geometry but any assessment of the magnitude of these effects must take into account the sediment inputs from the Colo, Macdonald and other downstream tributaries as well as the exchange of sediments between Broken Bay and the ocean. Thus the inputs from these tributaries must be considered when assessing, say, the tendencies towards a possible enlargement of the channels which, by promoting the incursion upstream of ocean salinity, would adversely affect the quality of water for irrigation. Again, the possibility of such an adverse effect must be borne in mind when considering the consequencues of extracting sand from these tributaries - for example the Macdonald River which otherwise appears to offer an attractive alternative source of sand to those upstream from Richmond Bridge (Ref. 14). Increased turbidity is reported in the lower reaches of the river. This may be due to dredging and to run back of fines from washing plants. This turbidity blocks off the sunlight from underwater plant life with adverse effects on aquatic life generally.

General Remarks and Recommendations

Apart from the more specific predictions given above, some of the effects of a reduction in sediment supply can be estimated, qualitatively, from a consideration of the two opposing processes of deposition and removal of material that determine, in the long term, the stability of the banks. The process of deposition is that of the deposition of sediments by flood waters, the process of removal is that of water current scour and the sloughing of banks caused by water logging and subsurface leaching by tunnelling, the material being carried away by the river. It is apparent, from local enquiries and from inspections of intact and damaged banks, that these two processes have, in most of the river reaches, at least until recently, achieved a balance over numerous floods and freshes. That is to say, depending on the condition of the catchments, the seasonal growth of vegetation on the banks, the rapidity of river flow (backwater effects etc.) and the rapidity of flood recession as affecting bank sloughing, a given stretch of bank may gain or lose material in any one flood, but over many floods the losses of material balance the gains. With the radical reduction of sediment load in the river, however, the losses of material will exceed the gains, resulting in increasing bank damage. This bank damage in the leveed reaches could result in disastrous breaches.

To ensure the maintenance of the river banks the dimunition of the processes of deposition, due to the diminished sediment supply from upstream, must be countered by measures which will diminish the processes of denudation.

Natural or artificial hollows behind river banks must be filled in or properly drained to prevent the ponding of water which can promote the sloughing of banks in flood recessions. The banks should be examined for signs of leaching of fine material especially in areas near the toes of the banks. This tunnelling is induced by the seepage of water from ponded areas or from underground water (e.g. a defective drain was responsible for the collapse of portion of a bank below Windsor in the fifties). In places where there is evidence of extensive tunnelling consideration should be given to seepage interceptors similar in function to the interceptors installed in the eastern bank of the river at the upper end of Argyle Reach. Generally it is not anticipated that the seepage interceptors required would be as elaborate as these; however, as the leaching of bank material by tunnelling is a process that can accelerate with time, the magnitude of the remedial works required can increase to the stage where in critical reaches of the river an elaborate and costly system similar to that installed at Argyle Reach is necessitated. Special attention should be given to locations where there is evidence of lateral shift of the river. This applies especially to the top end of Argyle Reach and to the banks at the mouth of Rickaby's Creek where extra rock protection against direct river scour is also called for. Activities promoting the erosion of banks such as unrestricted uses of power boats and the construction of launching ramps are to be resisted. Likewise the removal by extractive industries of material behind levee banks, conducive to the ponding of water, and the removal of gravel which might armour the river bed against scour are to be resisted.

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APPENDIX TO CHAPTER 4.

Assuming that the composition, determined in 1970-1971, of the material in the river bed and banks downstream from Penrith is due to the sedimentation regime that existed before the construction of the Warragamba Dam, we now apply eqn. 11 of Chapter 7 (see Ref. 1) to the sediment discharges from the Warragamba, Nepean and Grose catchments:-

$$M = 0{\cdot}55\,\frac{\overline{Q}_f + \overline{Q}_s}{\overline{Q}_s}$$

where "M" is the percentage of material < 0.074 mm in the channel perimeter*, "$\overline{Q}_f$" is the average annual supply of sediment < 0.074 mm and "$\overline{Q}_s$" is the average annual supply of bed material ≥ 0.074 mm (bed material by Schumm's definition - Ref. 1).

The average value of "M" in the perimeter of the river channel below the Grose River junction is 3.4. The total sediment discharge from the above three catchments before the construction of the Warragamba Dam = 1,275,000 + 500,000 = 1,775,000 tons per annum. The total discharge of bed material before the construction of the dam = $\frac{0.55}{3.4}$ x 1,775,000 = 287,000 tons per annum, the Warragamba Dam contribution being 206,000 tons per annum. After the construction of the Warragamba Dam, only the sediments from the Nepean and Grose catchments contain bed material. The total discharge of this bed material is $\frac{0.55}{3.4}$ x 500,000 = 81,000 tons per annum. The total sediment discharge from the three catchments is now 500,000 + 400,000 = 900,000 tons per annum. Hence in the new sedimentation regime obtaining after the construction of the Warragamba Dam, the percentage of material < 0.074 mm in the perimeter of the river channel below the Grose River junction will eventually be approximately 0.55 x $\frac{900,000}{81,000}$ = 6.1 (applying eqn. 11 of Chapter 7, given above).
The discharge of bed material from the Grose catchment = $\frac{0.55}{3.4}$ x183,000 = 29,600, say 30,000 tons per annum. The discharge of bed material from the Nepean catchment = 81,000 - 30,000 = 51,000 tons per annum which will eventually be equal to the bed material discharged in the reaches between Penrith and the Grose River junction after the construction of the Warragamba Dam.

The discharge of bed material in these reaches before the construction of the dam = 206,000 + 51,000 = 257,000 tons per annum. The total sediment discharge from the Warragamba and Nepean catchments = 400,000 + 317,000 = 717,000 tons per annum. Hence the percentage "M" of material < 0.074 mm in the perimeter of the channel between Penrith and the Grose River junction will be, eventually, approximately 0.55 x $\frac{717,000}{51,000}$ = 7.7 (applying eqn. 11 of Chapter 7 given above).

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* For the computation of "M" as the weighted mean of sediment < .074 mm. in the bed and banks of a channel see Ref. 7

To make plausible the statement that the river between Penrith and the Grose will tend to reduce its slope in response to a diminished supply of bed material from upstream sources, consider a river channel with sandy bed and banks whose width (average width 600 ft. between banks) and depth (top of bank to bed 36 ft.) roughly correspond to the average width and depth of the river channel between Penrith and the Grose. If there is sufficient depth of sand beneath its bed, the channel with sandy bed and banks will be free to adjust its slope so that its capacity to transport bed material is matched to the input of bed material at the upstream end of the channel.

Assume that the bulk of the bed material (sand) is transported along this channel by floods and freshes when the flow is between banks. In other words, assume that the total quantity of bed material transported by flows whose depths exceed 36 ft. is comparatively small. The reasonableness of this assumption is seen by giving the hypothetical channel a slope of 1.7 ft. per mile, which is the slope of the river between Penrith and the Grose. With a Chezy coefficient of 93, the velocity and discharge in the former channel when flowing bankfull are, respectively, 10 f.p.s. and 216,000 cusecs. This discharge is exceeded by the river at Penrith about once in 10 years so that in any long period the sum of the durations of overbank flows will be small compared with the sum of the durations of the flows in floods and freshes when the depths are less than, or equal to bankfull.

Let Q_s = Discharge of bed material (sand, cusecs)
Q = Water discharge (cusecs)
v = Water velocity (ft/sec)
d = Depth of water in channel (ft.)
w = Average width of channel (ft.)
S = Longitudinal slope of channel
D_{50} = Median grain size of bed material = 0.45 mm

This is the median grain size of the bed material (sand) in the river bed between Penrith and the Grose and is about the median size of the sand in the sandy reaches of other N.S.W. coastal rivers.

The following formula for the transport of sand D_{50} = 0.45 mm, has been derived by the writer from the curves given by Colby (2)

$$Q_s = 2.6 \times 10^{-4} w (1.8 + 0.4 d^{1/2}) v^2 \qquad (1)$$

In the velocity range 4 f.p.s. to 10 f.p.s. and the depth range 1 ft. to 100 ft., this formula fits the Colby curves quite well. According to the paper given in Reference (3) below, computations based on the Colby relationships show much closer agreement with observations than those based on other relationships.

Now $$Q = w d v \qquad (2)$$

since "w" is large compared with "h"

Also $Q = Cwd^{3/2}h$ (3)

where "C" is the Chezy coefficient.

From (1), (2) and (3) we derive the following expression for "Q_S"

$$Q_S = 2.6 \times 10^{-4} C \left(\frac{1.8 + 0.4d^{1/2}}{d^{1/2}}\right) S^{1/2} Q \qquad (4)$$

In the range "d" = 6 ft. to "d" = 36 ft. (the depth of ranges of floods and freshes up to bankfull stage), the values of $\frac{1.8+0.4d^{1/2}}{d^{1/2}}$ range from 1.1 to 0.7 respectively, with an average value of 0.90. We may, therefore, replace (4) by its approximate equivalent:

$$Q_S \approx 2.6 \times 10^{-4} C \times 0.9\, S^{1/2} Q$$

i.e. $$Q_S \approx 2.34 \times 10^{-4} C\, S^{1/2} Q \qquad (5)$$

Let "$\overline{Q}_F$" = Average annual quantity of water discharged in floods and freshes

" "$\overline{Q}_S$" = Average annual supply of bed material at the upstream end of the channel

Then from (5) we obtain

$$S \approx \frac{1.8 \times 10^{7}}{C^2}\left(\frac{\overline{Q}_S}{\overline{Q}_F}\right)^2 \qquad (6)$$

The value of "$\overline{Q}_S$" in the reaches between Penrith and the Grose River junction = "$\overline{Q}_S'$" = 257,000 tons per annum = 231,000 cu.yds. per annum before the construction of the dam. The value of "$\overline{Q}_S$" in these reaches after the construction of the dam = "$\overline{Q}_S''$" = 51,000 tons per annum = 46,000 cu.yds. per annum. Referring to eqn. 6, the ratio $= \left(\overline{Q}_S''/\overline{Q}_S'\right)^2 = 0.04$. This ratio would only be partly offset by the reduction in the value of $\overline{Q}_F$ after the construction of the dam and it is clear, therefore, despite the approximate nature of the argument, that the river channel will tend to reduce its slope.

A general reduction in slope by incision, however, will be prevented by the presence of rock and gravel at or near the surface of the bed (4) and so the river will tend to achieve this reduction in slope by increasing its sinuosity.

The value of "M", the percentage of fine sediment in the perimeter of the channel will increase from M' 3.4 to M'' 7.7 (see the text above). An increase in sinuosity is then indicated by eqn. 2 Ref. (1). The increase in sinuosity indicated by this equation appears to be less than that implied above; however it must be borne in mind that Schumm's equation applies to a channel which can change its slope both by changing its incision and by changing its sinuosity whereas the channel between Penrith and the

Grose junction can only change its slope by changing its sinuosity.

An estimate is now made of the effects of changes in the sedimentation conditions on the levees below the Grose Junction. Using equation (8) in Chapter 7 we have:-

$$\overline{Q}_s = \frac{k}{100}\,\frac{M^c}{Q_m^b}\int_0^{p(Q_{h_L})} Q^n\,dp$$

where "Q_m" is the mean annual discharge, "M" and "$\overline{Q}_s$" have been defined above, "k", "b", "c", "n" are constants, "Q" is the instantaneous water discharge in cusecs, "p" is the percentage of the time that the discharge is less than or equal to "Q" and "$p(Q_{h_L})$" is the percentage of the time that the discharge is less than or equal to the flood discharge "Q_{h_L}" at the top end of the floodplain when the water in the channel is running at levee crest level "h_L" at that location. For the Hawkesbury River flood plain, "Q_{h_L}" is about 350,000 cusecs and "h_L" is about 45 feet above mean sea level. Now $n = 2 - 1{\cdot}73\gamma$ (see equations 6 and 7 Chapter 7). For purposes of this estimate adopt the value γ = 0.45 given on page 244 of Ref. (5). Then n =1.22. For the same purpose (see eqn. 5 Chapter 7) we adopt the values b = 0.38 and c = 0.39 for the exponents of "Q_m" and "M" given in eqn. 4, page 257 of Ref. (1).

The above equation can then be written as:-

$$\int_0^{p(Q_{h_L})} Q^{1{\cdot}22}\,dp = \frac{100}{k}\,\frac{Q_m^{0{\cdot}38}}{M^{0{\cdot}39}}\,\overline{Q}_s$$

From the 1935-1952 flow duration curve for the Nepean River at Penrith (6) and subsequent flood data, it is estimated that the mean annual discharge before the construction of the Warragamba Dam = $\overline{Q}'_m$ = 2400 cusecs. The mean annual discharge after the construction of the dam = $\overline{Q}''_m$ = 2000 cusecs.

Before the construction of the dam M' = 3.4. After the construction of the dam M'' = 6.1. Before the construction of the dam $\overline{Q}'_s$ = 287,000 tons per annum = 258,000 cu.yds. per annum. After the construction of the dam $\overline{Q}''_s$ = 81,000 tons per annum = 73,000 cu. yds. per annum (see the main text).

Substituting the values "Q'_m", "Q''_m", "M'", "M''", "$\overline{Q}'_s$" and $\overline{Q}''_s$ in the above equation we see that the value of $\int_0^{p(Q_{h_L})} Q^{1{\cdot}22}\,dp$ after the construction of the dam will be eventually reduced by about 75% of its value before the construction of the dam. Rough estimates, based on the 1935-1952 flow duration curve for the Nepean River at Penrith (6) and data on subsequent floods, indicate that for the existing $p(Q_{h_L})$ = p(350,000), reductions in discharges due to the dam would reduce the value by less than 50%, not by 75% as deduced above.

The value of this integral must, therefore, be reduced by a reduction in the value of "$P(Q_{h_L})$" i.e. by a reduction in the value of "Q_{h_L}" which implies a lowering of the levee crest level "h_L".

Using eqn. (10) Chapter 7, we have for the level "h_c" of the channel bed above datum:-

$$h_c = h_L - gM^h Q_m^\ell$$

Consider the term $gM^h Q_m^\ell$. The ratio of $g(M'')^h (Q''_m)^\ell$ to $g(M')^h (Q'_m)^\ell$ is $\left(\frac{6\cdot 1}{3\cdot 4}\right)^h \left(\frac{2000}{2400}\right)^\ell = 1\cdot 8^h \times 0\cdot 83^\ell$

which is greater than 1 since $0 < h < 1$ and $0 < \ell < 1$ (see eqn. 5 p. 258 of Ref. (1). Hence the term $gM^h Q_m^\ell$ will increase after the construction of the dam and, since "h_L" decreases, it follows from the above equation that the level "h_c" of the channel bed above mean sea level will decrease. The decreases in the levels of the levee crests and the channel bed along the flood plain are given by eqns. 13 and 14 Chapter 7. It can be shown, by substituting the two sets of values of "Q_m" and "M" in equation 1 Chapter 7, that the width of the leveed channel will tend to narrow (in comparing the new and old values note that the exponents "b" and "C" of "Q_m" and "M" in this equation are both positive and less than unity).

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(4) Johnson J.H. "An Investigation of Groundwater Conditions of the Nepean River Valley, Penrith, N.S.W." January 1961. Water Supplies Branch Water Conservation and Irrigation Commission, unpublished.

(5) Leopold L.B., Wolman M.G. and Miller J.P. "Fluvial Processes in Geomorphology" 1964.

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CHAPTER 5: THE EFFECTS OF SPEEDBOAT ACTIVITIES ON RIVER BANKS.

Introduction

This report is based on observations and enquiries made by the writer over the period 1970 to 1973. In this report use was made of the valuable experimental data on speedboat waves presented in the N.S.W. Public Works Department of 1964 (Ref. 1). Speedboat and water skiing activity in N.S.W. is now at its greatest on the Hawkesbury River and has practically excluded all other aquatic activities in the river above Wiseman's Ferry.

Significance of Speedboat Waves

Field observations confirmed the statement in the P.W.D. report that the waves propagated by the skiers are quite small, the maximum height being about 1.25 inches, and that the highest waves are those generated by speed boats at the relatively low speeds given in the report, which are below the "planing" speeds. At planing speeds the waves are relatively small. The high waves, are therefore, made by speed boats travelling at intermediate speeds in the intervals between ski runs. As the waterways become more crowded with skiers, the intervals of lower speed and high wave generation proportionately increase.

The P.W.D. report gives the value of 2.12 Kilowatt-hours per year per foot length of bank for the waves generated by speed boats. This value was adopted for comparative purposes although enquiries in the field have disclosed that there has been an increase in the number of speedboats on the river since 1964. Indeed the number of speedboats operating on weekends in reaches of the river above Sackville has now reached saturation.

The fetches given on pages 8 and 9 of the P.W.D. report are for winds blowing along more or less straight reaches of the river producing waves which meet the banks of the bends at the ends of these reaches. However, the energy of waves which reach such a bank is only a fraction of the total energy of the waves generated by the winds blowing along the reach because, due to refraction by shoals and bars, these waves lose their energy to the banks as they proceed along the reach. For a given fetch, the energies of wind waves impinging on a bank depend on the direction in which the bank is facing, being greatest and least when the bank is facing south-west and north-east respectively. The appropriate average fetch for waves impinging on banks between Windsor and Sackville is about 0.2 miles. Assuming this length of reach, and Weather Bureau wind statistics for Richmond,* the magnitudes and energies of wind generated waves impinging on the banks facing in the above two directions were computed using the methods described in References 2 and 3. At any location along the meandering river above Sackville, the magnitudes and energies of the wind waves impinging on a bank will be one or the other, or will lie between those computed above. Table I gives the computed wave energies due to wind and the energy of speedboat waves:

Wave Energies between Windsor and Sackville

		Total Wave Energy per foot of bank per annum - Kilowatt-hours
(1)	Banks facing N.E.	1.39
(2)	Banks facing S.W.	5.29
(3)	Average of (1) and (2)	3.34
(4)	Speedboats (from P.W.D. report)	2.12

Table 1

The attached figure shows the distribution of wave energies and speedboat waves (1, 2, 3 and 4 in the above table) in the various wave height classes. The distribution of speedboat energies has been inferred from data in the P.W.D. report. This diagram gives the height class of the waves which impart the maximum energies to the banks. These are given in Table 2.

* In applying these statistics to winds on the river, no account was taken of the sheltering effects of river banks and hence the figures for actual wave energies would be less than the computed wave energies. The incident wave energy calculated from observations of speed boats is not subject to any such reduction.

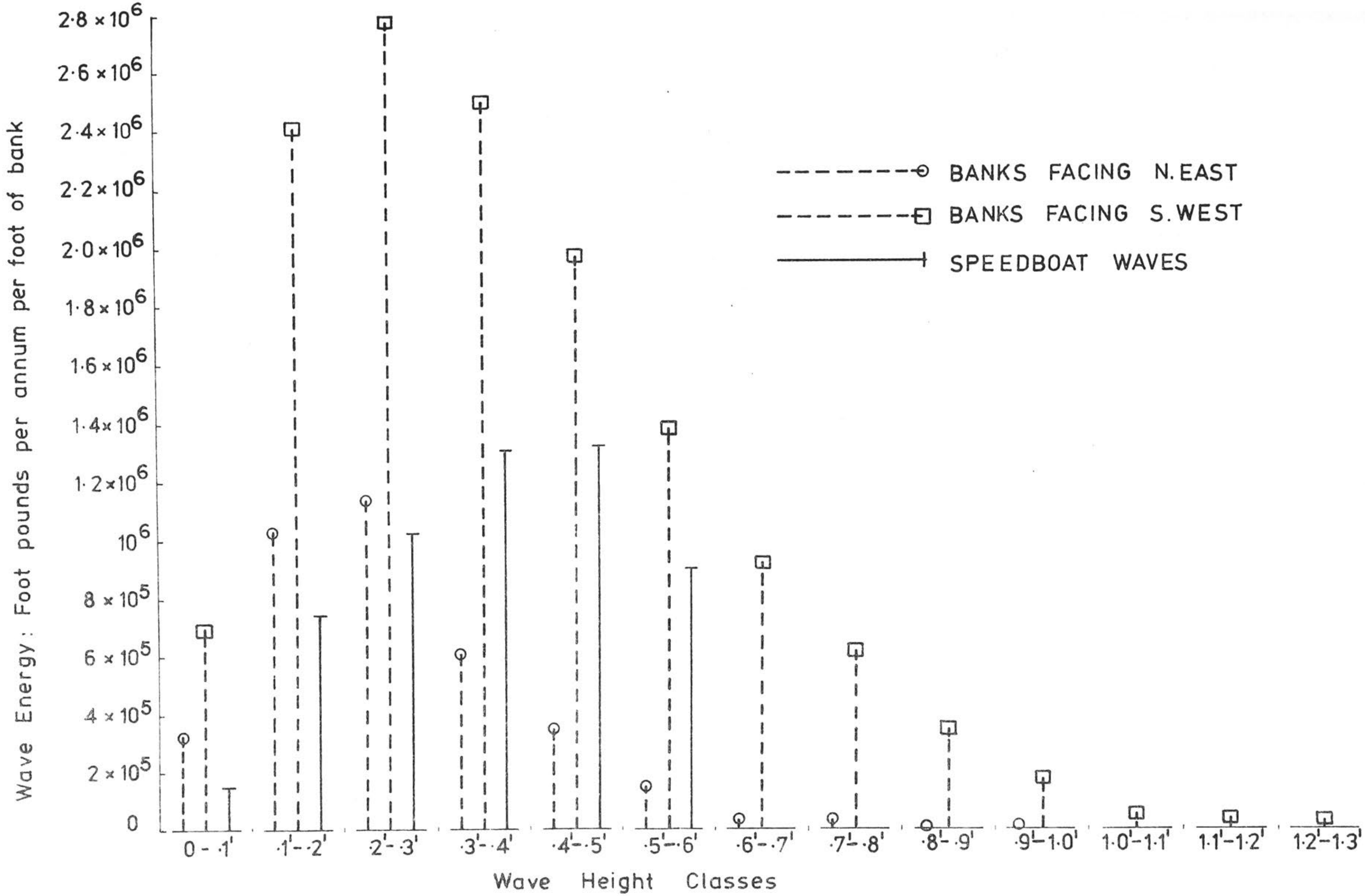

FIGURE 5·1 : DISTRIBUTION IN HEIGHT CLASSES OF WAVE ENERGIES PER FOOT OF BANK PER ANNUM

Maximum Wave Energies between Windsor and Sackville

	Height Class of Waves imparting Maximum Energy per foot of bank per annum	Wave Energy per foot of bank per annum foot pounds	Wave Energy per foot of bank per annum K.W.H.	Power per foot of bank Horsepower
(1)	0.2 ft. - 0.3 ft.	1.13×10^6	0.43	.005
(2)	ditto	2.71×10^6	1.02	.005
(3)	ditto	1.92×10^6	0.73	.005
(4)	ditto	1.32×10^6	0.49	.025

Table 2

The criteria of annual energy per foot of bank and power per foot of bank are bases of comparison of the relative importance of speedboat waves and wind waves in promoting bank erosion because the same physical processes are involved.

