Recurrence frequency of flood levels in the Tuggerah lake system. February 1971.

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Publication details:
Commissioning Body: Electricity Commission of New South Wales
Report No. UNSW Water Research Laboratory Report No. 123

Publication Date:
1971

DOI:
https://doi.org/10.4225/53/57a17218c046d

THE UNIVERSITY OF NEW SOUTH WALES
water research laboratory
Manly Vale, N.S.W., Australia

Report No. 123

RECURRENCE FREQUENCY OF FLOOD LEVELS IN THE TUGGERAH LAKE SYSTEM

by

K.C.Yong and P.B.Stone

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KEY WORDS

Hydrograph analysis
Lakes
Rainfall
Runoff
Unit hydrographs

0-85824-009-2

Preface

The present study was undertaken by the Water Research Laboratory of the University of New South Wales at the request of the Electricity Commission of New South Wales.

Throughout the study close liaison was maintained with the Engineering Staff of the Electricity Commission and the assistance of Messrs. C.G. Coulter and A.N. Lamb is gratefully acknowledged.

The study was undertaken by Mr. K.C. Yong, engineer on the staff of the Water Research Laboratory under the supervision of Mr. P.B. Stone and the direction of Mr. D.N. Foster.

D.N. Foster,
Acting Officer-in-Charge.

Summary.

This report describes the results of an investigation carried out to estimate the flood levels in Tuggerah, Budgewoi and Munmorah lakes making use of the rainfall-runoff data available over the past seven or eight years.

Unitgraphs were derived for Wyong and Ourimbah creeks and synthetic unitgraphs computed for Wallarah Creek and the remaining catchment areas surrounding the lakes.

Inflow hydrographs were computed by applying design rainfalls to the unitgraphs. These inflows were routed through the storage system of three lakes, taking into account discharge characteristics of Budgewoi channel, discharge characteristics of constriction at Toukley Bridge and outflow characteristics at the Entrance channel to arrive at the resulting lake levels for floods of various recurrence frequencies.

These flood levels can be used to estimate the design basement level for power stations proposed for this area.

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1. Introduction

This report deals with flood levels in the Tuggerah Lakes system (Lakes Munmorah, Budgewoi and Tuggerah). The work was commissioned by the Electricity Commission of New South Wales whose interest in flood levels is related to the design of power stations on the low lying land adjacent to the lakes. The information needed was the flood level in the lakes for each of a number of return periods.

Two methods were used ; an analytic rainfall-runoff analysis and an historical analysis of lake levels.

2. Analysis of Historical Data

For recent years (1961-1969) records of flood levels were available (Ref. 4) and prior to this historical information of reported lake levels has been assembled (Ref. 5). In addition, enquiries were made of the Department of Main Roads who have recently built a road bridge in the area.

The data obtained from the various sources are summarised in Table 1.

Table 1: Summary of Flood Data

Year	Lake Level RL.ft.	Remarks
1927 1931 1941 1946	101* + 3'-5' 101 + 3'-5' 101 + 3'-5' 107.5	Data taken from Ref. 5 (highest reported flood level - RL.107.5). According to Mr. Hutton the floods of 1927 and 1949 were generally the same heights within one or two inches (Bannister and Hunter's report dated 10.12.64).
1949	107.72	This was the highest reported flood level in the boatshed but the flood level taken by Mr. Hutton+ was RL. 107.28'.

* Minimum lake level is assumed at RL. 101'.0

\+ Mr. Hutton is a local resident who lives adjacent to the northern approaches of the existing wooden bridge. The information given by Mr. Hutton is contained in a report submitted by Bannister and Hunter, Land Engineering and Mining Surveyors, to the Division Engineer, Department of Main Roads, Newcastle, on 10th December 1964. The report was made available by engineers of the Department of Main Roads, Sydney.

Table 1 (cont'd.) Summary of Flood Data

Year	Lake Level RL. ft.	Remarks
1953	101 + 3'-5'	Data taken from Ref. 5.
1961	102.3	Data taken from Ref. 4.
1962	104.0	
1963	105.2	
1964	106.0	
1965	101.5	
1966	101.8	
1967	102.35	
1969	102.07	

There was a slight variation in the maximum reported flood level from the various sources and it was assumed that the maximum level achieved since 1900 was RL. 107.6. A simplistic analysis of these data leads to the conclusion that the recurrence interval for a lake level of 107.6 was 70 years. This period may be reduced if a higher level which was not reported occurred in the period. However, it may be said that a crude analysis of the historical data gave a recurrence interval of 70 years for a lake level of RL. 107.6.

From 1961 to 1969 accurate data of significant lake level rises were available in reference 4. This information was extrapolated using Gambel's theory of extreme value statistics. This theory is expressed in the formula:-

$$P = 1 - e^{-e^{-b}}$$

where $$b = \frac{1}{0.7797\sigma} (X - \bar{X} + 0.45\sigma)$$

the variables being defined as

P = the probability of an occurrence of a value equal to or greater than x = $1/t_p$

t_p = return period in years

e = base of Naperian logarithms

b = constant

$\bar{X}$ = average of flood levels in the series

σ = standard deviation of the series

The extrapolation based on this theory is shown in Figure 1 from which it was deduced that the return period for a lake level of RL. 107.6 is 80 years, comparable with the estimate of 70 years made from the incomplete set of data. The remainder of this report deals with analytic method of predicting lake levels using rainfall-runoff analyses and the results of a mobile bed model study.