It can be seen from Table 1 that the total wave energy per foot of bank per annum due to speedboats is about two thirds of that due to wind. However, Table 2 shows that the heights and the powers of the speedboat waves delivering the greatest energy per foot of bank per annum are greater than the heights and powers of the wind waves in the same category.

Thus it should be noted that the frequency distribution of wave energy shows that waves produced by speedboats of height range 0.4 ft. to 0.5 ft. are the most frequent by comparison with wind waves of height range 0.2 ft. to 0.3 ft. The effect of the larger waves is to extend the bottom disturbance of the sediment under orbital motion further out into the channel where the normal current is more likely to remove it - that is to say, speedboat waves can be expected to be more disturbing to banks than wind waves.

Using energy expenditure criteria in comparing the erosive effects of speedboat waves with the erosive effects of floods is misleading, not only because of the different physical processes involved but because it overlooks the fact that floods deposit material as well as remove it.

To date, the changes which have occurred in the banks of the river downstream from Windsor have been, since the earliest days of settlement, fluctuations around positions of equilibrium - that is to say, along alluvial reaches of the river there have been accretions to banks of material deposited by floods alternating with the removal of material from these banks as a result of floods.

The scour and depositional effects of a flood vary with the seasonal condition of the vegetation on the bank. The variable flood hydrographs and backwater effects of the Colo and Macdonald rivers produce floods with a big variation in flow velocities and associated scour and depositional effects; there are differing rates of flood drawdown which may or may not cause the sloughing of waterlogged banks. Waves generated by wind participate in this natural balance of deposition and erosion by undercutting and removing flood deposits, especially when wind squalls occur after floods in the period before the deposits have been stabilised by vegetation. It is clear that the addition of waves generated by speedboats will upset this natural balance and promote bank erosion.

Field Observations

Field observations disclose the following features:-

(1) Bank damage is heaviest in areas at, or in the vicinity of sites where speedboats arrive and depart. The areas are characterised by small beaches made up of material from the banks behind them. In these areas where the boats are moving at speeds below "planing" speeds occur the heaviest concentration of large waves. Here and there, to prevent erosion, rubble or motor car tyres have been placed at the toes of banks to prevent wave damage. Some of the material in these beaches is material eroded from the banks as a result of people walking up and down the banks and removing the grass from them. In some cases the beaches have been artificially constructed. In many cases inspected, however, the beaches have been formed as a result of banks sloughing after undercutting of the toes of the banks by wave action. Extensive bank damage as a result of undercutting was seen by the writer in Swallow Rock Reach and Upper Crescent Reach (and was reported elsewhere along the river). Noted were the large number of willow trees standing out from the banks on peninsulas or on islands, trees with exposed roots and trees which had toppled into the river.

(2) Recent damage to the banks was seen in areas near water-skiing resorts. Typical was a portion of bank, located near the upstream boundary of Bungonia Park, which had sloughed last January. Extensive damage was noted along the banks of Mr. D. Walker's property which adjoins Upper Crescent Reach. One sloughed section of his banks was about 150 feet long and the toe of this section appeared to have retreated shorewards about 10 feet in the recent past (in the last year according to Mr. Walker). The sandy beach, consisting of material removed from the bank, met the bank at about mean high water level. The toe of the bank at this level was undercut, in some places up to 9 inches and this undercutting was clearly due to wave action.

(3) River banks below Windsor were inspected by the writer after the November 1969 flood. It was noted that flood deposits on banks were being undercut by wave action in the intertidal zone causing extensive slippings and sloughing of deposits down the banks. No extensive wind blows occurred at these locations in the period when the observations were made and it was concluded that the waves causing the undercutting were produced by speed boats. This confirms the reports of other observers, the inference being that speed boat waves are an important part, if not the major part of the total annual wave action which removes fresh flood deposits from banks.

(4) An experiment was carried out by the writer in the course of a physical survey of the river in April 1971. A five ton cruiser was used in the experiment. The cruiser was 26'-0" long, with a breadth of 10'-6" and a draft of 3'-0". A site in York Reach was chosen, where a small beach had formed in front of an eroding bank. Twentyfive passes were made in front of this bank by the cruiser travelling at a speed of 7 knots. The passes were made at about mean high water, at a distance of about 40 feet from the bank, in a depth of about 10 feet of water. About 10 waves impinged on the bank in each pass, the average height of the waves was about 1'-0" and the average period was about 1.8 seconds. At the conclusion of the experiment it was noted that numerous small pieces of the bank had fallen onto the beach as a result of undercutting by these waves.

(5) Reeds occur below Sackville and mangroves below Wiseman's Ferry. This vegetation protects the banks against wave action. However, in the vicinity of water ski take-offs, where this vegetation has been cleared away, bank erosion has been noted.

Conclusions

Speedboat waves promote damage to river banks. To quote Professor C.H.Munro: "From my own observations.....it is clear that there is insidious and continuous erosion due to speedboats" (Ref.4). The significance of these waves is seen in the fact that the configurations of the river banks are the outcome of processes of erosion and deposition which, prior to the advent of speedboats, were in equilibrium over a long period. This equilibrium is expressed by the relation: Deposition of material by floods and freshes - removal of material by scour, sloughing of banks as a result of rapid flood drawdown and undercutting by wind waves. The addition of speedboat waves will tip this balance in the direction of net erosion of the banks. Aggravating this imbalance and producing more serious erosion problems will be the future diminution of material deposited on banks by floods and freshes resulting from the cutting off by the Warragamba Dam of sand supplied to the river and the removal of sand upstream by extractive industries.

The wave erosion of the banks is more serious in the narrow crowded reaches of the river above Sackville where the riverine vegetation is inadequate to protect the banks from wave action. This protection can only be given by such measures as rubble or auto tyres placed along the toes of the banks. Under existing conditions extensive protection is required and it would be more economical, as well as desirable in preserving the overall amenities of the river, if speedboat activities were restricted in these reaches. Downstream from Sackville reeds and mangroves, where they exist in quantity, mitigate the effects of wave action and the removal of this vegetation should be resisted. Indeed, consideration might be given to encouraging the growth of this vegetation in these reaches of the river. Quantitative design criteria for the use of vegetation in damping out waves is given in Reference 5.

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CHAPTER 6: THE PREDICTION OF SALINITIES AND THE DISPERSION OF POLLUTANTS IN TIDAL RIVERS AND ESTUARIES.

Introduction

This chapter is in two parts. Part 1 presents methods of predicting dry weather salinities at a given location in the tidal reaches of a river and a mathematical model for predicting salinities at any location in a tidal river. Part 2 presents methods of predicting the concentrations of dissolved substances introduced into tidal rivers and estuaries. These parts complement one another. From data on salinities obtained by the methods described in Part 1, the concentrations of other dissolved substances can be deduced by methods described in Part 2. Again, the salinity as well as the concentrations of other dissolved substances can be deduced by the computational methods of Dailey and Harleman (1) which are outlined in Part 2.

The relevant features of a tidal river are shown in Figure 6.1.

The intrusion of saline water from the ocean into an estuary can be placed in the categories of stratified or mixed estuaries - or in the categories of stratified, partially mixed (or partially stratified) and well mixed estuaries. In a stratified estuary tidal activity is insufficient to cause mixing of the salt water and fresh water and the salinity intrusion takes the form of a wedge of almost undiluted ocean water extending upstream along the bottom. In a partially mixed estuary the discontinuities of the wedge are replaced by longitudinal and vertical salinity gradients and the more the estuary approaches the well mixed condition the smaller are these gradients. The ratio of the mean upland discharge (the volume of upland river water, flowing at mean annual discharge, entering the estuary over a tidal cycle) to the tidal prism (the volume of water flowing into the estuary in a tidal cycle) gives an indication of the mixing category appropriate to a given river. High ratios, intermediate ratios and low ratios indicate, respectively, stratified, partially mixed and well mixed estuaries. The rivers on the east coast of N.S.W. range from being partially mixed to being well mixed, approaching the well mixed condition in dry seasons.

Figure 6.1 indicates the mean (i.e. averaged over a tidal period) current velocities in a partially mixed estuary. The density differences cause a large scale gravitational circulation in which saline water drifts upstream along the bottom and downstream near the surface; in other words ebb velocities predominate over flood velocities in the upper strata but flood velocities predominate over ebb velocities near the bottom. The significance of the bottom drift in determining estuarine shoaling is discussed in Part 1, Section 2.

In the fresh water reaches of a tidal river the longitudinal dispersion coefficients for unsteady flow can be predicted with good accuracy. In the saline reaches where the longitudinal density gradient is primarily responsible for dispersive mass transfers, the longitudinal dispersion coefficients are very much greater than they are in the fresh water reaches. Until quite recently, there was no means of predicting these dispersion coefficients. Now, however, with the publication of the work of Thatcher and Harlemann in 1972 (10), it is possible to predict these coefficients which are essential to the determination of salinities and the concentrations of dissolved substances.

In the main, this chapter deals with tidal rivers and estuaries which can be treated, with appropriate schematisations, as single or branched one dimensional channels (i.e. channels wherein the concentrations of dissolved substances are uniform over the cross sections). Some two dimensional treatments are also described.

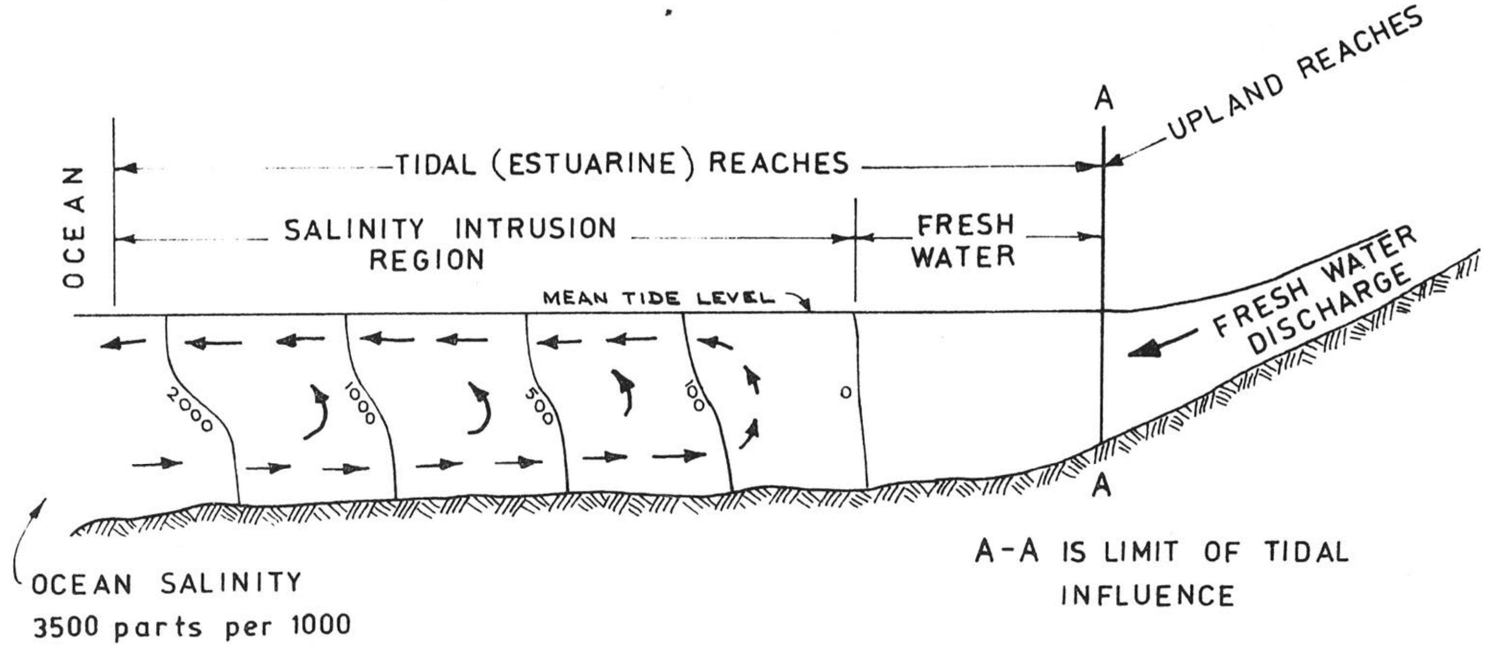


FIGURE 6·1: AVERAGE CURRENT AND SALINITY DISTRIBUTION (AVERAGED OVER A TIDAL PERIOD) IN A TIDAL RIVER.

PART 1: PREDICTIONS OF SALINITIES

Introduction

For most practical purposes "salinity" may be defined as the ratio of the total weight of dissolved solids to the weight of the water sample (2). In the tidal reaches of a river the total amount of dissolved solids contributed by fresh water flow is generally quite small compared with the total amount of dissolved solids resulting from the intrusion of sea water. Unless otherwise stated, the term "salinity" in this report applies to the dissolved solids resulting from the intrusion of sea water.

Part 1 is in two sections. Section 1 presents methods of predicting dry weather salinities at a given location (i.e. "at a station" salinities) in the tidal reaches of a river under natural conditions or under the changed conditions of fresh water flow resulting from the construction of a dam on the river above the limit of tidal influence. These methods are based on records of salinity observations made at the location in question and are applicable when there has been no appreciable change in the channel geometry of the river by major works.

Section 2 outlines methods of predicting salinities at any location in a tidal river. The methods, which are based on the computer solution of the hydraulic equations and the convective-dispersive equation, are more general than those given in Section 1 and can be used to predict the future salinity regime of a river whose flow behaviour has been significantly altered by major works such as dredging, channel training and reclamations.

The effects on shoaling of drift currents associated with the two dimensional salinity distribution in partially mixed estuaries are discussed. Hydraulic models are dealt with briefly in this part; they are dealt with more fully at the end of Part 2.

PART 1 - SECTION 1: PREDICTION OF SALINITIES AT A STATION.

Formulae are presented for use in predicting "at a station" salinities in the tidal reaches of rivers in periods of low river flows occurring naturally or as modified by a dam above the limit of tidal influence. The first formula presented is one which has been used by the Metropolitan Water Sewerage and Drainage Board, the second formula has been derived by the writer and is considered as meriting further investigation.

In a dry period the salinity at a station at one stage of a tidal cycle differs by only a small amount from the salinity at the same stage of the next tidal cycle. Within a tidal cycle, however, there is considerable variation in salinity brought about by the gross tidal movement past the station of water of varying salinity, the salinity being a minimum at local slack water at the cessation of the flood tide. For brevity, these stages of the tidal cycle are termed, respectively, "low water slack" and "high water slack". As the maximum salinities usually have the greatest significance in planning it is suggested that the above formulae be based on salinities observed at local high water slack (if desired the same formulae, embodying different constants, could be based on salinities observed at any other stage in the tidal cycle, including low water slack).

Accordingly, the prediction of the instantaneous salinity at a station involves (a) the prediction, by one of the abovementioned formulae, of the salinity at the local high water slack preceding the instant in question and (b) the prediction of the change of salinity between these two instants. These predictions are dealt with under headings I and II below. An outline of a procedure for investigating salinities at a station is given under heading III. There is an appendix to this part giving the derivation of the second formula in the material under heading I.

I. The Prediction of Dry Weather Salinities at Local High Water Slack

Salinities at a station in the estuarine reaches of a river vary in the depth of water in the channel and this variation depends on the distance of the station from the mouth of the river and with the degree of stratification in the estuarine reaches. The Hawkesbury River, Clarence River and other N.S.W. coastal rivers are partially mixed under average conditions of river flow and are well mixed under conditions of prolonged dry weather flow. This is discussed in the appendix to this part. At the distances from the mouths of these rivers, where the water is used for irrigation and local water supply the variation of salinity with depth is small. For irrigation and local water supply, surface salinities would be the most significant; for the disposal of waste waters the salinity-depth profile might be required (see Heading III below).

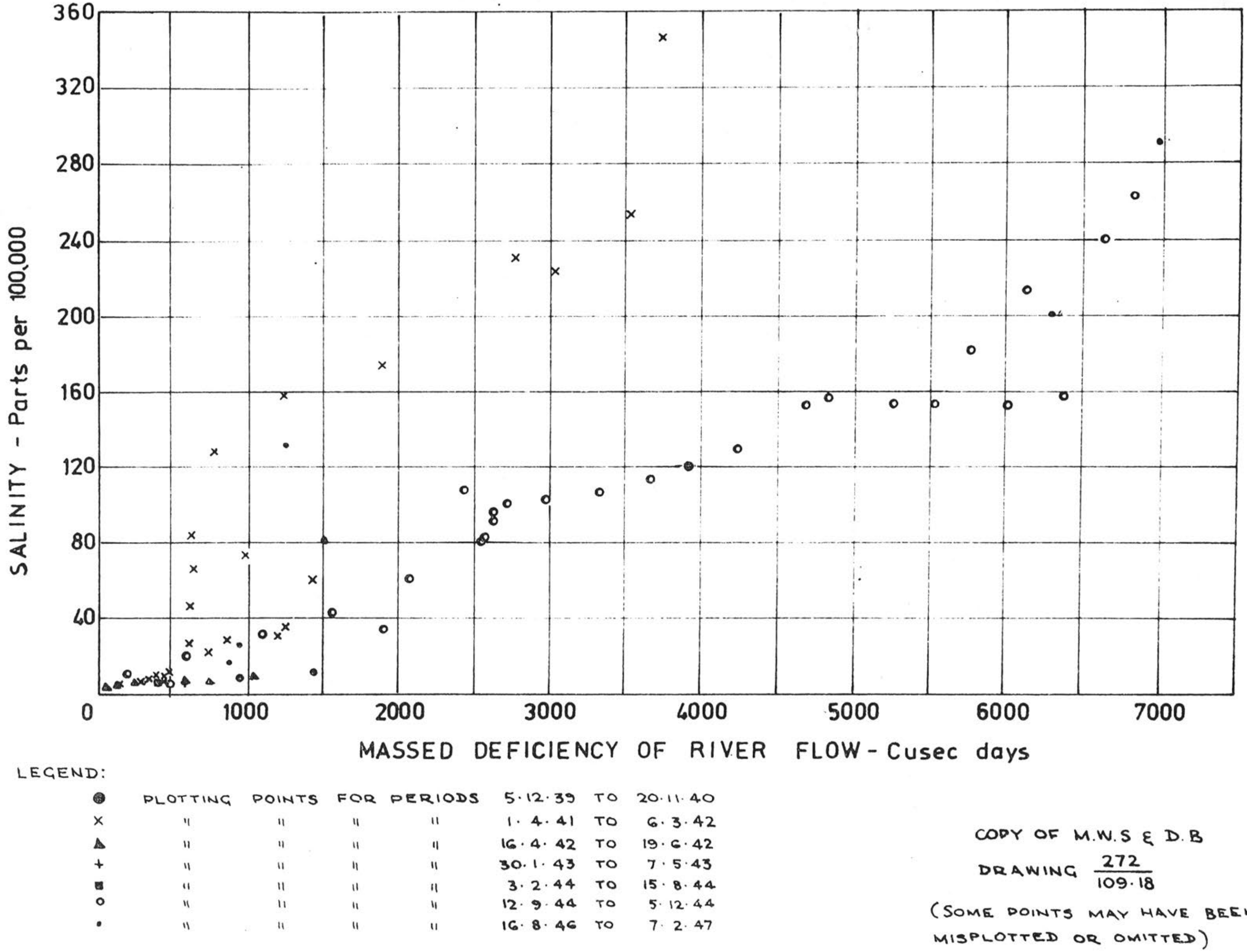


FIGURE 6·2: RELATIONSHIP BETWEEN SALINITY AND CUMULATIVE DEFICIENCY OF RIVER FLOW BELOW 40 CUSEC DAYS.

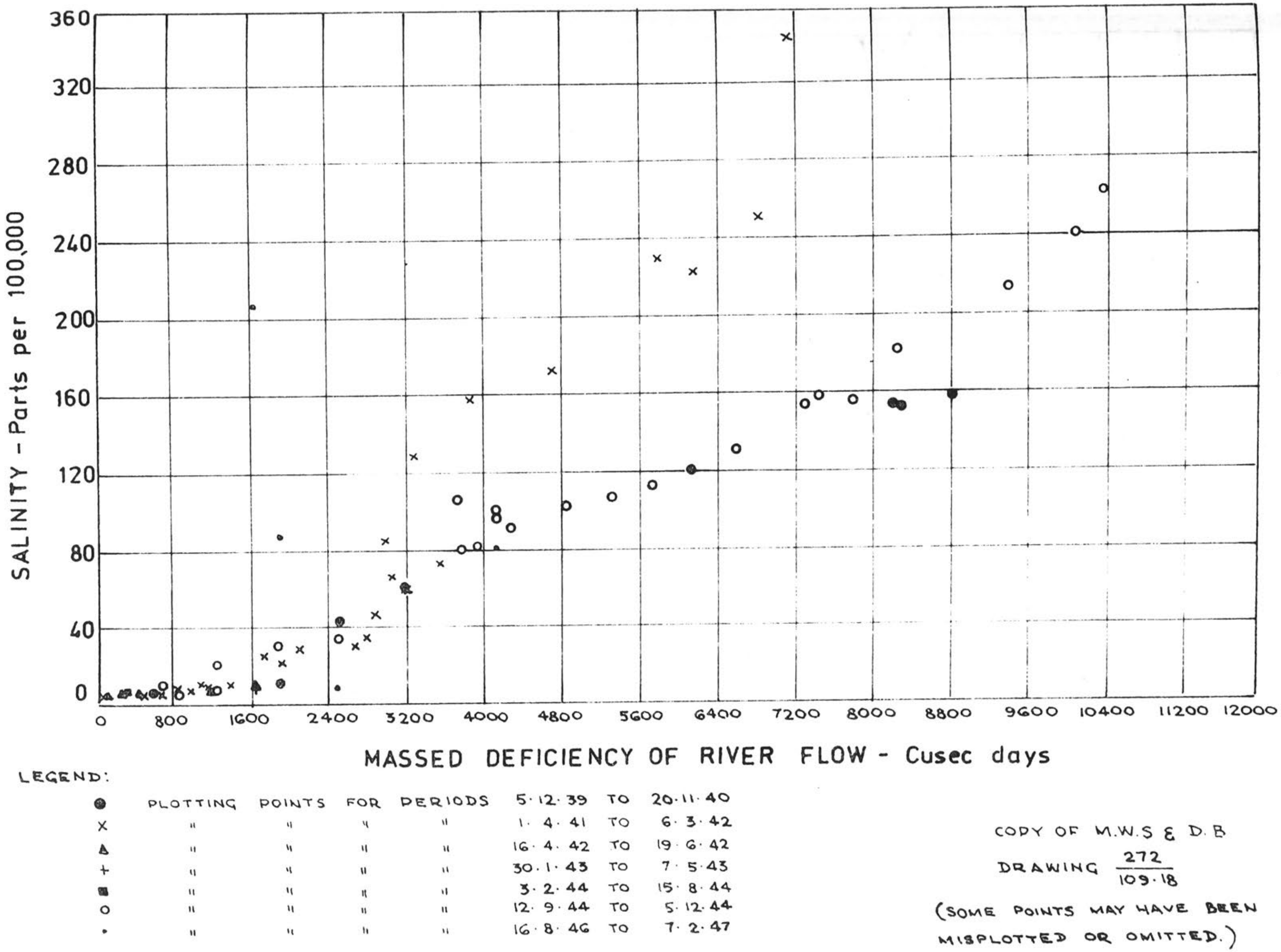
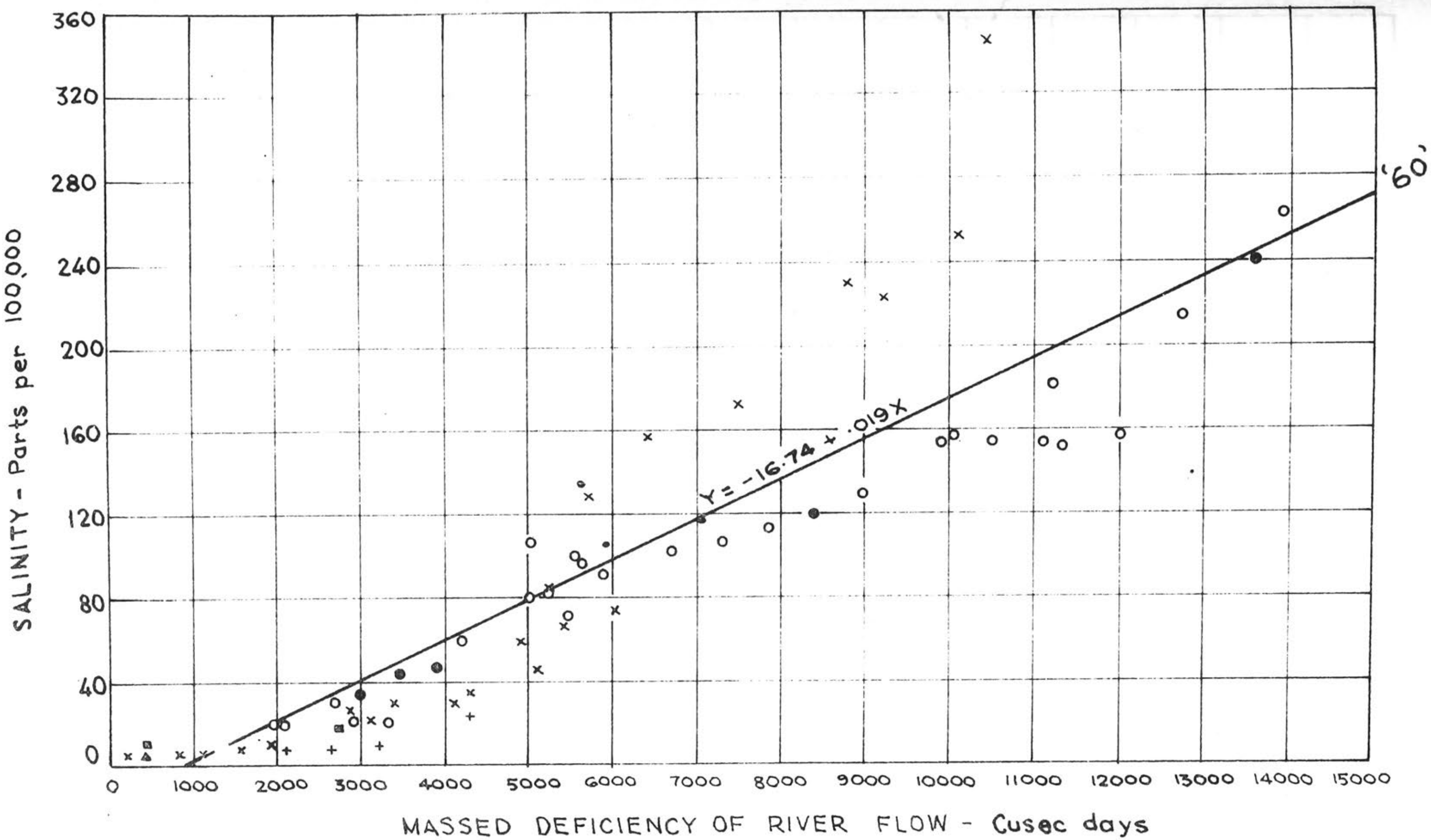


FIGURE 6·3: RELATIONSHIP BETWEEN SALINITY AND CUMULATIVE DEFICIENCY OF RIVER FLOW BELOW 50 CUSEC DAYS.



LEGEND:

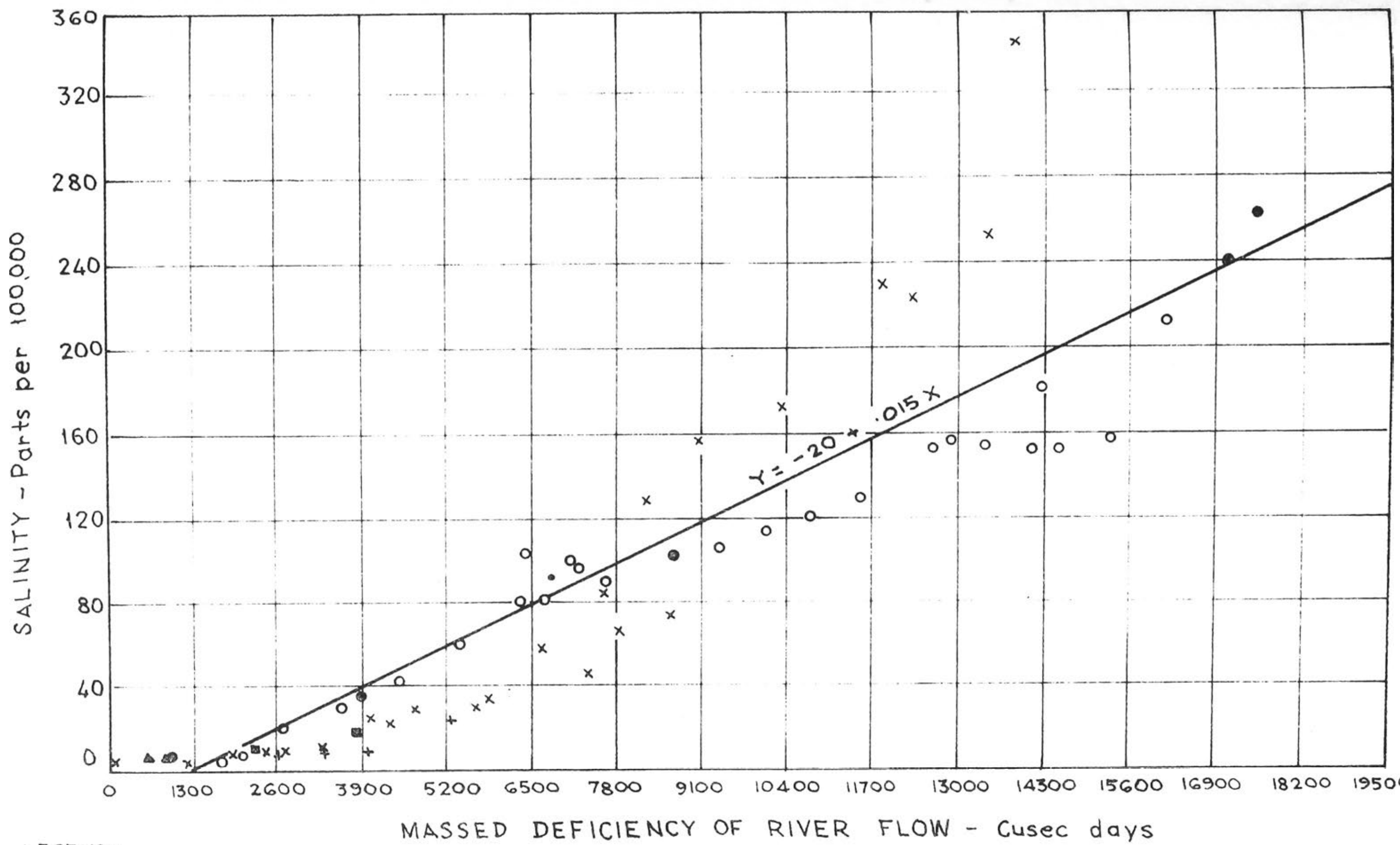
●	PLOTTING	POINTS	FOR	PERIODS	5·12·39	TO	20·11·40
×	"	"	"	"	1·4·41	TO	6·3·42
▲	"	"	"	"	16·4·42	TO	19·6·42
+	"	"	"	"	30·1·43	TO	7·5·43
■	"	"	"	"	3·2·44	TO	15·8·44
○	"	"	"	"	12·9·44	TO	5·12·44
∘	"	"	"	"	16·8·46	TO	7·2·47

COPY OF M.W.S & D.B

DRAWING $\frac{272}{109 \cdot 18}$

(SOME POINTS MAY HAVE BEEN MISPLOTTED OR OMITTED)

FIGURE 6·4: RELATIONSHIP BETWEEN SALINITY AND CUMULATIVE DEFICIENCY OF RIVER FLOW BELOW 60 CUSEC DAYS.



LEGEND:

●	PLOTTING POINTS FOR PERIODS	5·12·39	TO	20·11·40
×	" " " "	1·4·41	TO	6·3·42
▲	" " " "	16·4·42	TO	19·6·42
+	" " " "	30·1·43	TO	7·5·43
■	" " " "	3·2·44	TO	15·8·44
O	" " " "	12·9·44	TO	5·12·44
•	" " " "	16·8·46	TO	7·2·47

COPY OF M.W.S & D.B

DRAWING $\frac{272}{109 \cdot 18}$

(SOME POINTS MAY HAVE BEEN MISPLOTTED OR OMITTED)

FIGURE 6·5: RELATIONSHIP BETWEEN SALINITY AND CUMULATIVE DEFICIENCY OF RIVER FLOW BELOW 70 CUSEC DAYS.

In these estuarine reaches it is observed that when the fresh water discharge falls below a certain threshold value, the salinity at a station, which may normally be negligible, commences to rise and continues to rise as long as the fresh water discharge remains below this threshold value. At Sackville on the Hawkesbury River, the threshold discharge is approximately 60 cusecs (3). See also M.W.S.& D.B. Drawings $\frac{\text{H1}}{109.18}$ and $\frac{\text{H4}}{109.18}$.

The instant that the fresh water discharge falls below the threshold value (the value applicable at the station being considered) is taken as the time of commencement of the dry period in the formulae which are given below:-

Let T = time elapsing since the commencement of the dry period (days)

S = the salinity at the station at high water slack (the salinity may be at the surface, at a fixed depth below the surface or it might be the depth averaged salinity). Salinity is in parts by weight per 100,000.

$[Q]$ = the threshold discharge for the station (cusecs)

Q = fresh water discharge (variable) at any time in the dry period (cusecs)

$\sum_{0}^{T} Q \Delta T$ = total quantity of fresh water discharged from commencement of the dry period to time T (cusec days).

Then $[Q]\,T - \sum_{0}^{T} Q \Delta T$ is the difference between the total quantity of fresh water discharged in the period T at the constant threshold discharge rate and the total quantity of fresh water discharged in the same period. This is called the cumulative deficiency (up to time T) of the river flow in relation to $[Q]$. It is also called the 'massed deficiency' of river flow on M.W.S. & D.B. Drawing $\frac{272}{109.18}$ (Ref. 3). A copy of this drawing, in four sheets (Figures 6.2, 6.3, 6.4, 6.5) is attached.

The M.W.S. & D.B. has used the following empirical formula:

$$
\begin{aligned}
S &= b + mX \\
&= b + m\left([Q]\,T - \sum_{0}^{T} Q \Delta T\right) \qquad (1)
\end{aligned}
$$

where $X = [Q]\,T - \sum_{0}^{T} Q \Delta T$

In the application described in Ref. 2 the salinity is depth averaged and is the salinity at Mean High Water (personal communication from Mr. Greiss of the M.W.S. & D.B.). The change from Mean High Water to Mean High Water Slack would not alter the formula apart from changed values of the constants. The quantities b, m AND $[Q]$ are determined by a graphical analysis of salinities observed over several dry periods. This is done by assuming a series of values of $[Q]$ and, for each value of $[Q]$ plotting salinities S against X and drawing the straight line about which these plotted points show the least scatter. The value of $[Q]$ which gives the least scatter for all the straight lines is then chosen and the corresponding values of b and m are adopted. The values of $[Q]$, b and m derived from analyses of salinities at Sackville (Ref. 2) were $[Q]$ = 60 cusecs, b = - 16.74 and m = 0.019 (see the plot labelled '60' on Fig. 6.4 of the attached copy of Drawing $\frac{272}{109.18}$ where 60 is the value of $[Q]$ and the relationship $Y = -16{\cdot}74 + 0{\cdot}019X$ is written above the straight line of best fit; here the salinity is denoted by Y instead of S).

As an example of the application of this formula, consider the salinities at Sackville for the dry period Jan. - Oct. 1966 shown on M.W.S. & D.B. Drawing $\frac{H4}{109.18}$:-

Period	Discharge cusecs (average for month) Q	Number of days in month ΔT	(a) Total discharged in month cusec-days $Q \Delta T$	(b) $[Q] \Delta T = 60 \Delta T$ cusec-days	Deficiency for month +(b) - (a)
Jan.	45	31	1395	1860	465
Feb.	75	28	2100	1680	-420
March	60	31	1860	1860	0
April	40	30	1200	1800	600
May	37	31	1147	1860	713
June	57	30	1710	1800	90
July	40	31	1240	1860	620
Aug.	45	31	1395	1860	465
Sept.	53	30	1590	1800	210
Oct.	60	31	1860	1860	0
Cumulative Deficiency = $X = [Q]T - \sum_{0}^{T} Q \Delta T$ =					2743

The salinity by the above formula at the end of October = S = - 16.74 + 0.019 x 2743 = 35 parts per hund. thous.

On Drawing $\frac{H4}{109.18}$ chlorinities are shown instead of salinities. Using the relationship: salinity = .03 + 1.805 chlorinity, the chlorinity to the end of October by the above formula = 19. This is in very good agreement with the chlorinity of 20 parts per hund. thous. shown on the drawing. Applying the same formula to the chlorinity at Sackville in the dry period between June 1968 and January 1969 we obtain a chlorinity of 39 at the end of January 1969. This is not in good agreement with the chlorinity of 85 at the end of January which is plotted on Drawing $\frac{H4}{109.18}$. The discrepancy is much worse if we examine the same plotted chlorinity records towards the end of October 1968 when the chlorinity is plotted as 180 per hund. thous. whereas the chlorinity given by the above formula is 13 parts per hund. thous. Not even the complete cessation of fresh water flow in the Colo and Macdonald Rivers in the period of record nor an abnormally high tide could account for such a huge discrepancy. Moreover the plotted chlorinity plunges from 180 in the last week of October to 40 in the first week of November despite the fact that the cumulative discharge deficiency increased between the two dates and continued to increase up until the end of November 1968. It would seem that the chlorinities for these months have been either incorrectly measured or misplotted on the drawing.

The following formula for predicting salinities at a station, derived by the writer, is considered to merit further investigation:-

$$\frac{S}{S_o} = e^{-(b-mX)^2} \tag{2}$$

i.e.

$$\sqrt{\log_e \frac{S_o}{S}} = b - mX \tag{2a}$$

where S_o is the ocean salinity, b and m are constants and X is the cumulative deficiency of the river flow. The derivation of this formula is given in the appendix. It is derived by generalising an expression obtained by Gole and Thakar for the dry season salinities in the Hooghly Estuary, India (4). Note that the variable, cumulative deficiency of river flow $X = [Q]T - \sum_0^T Q\Delta T$ appears in the M.W.S. & D.B. formula and in formula (2). It would appear that this is a basic variable in any formula which best fits the record of dry weather salinities at a station in a well mixed estuary.

As before the values of b, m and $[Q]$ in formula (2) can be obtained by a graphical analysis of salinities observed over several dry periods. Using formula (2a) this is done by assuming a series of values of $[Q]$ and, for each value of $[Q]$ plotting values of $\sqrt{\log_e \frac{S_o}{S}}$ against X and drawing the straight line about which these plotted points show the least scatter. The value of $[Q]$ which gives the least scatter for all the straight lines is then chosen and the corresponding values of b and m are adopted.

In the Hooghly Estuary, the discharges from tributaries are negligible compared to the dry weather river discharges. Therefore, in cases where the discharges downstream from a station are a significan fraction of the river discharge, formulae (1) and (2) may not provide a good fit of the observed salinities at the station. In such cases, if formulae (1) and (2) are found not to apply, it is suggested that a trial be made of the following empirical equation:-

$$f\left(\frac{S}{S_o}\right) = b - mX \tag{3}$$

A special form of $f\left(\frac{S}{S_o}\right)$ is $\left(\frac{S}{S_o}\right)^{\alpha}$ where the exponent α is determined by trial. As before b and m are constants and X is the cumulative deficiency of river flow. In evaluating $X = [Q]T - \sum_0^T Q\Delta T$, Q would be taken as being equal to the sum of the fresh water discharges

II. Salinity Fluctuations within a Tidal Cycle

Let t = time elapsing within a tidal cycle since high water slack at a station, distant x from the entrance of an estuary. Then for salinity fluctuations within a tidal cycle, we have for low fresh water flows:-

$$\frac{\partial S}{\partial t} + (V_T - V_F)\frac{\partial S}{\partial x} = 0 \qquad \text{(Ref. 5 p.20)}$$

where V_T = tidal flow velocity (velocity positive in upstream direction)

" V_F = fresh water flow velocity

Now in a dry period $V_F \ll V_T$ and hence V_F can be neglected. We then have $\frac{\partial S}{\partial t} = -V_T \frac{\partial S}{\partial x} = -P\cos(\omega t - \phi)\frac{\partial S}{\partial x}$, if we assume that the tidal flow velocity can be approximated to by a simple harmonic fluctuation. Here P is the amplitude of the velocity fluctuation at x, ω is the angular speed and ϕ is the phase lag of high water slack at x behind high water slack at the ocean entrance.

It follows that the salinity at time t at x: $S_t = f(P, x, \phi, t)$

But P is a function of x and the tidal range R at the entrance, and ϕ is a function of x

$$\therefore \quad S_t = g(R, x, t)$$

The salinity at high water slack = $S = g(R, x, 0)$

$$\therefore \quad \frac{S_t}{S} = \frac{g(R,x,t)}{g(R,x,0)} = h(R, x, t)$$

Writing this equation in terms of the salinity at a station, we have:-

$$\frac{S_t}{S} = h(R, t)$$

Hence for a given tidal range at the entrance we plot, from the observed salinities S in the tidal cycle, a curve showing the variation of the ratio $\frac{S_t}{S}$. Repeating this for various ocean tidal ranges we can obtain a series of curves like those in Fig. 6.6.

Thus using one of the formulae in Section (a) to obtain S and an appropriate curve to obtain $\frac{S_t}{S}$, the salinity S_t at any instant in a dry season can be predicted.

It is of interest to note that the instantaneous salinities at stations in the Hudson River Estuary follow roughly the sinusoidal pattern of the tidal fluctuation (6). Since the mixing characteristics of the Hawkesbury and other N.S.W. coastal rivers approximate to those of the Hudson River, it is expected that the 'at a station' salinities of these rivers will also tend to vary sinusoidally with the tidal fluctuations.

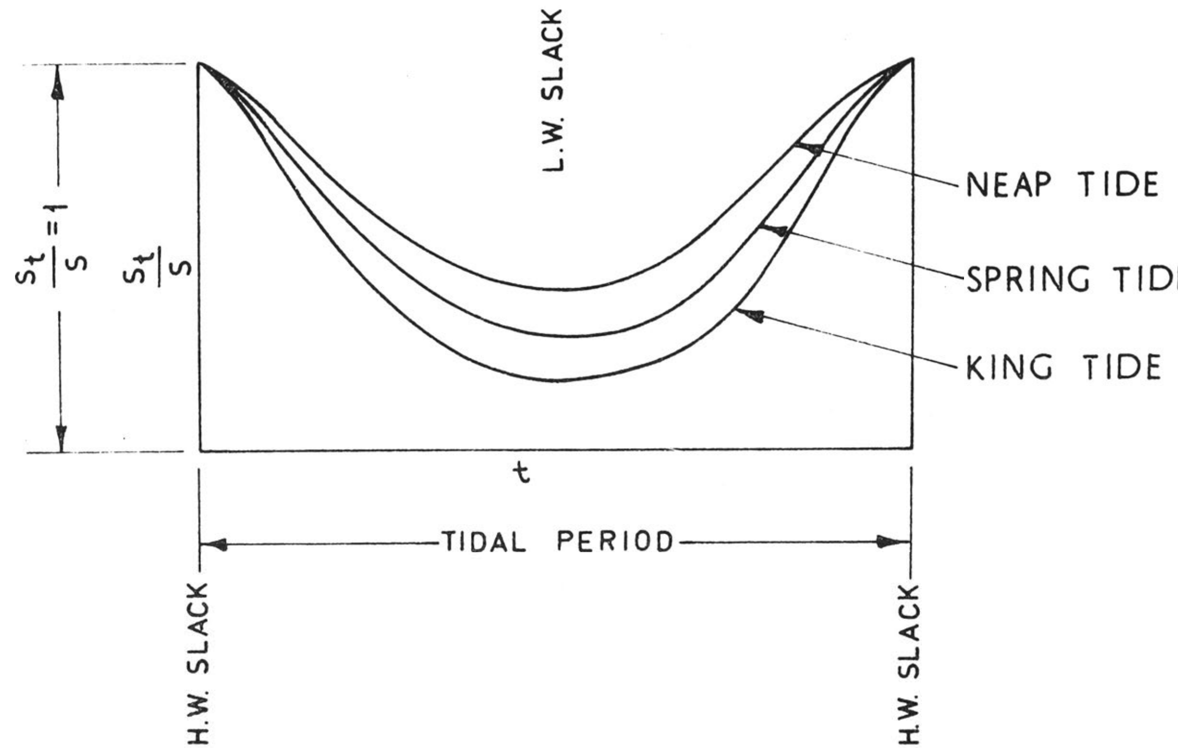


FIGURE 6·6: VARIATION OF SALINITY IN A TIDAL PERIOD.