3. Catchments

3.1 Catchment Areas

Floods in the lake system are the result of rainfall on the surrounding catchment areas and rainfall on the lakes. Four catchment areas were used in this analysis, namely:-

- (i) Wyong Creek upstream of Wyong Weir (134 sq. miles)
- (ii) Ourimbah Creek (54.45 sq. miles)
- (iii) Wallarah Creek(12.4 sq. miles)
- (iv) Remaining areas (57.5 sq. miles)

The remaining areas were generally small areas adjacent to the lakes and containing no major stream. The drainage patterns to the individual lakes are shown in Table 2.

Table 2: Inflow Distribution

Lake	Lake area sq. miles	Components of drainage areas feeding into lake sq. miles	Summation of areas sq. miles	Percentage of total
Tuggerah	22.4	(1) Wyong Creek at Wyong Weir = 134 (2) Ourimbah Ck. = 54.45 (3) 70 per cent of remaining areas=40.25	228.70	88.5
Budgewoi	5.5	(1) Wallarah Ck. = 12.4 (2) 15% of remaining areas = 8.6	21.0	8.1

Table 2 (cont'd.) Inflow Distribution

Lake	Lake area sq. miles	Components of drainage areas feeding into lake sq. miles	Summation of areas sq. miles	Percentage of total
Munmorah	3.0	(1) 15% of remaining area = 8.6	8.6	3.4
Total	30.4	Total	258.3	

3.2 Critical Storm Duration

For runoff from the catchments into the lakes the critical storm duration will be short but due to the large storage capacity of the lakes the critical storm duration for lake level will be increased above that for the streams. Tests were made of storms of durations of 6, 12, 18, 24, 30, 36, 48 and 96 hours. For all recurrence intervals, the following were the critical storm durations.

Table 3: Critical Storm Duration

Wallarah Creek	24 hours
Ourimbah Creek	48 hours
Wyong Creek	48 hours
Tuggerah Lakes	96 hours

4. Rainfall

Rainfall data were needed in estimating the magnitudes of floods of various recurrence intervals and in deriving unitgraphs for sub-catchments in the area.

The design rainfalls with return periods of 10 years, 100 years and 1000 years were obtained by using the methods contained in the Australian Rainfall and Runoff Standard (Ref. 1). The probable maximum precipitation (P.M.P.) was obtained by considering a thunderstorm model and by maximising and transposing the Dunedoo storm of February 1955.

4.1 Rainfall Data

Rainfall data are generally available for the catchment over the period of interest from the Bureau of Meteorology. There are daily rainfall stations at Wyong, Ourimbah, Mangrove Mountain, Jilingolio (near Kulnura), Bebeah and Wyee. Pluviometer stations exist at Bucketty, Congewoi and Munmorah for which records are available. A pluviometer was installed at Kulnura in 1969 by a private company but the records were not available for this investigation. The locations of these stations are shown in Figure 2.

4.2 Probable Maximum Precipitation

In the derivation of probable maximum precipitation a thunderstorm model was used for durations up to 24 hours. For durations beyond 24 hours maximized and transposed depth area duration data from the United States were used.

The Dunedoo storm of February 1955 was transposed to the Tuggerah catchment as a check on rainfall values obtained by other methods.

The catchment characteristics used in rainfall calculations are shown below:-

Catchment	Area (sq. miles)	Inflow Barrier (feet)
Wyong Creek	134	500
Ourimbah Creek	54.25	500
Wallarah Creek	12.4	100

4.21 Thunderstorm Model

The thunderstorm model gave the following rainfall intensities.

Duration (hours)	P.M.P. (inches)		
	Wyong Ck.	Ourimbah Ck.	Wallerah Ck.
6	13.6	14.7	17.0
12	17.0	19.2	22.0
18	20.4	23.0	24.9
24	23.0	25.0	26.8

4.22 Transposed U.S.A. Data

The maximum depth area duration (D.A.D.) data obtained from Chow (Ref. 12) was interpolated and extrapolated. The data were transposed from an assumed 12 hour persisting 1000 m.b. dewpoint of 78°F to an assumed dewpoint of 70°F for an inflow barrier at 500 ft. The results of this transposition are listed below.

Duration (hours)	P.M.P. (inches)		
	Wyong Ck.	Ourimbah Ck.	Wallarah Ck.
36	25.5	27.2	29.0
48	26.5	28.1	30.1
72	27.3	29.1	31.0
96	28.0	29.8	32.0

4.23 Transposed Dunedoo Storm

From published data on the Dunedoo storm the dew point and inflow barriers were calculated as 68°F and 1340 ft. respectively. For the Tuggerah catchment a dew point of 70°F and an inflow barrier of 500 ft. were assumed as giving the probable maximum precipitation. This resulted in a transposition factor of 1.22 which when applied to the Dunedoo values gave the following estimated Tuggerah rainfalls.

Transposed Dunedoo Storm

Duration (hours)	Precipitation (inches)		
	Wyong Ck.	Ourimbah Ck.	
6	6.5	6.6	
12	10.0	10.5	
18	13.4	14.0	
24	15.6	16.2	
36	20.5	21.2	
48	21.4	21.8	
72	21.7	22.3	
96	24.2	25.0	(extrapolated)

4.3 Summary of Rainfall Results

Figure 3 contains the results of all rainfall analyses for the catchment. From this it can be seen that the maximised Dunedoo storm approximates to a 1 in 1000 year rainfall.