III. Procedures for Investigating Salinities at a Station

It can be assumed that at any station where water is used for irrigation the threshold discharge [Q] in Section (a), below which river discharges, if they persist, will result in marked rises in salinities, would not be greater than about 100 cusecs. In the Hawkesbury River at Sackville the threshold discharge is 60 cusecs and at Duckenfield, three miles below the confluence of the Paterson and Hunter River, the threshold discharge is 100 cusecs (personal communication from Mr. Wetherall, Department of Agriculture, East Maitland). Consequently at stations where water is used for irrigation, observations of salinities need only commence when river discharges fall below, say, 500 cusecs.

As well as river discharges the discharges in the principal tributaries downstream from the station should be observed. If the discharges in these tributaries are a significant fraction of the river discharges then formula (3), given in Section (a), may best fit the observed salinities.

At the very least, salinities should be observed and recorded near the surface and near the bed of the river even if the variation of salinity with depth is small and only surface water is being used for irrigation. With the growth of settlement disposal of waste waters via the river might become a problem and the design of an efficient means of disposing of these waste waters requires a knowledge of the variation of salinity with depth even if it is small (7). It is recommended that salinity observations be made fortnightly at a station in association with the spring tides. Salinities should be observed at two successive high water slacks and the corresponding low water slacks to obtain the average high water and low water slack salinities. The times of occurrence of these tides at the ocean entrance can be obtained from standard tide tables and the local times of occurrence can then be obtained from the tidal gradient plans of the Public Works Department of N.S.W. which give the time lags of high and low water at locations along a river behind high and low water at the entrance. See, for example, P.W.D. Plan Catd. No. 116 of the Clarence River. It should be noted that high and low water slacks at a station do not occur at the same time as high and low water at the station and the time differences are to be obtained by observation.

Observations of salinity fluctuations between high water slack and low water slack are required for predictions of salinities at any instant in a tidal cycle (see heading II). The observations should be made at hourly intervals so that estimates can be made of the percentage of time in dry weather that the salinity of the water is below an acceptable limit and can be used for irrigation.

Observations should also be made of the dissolved solids in the fresh water flows from the headwaters of the river and its tributaries. Normally in the estuarine reaches of a river the total amount of dissolved solids from other sources is small compared with the amount of dissolved solids resulting from the intrusion of sea water. However, depending on the catchment geologies, in times of extreme drought the amounts of dissolved solids brought down in the flows of the river or its tributaries may constitute a significant proportion of the salinity in the upper tidal reaches. This has apparently been the case in the upper tidal reaches of the Hawkesbury in times of extreme drought (8) when groundwaters infiltrating through the saline Wianamatta Shales have constituted a large proportion of the river flow. In any case the contributions to salinity of fresh water flow should be assessed, bearing in mind that the tolerance of certain fruit crops can be as low as 40 parts per hundred thousand (9).

In addition to the abovementioned applications, data on salinity fluctuations at a station and the distribution of salinities along an estuary are required for computing the concentrations of other dissolved substances which may be introduced into the estuary (see the appendix to Part 2).

PART 1, SECTION 2: PREDICTION OF SALINITIES ALONG A TIDAL RIVER.

I. Mathematical Models

The mathematical model of M.L.Thatcher and D.R.F.Harleman is presented in Reference 10. This publication contains a good review of previous investigations in this field. The model in this publication predicts the salinities as they vary with time and location along the river in response to temporal variations in fresh water inflows and to variations in tidal amplitudes at the ocean. The predictions of salinity are limited to the one dimensional formulation wherein the salinity at any location along the river is averaged over the channel cross section. However, a method of schematising the geometries of river reaches is employed whereby due allowance is made for the storage effects of embayments and expanses of shallow water which adjoin the main channel. The mathematical model is applicable to tidal rivers wherein it can be assumed that salinities do not vary laterally in a cross section but may vary vertically insofar as the river estuary falls between the partially mixed and well mixed categories. The coastal rivers of N.S.W. and, indeed, most tidal rivers fall between these categories (p. 116 Ref. 7).

The mathematical model embodies the finite difference solutions, by computer, of the continuity and dynamical equations which define the tidal motion and the convective-dispersion salinity equation. The dynamical equation and the salinity equation are coupled by the inclusion in the dynamical equation of a density term which is directly related to salinity.

The outstanding feature of the mathematical model is the expression for the longitudinal dispersion coefficient E in the salinity equation (p.56 Ref. 10):-

$$E = E(x,t) = K \left| \frac{\partial \overset{\circ}{S}}{\partial \overset{\circ}{x}} \right| + E_T \qquad \text{(p. 83, 99 Ref. 10)}$$

where $K = 0{\cdot}002\ U_0 L\ (\mathbb{E}_D)^{-1/4}$ (p. 183, 187 Ref. 10)

where $\overset{\circ}{S} = \frac{S}{S_0}$, the ratio of the salinity S at distance x from the entrance to the ocean or bay salinity S_0

and $\overset{\circ}{x} = \frac{x}{L}$, the ratio of the distance x from the entrance to the total length of the estuary L

U_0 = maximum cross-sectional velocity at the mouth of the estuary

L = total length of estuary (i.e. up to the limit of tidal influence of a river)

$\mathbb{E}_D$ = estuary number $= \frac{P_T\ \mathbb{F}_D}{Q_f\ T}$ (p. 145, 147 Ref. 10)

P_T = tidal prism = total volume of water entering the estuary on the flood tide

T = tidal period

$\mathbb{F}_D$ = densimetric Froude number evaluated at the entrance to the estuary $\frac{U_o}{\sqrt{gh \frac{\Delta\rho}{\rho}}}$

h = depth of water at the entrance

$\frac{\Delta\rho}{\rho}$ = maximum change in density from the fresh water end to the mouth of the river which may be the ocean or a bay

Q_f = fresh water inflow

$E_T = E_T(x,t)$ = longitudinal dispersion coefficient for a completely mixed estuary or for the fresh water region of same

$= 77\, n\, u\, R_h^{5/6}$ (p. 37 Ref. 10)

where

n = Manning's n

u = velocity averaged over a cross section

R_h = hydraulic radius

At each stage in the computations E is evaluated for use in the next stage from the channel geometry, channel resistance and the computed salinities and discharge. The computations of the dispersion coefficients commence, therefore with an initial water surface height and discharge profile along the river to the entrance and an initial salinity distribution along the river. If, apart from an initial fresh water discharge and ocean tidal amplitude, these initial data are not known as in the case, say, of a river whose behaviour is to be modified by major works, then a sufficiently accurate approximation to such data can be obtained by preliminary computations based on quasi steady-state studies similar to that described on pages 69 and 71 of this publication. In the preliminary computations the abovementioned initial fresh water discharge and ocean tidal amplitude would be held fixed and computations would proceed from assumed initial conditions until convergence was obtained.

For the fresh water reaches of a river, the unsteady flow dispersion coefficient E can be determined from the tidal velocity, the hydraulic radius and Manning's n (11). On the other hand, the estimation of E for the saline reaches has hitherto been the major difficulty in studies of estuarine dispersion. Now E can be determined from the gross parameters of the estuary by means of the above expression for E given by Thatcher and Harleman and so can be applied in dispersion studies of a river whose flow characteristics have been altered by major works. It should be noted, however, that this expression for E, while it is applicable to tidal rivers which are single or multi branched in their fresh water reaches, is strictly only applicable to a river which has a single channel in the saline reaches. This is implicit in the formulation of the densimetric Froude number which is defined above. For the case of relatively small tributaries connected to the saline reaches of a relatively large estuary, reference should be made to pages 161 and 164 of this publication (10).

In the Thatcher and Harleman model, velocities and water surface heights are computed from the hydrodynamic equations by means of an explicit finite difference scheme. Salinities are computed by means of an implicit finite difference scheme. The hydrodynamic and salinity computations are coupled by the salinities, and the interdependence of these computations is shown by the diagram on page 43 of Reference 10. The estuary is divided into segments of equal length and the convergence criteria for this segmentation are given on pages 129, 130 of the reference. On pages 212 and 213 of same, costs in computer time are given for the application of this computer model to the Delaware and Potomac Rivers, using an IBM 360 computer. On the basis of these costs it is considered that the cost in computer time of determining the transient salinities in the Hawkesbury for an entire year would lie somewhere between $100 and $300.

An alternative model is the finite element model of Dailey and Harleman (1). This model can be used to predict salinities and the concentrations of non conservative substances. It can be applied predictively to dispersion studies in tidal rivers and estuaries where the above dispersion coefficient formulated by Thatcher and Harleman is valid.

An outline of the Dailey and Harleman model is given in Part 2.

A model for computing the longitudinal and vertical distributions of salinities and velocities, averaged over a tidal cycle, is given by Fisher, Ditmar and Ippen (12). This is an analytical model involving numerical integration. The data required are the geometry of the estuary, the fresh water discharge, the tidal range at the entrance and the longitudinal distribution of the cross sectional averaged salinity which is averaged over a tidal cycle. The longitudinal salinity distribution can be obtained from field observations, from a physical model or the computational model of Thatcher and Harleman. Applications of the results obtained by the two dimensional model to the flushing of pollutants in partially mixed estuaries is described in Part 2.

This model can be used to determine the location of the null point in an estuary. This is the point where the bottom velocity, averaged over a tidal cycle is zero (downstream from the null point the net bottom velocity is away from the mouth, upstream it is towards the mouth).

II. Shoaling Patterns in Estuaries

In many estuaries the location of heavy shoaling is in the vicinity of the null point (13). Examples are the Savannah Estuary (14) and the Delaware Estuary (15). The significance of the null point is discussed by Partheniades in Chapter 26 of "River Mechanics" (16). He points out that most of the suspended sediment near the bed of an estuary will have been deposited at times near high water and low water slack and for that deposited sediment to advance upstream or downstream, it must be scoured and resuspended by the shears associated with the tidal velocities. In Chapter 25 of the same book (16) Partheniades points out that because of consolidation processes, the critical velocities for erosion of bed materials are generally greater than the settling velocities of the same materials. In fact, the critical velocities for the erosion of cohesive beds, depending on the physico-chemical properties of the material, may increase with decreasing mean particle size, whereas the critical velocities for deposition decrease with mean particle size. This is particularly true for soils in the fine silt and clay range.

Under average fresh water flow conditions, the net velocity near the bottom (i.e. the near bottom velocity averaged over a tidal cycle) is by itself too weak to scour the bed material, being of an order of magnitude smaller than the instantaneous tidal velocities which do scour the bed. With distance upstream, the tidal velocities decrease and eventually a limit is reached above which these velocities are less than the critical values associated with the bed material. This limit Partheniades calls "the point of no scouring". This point and the null point, he says, determine the shoaling pattern in the estuarine reaches of a tidal river. He classifies estuaries as being "tide controlled" or "salinity intrusion controlled" depending on whether the shoaling zones are determined by, respectively, the point of no scouring or the null point. The effects in these two categories are not independent since tides, fresh water flows and salinity intrusion are interrelated.

The diagrams in Fig. 6.7 serve to clarify the descriptions in the text of Chapter 26 (16). The estuarine shoaling pattern in diagram (a) is not in either category. This is the case where the null point lies upstream of the point of no scouring and sediments originating from the upstream catchment deposit upstream of the null point. This may be a considerable distance upstream from the null point in the case of cohesive sediments which only require a very small salinity to flocculate; indeed certain clay minerals such as kaolinite flocculate more readily in distilled water than in saline water (17). The position of the null point will alter in accordance with fresh water flows and the ocean tides. The shoaling zone in estuaries where deposition is associated with the null point will, therefore, assume an average position with regard to that point. In the case of the Thames Estuary (16), there are two separate shoaling zones corresponding to the two distinct positions assumed by the null point in high winter flows as opposed to low summer flows. Again, in times of flood, sediments deposited as shown in diagram (a) may be eroded and deposited in the vicinity of the estuary entrance whence they are carried upstream by bottom currents under average conditions of flow.

Agencies which have apparently been overlooked by these and other authors are the activities of marine creatures in the bed materials of estuaries. In a personal communication to the writer, Dr.

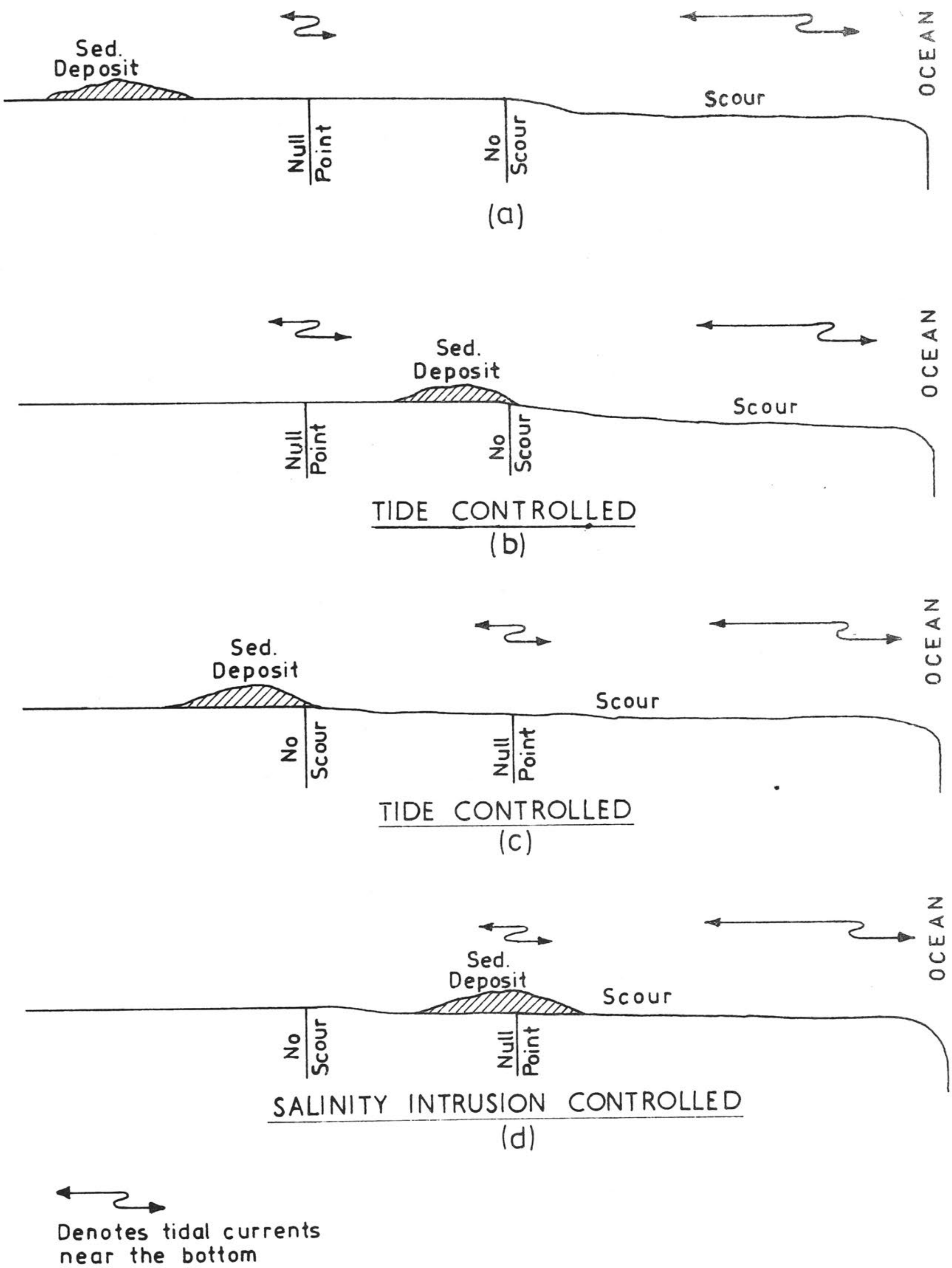

Sed. Deposit
Null Point
No Scour
Scour
OCEAN
(a)
Sed. Deposit
Null Point
No Scour
Scour
OCEAN
TIDE CONTROLLED
(b)
Sed. Deposit
No Scour
Null Point
Scour
OCEAN
TIDE CONTROLLED
(c)
Sed. Deposit
No Scour
Null Point
Scour
OCEAN
SALINITY INTRUSION CONTROLLED
(d)
Denotes tidal currents near the bottom

FIGURE 6·7

Hutchings, the Acting Curator of Marine Invertebrates at the Australian Museum, said it was quite possible that worms, crabs, vivalves, small burrowing fish and shrimps could stir up the mud and facilitate its entrainment by low velocity currents to the extent that large quantities of mud would be moved thereby along an estuary. She also said that these creatures, especially the worms, changed the physical and chemical properties of the bed material, thus modifying its resistance to erosion. It is possible, therefore, that despite the laboratory experiments on cohesive sediments described by Partheniades (16), the activities of marine animals in these sediments are such as to reduce the values of the critical velocities for their entrainment towards those of their settling velocities. In these estuaries the sediments would tend, therefore, to settle in the vicinity of the null points. On the other hand, as pointed out by Dr. Hutchings, pollution could have lethal effects on these animals and radically alter the shoaling pattern.

III. Physical Models

For reasons of economy, a physical model simulating the salinity behaviour in a tidal river must be constructed to a distorted scale. Modelling scales which have been widely used are 1/1000 horizontal and 1/100 vertical. Practical problems encountered in the construction of these models are given in Reference 18. It is shown in Part 2 that a distorted scale model can only be used to model dispersion in the saline reaches of a tidal river. For a river with a single channel in the saline reaches a computer model would be cheaper because the dispersion coefficients can be deduced from the gross parameters of the channel (10) as described earlier. On the other hand, a physical model would be an attractive alternative to a programme of field observations of salinities if the river is branched in the tidal reaches, especially if the flow behaviour of the river is to be changed by major works, in which case the computer model is subject to the limitation that the dispersion coefficients cannot be obtained from the formulation of Thatcher and Harleman. Again, physical models to a distorted vertical scale can simulate salinity distributions in the vertical as well as along the channels (18). Salinity models are also discussed in Part 2 in connection with physical models for studying the dispersion of other dissolved substances.

APPENDIX TO PART 1: THE PREDICTION OF SALINITIES IN TIDAL RIVERS.

A formula has been derived by Gole and Thakar in their investigation of dry weather salinities in the Hooghly Estuary, India (4).

The equation on which the formula is based implies that the dispersion along an estuary in a period of low weather flow can be regarded as a one dimensional process. In the notation of the authors the dispersion equation is

$$\frac{\partial S}{\partial t} = V_f \frac{\partial S}{\partial x} + \frac{1}{A} \frac{\partial}{\partial x}\left(DA \cdot \frac{\partial S}{\partial x}\right) \tag{1}$$

where
- S = surface salinity (see below)
- t = time (zero at commencement of the dry period)
- V_F = velocity of fresh water flow
- x = distance along the estuary measured upstream from the mouth
- A = cross sectional area of waterway at mean tide level
- D = "apparent diffusion coefficient which takes account of effects of turbulent diffusion and dispersion and density-dependent internal circulation".

The salinities investigated by Gole and Thakar were surface salinities. Salinities at other depths would be expressed by the same formula but with different values of the constants embodied in the formula.

Gole and Thakar considered equation (1) as applying to a reach of the river - that is to say, the equation was considered as being written in "local form" and thus the cross sectional area A could be regarded as being constant along the reach. They assumed that the apparent diffusion coefficient was given by the expression

$$D = \frac{D_o B}{x + B - Vt} \tag{2}$$

where D_o, B and V are constants.

On this assumption they obtained the following formula which is a solution to equation (1):-

$$S = S_o e^{-(x+B-Vt)^2 \frac{V+V_f}{2 D_o B}} \tag{3}$$

where S_o is the ocean salinity and V_F is the fresh water flow (constant) velocity. This solution was found to fit reasonably well observed dry season salinities for a constant fresh water flow.

The formula given below is a generalisation by the writer of the above formula. The generalised formula is applicable to salinities corresponding to varying dry weather flows.

Let $[Q]$ = threshold discharge (see Section (1))

" Q = freshwater discharge

$\int_0^t Q\,dt$ = total quantity of fresh water discharged from commencement of the dry period (t = 0) to time t

so that $[Q]t - \int_0^t Q\,d\tau$ is the cumulative discharge deficiency (see Section (1)). Let S, S_o, x, A, D, D_o and B have the same meanings as they have in the expressions (2) and (3) of Gole and Thakar. It is assumed that the apparent diffusion coefficient is given by the expression:

$$D = \frac{D_o B}{x + B - \frac{1}{A}\left\{[Q]t - \int_0^t Q\,d\tau\right\}} \qquad (4)$$

With this expression for the diffusion coefficient, it can be proved by direct substitution that the following formula is a solution to equation (1)

$$S = e^{-\left(x + B - \frac{1}{A}\left\{[Q]t - \int_0^t Q\,d\tau\right\}\right)^2 \frac{[Q]}{2 D_o B}} \qquad (5)$$

Moreover, if the dry weather discharge Q is constant, expressions (4) and (5) reduce to (2) and (3) if we interpret V in the latter two expressions as the "deficiency velocity" corresponding to the river flow deficiency in relation to $[Q]$:

Thus at any instant τ in the dry period we have the river flow deficiency in relation to $[Q] = [Q] - Q$

The "deficiency velocity" $= \frac{1}{A}\left\{[Q] - Q\right\}$

$$= \frac{[Q]}{A} - \frac{Q}{A} = \frac{[Q]}{A} - V_F = V$$

Hence $\frac{[Q]}{A} = V + V_F$

Also $\frac{1}{A}\left\{[Q]t - \int_0^t Q\,d\tau\right\}$

$= \frac{1}{A}\left\{[Q]t - Qt\right\}$ since Q is constant

$= \frac{1}{A}\left\{[Q] - Q\right\}t = Vt$

Putting $\frac{[Q]}{A} = V + V_F$ and $\frac{1}{A}\left\{[Q]t - \int_0^t Q\,d\tau\right\} = Vt$ in (4) and (5) we obtain (2) and (3). The formula of Gole and Thakar was devised to fit the observed dry weather salinities along the length of the Hooghly Estuary. Both their expression for a constant dry weather flow and the generalised expression for variable dry weather flow can be put in a simplified form to fit the observed dry weather salinities at a station. In (5) put

$$b = \sqrt{\frac{[Q](x + B)}{2 A D_o B}} \quad \text{and} \quad m = \sqrt{\frac{[Q]}{2 A^2 D_o B}}$$

Then for salinities at a station (5) becomes:

$$S = S_o\, e^{-\left(b - m\left\{[Q]t - \int_0^t Q\,d\tau\right\}\right)^2} \qquad (6)$$

Replacing the integral $\int_0^t Q\,d\tau$ in (6) by the summation $\sum_0^T Q\Delta T$ (where T is the time elapsing since the commencement of the dry period) we obtain

$$S = S_o e^{-\left(b - m\left\{[Q]T - \sum_0^T Q\Delta T\right\}\right)^2} \qquad (7)$$

i.e. $$\frac{S}{S_o} = e^{-(b-mx)^2} \qquad (8)$$

where $x = [Q]T - \sum_0^T Q\Delta T$ is the cumulative deficiency of the river flow.

The Hooghly may be regarded as a well mixed estuary under conditions of dry weather flow (p.277 Ref.4). An examination of the C.S.I.R.O. Oceanographical Station Lists indicates that for low flows the Clarence River and the Hawkesbury River may also be regarded as well mixed estuaries. For both these rivers, at stations distant about 10 miles from their entrances, the ratio of the bottom salinities to the depth-averaged salinities is about 1.1 under average dry weather flow conditions. This is approximately the ratio of the bottom salinity to the depth-averaged salinity given by the curve corresponding to maximum mixing in Fig. 20, page 48, of the publication in Reference 5; the test station for the curves in Fig. 20 are located at about the same relative distance from the flume entrance as the abovementioned stations are from the river entrances. Consequently, formula (8) above should be applicable to salinities in the Clarence River, the Hawkesbury River and other coastal rivers.

PART 2: PREDICTION OF CONCENTRATION OF DISSOLVED SUBSTANCES IN TIDAL RIVERS AND ESTUARIES

Introduction

In Section 1 mathematical models for predicting the concentrations of dissolved substances are described. These concentrations may vary both spatially and temporally and the substances include industrial and municipal wastes. Dissolved substances are classified as being conservative or non-conservative. A substance is said to be conservative if none of the substance is lost across the flow boundaries or created or destroyed within the flow. Thus the saline intrusion from the ocean is composed of conservative substances. Waste waters from various undertakings may contain conservative substances in easily detectable concentrations such as sulphates which do not appear in the natural catchment flow and may serve to identify the source of waste water pollution. On the other hand, dissolved oxygen is generally non-conservative because it may be used up by the biochemical oxygen demand of pollutants or it may be produced by algae or absorbed from the atmosphere. Radioactive material is non conservative.

Simple computational models on the flushing of substances are described. These methods would be useful in preliminary investigations. More complex one and two dimensional models are outlined. Included are the mathematical models of Thomann and O'Connor and Thomann for determining the effects on water quality of inputs of substances which can interact with one another. These models would be valuable adjuncts to estuary planning and management.

The mathematical model of Dailey and Harleman is outlined. This model uses the formulation of the dispersion coefficient given by Thatcher and Harleman (10) and thus is a truly predictive model.

Physical models are described in Section 2. In the appendix to this part formulae are derived for determining the concentrations of dissolved substances from the salinities in estuaries. Field observations for determining the distributions of salinities in the Hawkesbury River and its tributaries are outlined in the appendix and departments possessing salinity data for this river and other coastal rivers are listed.

PART 2, SECTION 1: MATHEMATICAL MODELS

One of the simplest models is that given by Diachishin, Hess and Ingram (19) which is based on the tidal prism concept. It is assumed that the entire volume of water in an embayment between mean high water and mean low water is available for the disposal of a pollutant and that in each tidal cycle the prism is renewed with a supply of fresh sea water that completely mixes with the water below low tide. A simple formula is derived for the detention time of the pollutant. By assuming complete mixing in each tidal cycle this model overvalues the cleansing action of the tide.

An improvement on this model is that of Ketchum (20, 21). This model gives an estimate of the average concentrations of a pollutant in successive volume segments of an estuary. The data required are the river flow, the tidal heights along the estuary and the estuary geometry. The tidal data can be obtained from the tidal gradient plan. The estuary is divided up into segments, the segments being so defined that the distance between their inner and outer boundaries is equal to the average excursion of a particle of water on the flood tide (the average excursion is derived from the volume entering each part of the estuary on the flood tide). A basic assumption of the theory is that the water within each segment is completely mixed at high tide. Also, it is assumed that in each tidal cycle, there moves seawards a volume of fresh water equal to the volume introduced by the river in the same period of time. Simple methods are given for computing the total accumulation of river water and its contained pollution within the estuary and the average length of time this polluted water has been in the estuary.

The success of the method depends, to a large extent, on the number of segments involved in the schematisation of a given estuary. This is discussed by Ippen in Rèference 22. In Reference 23, Ketchum, Refield and Ayers give a simple formula for the flushing time in an embayment which is based on observations of the average salinity.

In Reference 24 relationships are derived for a partially stratified estuary which express the time required for a pollutant, assumed to be originally uniformly mixed throughout the estuary, to be replaced by tidal action. Data required are velocities at the entrance and in the estuary over at least a tidal cycle, the velocities being determined at various depths, so that the upper layer with a net seaward drift and the lower layer with a net landward drift can be determined. An objection to this model is the difficulty of obtaining field measurements of these net landward and seaward drifts which are small compared with the instantaneous tidal velocities.

More accurate predictions have been made using analytic methods based on models wherein the smallest unit of time is a tidal cycle. These have been termed 'Non-tidal advective models' by Harleman (1). Non tidal advective models are discussed by Harleman in Chapter II of Reference 25. Using such models, solutions for the concentration of pollutants in simple estuaries of uniform cross section have been obtained by Holley and Harleman (26). These solutions are restricted to the fresh water (uniform density) reaches of tidal rivers where dispersion coefficients developed from the work of Taylor (27) apply.

In the appendix to this part it is shown how the dispersion coefficient, corresponding to the longitudinal distribution of salinity averaged over a tidal cycle, can be derived from salinity observations. Similarly the high water slack and low water slack dispersion coefficients can be derived from salinity observations. These dispersion coefficients are required in the non tidal advective models described herein for studying water quality. The observations of salinities are described in the appendix. Also in the appendix formulae are derived for determining the concentrations of dissolved substances from the salinities. Salinities can also be obtained from a physical model or from one or the other of the mathematical models outlined in this chapter (1, 10). In the fresh water reaches of a tidal river the dispersion coefficients averaged over a tidal cycle can be obtained from the formula given by Harleman in Reference 30.

Analytical solutions for the concentrations of non-conservative substances in estuaries with simplified geometries are given by O'Connor (28). The solutions are for high water and low water slack conditions and would appear to be of limited application because the dispersion coefficient is assumed to be constant for a given estuary.

A mathematical model is given by Thomann (29) for the responses of any body of water to sources and sinks of substances which may or may not be conservative. In Thomann's paper the responses are the concentrations of dissolved oxygen resulting from time varying sources and sinks of dissolved oxygen. Data required for the model include velocities and diffusion coefficients (for evaluating the advective and dispersive transfers), inputs of biochemical oxygen demand and decay rate of same, and other sources and sinks of dissolved oxygen such as re-aeration and the respiratory and photosynthetic action of aquatic plants.

As a special case, Thomann outlines the modelling of a one dimensional estuary, the smallest unit of time being a tidal cycle (the non tidal advective case) which is the time scale appropriate to most investigations of water quality (i.e. apart from sudden spills requiring hour by hour determination of concentrations). Constant fresh water discharge and ocean tidal fluctuation are assumed but the sources and sinks of dissolved oxygen vary with time. The estuary is divided up into segments and the water in these segments is assumed to be completely mixed; thus the partial differential equation for the concentration of dissolved oxygen along the estuary is replaced by a series of simultaneous linear differential equations, one for each segment, expressing the time rate of change of concentrations resulting from the varying sources and sinks of dissolved oxygen. The model provides a means of assessing the effects of an input (variable sources and sinks of dissolved oxygen) in one segment on the output (concentration of dissolved oxygen) in another segment. This is done by means of a transfer function, one for each pair of segments, relating the inputs to the outputs. As the equations are linear, the effects on one segment of inputs in several other sections, and vice versa, can be added. The transfer functions are independent of the inputs and depend only on the hydrodynamic characteristics of the estuary which determine the advective and diffusive exchanges and the re-aeration coefficients.

Time varying and steady state water quality models are described by O'Connor and Thomann in Chapter III of Reference 25. In the steady state model the concentrations do not vary with time (invariable sources and sinks and reaction rates) and the abovementioned differential equations (29) are replaced by a set of simultaneous equations. Single stage, two stage (e.g. biochemical oxygen demand and dissolved oxygen) and multi stage reactions can be incorporated in the model. In a time varying model the differential equations are replaced by simultaneous finite time increment equations expressing the concentrations at time $t+\Delta t$ in terms of the concentrations at time t and the inputs at times t and $t+\Delta t$. Computations commence with the initial values of the concentrations and continue until the specified time span has been exhausted.

O'Connor and Thomann (25) describe a two dimensional model of an embayment giving the steady state concentrations (varying laterally) resulting from invariable sources and sinks. This model can be extended to give time varying concentrations due to varying inputs (see above). The principal difficulty in setting up a two dimensional model is the evaluation of the non tidal adective dispersion coefficients. These coefficients, however, can be determined from the concentrations of conservative dissolved substances introduced into the mathematical model of Fischer (31) described below. The dispersion coefficients are determined by reversing the roles in the abovementioned model of O'Connor and Thomann, of the concentrations and the dispersion coefficients so that the dispersion coefficients are the unknowns which are to be determined from the concentrations (see pages 132 and 133 of Reference 25, noting that for a conservative substance the right hand side of equation 3.48 is zero).

In a two dimensional embayment grid, the number of dispersion coefficients to be determined exceeds the number of equations relating the dispersion coefficients to the concentrations in the grid squares corresponding to a given input of substance. In a square grid of n^2 squares there are n^2 equations and $2n(n-1)$ unknowns. To obtain sufficient equations for the dispersion coefficients, the input of substance should be altered and a second application of Fisher's model made to determine the corresponding concentrations. The two sets of simultaneous equations corresponding to the two sets of concentrations will then be more than adequate for determining the dispersion coefficients. The non tidal advective velocities to be used in these models can be obtained from a physical model. See Section 2 of this part.

A two layered segmented model of the dispersion and flushing of pollutants in partially stratified estuaries is given by Pritchard (7). This model gives the concentrations, averaged over a tidal cycle, of a pollutant discharged at a fixed rate into a constant discharge of river water entering the estuary. It requires a knowledge of the longitudinal and vertical distributionsof the average (averaged over a tidal cycle) salinities. If the distribution of the average longitudinal salinity is known then the vertical distributions of the average salinities along the estuary can be determined from the model of Fisher, Ditmar and Ippen (12) described in Part 1, Section 2. The horizontal salinity distribution can be obtained from field observations or a model or by the computational models of Thatcher and Harlemann (10) or the model of Dailey and Harleman (1). In Pritchard's model it is assumed that there is immediate mechanical mixing of pollutants introduced into a segment of the estuary - in other words high local concentrations in the vicinity of an outfall are ignored. Pritchard's model can also be used to compute the steady state distribution of temperature along a partially stratified estuary resulting from the constant discharge into the estuary of hot water at a fixed temperature (25).

A mathematical model for computing the concentrations of pollutants in embayments with or without rivers entering the embayments is given by Fischer (31). Flows and dispersive processes in the embayment are two dimensional, varying laterally and assumed to be independent of depth; flows and dispersive processes in the river are assumed to be one dimensional. In the two dimensional model the displacements of conceptual marker particles over the duration of a flood tide or an ebb tide are determined. A diffusive step is carried out by assigning to each grid point the concentration associated with a marker particle. This concentration is the average of the concentrations of the five grid points which are closest to that particle at the commencement of the tidal phase.

The spacing of the computational grid of the embayment is determined from the average spread of a dispersing cloud at the end of a tidal phase (flood or ebb) associated with a slug of pollutant which has been introduced into the embayment at the beginning of the tidal phase. Formulae for the spread of the cloud, based on the average velocity over a tidal phase of the centroid of the cloud and the average depth of water traversed by the centroid are given on pages 129 and 130 of Reference 31.

In the river, which may be branched, the channels of the one dimensional network are divided schematically into segments of uniform depth and width and the water within each segment is subdivided into volume elements each having its own concentration. The elements are moved up and down the segments and diffusion occurs between adjacent elements. Flow from one segment to another is simulated by subtracting volume from the endmost element of the outflow segment and creating with that volume new elements in the inflow segments. Each time step in the programme consists of three parts: (1) An advective step in which the elements are moved along the segments. (2) A diffusive step in which mass transfer occurs between adjacent elements and (3) An interaction step in which the growths or decays of the concentrations of the interacting water quality parameters are computed. A detailed description of this one dimensional programme is given in Reference 32.

In the river Fischer (31) computes the velocities and water surface heights by using the method of characteristics on a fixed grid; in the embayment they are computed on a square grid according to the rules given by Lendersee (33). Alternatively the velocities and water surface heights can be obtained from a physical model. In an investigation of the concentrations of non conservative substances, the Fischer model might be used to determine the dispersion coefficients from the concentrations of hypothetical conservative substances introduced into the model (as outlined above in the discussion on the models of O'Connor and Thomann). The dispersion coefficients so determined would then be used to obtain, from the models (25, 29) described above, the concentrations of non conservative substances.

A diagram showing the roles of a physical model, Fischer's model and a two dimensional water quality model, such as that described by O'Connor and Thomann, is given in Section 2.

The computer model of Dailey and Harleman (1) predicts time varying concentrations in single or branched one dimensional channels. The computational steps are as follows:- At a given time step the hydraulic equations are solved, these equations including the density effects of the longitudinal salinity distribution. The salinity distribution at the previous time step is used. From this salinity distribution new dispersion coefficients are computed for the grid points using the formulation of the dispersion coefficient given by Thatcher and Harleman (see Part 1 Section 2 and Reference 10). With these dispersion coefficients the new salinity distribution is determined and the concentration distributions of the other components are computed sequentially (in this case the components are temperature excess, biochemical oxygen demand and dissolved oxygen deficit).

The numerical procedure uses finite elements incorporating the method of weighted residuals. This procedure is said to yield higher numerical accuracy and to use less computer time than is the case with standard finite difference procedures and the procedure based on the method of characteristics.

Consider a one dimensional estuary. By way of definition let K_α denote the scale ratio of a prototype quantity α to the model quantity α

Let K_x = horizontal distance scale ratio
" K_y = vertical " " "
" K_z = " " " "
" K_t = time scale ratio
" K_u = velocity scale ratio
" K_c = Chezy coefficient scale ratio
" K_n = Manning's " "
" K_E = Dispersion coefficient scale ratio
" K_R = Reynolds number scale ratio

Then from the hydrodynamic equations and the salt diffusion equation the following relationships are obtained:-

$$K_t = K_x / K_z^{1/2}$$
$$K_u = K_z^{1/2}$$
$$K_c = K_x^{1/2} / K_z^{1/2}$$
$$K_n = K_z^{2/3} / K_x^{1/2}$$
$$K_E = K_z^{1/2} K_x$$
$$K_R = K_z^{3/2}$$

These relationships imply that prototype and model Froude numbers are the same. Assuming the formula for E given by Thatcher and Harleman (10) we have:-

$$E = K \left|\frac{\partial \overset{\circ}{S}}{\partial \overset{\circ}{x}}\right| + E_T ,$$

where the quantities on the right hand side are defined in Part 1, Section 2. Applying the above scale ratios to this formula we have the following requirements:-

$$E_{PROTOTYPE} = K_z^{1/2} K_x \left[K \left|\frac{\partial \overset{\circ}{S}}{\partial \overset{\circ}{x}}\right| \right]_{MODEL} + \frac{K_z^2}{K_x^{1/2}} \left[E_T\right]_{MODEL}$$

On the other hand the hydrodynamic and salt balance require that:-

$$E_{PROTOTYPE} = K_z^{1/2} K_x \; E_{MODEL}$$

Over the whole length of a tidal river these two requirements can only be met if $K_z^{1/2} K_x = K_z^2 / K_x^{1/2}$ i.e. if $K_x = K_z$. However, in the saline reaches of a river the term $K \left|\frac{\partial \overset{\circ}{S}}{\partial \overset{\circ}{x}}\right|$, the so called densimetric term, is so much bigger than E_T that the latter term can be neglected and hence in these reaches the distorted scale model will correctly simulate the dispersion coefficient.

It follows that a distorted scale model can only be used to simulate the dispersion of a dissolved substance in the lower saline reaches of a river and that the model must itself be a salinity intrusion model connected to a body of water of the same salinity as the prototype ocean. In bodies of water of uniform density, i.e. in the fresh water reaches of tidal rivers or in embayments where the salinity is nearly that of the ocean a distorted scale model cannot be used for this purpose.

For the scales $K_x = 1000$ and $K_z = 100$, scales which have been widely used, the Reynolds number scale ratio is $K_R = 100^{3/2} = 1000$. In the lower reaches of a typical N.S.W. coastal river the average value of the prototype Reynolds number would be about 2×10^6 and hence the corresponding model Reynolds number would be $2\times10^6/1000 = 2000$. This is a low Reynolds number and the model will not simulate the fully developed prototype turbulence to which the Manning and Chezy resistance coefficients apply and which provides the degree of mixing required by the dispersion coefficient. To overcome this defect, resistance elements in the form of vertical strips (18) have been used.

With the exception of temperature distributions a physical model can only be applied to conservative substances. This is seen in the fact that for a prototype substance with a decay rate μ, the model substance would have to have a decay rate of $K_t\mu = \frac{K_x}{K_z^{1/2}}\mu$. For scales $K_x = 1000$ and $K_z = 100$ this implies that the model substance would have to have a decay rate of 100 times the prototype substance - and a substance with this property would be difficult to find.

For longitudinal temperature distributions the scale relationship can be derived from the following equation

$$\frac{\partial}{\partial t}(hT) + \frac{\partial}{\partial x}(uhT) - \frac{\partial}{\partial x}\left(hE\frac{\partial T}{\partial x}\right) = -\frac{K(T-E_T)}{\rho c_p}$$

This equation is the one dimensional equivalent of 4.8 given by Edinger in Chapter IV of Reference 25. If the model is to simulate temperature distributions in the saline reaches of a river so that $K_E = K_z^{1/2} K_x$ and if density ρ, specific heat c_p and cooling coefficients across the water surface are the same in model as in prototype, then we must have:-

$K_z / K_t = 1$ i.e. $K_x = K_z^{3/2}$. A model with scales $K_x = 1000$ and $K_z = 100$ would satisfy this requirement.

As pointed out in Part 1, a computer model would serve better for dispersion studies of conservative substances in a tidal river which has a single channel in the saline reaches. On the other hand, for reasons pointed out in Part 1, a physical model might serve better for dispersion studies in rivers which are multi branched in these reaches. It is a reasonable assumption that in such a river, the densimetric dispersion coefficients, while they might differ from the dispersion coefficients given by the formula of Thatcher and Harleman (10) for a single channel, will nevertheless conform to the scale relationship implied by that formula:-

$$E_{PROTOTYPE} = K_z^{1/2} K_x E_{MODEL}$$

This model can be used to measure the salinities required for determining dispersion coefficients required in the mathematical water quality model of Thomann (29) and O'Connor and Thomann (25). The method of determining these non tidal advective dispersion coefficients from the longitudinal salinity distribution is given in the appendix to this part.

For measuring salinities a physical model could be justified as an alternative to expensive and time consuming field observations (see Part 1 and the appendix to this part). It should be borne in mind, in considering the use of a computational model for obtaining salinities in the Hawkesbury River, that with the Colo River, Macdonald River and Mangrove Creek as principal tributaries, this river is multi-branched in the saline reaches and hence the abovementioned computational models do not apply if there is significant fresh water flow in these tributaries. If these flows are small the schematisation given by Thatcher and Harleman (10) can be applied in the computation of salinities in the main river channel. In this schematisation the branches are treated as side channel storages. The non advective dispersion coefficients in the fresh water reaches can be obtained from the tidal velocities given by the physical model, using the formula given by Harleman in Reference 30. Alternatively, the tidal velocities can be obtained by cubature, using data given by the tidal gradient diagram of the river (34).

Assuming scales $\kappa_x = 1000$ and $\kappa_z = 100$, the minimum space required for a model of the tidal reaches of the Hawkesbury River and its tributaries is estimated to be 90 feet x 150 feet. It is assumed that in this model the layout of the river and its tributaries would have been radically altered to conserve space.

In a two dimensional model (velocities u and v varying laterally) of an embayment $\kappa_x = \kappa_y$, $\kappa_u = \kappa_v$ and the other hydrodynamic scale ratios are those listed for the one dimensional model. In an embayment of uniform salinity, however, the scale ratios for the dispersion coefficients ($\kappa_{Ex} = \kappa_z^{1/2} \kappa_x = \kappa_{Ey} = \kappa_z^{1/2} \kappa_y$) inferred from the diffusion equation, are only compatible with the scale ratios for the dispersion coefficients ($\kappa_{Ex} = \kappa_z^2/\kappa_x^{1/2} = \kappa_{Ey} = \kappa_z^{1/2}/\kappa_y^{1/2}$), inferred from the expressions of Elder quoted by Fisher on pages 128, 129 of Reference 31, if $\kappa_x = \kappa_y = \kappa_z$. Models with undistorted scale ratios are only feasible for small relatively deep embayments.

The probable effect of surges in embayments is to increase the dispersion coefficients given by Elder, especially the dispersion coefficients transverse to the flow streamlines. It is estimated that the average magnitude of the fluctuating velocities associated with a surge of 1 minute period and 3 inches amplitude (the maximum amplitude of the surges in Port Kembla Harbour is about 6 inches (35)) would be roughly 0.3 f.p.s., which is of the same order of magnitude as the tidal velocities.