5. Stream Flows

5.1 Gauging Stations

There are three gauging stations in the catchment that are of assistance in deriving unitgraphs. Wyong Creek gauging station came in-to operation in 1959. It is a daily read station and gauges only Wyong Creek. Further downstream Wyong weir gauging station gauges both Wyong and Jilliby Creeks, is continuously recording and has been in operation since 1966. The Wyong Shire Council pumps about 11 c.f.s. for town water supply from upstream of the weir. The Wallarah Creek gauging station is a continuously recording station and has been in operation since 1965. The rating curve is satisfactory only for flows below 120 c.f.s. The Ourimbah Creek gauging station is a continuously recording station and has been in operation since 1965.

5.2 Unitgraph Derivation

It is desirable in deriving unitgraphs to have six events from which unitgraphs can be derived. An average of six such unitgraphs gives a reliable result for flood routing analyses.

For each of the Wyong weir catchment and the Ourimbah Creek catchment there were two flood events and these were used to obtain the two hour unitgraphs shown in Figure 4.

There were no suitable events at the Wallarah Creek gauging station and a synthetic unitgraph was derived using the procedure described by Cordery (Reference 3). The remaining areas surrounding the lake were lumped as a single catchment whose synthetic unitgraph was derived by the Cordery method. Flow from this area was proportioned to each of the lakes in the ratio of the catchment area tributary to each lake. These ratios are shown in Table 2.

All unitgraphs derived and synthetic are shown on Figure 4.

6. Lake and Channel Topography

6.1 Storage Elevation Relationships

The storage-elevation relationships for the three lakes shown in Figure 5 were obtained by assuming that there was a uniform ground surface slope from lake level to the 50 foot contour shown on the military map of the area. The relationship shows the volume of water stored in each of the lakes as prism storage above RL. 101.

6.2 Channel Characteristics

In previous sections it was shown how hydrographs were obtained for inflow into the several lakes. It was further assumed that water level rises in each of the lakes occurred uniformly over the whole of the lake surface. The flow between lakes and from Tuggerah Lake to the sea is controlled by discharge characteristics of three channels; Budgewoi channel, Toukley Bridge channel and the Entrance channel.

The survey information from which channel areas of the Budgewoi channel and the Toukley Bridge channel were calculated are shown in Figures 6 and 7 respectively. A Manning's 'n' of 0.03 was adopted for the calculation of flow in these interconnecting channels.

Calculation of the characteristics of the channel at the Entrance comprised a major section of the investigation and will be treated separately in Section 7.

7. Model Study of the Entrance Channel

One of the factors influencing lake levels is the discharge through the channel at the Entrance. Since the critical duration for lake flooding is of the order of days, a considerable amount of scour could be expected. To obtain an estimate of this scour and its effect on the discharge from Tuggerah lake, a small scale mobile bed model was tested.

7.1 Survey Information

The topography of the Entrance area as surveyed by staff of the Water Research Laboratory is shown in Figure 8. Figure 9 is a general view of the area. To check for shallow bedrock which would form a limit to scour a seismic survey was made with the assistance of personnel from the Public Works Department. This showed that there was no rock above RL. 83. Details of the survey are given in Appendix 1.

A typical cross section of the entrance channel (Figure 10) was used for no-scour calculations of flow.

7.2 Scale Ratio

7.21 Linear Ratios

Linear scale ratios (prototype/model) of 48 horizontal and 24 vertical were chosen.

7.22 Scour Velocity Ratio

A shear velocity scale was obtained as

$$v_r^* = (h_r S_r)^{\frac{1}{2}}$$

$$= h_r L_r^{-\frac{1}{2}} = 3.5$$

To achieve similarity of scour velocities a particle fall velocity ratio was needed which was equal to the shear velocity ratio

$$\text{i.e.} \quad W_r = v_r^* = 3.5$$

A sample of sand from the Entrance was analysed to give the grading curve in Figure 11. From this a required grading curve was calculated for material with a specific gravity of 1.34, a value which is attained by coal from the Rosewood colliery in Queensland. A grading curve for Rosewood coal is also shown on Figure 11. This matches the required grading very well except that it lacks some of the very fine fractions. This coal was then selected as mobile bed material for the model.

7.23 Friction Ratio

If the model is to reproduce level differences as well as scour patterns the frictional characteristics of the model must be a scale representation of the frictional characteristics of the prototype. This requirement was checked.

Using Chezy's formula

$$V = C(R\ S)^{\frac{1}{2}}$$

and Keulegan's expression

$$C = 32.6 \log \frac{12R}{d_{90}}$$

where V = velocity

C = Chezy's constant

R = hydraulic radius

d_{90} = particle grain size (90%)

S = slope

it is possible to obtain

$$S_r^{-\frac{1}{2}} = (\log \frac{12R}{d_{90}})_r$$

For the scales chosen $S_r^{-\frac{1}{2}} = 1.41$

Then using R = 4 feet (prototype) and the grain size values from Figure 11

$$(\log \frac{12R}{d_{90}})_r = 1.45$$

which being agreement of slopes to within 6 per cent was accepted as satisfactory.