A two dimensional physical model can provide the hydrodynamic data for mathematical models of dispersion processes. Fig. 6.8 shows the role of a physical model in water quality studies.

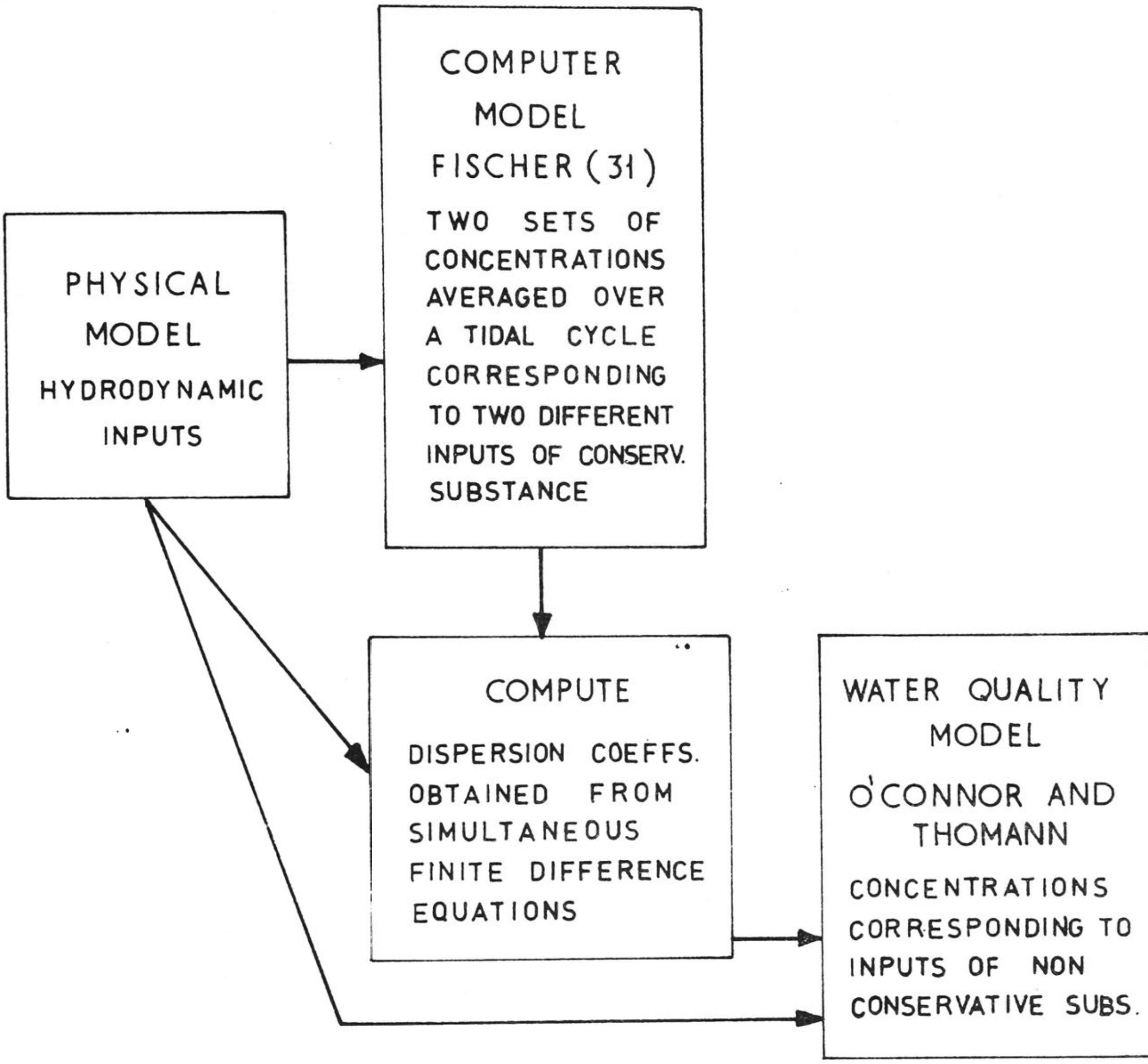

PHYSICAL
MODEL
HYDRODYNAMIC
INPUTS
COMPUTER
MODEL
FISCHER (31)
TWO SETS OF
CONCENTRATIONS
AVERAGED OVER
A TIDAL CYCLE
CORRESPONDING
TO TWO DIFFERENT
INPUTS OF CONSERV.
SUBSTANCE
COMPUTE
DISPERSION COEFFS.
OBTAINED FROM
SIMULTANEOUS
FINITE DIFFERENCE
EQUATIONS
WATER QUALITY
MODEL
O'CONNOR AND
THOMANN
CONCENTRATIONS
CORRESPONDING TO
INPUTS OF NON
CONSERVATIVE SUBS.

FIGURE 6·8

APPENDIX TO PART 2: THE DETERMINATION OF NON TIDAL ADVECTIVE DISPERSION COEFFICIENTS AND THE CONCENTRATIONS OF SUBSTANCES IN THE SALINE REACHES OF TIDAL RIVERS.

Let x = distance along an estuary measured upstream from the mouth
" $\bar{s}$ = salinity averaged over a tidal cycle
" $\bar{A}$ = area of waterway averaged over a tidal cycle
" $\bar{E}$ = non tidal advective dispersion coefficient
" Q_f = fresh water discharge (assumed constant)

Then for a constant fresh water discharge and an unvarying tidal oscillation at the entrance, we have

$$Q_f \frac{\partial \bar{s}}{\partial x} + \frac{\partial}{\partial x}\left(\bar{A}\,\bar{E}\,\frac{\partial \bar{s}}{\partial x}\right) = 0$$

i.e. $$Q_f\,\bar{s} + \bar{A}\,\bar{E}\,\frac{\partial \bar{s}}{\partial x} = \text{cons}$$

At the limit of salinity intrusion $\bar{s} = 0$ and $\frac{\partial \bar{s}}{\partial x} = 0$ and therefore cons = 0

$$\therefore\ \bar{E} = \frac{-Q_f\,\bar{s}}{\bar{A}\,\frac{\partial \bar{s}}{\partial x}} \qquad (1)$$

For (1) see the chapter by Harleman in Reference 25. Let c_ℓ = concentration, averaged over a tidal cycle, of a dissolved substance at the average upstream limit of the salinity intrusion which is distant ℓ from the mouth. It is assumed that the substance being studied is injected into the freshwater flow at a constant rate q and that the location of the injection point is sufficiently far upstream from the point ℓ for complete cross sectional mixing to occur at ℓ

We then have $$Q_f \frac{\partial \bar{c}}{\partial x} + \frac{\partial}{\partial x}\left(\bar{A}\,\bar{E}\,\frac{\partial \bar{c}}{\partial x}\right) = 0 \qquad (2)$$

i.e. $$Q_f\,\bar{c} - \bar{A}\,\bar{E}\,\frac{\partial \bar{c}}{\partial x} = \mu_1$$

Substituting for E from (1) we obtain

$$\frac{\partial \bar{c}}{\partial x} - \frac{1}{\bar{s}}\,\frac{\partial \bar{s}}{\partial x}\,\bar{c} = -\frac{\mu_1}{Q_f\,\bar{s}}\,\frac{\partial \bar{s}}{\partial x}$$

where μ_1 is a constant

Integrating again we obtain

$\bar{c} = \mu_2\,\bar{s} + \frac{\mu_1}{Q_f}$ where μ_2 is a constant.

From the boundary conditions $\bar{c} = c_\ell$ at $\bar{s} = 0$ and $\bar{c} = 0$ at $\bar{s} = s_0$, the ocean salinity at $x = 0$, we obtain

$$\bar{c} = \left(1 - \frac{\bar{s}}{s_0}\right) c_\ell \qquad (3)$$

At point ℓ the salinities are zero or are so small river water can be regarded as being undiluted by salt water. At ℓ, therefore $c_\ell = \frac{q}{[illegible]}$ and we obtain $\bar{c} = \left(1 - \frac{\bar{s}}{[illegible]}\right)\frac{q}{[illegible]}$

(4)

Similarly for the high water slack and low water slack salinities S_{HS} and S_{LS}, we obtain the following expressions:

$$C_{HS} = \left(1 - \frac{S_{HS}}{S_o}\right) \frac{q}{\gamma Q f} \tag{5}$$

$$C_{LS} = \left(1 - \frac{S_{LS}}{S_o}\right) \frac{q}{\gamma Q f} \tag{6}$$

Within a tidal cycle concentrations of dissolved substances at a station vary as water is moved up and down the estuary. The variation of concentration at a station of a conservative substance within a tidal cycle is given by the following advective equation:

$$\frac{\partial c}{\partial t} + v_T \frac{\partial c}{\partial x} = 0 \tag{7}$$

where v_T is the tidal velocity .

Put $$c = \left(1 - \frac{S}{S_o}\right) \frac{q}{\gamma Q f} \tag{8}$$

Then it can be shown by direct substitution that (8) satisfies (7). Equations (4), (5) and (6) are special cases of (8).

For a constant fresh water flow, tidal fluctuation and injection rate the concentrations of non conservative substances change very little from one tidal cycle to the next. If then $\bar{c}$ = the concentration at a station, averaged over a tidal cycle, at a given date, of a non conservative (or conservative substance), the instantaneous concentration at a station within a tidal cycle is given by:

$$c = \frac{\left(1 - \frac{S}{S_o}\right) \bar{c}}{1 - \frac{\bar{S}}{S_o}} \tag{9}$$

where S is the instantaneous salinity at the station. Equation (9) satisfies (7). Equation (8) is a special case of (9).

Similarly if C_{HS} and C_{LS} are the concentrations at high water slack and low water slack we have

$$c = \frac{\left(1 - \frac{S}{S_o}\right) C_{HS}}{1 - \frac{S_{HS}}{S_o}} \tag{10}$$

$$c = \frac{\left(1 - \frac{S}{S_o}\right) C_{LS}}{1 - \frac{S_{LS}}{S_o}} \tag{11}$$

Assume that a dissolved substance in an estuary is carried up a tributary by tidal action. Let c_J and S_J be, respectively, the mean concentration of a substance and the mean salinity at the junction of the tributary and the estuary. Then for a conservative substance it can be shown that the average concentration $\bar{c}$ at a station in the tributary, when the average salinity at the station is $\bar{S}$, is given by

$$\bar{c} = \frac{\bar{s}}{\bar{s}_\gamma} \; \bar{c}_\gamma \tag{12}$$

In this case, for a conservative or non conservative substance, it can be shown that the instantaneous concentration at a station is given by

$$c = \frac{s}{\bar{s}} \; \bar{c} \tag{13}$$

where s, $\bar{s}$ and $\bar{c}$ refer to the quantities observed at a station.

Expressions identical in form with (12) and (13) can be obtained wherein the concentrations and salinities averaged over a tidal cycle are replaced by their high water and low water slack values. The field salinity observations required to obtain the salinities at a station are described in Part 1, Section 1.

In cases more complex than those described above, the values of $\bar{c}$, c_{HS} or c_{LS} can be computed from the mathematical models of O'Connor and Thomann (25) and Thomann (29), described in the main text if the dispersion coefficient $\bar{E}$, E_{HS} or E_{LS} are known. These in turn require a knowledge of the distribution of $\bar{s}$, s_{HS} or s_{LS} along the estuary and its tributaries (see (1) above and expressions identical in form with (1) for E_{HS} and E_{LS}). These salinities can be obtained from a physical model. The limitation set on computer models (1, 10) for determining salinities in a river with tributaries in the saline reaches is described in the main text.

The determination of the distribution of these salinities in the Hawkesbury River and its tributaries requires the following field observations:-

A minimum of twenty recordings of depth averaged salinities at stations along the main river from Broken Bay to Sackville and a minimum of five recordings at stations along the Colo and Macdonald Rivers and Webb's Creek. The depth averaged salinity at a station would require a minimum of two observations: one near the surface and one near the bottom. Several sets of these 35 records of depth averaged salinities would be required to accord with varying fresh water flows. The observations in each set would be made, say at spring tides, and at each station salinities would be observed at two successive high water slacks and the two corresponding low water slacks; these four sequences of observations enable estimates of salinities to be made which take into account the effects of varying tidal fluctuations. The observations would be made on the same tidal fluctuations as they propagate from station to station up and down the river. Five launches would be required, two for the river and three for the tributaries operating continuously over a period of about 24 hours.

A physical model checked against a limited record of salinities might be a less expensive alternative to the above field observations in determining these salinity distributions along the river and its tributaries.

The following departments have data on the salinities in the Hawkesbury River and other coastal rivers:-

The Department of Public Health N.S.W.

The Commonwealth Scientific and Industrial Research Organisation, Fisheries and Oceanography Division, Cronulla.

State Fisheries.

The Department of Agriculture N.S.W.

The Metropolitan Water, Sewerage and Drainage Board.

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CHAPTER 7: LEVEED RIVERS IN COASTAL FLOOD PLAINS: REGIME STUDY.

Introduction

The natural levees of the large rivers on the coast of New South Wales are among the highest in the world. Generally, they are suited to intense cultivation and they prevent the frequent flooding of the lands behind them by freshes and minor river floods.

Neither in libraries here nor in the libraries which he has visited in U.S.A. has the writer been able to find anything of a quantitative nature on the regime of leveed rivers or on the formation of their levee banks. Professor S.A. Schumm, an authority on river regime, informed the author (by letter of 23.8.71) that he did not know of references to this subject. Accordingly, the regime relationships presented in this report are the result of an independent investigation. The relationships for the levels of the levee crests and channel bed are based on the assumption that a leveed channel will adjust its dimensions so as to -

(a) match its capacity for transporting bed material to the supply of bed material from upstream sources,and

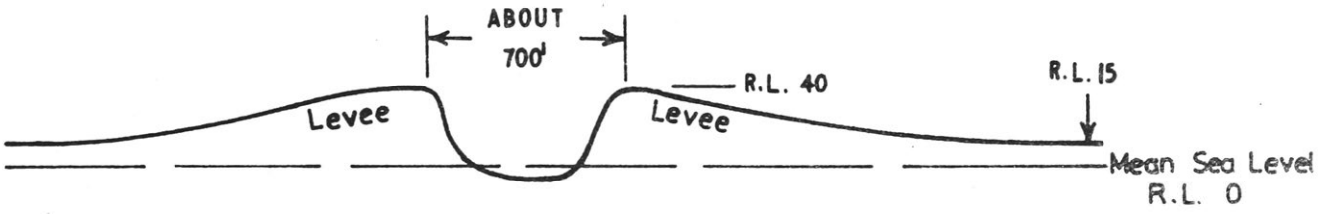
(b) ensure that the channel depth is consistent with the stability of the banks determined by the proportion of fine sediment in the channel perimeter.

Fig. 7.1 is an average cross section of the Hawkesbury R. along Freeman's Reach (the reach immediately downstream from Richmond Bridge). Here the crests of the levee banks are 25 feet above the flood plain behind them. The levees of other large N.S.W. coastal rivers are of comparable heights.

Fig. 7.2 shows diagrammatic cross sections of leveed rivers in flood plains. The heights above base level of the river bed, the levee crest and the flood plain are denoted, respectively, by "h_c" "h_L" and "h_{FP}". The case illustrated by cross section (b), where the river bed level is greater than the level of the flood plain behind the levees is not encountered on our coastal rivers but is encountered elsewhere (1,2).

In the case of the Hawkesbury River and other coastal rivers with drowned valleys, the present flood plains came into existence as deltas as the rivers filled their valleys with sediments in response to rises in mean sea level following periods of glaciation (see Chapters 1 and 2). This growth of flood plains is described in References 3,4,5 and 6. In certain cases a stream discharging into waters impounded by a dam will lay down deposits which model the formation of these river flood plains. The processes involved in the formation of the sedimentary deposits laid down by these streams, in response to a rise in base level are similar to the processes involved in the formation of sedimentary deposits laid down by a river in response to a rise in mean sea level. An example (9) is the delta built up by the Washita River behind the Denison Dam in Texas within a decade after the filling of the dam. This delta is in the form of a floodplain wherein the river flows between levees. With the growth of the deltas forming the flood plains of our coastal rivers there were primary levee formations (termed 'primary' to distinguish them from the levees formed after the river had changed course in the emergent flood plain). These primary levee formations are seen in the deltaic forms of small streams flowing into lakes such as Middle Ourimbah Creek entering Lake Narrabeen, Ourimbah Creek entering Tuggerah Lake, and Macquarie Rivulet entering Lake Illawarra (Ref. 7).

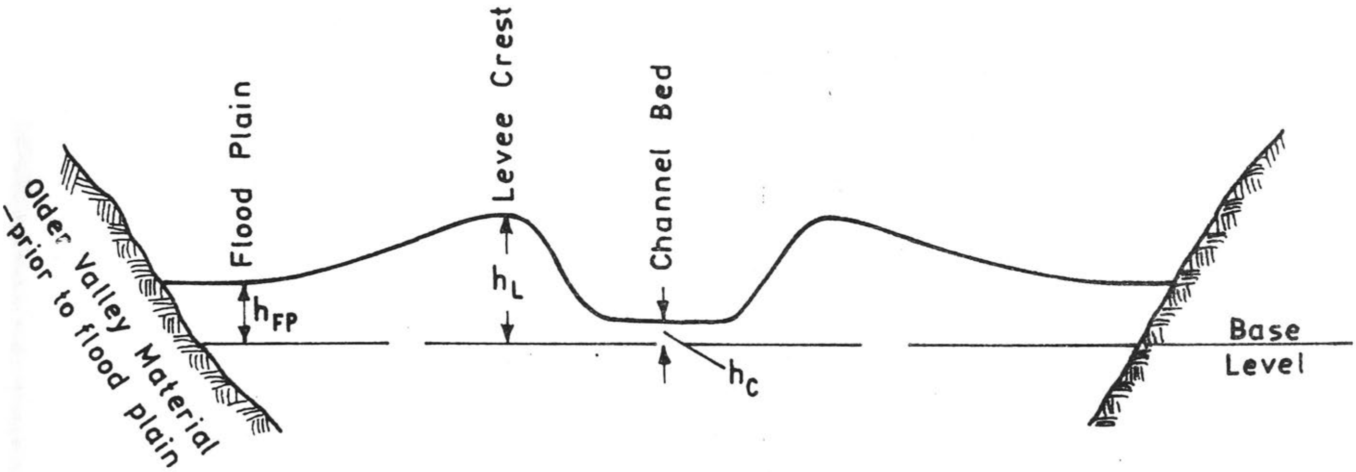
In its emergent flood plain a river changes its course by breaching its levee banks in floods ("avulsions"). Along its new course the river then proceeds to build new levees. This build up of new levees may be considered as being made up of two complementary processes: a process of bank edge deposition and a process of secondary deltaic growth (termed "secondary" to distinguish the deltaic extension of the levee banks along the flood plain from the primary deltaic growth of the whole flood plain itself, referred to above). In the process of bank edge deposition, the momentum transfer between the flow in the channel and the flow along the banks causes sediment to be transferred from the channel to the banks where, provided that the down valley slope is not excessive, (Ref. 8 pp. 101 and 102), the velocity is checked and the sediment is deposited. To quote from p. 98 Ref. 8: ". . . . . .when the flow leaves the stream its velocity is checked, and as a result the stream is unable to carry its load and deposits material adjacent to the bank". Vegetation growing along the banks promotes



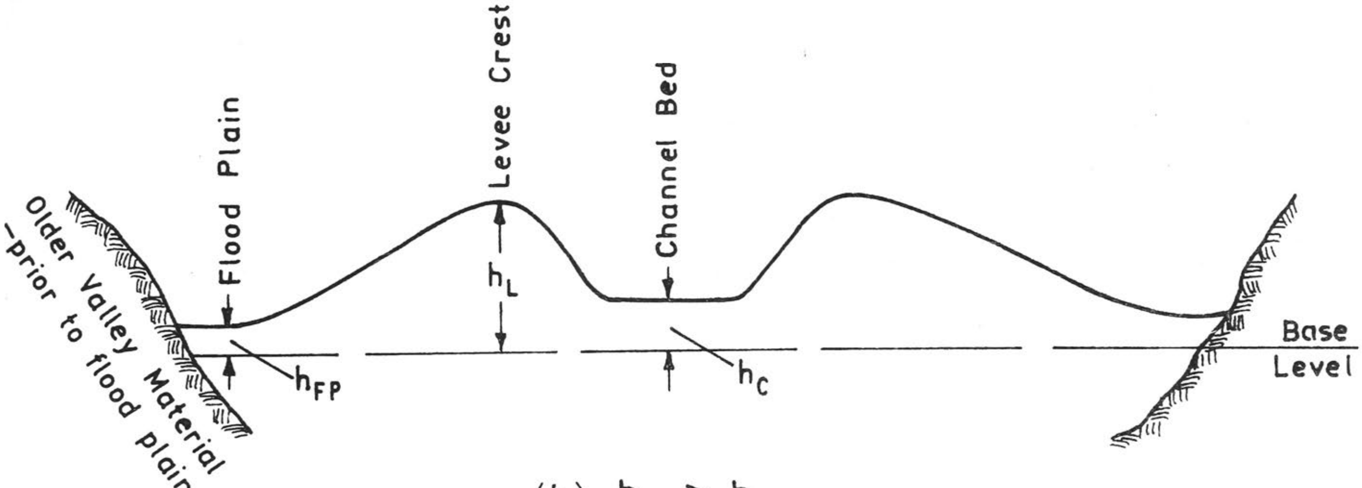
AVERAGE CROSS SECTION (Diagrammatic)
OF FREEMAN'S REACH OF THE HAWKESBURY RIVER
SHOWING THE LEVEE BANKS.