7.24 Scour Time Ratio

In a model of this type used to predict rates of scour it is desirable to have verification data to establish a scour time scale. No such data are every likely to be available and the work of Zwamborn (Refs. 9 and 10) was used to establish a scour time scale of ten times the hydraulic time scale.

7.25 Summary of Scales

The following list gives the numerical values of the scales used in the model study.

horizontal	48
vertical	24
velocity	4.9
discharge	5660
hydraulic time	9.8
scour time	98 ≑ 100

7.3 Model Construction

The model was constructed in accordance with the survey shown in Figure 8. The rock was modelled in sand cement mortar into which were fitted rows of vertical pins. These pins were cut to the level of the sand surface and were used to obtain the correct level for the coal which was used to represent sand. In this way the model could be quickly re-instated to its pre-scour configuration.

A large tail box served as a coal trap and along all of its exterior sides a line crest weir was set to give mean sea level in the tail box.

Water was fed into the upstream limit of the model through an orifice meter.

7.4 Testing Program and Results

Each test consisted of running a steady discharge through the model and measuring lake level, waterway cross sectional area and typical waterway top width in the channel. Discharges used were 5000, 10,000, 15,000 and 20,000 c.f.s.

The results plotted in Figures 12 and 13 show that for discharges of 10,000 c.f.s. to 20,000 c.f.s. after initial scour the waterway areas stabilised at just below twice the pre-scour values. Figure 19 shows the comparison between field measurement, model results and computed values.

8. Inflow Hydrographs

8.1 Temporal Pattern of Storm

The temporal pattern for design storms follows the Laurenson patterns (Ref. 1) for recurrence intervals of 1000 years or less and the Hirschfield pattern (Ref. 7) for the probable maximum precipitation (P.M.P.) These patterns are shown in Figure 14. The duration for all design storms was 96 hours.

8.2 Hydrograph Synthesis

Inflow hydrographs were synthesised using the unitgraph procedure. The results are given in Figures 15 to 18 incl. These synthesised hydrographs were then applied to the lake storage areas in the ratios shown in Table 2.

9. Flood Routing

9.1 Flood Routing Program

A Fortran IV program was written to route the floods through the lake system. The input data are the inflow hydrographs and the rainfall on the lakes. Lake and channel characteristics are fixed parameters of the program which may be changed by altering statements in which they appear. The program outputs maximum lake levels. The program is written to run on the CDC3200 computer at the National Standards Laboratory. The details of the computer programme are given in Appendix II.

9.2 Program Verification

The flood of June 1967 was used to check that the assumptions of channel characteristics as used in the program were reasonable. The inflow hydrographs are tabulated below.

Table 4: Summary of June 1967 Flood Inflows

Day	Hrs.	$Q_{Wyong\ Weir}$ 1	$Q_{Ourimbah}$ 2	$Q_{remaining\ areas}$ = 0.6 × $Q_{Wyong\ Weir}$ 3	$Q_{Wallarah}$ 4	$Q_{rainfall}$ onto Tuggerah 5	$Q_{rainfall}$ onto Budgewoi 6	$Q_{rainfall}$ onto Munmorah 7
21	0	0	0	0	0	0	0	0
	6	200	150	120	30	1650	405	230
	12	400	250	240	70	1370	330	183
	18	650	300	390	100	930	220	125
22	24	1100	600	660	160	870	210	115
	30	3000	1000	1800	220	1490	360	200
	36	11500	1800	6900	350	2480	600	330
	42	17800	3100	10680	600	3600	870	480
23	48	18400	5500	11040	320	1980	480	265
	54	17000	7080	10200	160	250	60	30
	60	11500	4500	6900	100	0	0	0
	66	8300	2600	4980	80			
24	72	5300	1600	3180	50			
	78	4400	1000	2640	40			
	84	3500	750	2100	30			
	90	2800	650	1680	20			
25	96	2400	400	1440	10			
	102	1900	300	1140	0			
	108	1500	250	900				
	114	1300	200	780				

Table 4 (cont'd.): Summary of June 1967 Flood Inflows

Day	Hrs.	Q Wyong Weir 1	Q Ourimbah 2	Q remaining areas = 0.6 x Q Wyong Weir 3	
26	120	1000	150	600	
	126	700	100	420	
	132	600	80	360	
	138	500	50	300	
27	144	400	30	240	
	150	350	0	210	
	156	300		180	
	162	200		120	
28	168	100		60	

It was assumed in this program that the Manning 'n' for the Entrance channel was 0.02 and that scour at the Entrance gave a channel with a cross sectional area of twice the pre-scour area.

The program predicted a lake level of RL. 103.95 compared with a measured lake level of 103.9. This indicates that for this size of flood the assumptions made yielded reasonably accurate results. However, because of inaccuracies in rainfall and unitgraph prediction and uncertainties of how the Entrance will scour at higher discharges it cannot be expected that this order of accuracy can be maintained for extreme floods.

9.3 Flood Levels

The previously developed program was used to predict lake levels for floods with recurrence intervals of 10 years, 100 years, 1000 years and for the flood resulting from the probable maximum precipitation. The results of this work are shown in Table 5 and plotted in Figure 1.

Table 5: Flood Levels and their Recurrence Frequency.

Recurrence Frequency (yrs.)	Flood Levels in Lake (RL. ft.)	Remarks
10	106.3	For sea level at RL. 101, Manning's n=0.03 and normal outflow* at the entrance channel.
	105.6	For sea level at RL. 101 Manning's n=0.03 and 2 x normal outflow* at the entrance channel.
	107.0	For sea level at RL. 103, Manning's n=0.03 and normal outflow* at the entrance channel.
	105.8	For sea level at RL. 101, Manning's n=0.02 and normal outflow* at entrance channel.
	105.5	For sea level at RL. 101, Manning's n=0.02 and 1.5 x normal outflow* at entrance channel.
100	108.0	For sea level at RL. 101, Manning's n=0.03 and normal outflow* at entrance channel.
	106.9	For sea level at RL. 101, Manning's n=0.03 and 2 x normal outflow* at the entrance channel.
	108.4	For sea level at RL. 103, Manning's n=0.03 and normal outflow* at the entrance channel.
	107.5	For sea level at RL. 101, Manning's n=0.02 and normal outflow* at the entrance channel.
	106.7	For sea level at RL. 101, Manning's n=0.02 and 1.5x normal outflow* at the entrance channel.
1000	109.7	For sea level at RL. 101, Manning's n=0.03 and normal outflow* at the entrance channel.
	108.2	For sea level at RL. 101, Manning's n=0.03 and 2 x normal outflow* at the entrance channel.
	110.0	For sea level at RL. 103, Manning's n=0.03 and normal outflow* at the entrance channel.

*Normal outflow is calculated using the assumed constant cross-sectional area of the entrance channel (see Figure 10).

Table 5 (cont'd.) Flood Levels and their Recurrence Frequency.

Recurrence Frequency (yrs.)	Flood Levels in Lake (RL. ft.)	Remarks
1000	109.2	For sea level at RL. 101, Manning's n=0.02 and normal outflow* at the entrance channel.
	108.1	For sea level at RL. 101, Manning's n=0.02 and 1.5 x normal outflow* at the entrance channel.
P.M.P.	110.5	For sea level at RL. 101, Manning's n=0.03 and normal outflow* at the entrance channel.
	108.9	For sea level at RL. 101, Manning's n=0.03 and 2 x normal outflow at the entrance channel.
	110.8	For sea level at RL. 103, Manning's n=0.03 and normal outflow* at the entrance channel.
	110.0	For sea level at RL. 101, Manning's n=0.02 and normal outflow* at the entrance channel.
	108.8	For sea level at RL. 101, Manning's n=0.02 and 1.5 x normal outflow* at the entrance channel.

* Normal outflow is calculated using the assumed constant cross-sectional area of the entrance channel (see Figure 10).

Inspection of this table shows that the parameters of the Entrance channel were varied over the full range possible. The most probable value of lake level is that given by a channel with a Manning's 'n' of 0.03 and twice the pre-scour cross sectional area. Further, it is estimated that the sum of all errors will result in a possible variation of ± 1 foot in this level. Table 6 lists the predicted values of flood levels in the lakes.

Table 6: Maximum Flood Levels

Recurrence Interval (years)	Lake Level
10	105.6
100	106.9
1000	108.2
P.M.P.	108.9

10. Storm Surge

The increase in water level on the downwind side of a lake due to wind shear at the surface can increase flood levels. Storm surges of up to 15 inches have been reported (Ref. 14). During flood time, however, average depths in the lake are increased and since the relationship

$$\frac{dh}{dx} = \frac{kw^2}{gd}$$

governs storm surge an increase in average depth will cause a decrease in storm surge.

It was calculated that for a wind speed of 60 m.p.h. over a fetch of 10,000 ft. a surge of 6 inches could be expected.

11. Conclusions

Scour at the Entrance will reduce flood level by as much as 1 foot below what would have existed without any scour.

The maximum flood level to be expected in the lakes is RL. 109.4 which will only occur if a 60 m.p.h. wind blows during the peak of the hydrograph in the lake. Otherwise a level of RL. 108.9 will be the maximum.

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Appendix I Seismic Survey - Entrance North Sandspit dated 15th Sept. 1969.

The following are the results of a seismic survey of the entrance area carried out by the Hydraulic and Soils Laboratory of the Public Works Department on behalf of the Water Research Laboratory, University of New South Wales. The details are given in the following table.

Table A1.

South	G1/G2	G12/G1	G2/G3	G11/G12
V1	900	900	900	900
V2	4800	5000	6500	6000
C1	40	42	40	40
V2/V1	5.34	5.56	7.22	6.66
K_1	0.413	0.416	0.435	0.430
D1=C1xK1	16.5	17.5	17.4	17.2
Avge. D1	17.0		17.3	
Avge. D1 at centre peg	17.5			
Avge. D1 full run	16.9			
Avge. V_1 f.p.s.	900			
Avge. V_2 f.p.s.	5575			
Avge. V1 full run	960			
Avge. V2 full run	6425			
Distance ft.	100		200	

Position and bearing of run is shown in Figure 8 as A-A

Notes : V_1 - velocity of first layer
V_2 - velocity of second layer
C_1 - critical distance in feet from geophone to velocity change point
D_1 - apparent depth of first layer in feet

$$K_1 = \frac{1}{2} \frac{V_2 - V_1}{V_2 + V_1}$$

Table A1 (cont'd.)