SCALES - Horizontal: 1" = 800' Vertical: 1" = 100'

FIGURE 7·1

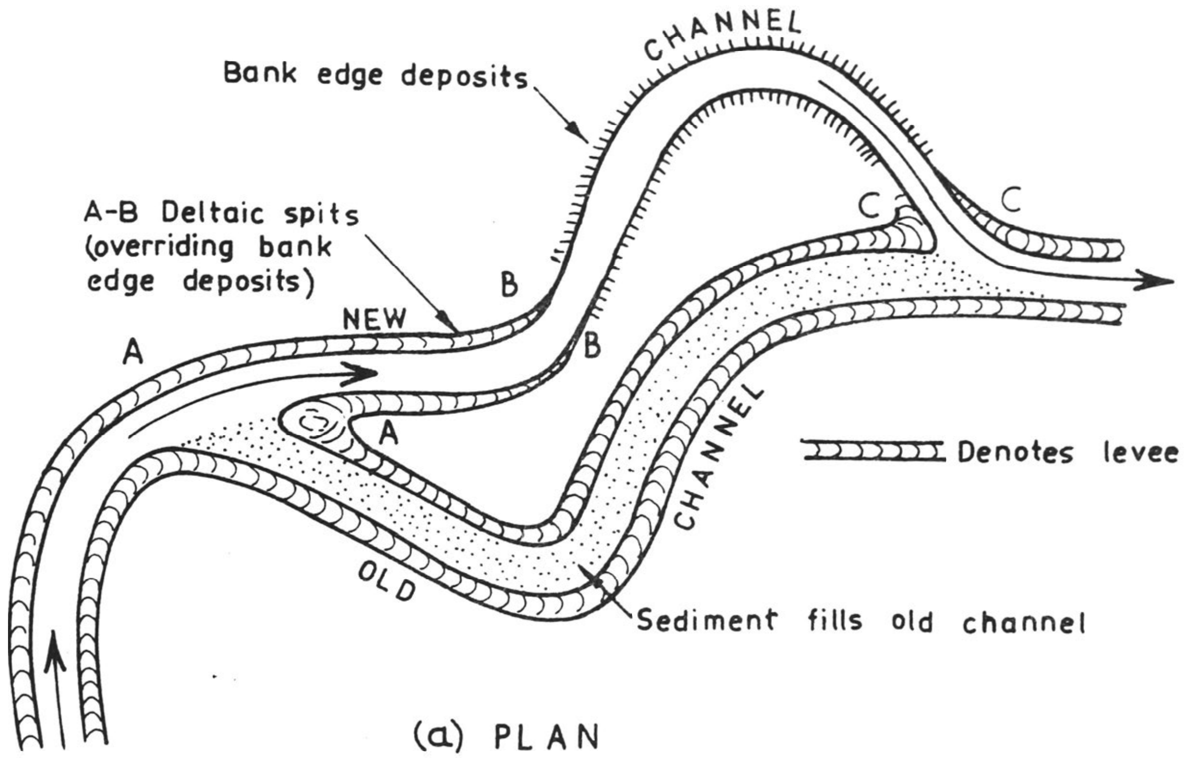


(a.) $h_{FP} > h_C$

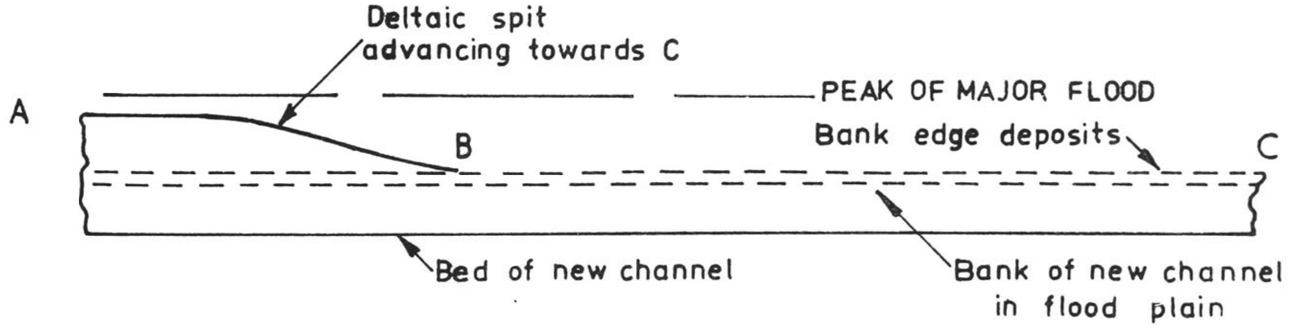


(b.) $h_C > h_{FP}$

FIGURE 7·2



(a) PLAN



(b.) LONGITUDINAL SECTION

FIGURE 7·3: SKETCHES ILLUSTRATING THE GROWTH OF LEVEES this process (p.99 Ref. 8).

Secondary deltaic growth is exemplified by the levees of Bardenarang Creek which connects the low lying areas of Pitt Town Bottoms with the Hawkesbury River. The sediment laden waters from the river in flood flow back along the creek into the ponded water of the Bottoms, depositing sediment to form these levees which taper spit-wise back from the river. The levee crest level drops from RL 27.0 ft. Standard Datum at the creek mouth to RL 12.0 in 9000 feet while the bed is approximately horizontal over this distance at RL. 3.0.

Similar levees extending back spit-wise from the river can be seen along other creeks which discharge river flood waters into back-waters.

The two complementary processes involved in the growth of levees along a new river channel are illustrated by Figure 7.3.

At A-A the leveed river has breached its banks and is flowing along a new channel to rejoin the existing channel at C-C (which like Bardenarang Creek might have been serving as an outlet for drainage and an inlet for floodwaters before the river breached its banks at A-A). Bank edge deposits have formed levees along the new channel and these levees have channelised overbank flows so that the deltaic spits growing from the breached levee banks follow the sinuous course of the new channel. To quote Dunbar and Rodgers (10) on the ability of levees to channelise overbank flows and to promote their further growth: "Once formed they tend to accentuate this difference in current and hence to perpetuate themselves, developing a definite crest next to the channel and an outward slope toward the flood plain". As bank edge deposits are produced by floods as soon as they exceed bankfull stage and as the higher portions of the deltaic spits are associated with the less frequent higher stage floods, the rate of vertical growth of a levee at any location along a new channel diminishes with the height of the levee crest above the flood plain.

This hypothesis of the processes of levee growth not only explains the formation of levees along meandering rivers but also makes plausible the extension of some of the regime relationships derived for non leveed rivers to rivers with natural levees.

Schumm (11) gives the following regime equations (which are for rivers without natural levees - letter to writer of 29.3.71):-

$$w = \frac{37 Q_m^{0.38}}{M^{0.39}}$$

$$L = \frac{1890 Q_m^{0.34}}{M^{0.74}}$$

$$P = 0.94 M^{0.25}$$

where W = channel width

L = meander wave length

P = sinuosity (ratio of channel length to valley length)

Q_m = mean annual discharge

M = percentage of silt and clay (sediment finer than 0.074 mm) in the sediments forming the perimeter of the channels.

Similar expressions for "W" and "L" involving the mean annual flood instead of the mean annual discharge are given by Schumm.

"M" has been found to be inversely related to the percentage of the total sediment load that is sand or bed material load, Q_t, at mean annual discharge, $M = 55/Q_t$ (11). (Confirmed also by the model study described in Chapter 8).

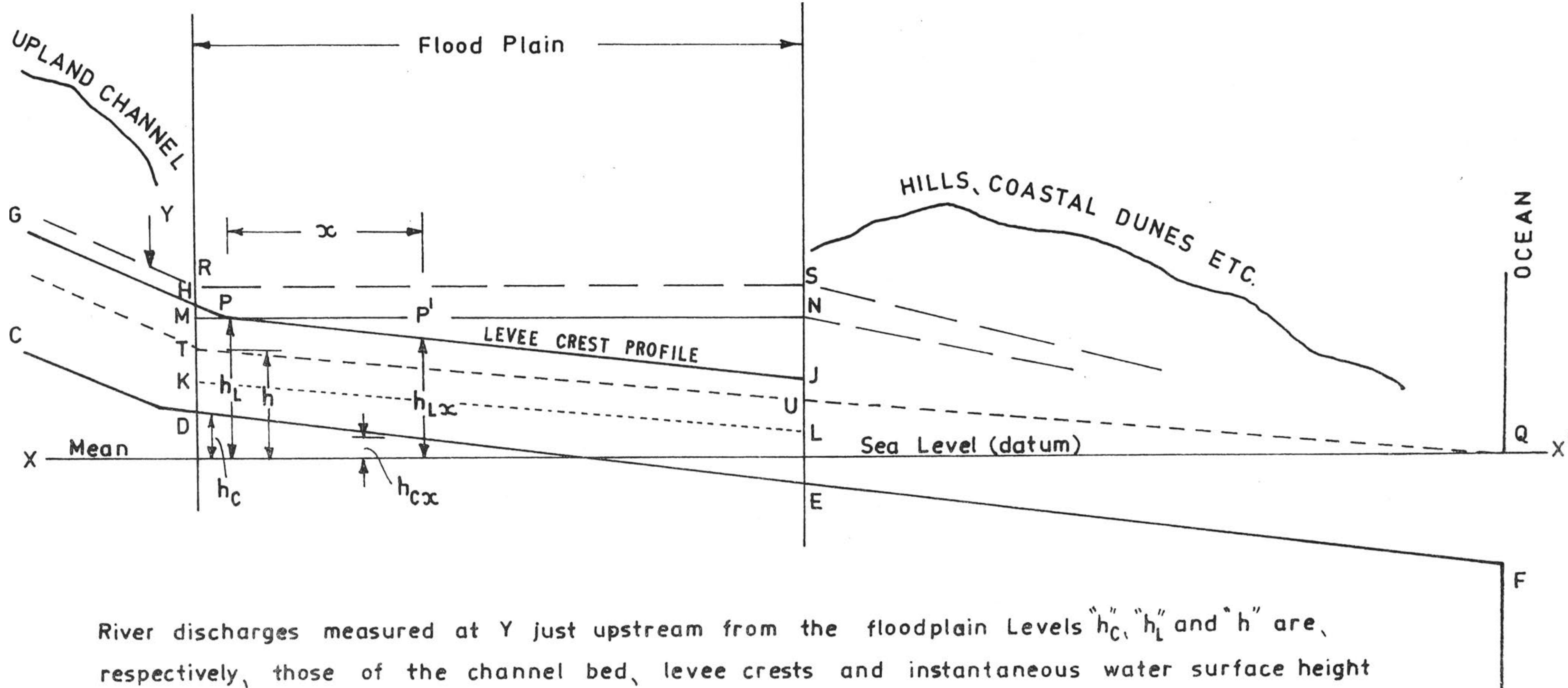
Because levees are initiated by bank edge deposits along a channel, it is to be expected that similar expressions for "W" "L" and "P", with modified coefficients and exponents, will apply to our leveed rivers. We assume, therefore, that for a leveed channel :

$$W = a \frac{Q_m^b}{M^c} \qquad \text{------------} \qquad (1)$$

As an example of the application of these regime expressions, consider the changes in sinuosity "P" which have occurred in the lower Hunter River between Maitland and Morpeth over the last hundred years or so. Since 1860 the length of the river channel has decreased from 15 miles to 6 miles. To quote from the Hunter River Flood Mitigation Report 1969 of the Public Works Department (12) "During each major flood, this tendency for the river to straighten itself became more evident and with some loops cut off, the present channel has developed more or less by natural means".

Examining Schumm's relationship for "M", namely $M = 55/Q_t$ we have, from his definition, $Q_t = \frac{100 Q_s}{Q_{total}}$ where "$\overline{Q}_s$" and "Q_{total}" are the average annual discharges of bed material load (sand) and total load respectively.

Then $M = 0{\cdot}55 \dfrac{Q_{total}}{Q_s}$



River discharges measured at Y just upstream from the floodplain Levels "h_c", "h_L" and "h" are, respectively, those of the channel bed, levee crests and instantaneous water surface height at location P at the upper end of the floodplain. Levels "h_{cx}" and "h_{Lx}" are those of the channel bed and levee crests at location P' at a distance "x" along the channel from P.

FIGURE 7·4

From Schumm's expression for "P" ($P = 0{\cdot}94\ M^{0{\cdot}25}$) we have $P = a_1 M^{b_1}$ where "a_1" and "b_1" are appropriate to local coastal rivers.

$$\text{Then} \quad P = (0{\cdot}55)^{b_1} a_1 \left(\frac{Q_{total}}{\bar{Q}_s}\right)^{b_1}$$

Hence, according to this expression, an increase in the proportion of bed material load implies a reduction in the sinuosity of the river channel.

Schumm implies that such an increase in the proportion of bed material load can result from increased erosion in the catchment area which can be brought about by deforestation or by an increase in the area under cultivation and, indeed, to quote from the abovementioned report (12): "The catchments of the Hunter River and its tributaries have been extensively denuded of trees and the lands have been badly used in the past. This has caused heavy erosion of large areas and a rapid runoff of rainwater which results in higher floods and siltation in the lower river". Hence the straightening of the channel of the Hunter River, according to the above expression for the sinuosity is consistent with an increase in the coarser fraction of the sediment load resulting from increased catchment erosion. This tendency is seen in the Macdonald River where excessive inputs of sand resulting from catchment erosion (see Chapter 1) have caused the river to straighten by shortening some of its meander loops. These decreases in sinuosity (increases in slope), resulting from an increased supply of bed material, are consistent with equation 6 in the appendix to Chapter 4.

Fig. 7.4 is a schematic cross section showing flood waters from an upland river channel flowing into a leveed river channel traversing a floodplain. Line CD is the lower end of the upland channel bed profile, DE is the channel bed profile in the floodplain and EF is the channel bed profile in the lower estuarine reaches of the river. Downstream from E the floodplain is assumed to be constricted by hills, coastal dunes etc. XX' is the base level = mean sea level in this case. HJ is the longitudinal profile of the levee crests. GH is the profile of the upland channel water surface when the discharge is running at full levee crest level between H and point P at the upper end of the floodplain, where this discharge meets the floodwaters ponded between D and E. The profile of the floodplain behind the levees is shown by the dotted line KL. Let "h_L" and "h_C" be, respectively, the levee crest level and the level of the channel bed at P, in relation to mean sea level. MN and RS are successive profiles of the surfaces of floodwaters ponded between D and E.

When the ponded surface of the floodwaters (indicated by MN) has risen to P it is assumed that the flow velocity between the levees downstream from P is small and hence the discharge of bed material, which is restricted to the cross section between the crests of the levees, ceases just below P. Let "Q" be the instantaneous water discharge in the river at a station just upstream from the floodplain. It is assumed that the discharge in the leveed channel at P is equal to "Q" when the level of the ponded water in the floodplain is less than the levee crest level "h_1".

Let "h" be the level of the channel water surface at P at a given instant when the level of the ponded floodwaters is less than "h_L" (the longitudinal profile of the water surface in the channel at this instant is shown by the dashed line TU).

Assuming a median grain size (D_{50}) of 0.45 mm for the channel bed material, a size which applies to the Hawkesbury River and other N.S.W. coastal rivers (see Chapter 1), equation 1 in the appendix to Chapter 4 gives the rate of transport of bed material:-

$$Q_s = 2.6\times10^{-4} w (1.8 + 0.4\, d^{1/2}) v^2$$
$$= 2.6\times10^{-4} w (1.8 + 0.4 [h-h_c]^{1/2}) v^2 \quad \text{------} \quad (2)$$

where Q_s = discharge of bed material (cusecs)

" v = mean water velocity (ft./sec.)

" w = bed width of channel (ft.)

Equation 1 can be replaced by the following equation, which is a close approximation for depths of flow greater than 10 ft. (the choice of equation does not affect the conclusions to be drawn from this regime study; the choice of eqn. 3., however, results in a regime formula wherein the evaluation of constants which best fit field data is made easier).

$$Q_s = 4.16\times10^{-4} w (h-h_c)^{0.27} v^2 \quad \text{----------} \quad (3)$$

Now $Q = w(h-h_c)v$, which is valid for the floodplain reaches of our coastal rivers wherein the ratio of width to depth of the leveed channels is large

$$\therefore Q_s = 4.16\times10^{-4} \frac{Q^2}{w(h-h_c)^{1.73}} \quad \text{----------} \quad (4)$$

Substituting in equation 4 the value of "w" given by eqn. 1 we obtain:-

$$Q_s = \frac{4.16\times10^{-4}}{a} \frac{M^c}{Q_m^b} \frac{Q^2}{(h-h_c)^{1.73}} \quad \text{----------} \quad (5)$$

Applying the at-a-station relation between river channel depth and discharges, given on page 244 of Ref. 13, to a leveed channel we obtain:-

$$h - h_c = p Q^r \quad \text{----------} \quad (6)$$

where "p" and "r" are constants.

Substituting the value of $h-h_c$ given by eqn. 6 in eqn. 5 we obtain:- $Q_s = \frac{4.16\times10^{-4}}{a} \frac{M^c}{Q_m^b} \frac{Q^2}{p^{1.73} Q^{1.73r}}$

$$\text{i.e. } Q_s = k \frac{M^c}{Q_m^b} Q^n \quad \text{----------} \quad (7)$$

where $k = \dfrac{4.16\times10^{-4}}{a\, p^{1.73}}$

and $n = 2 - 1.73r$

Let "$\overline{Q_s}$" be the average annual supply of bed material from the catchment upstream from the floodplain. In accordance with Schumm's definition (11) this embraces all sediment with D_{50} size greater than 0.074 mm. For the effects of sediment supply on the growth of levees see page 99 of Ref. 8 and page 70 of Ref. 14.

Based on the fact that when levees are fully developed negligible quantitites of bed material are deposited laterally beyond the leveed channel, we now make use of the continuity equation for the transport of bed material:-

For equilibrium the average annual movement of bed material past P = the average annual supply of bed material from the catchment upstream from the floodplain = $\overline{Q_s}$

The average annual movement of bed material past P = the bed material moved, on an annual average basis, by all channel discharges "Q" less than or equal to the channel discharge "Q_{h_L}" at which the level of the water in the channel at P equals "h_L", the level of the water ponded over the floodplain.

Let the water flow duration curve at the station just upstream from the floodplain be given in terms of the percentage "p" of the time that the discharge is less than or equal to "Q". Let "T" = number of seconds in a year.

Then from eqn. 7: $Q_s \frac{\Delta t}{T} = k \frac{M^c}{Q_m^b} Q^n \frac{\Delta t}{T}$

$$= \frac{k}{100} \frac{M^c}{Q_m^b} Q^n \Delta p$$

$$\therefore \overline{Q_s} = \frac{1}{T} \int_0^{t(Q_{h_L})} Q_s \, dt$$

$$= \frac{k}{100} \frac{M^c}{Q_m^b} \int_0^{p(Q_{h_L})} Q^n \, dp \quad \text{------------------} \quad (8)$$

where "$t(Q_{h_L})$" and "$p(Q_{h_L})$" are, respectively the number of seconds in a year and the percentage of the time that the discharge is less than or equal to "Q_{h_L}".

In deriving eqn. 8 it has been assumed that eqn. 6 is applicable to discharges at P in the falling stages as well as the rising stages of a flood. This is approximately true as long as the peak flood discharge is less than "Q_{h_L}", but not necessarily so otherwise. However, the annual discharge of bed material attributable to the falling stages of floods with discharges greater than "Q_{h_L}" is only a small fraction of the annual discharge of sediment past P and hence a small adjustment to the quantities "k" and "n" in eqn. 8 would accommodate all discharges. It must be borne in mind that eqn. 8 is a regime relation applicable to leveed rivers in coastal flood plains having sandy beds, with D_{50} sizes in the 0.4 mm to 0.5 mm and that the values of "k"

and "n" are to be found by statistical analyses of field data. This being so, the adjustment to these coefficients involved in the application of eqn. 6 to all discharges, would be much less than the scatter in their values determined from field data, a scatter to be expected in any regime formula based on a conceptual model with a small number of parameters.

The levee crest level "h_L" is obtained from eqn. 8 and the relationship that exists between the surface level of the water ponded over the floodplain and the discharge at the station just upstream from the floodplain. The argument above concerning floods with discharges in excess of "Q_{h_L}" implies that in determining "h_L" from eqn. 8 the surface levels of the ponded waters to be considered are those corresponding to the rising stages of each flood. The relationship between the ponded water levels and the discharges would be obtained from flood records or, if these records were inadequate, by computation. For a flood with a given discharge hydrograph, the surface level "h" of the ponded water can, in the case of the floodplain shown in Fig. 7.4, be derived from eqn. 9:-

$$\text{Inflow} = Q = \frac{dS}{dt} + \text{Outflow}$$

$$\text{i.e.} \quad Q = \frac{dS}{dh}\frac{dh}{dt} + f(h) \qquad (9)$$

where S is the storage in the floodplain

$\frac{dS}{dh}$ is the rate of increase of storage with

$f(h)$ is the outflow which varies with "h" (the effect of ocean tides on major flood discharges in large rivers is negligible)

$Q = Q(t)$ is the discharge of a flood with a given hydrograph

The relationship between "h" and "Q" will vary with the flood being considered and the establishing of an average relationship between these two quantities necessitates analyses of a range of floods with varying flood discharge hydrographs. In the case of the Hawkesbury River floodplain the relationship between "h" and "Q" varies not only with the upland flood discharge hydrograph but also with flood discharges in the Colo and Macdonald Rivers downstream from the floodplain, and many more floods would have to be analysed in establishing an average relationship between "h" and "Q".

Having established this relationship, a trial value of "h" is chosen and the percentage of the time "$p(Q_h)$" that the discharge is less than the corresponding discharge "Q_h" is obtained from the discharge-duration curve. Using this percentage "$p(Q_h)$" the annual discharge of sediment past P is computed from eqn. (8). This procedure is repeated with other trial values of "h" until the computed annual bed material discharge past P is found to be equal to the bed material "$\overline{Q_s}$" supplied annually from upstream. The corresponding value of "h" is then equal to "h_L", the level of the levee crest.

Implicit in the use of the relationship between "h" and "Q" is the assumption that this relationship is independent of the geometry of the leveed channel in the floodplain. This assumption is warranted by the fact that in nature there are openings in the levees at intervals along the channel permitting the ingress of water from the channel to the floodplain behind the levees. These openings suffice for the rapid filling up of the floodplain, otherwise when the levees are overtopped there would be heavy scour with the enlargement of existing openings or the formation of new ones. Thus we have established through eqn. (8) that "h_L" directly depends on "$\overline{Q}_s$" in the sense that if "$\overline{Q}_s$" increases then "h_L" increases and if "Q_s" decreases then "h_L" decreases.

It is to be borne in mind that eqn. 8 only applies at the top end of the floodplain where the channel discharge, as long as it is confined between levees is equal to the discharge at a station in the river just upstream from the floodplain. This is not true further downstream. Moreover downstream, especially near the floodplain exit, it is not true that the flow velocities in the leveed channel are negligible when the level of the ponded waters rise above levee crest level.

As described below, an expression for the crest levels of levees downstream from P is obtained by applying the form of Schumm's expression for channel slope (11) to a leveed channel. It is, of course, evident that an increase or decrease in "h_L" at P implies, respectively, an increase or decrease in levee crest levels downstream from P.