	G3/G4	G10/G11	G4/G5	G9/G10
V1	850	800	850	1100
V2	5700	10,000	5800	5300
C1	37	32	37	54
V2/V1	6.71	12.5	6.82	4.82
K1	0.431	0.465	0.432	0.405
D1- C1xK1	15.9	14.9	16.0	21.8
Avge. D1	15.4		18.9	
Avge. D1 at centre peg	15.5			
Avge. D1 full run	16.9			
Avge. V_1 f.p.s.	900			
Avge. V_2 f.p.s.	6700			
Avge. V_1 full run	960			
Avge. V_2 full run	6425			
Distance ft.	300		400	

Position and bearing of run is shown in Figure 8 as A-A

Notes:

V_1 - velocity of first layer
V_2 - velocity of second layer
C_1 - critical distance in feet from geophone to velocity change pt.
D_1 - apparent depth of first layer in feet

$$K_1 = \frac{1}{2} \frac{V_2 - V_1}{V_2 + V_1}$$

Table A1 (cont'd.)

	G5/G6	G8/G9	G6/G7	North G7/G8
V1	850	1700	870	870
V2	7200	7800	7700	5300
C1	29	53	33	39
V2/V1	8.47	4.59	8.85	6.09
K1	0.444	0.400	0.447	0.423
D1=C1xK1	12.9	21.2	14.7	16.5
Avge. D_1	17.1		15.6	
Avge. D_1 at centre peg	18.0			
Avge. D_1 full run	16.9			
Avge. V_1 f.p.s.	1070			
Avge. V_2 f.p.s.	7000			
Avge. V_1 full run	960			
Avge. V_2 full run	6425			
Distance ft.	500		600	

Position and bearing of run is shown in Figure 8 as A-A

Notes:
- V_1 - velocity of first layer
- V_2 - velocity of second layer
- C_1 - critical distance in feet from geophone to velocity change pt.
- D_1 - apparent depth of first layer in feet

$$K_1 = \frac{1}{2}\,\frac{V_2 - V_1}{V_2 + V_1}$$

Comments

The results of the seismic run indicate a change from low velocity material to medium velocity at an average depth of 16.9 feet over the full course. The resistivity run also indicates that there is no bedrock above this depth.

The medium velocity below this depth could indicate saturated highly compressed silt, sandy clay, or weathered rock. Resistivity readings to a depth of 60 feet at Peg 2 and 40 feet at Peg 5, however, were zero from about 8 feet which is not indicative of rock, and it is considered that no bedrock exists above these depths.

```
                                        3200  FORTRAN    (2.1)          11/09/70

      PROGRAM  FLOOD
C
C
C     ***************************************
C     *                                     *
C     * PROGRAMME FOR FLOOD ROUTING-TUGGERAH *
C     *                                     *
C     ***************************************
      COMMON XARRAY(648),YARRAY(648,3)
      DO 400 KK=1,4
      C=1.0/43560.0
      TIME=1.0
      INDX=1
C
C         ************************
C         *                      *
C         * READING OF INPUT DATA *
C         *                      *
C         ************************
C
      READ  (60,5) AN1,AN2,AN3
      READ  (60,15) HR,HRMIN,RLS
      READ  (60,25) S1T,S1B,S1M,OUTT,OUTB,OUTM
      READ  (60,35) RLT,RLB,RLM
      READ  (60,45) E11,E12,E13,E14,E15,E16,E17
C
C         *************************
C         *                       *
C         * PRINTING OF INPUT DATA *
C         *                       *
C         *************************
      WRITE(61,41)
      WRITE(61,12)AN1,AN2,AN3
      WRITE(61,14)HR,HRMIN,RLS
      WRITE(61,17)S1T,S1B,S1M,OUTT,OUTB,OUTM
      WRITE(61,19)RLT,RLB,RLM
      WRITE(61,22)E11,E12,E13,E14,E15,E16,E17
      WRITE(61,30)
C
C         ********************
C         *                  *
C         * FORMAT STATEMENTS *
C         *                  *
C         ********************
C
    5 FORMAT (3F6.2)
   15 FORMAT (3F6.1)
   25 FORMAT (6F6.1)
   35 FORMAT (3F6.1)
   45 FORMAT (7F6.1)
   41 FORMAT(30X,37H*************************************/30X,
     137H*                                   */30X,37H* PRINTING OF INPU
     2T AND OUTPUT DATA */30X,37H*                                   */
     330X,37H*************************************///)
C
C
   12 FORMAT(3X,4HAN1=,F6.2,10X,4HAN2=,F6.2,10X,4HAN3=,F6.2//)
   14 FORMAT(3X,3HHR=,F6.1,10X,6HHRMIN=,F6.1,10X,4HRLS=,F6.1//)
   17 FORMAT(3X,4HS1T=,F6.1,5X,4HS1B=,F6.1,5X,4HS1M=,F6.1,5X,5HOUTT=,
     1F6.1,5X,5HOUTB=,F6.1,5X,5HOUTM=,F6.1//)
   19 FORMAT(3X,4HRLT=,F6.1,10X,5X,4HRLB=,F6.1,10X,4HRLM=,F6.1//)
```

```
   22 FORMAT(3X,4HE11=,F6.1,5X,4HE12=,F6.1,5X,4HE13=,F6.1,5X,4HE14=,
     1F6.1,5X,4HE15=,F6.1,5X,4HE16=,F6.1,5X,4HE17=,F6.1//)
   30 FORMAT((12X,111H TIME(HRS)          RLT(FT)          RLB(FT)          RLM(
     1FT)              OUTT(CFS)          OUTB(CFS)            OUTM(CFS))//)
C
      QI1T=E11+E12+0.7*E13+E15
      QI1B=E14+0.15*E13+E16
      QI1M=E17+0.15*E13
C
C
      DO 65  JACK=1,4
      DO 110 KIM=1,27
      IF (TIME.GE.162.0) GO TO 10
C
      READ  (60,55) E1,E2,E3,E4,E5,E6,E7
   55 FORMAT (7F10.1)
      WRITE(61,24)E1,E2,E3,E4,E5,E6,E7
   24 FORMAT((3X,3HE1=,F10.1,3X,3HE2=,F10.1,3X,3HE3=,F10.1,3X,3HE4=,
     1F10.1,3X,3HE5=,F10.1,3X,3HE6=,F10.1,3X,3HE7=,F10.1)/)
C
      GO TO 20
   10 E1=E2=E3=E4=E5=E6=E7=0.0
   20 QIT=E1+E2+0.70*E3+E5
      QIB=E4+0.15*E3+E6
      QIM=E7+0.15*E3
C
      AT1=0.0
      DO 150 KPT=1,6
      DO 210 JTF=1,6
C
      QITF=QI1T+AT1*(QIT-QI1T)/HR+OUTB
      QIBF=QI1B+AT1*(QIB-QI1B)/HR+OUTM
      QIMF=QI1M+AT1*(QIM-QI1M)/HR
C
      SLOPET=(RLT-RLS)/1500.0
      SLOPEB=(RLB-RLT)/600.0
      SLOPEM=(RLM-RLB)/2000.0
C
      Y=(RLT+RLS)/2.0-101.0
      A=240.0*Y+150.0*Y**2+182.0
      R=A/(128.+150.*Y)
      SIGN=1.0
      IF(SLOPET.LE.0.0)  SIGN=-1.0
      OUTT=SIGN*2.25*A*R**0.667*SQRT(ABS(SLOPET))/AN1
C
      Y=(RLB+RLT)/2.0-101.0
      A=7400.+660.*Y
      R=A/(650.0+20.0*Y)
      SIGN=1.0
      IF (SLOPEB.LE.0,0)  SIGN=-1.0
      OUTB=SIGN*1.49*A*R**0.667*SQRT(ABS(SLOPEB))/AN2
C
      Y=(RLB+RLM)/2.0-101.0
      A=2003.0+195.0*Y
      R=A/(201.0+12.0*Y)
      SIGN=1.0
      IF (SLOPEM.LE.0.0)  SIGN=-1.0
      OUTM=SIGN*1.49*A*R*0.667*SQRT(ABS(SLOPEM))/AN3
C
      ST=(QITF-OUTT)*HRMIN+S1T
      SB=(QIBF-OUTB)*HRMIN+S1B
      SM=(QIMF-OUTM)*HRMIN+S1M
C
```

```
      RLT=2.75*C*ST/50000.0+101.0
      RLB=5.00*C*SB/20000.0+101.0
      RLM=3.85*C*SM/10000.0+101.0
C
      S1T=ST
      S1B=SB
      S1M=SM
C
      AT1=AT1+1.0
  210 CONTINUE
C
C         ***************************
C         *                         *
C         * PRINTING OF OUTPUT DATA *
C         *                         *
C         ***************************
C
      WRITE(61,40)TIME,RLT,RLB,RLM,OUTT,OUTB,OUTM
C
   40 FORMAT((12X,F7.1,3(8X,F7.2),3(9X,F10.1))//)
C
      XARRAY(INDX)=TIME
      YARRAY(INDX,1)=RLT-100.0
      YARRAY(INDX,2)=RLB-100.0
      YARRAY(INDX,3)=RLM-100.0
C
      INDX=INDX+1
      TIME=TIME+1.0
C
  150 CONTINUE
C
C
      QI1T=QIT
      QI1B=QIB
      QI1M=QIM
C
  110 CONTINUE
C
      IF (ABS(RLM-RLS).LE.0.01)  GO TO 400
C
   65 CONTINUE
C
C         ***************************************
C         *                                     *
C         * CALLING SUBROUTINE TO PLOT GRAPH    *
C         *                                     *
C         ***************************************
C
       CALL AUTOPLOT(XARRAY,YARRAY,+648,+3,6H*TIME*,8H*LAKERL*)
  400 CONTINUE
      END
```

Appendix II - Definition of Variables.