The level of the floodplain ("h_{FP}" in Fig. 7.2) will eventually alter with changes in the sediment supply, but this will be relatively slow compared with the alterations in the heights of the levees (the overbank deposition of bed material on the floodplain is negligible and the deposition of suspended material on the floodplain is very small). An example of the comparatively rapid changes in the heights of levees which can occur is given by Walker (15): "........up to one metre thickness of sandy alluvium is reported by local residents to have been deposited along the levee of the Macleay River just north of Kempsey during the major floods of 1949 and 1950". Over the period of time in which the levee crest levels adjust to changes in sediment supply, the water storage capacity of the floodplain will not alter significantly. Hence for practical purposes changes in levee crest levels (and channel bed levels) can be regarded as being independent of changes in "h_{FP}".

For the determination of "h_C" it is assumed that the depth $h_L - h_C$ of the leveed channel can be expressed by a regime relationship similar to that developed by Schumm (see eqn. 6, Ref. 11) for unleveed channels. The assumed relationship is: $h_L - h_C = eM^f Q_m^g$

$$\text{i.e.}\quad h_C = h_L - eM^f Q_m^g \qquad (10)$$

where "e" "f" "g" are constants $f, g > 0$ and "M", "Q_m" are the parameters defined earlier in this chapter.

Adopting Schumm's relationship for "M", quoted earlier, we have

$$M = \frac{55}{Q_t} = 55 \Big/ \frac{100\,\overline{Q}_s}{\overline{Q}_f + \overline{Q}_s} = 0{\cdot}55\left(\frac{\overline{Q}_f + \overline{Q}_s}{\overline{Q}_s}\right) \qquad (11)$$

where "$\overline{Q_f}$" is the average annual supply of suspended load material from the upstream sources. This embraces all sediment < 0.074 mm diameter. It is sediment in this size range that contributes to the stability of the banks by increasing their cohesiveness (11, 16) and by providing fertile constituents for the growth of vegetation. An increase in "$\overline{Q_f}$" usually implies (eqn. 11) an increase in "M" and this implies (eqn. 10) an increase in the depth $h_L - h_C$ of the leveed channel.

Consider now the leveed channel at location P' distant "x" downstream along the channel from P. Assume that "M" and "Q_m" are constant along the channel.

Let "h_{Lx}" = level of the levee crest at P'
" "h_{cx}" " " " channel bed at P'

Adopting the form of Schumm's expression (11) for the slope "S" of the bed of a leveed channel, we obtain:-

$$S = p M^{-q} Q_m^{-r} \qquad \text{------------} \quad (12)$$

Then from $h_{cx} = h_c - xS = h_c - pM^{-q}Q_m^{-r}x$ and
$h_L - h_c = eM^f Q_m^g$ (eqn. 10) $= h_{Lx} - h_{cx}$

we obtain:

$$h_{Lx} = h_L - pM^{-q}Q_m^{-r}x \qquad \text{------------} \quad (13)$$

$$h_{cx} = h_L - eM^fQ_m^g - pM^{-q}Q_m^{-r}x \qquad \text{--------} \quad (14)$$

If "M" and "Q_m" vary along the leveed channel then eqn. (12) would be replaced by $S_{x'} = pM_{x'}^{-q}Q_{mx'}^{-r}$ and the term $pM^{-q}Q_m^{-r}x$ in eqns. (13) and (14) would be replaced by the term $p\int_0^x M_{x'}^{-q}Q_{mx'}^{-r}\,dx'$ where "$M_{x'}$", "$Q_{mx'}$" and "$S_{x'}$" are the values of "M", "Q_m" and "S" at the point "x'"

Equations (8), (10), (11), (13) and (14) can be used to predict changes in leveed channels resulting from changes in the quantity of, and the nature of the sediment brought down from upstream sources. (In Ref. 11 the effects of these changes on unleveed channels are described). The overall effects of these changes when the water discharge statistics are unaltered can be deduced immediately from an inspection of eqns. 8, 10 and 11. This would be the case of a river wherein changes in sediment supply are the result of changes in catchment land use (clearing, timber getting, burnoffs, reaforesting etc.). These effects are listed in the following table:-

Table

Average annual supply of bed material $= \bar{Q}_s$	Percentage of total annual supply of sediment that is bed material $= \frac{55}{M}$	Levee Crest level above datum (M.S.L.)	Channel bed level above datum (M.S.L.)
Increases	Unaltered	Increases	Increases
Increases	Increases	Increases	Increases
Decreases	Unaltered	Decreases	Decreases
Decreases	Decreases	Decreases	Decreases

The above effects are consistent with those given on page 70 of Ref. 14.

In the case of a river with a dam upstream which alters the water discharge statistics as well as the sediment supply, new discharge duration curves must be computed as well as estimates made of the sediments held back by the dam before eqns. 8, 10 and 11 can be applied to determine likely changes in "h_L" and "h_C". In the case of the Hawkesbury River, wherein the Warragamba Dam has radically reduced the supply of bed material to the lower reaches of the river, equations based on the above equations indicate a lowering of the levee crests and the channel bed in the floodplain. Equations similar to eqns. (2) and (3) can be derived from the curves given by Colby (17) for the transport of sandy bed material with D_{50} sizes ranging from 0.2 mm to 0.8 mm. (For the accuracy of these curves see Chapter 4). Equations similar to eqn. (8) can then be derived which, together with eqns. (10), (11), (13) and (14) provide regime relationships applicable to all leveed streams with sandy beds in the above size ranges.

Thus the levels of the levee crests and channel bed in a flood plain have been found to be dependent on the average annual supply of bed material, the D_{50} size of the bed material, the proportion of fine material $<$ 0.74 mm in the total average annual supply of sediment, the stream flow duration curve at a station just upstream from the floodplain and the average relationship between the surface height of the water ponded in the floodplain and the instantaneous flood discharge at the above station. It is considered that Schumm's expressions (11) in modified form apply to the width, sinuosity, slope and meander wavelength of a leveed channel; these quantities are, therefore, each dependent on the proportion of fine material $<$ 0.074 mm in the annual average supply of sediment and the mean annual water discharge (or the mean annual flood (11)).

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CHAPTER 8: MODEL OF THE DEVELOPMENT OF A FLOOD PLAIN.

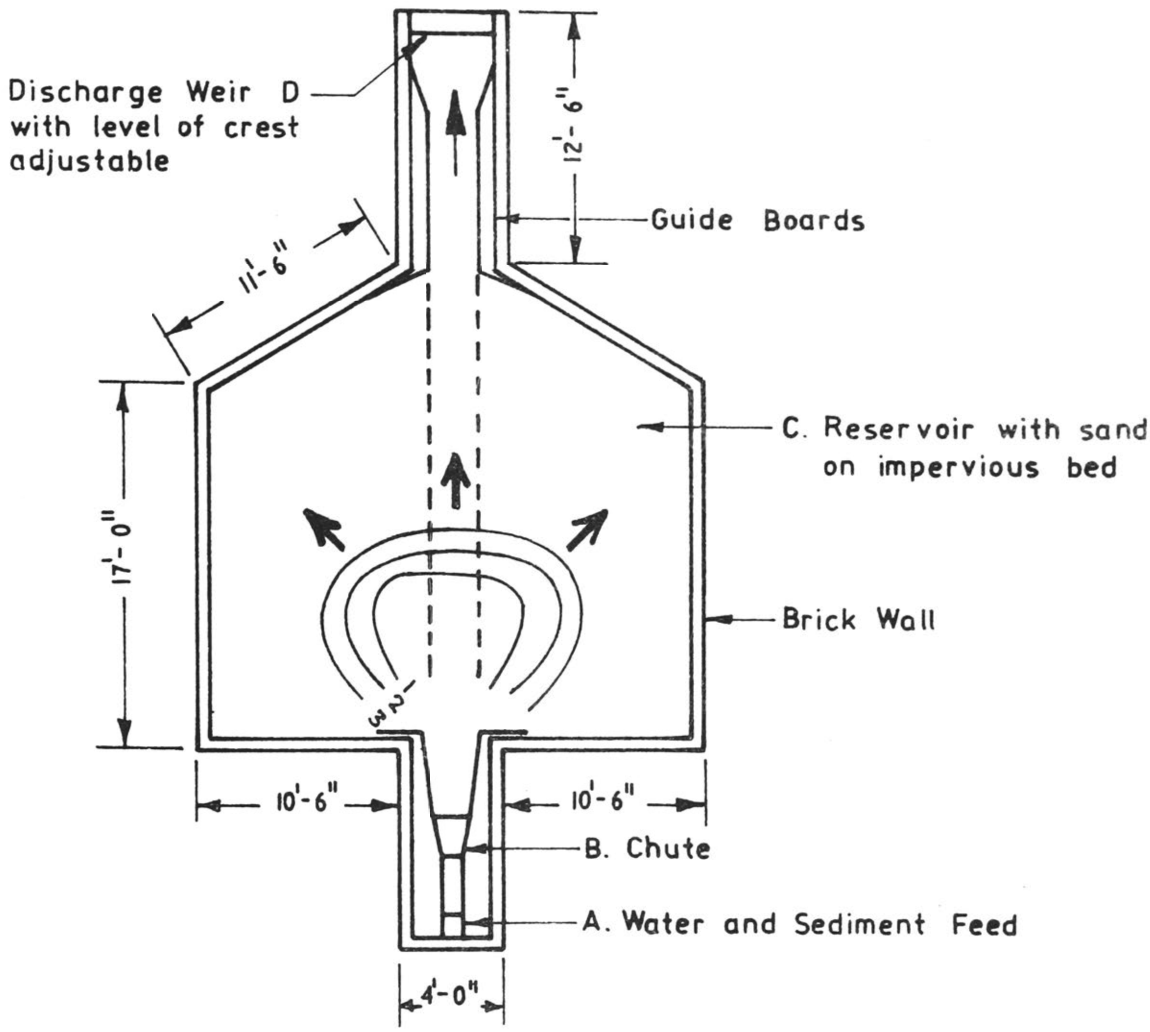
Introduction

A pilot model was constructed for the purpose of elucidating the processes involved in the formation of flood plains associated with levees, and for obtaining design information which would assist in the construction of moving bed models for investigating the effects of changes in sedimentation regime in the lower reaches of coastal rivers. The model can be regarded as that of a stream discharging sediments into the waters impounded by a dam, or a stream discharging sediments into a lake; as explained in the report on the regime study of leveed rivers in coastal flood plains, the processes involved in the formation of the deposits laid down by such a stream are similar to the processes involved in the formation of deposits laid down by rivers in drowned valleys in response to a rise in mean sea level since the last glacial phase.

The figure shows the essential features of the model which was operated with various rates of water and sediment discharge for a total of 127 hours. Measured discharges of water and sediment were fed in at "A", the sediment feed consisting of a hopper discharging sediment via a spout onto a moving belt which in turn delivered the sediment to a vertical chute which also received the water discharge. The sediment feed rate was varied by varying the distance between the spout exit and the moving belt. The water and sediment mixture flowed down the vertical chute and along the horizontal chute "B" (fitted with screens to damp out gross flow fluctuations) to the reservoir "C" wherein the sediment was deposited. The water level in the reservoir was controlled by the adjustable crest of the discharge weir "D". The concrete floor of the reservoir was covered with a blanket of sediment and the concrete floor and this initial blanket of sediment had a slope of .0027 from the exit of the feed chute to the discharge weir. An initial channel 1'-0" wide x 1-3/4" deep was excavated in the sediment blanket (shown dotted in the diagram). A sediment called "Windsor Black Loam" was used in these tests. The median diameter (i e. D_{50} size) was 0.021 mm and 13% by weight was less than 0.074 mm. This sediment was chosen because of all the commercially available sediments, it had by far the greatest percentage in the silt and clay sizes. This was considered desirable in that these fines are conducive to cohesivity and hence relatively stable channels in the deltaic deposits. Tests were made with various water discharges (up to 0.56 cusecs), and rates of sediment feed (zero to a maximum of 115 lbs/hr). The water surface in the reservoir was maintained at practically constant level, the average depth of water over the initial blanket of sediment being 3.5 inches, the purpose being to allow the simulated river with its sediment load to built up its own flood plain. The diagram shows successive stages of the deposition of sediment in the reservoir. The fan shaped deposits, labelled 1, 2 and 3, were made up of 0.675 tons, 0.955 tons and 1.52 tons of sediment.

Unfortunately, with the small median grain size of the sediment used, relatively large ripples developed in the deposits in all tests. The dimensions of the ripples, about 6" long and 3/4" high, were of the same order of magnitude as the dimensions of the deltaic formations which the model was intended to simulate and consequently the development of these forms was hindered. For example, the growth of levees by extension of the deltaic spits, downstream from the junction of the entrance channel with the reservoir, was hindered by the breaching of the banks by transverse flows between the crests and troughs of the ripples.

However, notwithstanding the distortions of formative processes caused by these ripples the model disclosed the following features of the growth of this type of bed load deposit (corresponding to the bed load deposits of a river flowing through a relatively narrow valley which expands abruptly into a broad reservoir of a dam or a lake):-



SCALE: 1" = 1'-0"

FIGURE 8·1 : PLAN OF PILOT MODEL.

(a) At any time most of the water flow on the delta was restricted to a central channel or one or two side channels.

(b) As a channel in the delta increased in length because of the sediment deposited by the channel, the resistance to flow increased, the sediment transport capacity decreased and the channel aggraded. Then a bank of the channel was breached and a new channel was scoured in the delta. One or two new channels were thus formed, which diverted flow away from the existing downstream channel. This portion of the existing channel then silted up completely. The above process was repeated with a new channel and so the delta grew forwards or sideways accordingly as a new channel was located along the centre or to one side of the delta.

(c) For a given upstream water discharge, increasing the rate of sediment input increased the rate of aggradation of the central channel and diverted flow and sediment transport to the side channels. Thus the sideways growth of the delta was greater than its growth forwards.

(d) For the same upstream water discharge, decreasing the rate of sediment input increased the rate of aggradation of the side channels and most of the flow was diverted to the central channel. Thus the forward growth of the delta was greater than its growth sideways.

(e) The percentage "M" of sediment $<$ .074 mm in the perimeters of the channels on the delta averaged 0.7. This is in good agreement with Schumm's relationship for "M" (1) given as equation 11 in Chapter 7.

(f) The observed sand discharges at the exit of the entrance channel were in good agreement with the discharges computed from the Colby relationships (2).

With a view to eliminating ripples, flume tests were carried out on various sediments. In the above model tests the maximum flow velocity attained in any test was 1.5 f.p.s. On the assumption that the maximum flow velocity in any test with a model of this size would not exceed 2 f.p.s., the velocity in the flume was maintained at 2 f.p.s. for all sediment tests.

The sediment already used in the model (D_{50}=0.21 mm) was tested with various admixtures of coarse sand (D_{50} = 2.0 mm) up to 10% by weight, but there was little reduction in the size of the ripples. "Pitt Town River Sand" (D_{50} = 0.56 mm) (supplied by Processed Sand Pty. Ltd.) was then tested in the flume. This sand produced negligible ripples and so could be used in future models. However, this sand has negligible fines less than 0.074 mm and it might be necessary to add a percentage of fines to provide enough cohesivity for the formation of stable channels and levee banks.

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CHAPTER 9: RECOMMENDATIONS

Introduction

These recommendations generally apply to all N.S.W. coastal rivers. The recommendations given under heading "A", however, apply to the Hawkesbury River with special force and urgency because of tendencies to altered regime of the river. The regime changes are described in Chapters 4 and 7 and the following tendencies are inferred: (a) for the river to become more sinuous downstream from Penrith and (b) for the levels of levee crests and channel bed to be lowered in the leveed reaches of the river. These tendencies, if unchecked, would be manifested in extensive river channel scouring, bank erosion, bank collapses and breaches in the levees.

A. Bank Stabilisation

(1) Extra stone protection should be given to banks in bends where they are subject to erosion by violent eddies when the river is in flood. The stone sizes in these situations should be at least double the stone sizes in straight reaches.

(2) To prevent bank sloughings induced by the leaching of bank material by tunnelling, the following checks and preventive measures are recommended:-

(a) The material in the river banks and banks of the drainage channels should be tested for susceptibility to tunnelling by applying the dispersability index test described in reference 25, Chapter 2.

(b) The river banks should be examined for signs of leaching of fine material, especially in areas near the toes of the banks.

(c) The areas behind the banks should be explored for tell-tale "sink holes" which attest to tunnelling. These sink holes can occur at considerable distances behind the banks.

(d) Special note should be made of local depressions and swampy patches behind the banks.

(e) Local depressions should be filled in and/or drained and swampy areas drained.

(f) Where there is evidence of tunnelling extending far back into the low regions of the floodplain consideration should be given to seepage interceptors similar in function to the interceptors installed by the N.S.W. Public Works Department in the eastern bank of the Hawkesbury River at the upper end of Argyle Reach. Generally it is not anticipated that the seepage interceptors required would be as elaborate as these; however, as the leaching of bank material is a process that can accelerate with time, the magnitude of the remedial works can increase to the stage where, in critical reaches of a river, an elaborate and costly system similar to that installed in Argyle Reach may become necessary.

(3) To prevent scour damage to levees it is essential that when levees are overtopped, floodwaters have accumulated behind the levees to a level that makes the local overflow head small - i.e. the local overflow velocities are less than the scour velocities. This implies that the floodways and inlet channels are adequate for admitting floodwaters to the storages behind the levees so that they are nearly full when overtopping occurs. Accordingly the following measures are recommended:-

(a) Floodways and inlet channels to storages behind levee banks should be kept clear of excessive vegetation and other blockages.

(b) In vulnerable sections restrictions might be placed on the usage of land on the levee crests to ensure that these are not bare of effective cover when they are overtopped.

(4) In reaches of the river where the banks consist of alluvial deposits, restrictions should be placed on the activities of power boats and/or special measures should be taken to protect the banks from wave action from same. The construction of footpaths and launching ramps should be controlled to ensure that they do not make the banks vulnerable to damage by floods.

(5) The removal of material from the bed and banks of the river by extractive industries should be discontinued as soon as it is feasible. Encouragement should be given to the exploitation of alternative sources of supply of building material. These include the extensive sand deposits in the Macdonald River and sand from crushed sandstone.

(6) There should be regular inspections of the banks (see heading "D" below).

B. <u>Land Usage</u>

(1) Generally the recommendations in Setchell's "Sydney 2000", prepared for the National Trust, merit serious consideration. To quote from this publication, in regard to the fertile lands of the Hawkesbury River: "The prime objective---------is to conserve the rural beauty of those sections of countryside which possess national significance, improving them wherever desirable or possible and, at the same time, promoting public enjoyment whilst interfering as little as possible with the rights of existing landholders.-------Continued primary production within the region is both desirable and economically sound. Where the retention of a particular primary industry is desirable to the conservation of scenic and tourist values, limited subsidisation of the establishment of a processing or marketing organisation might prove quite adequate to ensure the economic viability of currently depressed activities.--------The enforcement of large non-urban subdivision sizes, and the consequent removal of temptations to neglect agricultural pursuits in the hope of substantial land sale profits, will also serve to maintain the economic viability of those areas to the substantial relief of those landowners who do not wish to surrender their traditional livelihood."

(2) In considering proposals for the extraction of materials from areas adjoining the river, the following matters should be carefully examined in the light of adequate sub-surface exploration of the surrounding terrain: Possible disturbances to the water table, the fouling (turbidity) of the river by fine material from sand and gravel washings, the possible undermining of river banks by tunnelling promoted by seepage from water impounded in excavation pits behind the banks (see subsections (2)(d) and (2)(e) under heading "A" above) and the possibility of fouling of groundwater and river water by wastes if these excavation pits become wholly, or part of recreation lakes.

(3) The references given in Chapter 10 under the heading "Flood Plain Management" should be consulted when considering such matters as the zoning of flood plains, the regulation of building in flood prone areas and flood insurance schemes.

C. Soils

Drainage schemes should take into account not only the requirements for the conservation of wild life in swamp areas but also the composition of soils associated with the swamps. If "cat clays" (i.e. clays which release acid and salts on aeration) are associated with the swamps then serious problems can arise from improperly designed drainage works. See references 30, 32 and 34 in Chapter 2.

When considering the dumping of liquid or solid wastes in ground near a river, a lagoon or areas where the groundwater is used for irrigation account must be taken of the groundwater flow pattern, the fluctuations in the level of the water table, the depth of the soil, its permeability and its absorptive capacity. A system for evaluating the contamination potential of waste disposal areas is given by H.E. Le Grand ("A system for evaluating the contamination potential of some waste sites" 1964 Jour. Amer.Water Wks.Assoc. 56: pp.959-974).

D. River Salinity and Pollution

Salinity observations in tidal rivers should be made and analysed by the methods described in Chapter 6. From these analyses the dispersion coefficients in the saline reaches of a river can be inferred, and these can then be used to compute the concentrations of pollutants in these reaches, as described in Chapter 6. Apart from the disposal of sewage, pollution inputs to the river from future urban and non urban runoff require estimation. This estimation can be assisted by statistics given in the publication entitled "Environmental Study of Port Phillip Bay: Report on Phase One 1968-1971" - sponsored by the Melbourne and Metropolitan Board of Works and the Fisheries and Wildlife Department of Victoria.

E. River Inspections

Regular inspections of the tidal and upland reaches of each river system should be made. In the case of the Hawkesbury River system the employment of an officer full time on inspections would appear to be justified; a patrol officer who would be trained in the essentials of river behaviour, conversant with the acts and regulations of the various departments concerned with the river and who would effect liaison with the field officers of these departments. The following are some of the things he would report on: Obstructions of drains and floodways by vegetation, the illegal removal of material from, and in the vicinity of river banks, bank collapses and banks showing signs of instability, damage to banks by power boats, the building of boat ramps and pathways which might cause damage to banks in floods, the destruction of reeds and mangroves, the illegal dumping of wastes and the introduction of pollutants into the river, including washings of fine sediments by extractive industries. These, and numerous other activities detrimental to the river, if promptly reported to the appropriate authority, can be stopped before serious harm has been done.

CHAPTER 10: GENERAL BIBLIOGRAPHY

Introduction

This bibliography supplements the references given in Chapters 1 to 9; it is intended to be of assistance in additional studies which might be relevant to the contents of these chapters. Because of their wider applicability some of the publications already referenced in the previous chapters are included here.

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Admiralty Chart of Broken Bay (Northern portion) showing soundings 1952. Prints available from Navy No. 3351A/3a.

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