AN1, AN2, AN3 -	Manning's 'n' for the entrance channel, Toukley Bridge constriction and Budgewoi channel respectively.
C -	Conversion factor from c.f.s. to acre ft.
HR -	Constant = 36 (factor to convert 6 hrs. into 10 mins. interval)
HRMIN -	Constant = 600 (Number of seconds in 10 mins.)
S1T, S1B S1M -	Storage of Lake Tuggerah, Budgewoi, Munmorah respectively.
OUTT, OUTB, OUTM -	Outflow of Tuggerah, Budgewoi, Munmorah respectively.
RLT, RLB, RLM, RLS -	Reduced levels of Lake Tuggerah, Budgewoi, Munmorah and sea respectively.
E1, E2, E3, E4 -	Inflow of Wyong Creek, Ourimbah Creek, remaining areas and Wallarah Creek respectively.
E5, E6, E7 -	Rainfall on Lake surface of Tuggerah, Budgewoi and Munmorah respectively.
QI1T, QI1B, QI1M -	Inflow (initial) into Lake Tuggerah, Budgewoi, Munmorah respectively every 6 hrs.
KPT, JTF -	Constants increasing from 1 to 6 respectively.
QITF, QIBF, QIMF -	Computed inflow into Lake Tuggerah, Budgewoi, Munmorah every 10 minutes.
QIT, QIB, QIM -	Inflow(6hrs. later) for Lake Tuggerah, Lake Budgewoi and Munmorah respectively.
SLOPET, SLOPEB, SLOPEM -	Slope of outflow channels representing entrance channel, Toukley Bridge and Budgewoi channel respectively.
Y -	Averaged height of lake above 101.00 ft.
A -	Area of outflow channels.
R -	Hydraulic radius of channel
ST, SB, SM -	Computed water storage in Tuggerah, Budgewoi and Munmorah respectively at 10 min. intervals.

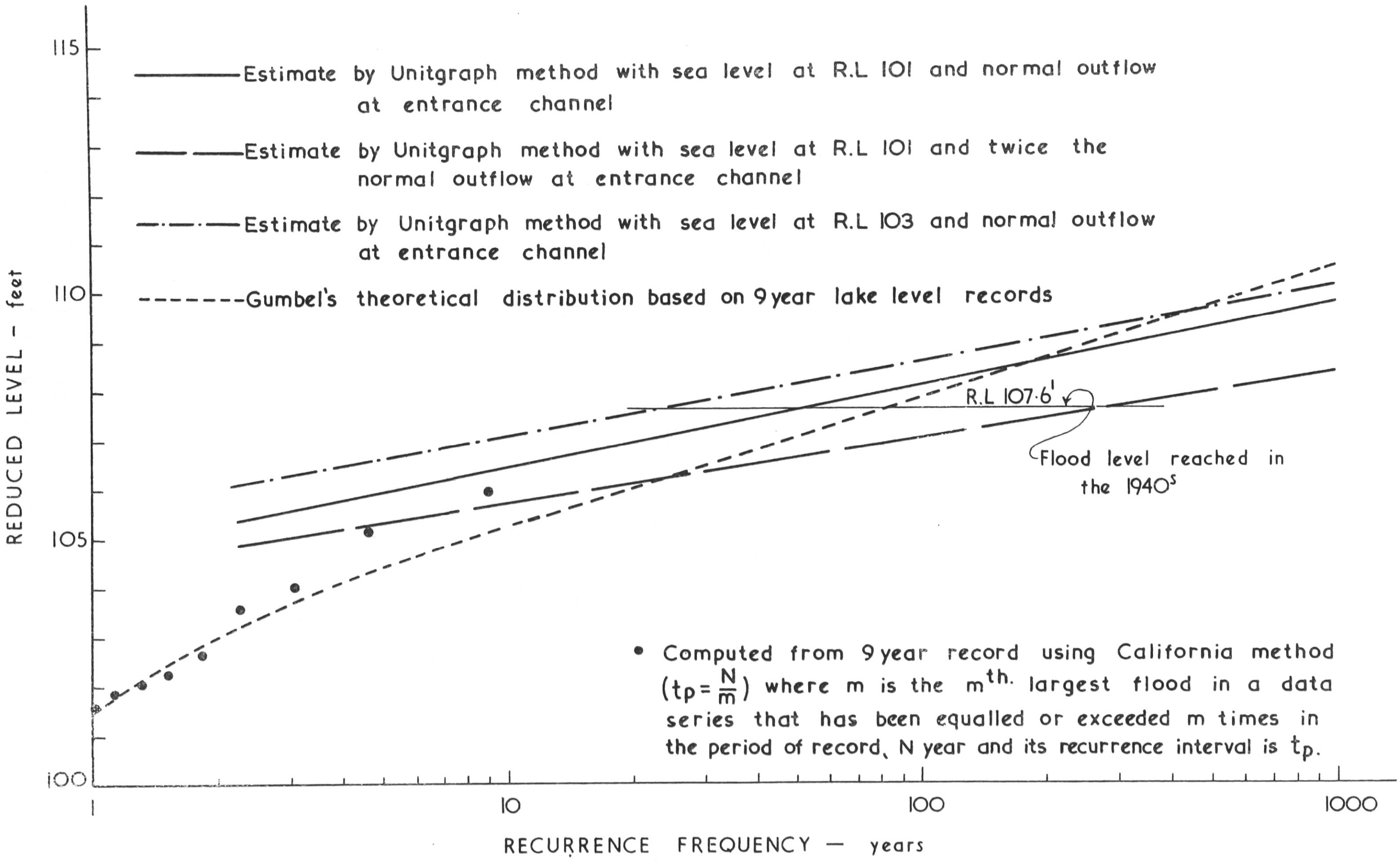

Figure 1: Flood stage-recurrence frequency relationship for Tuggerah Lake system.

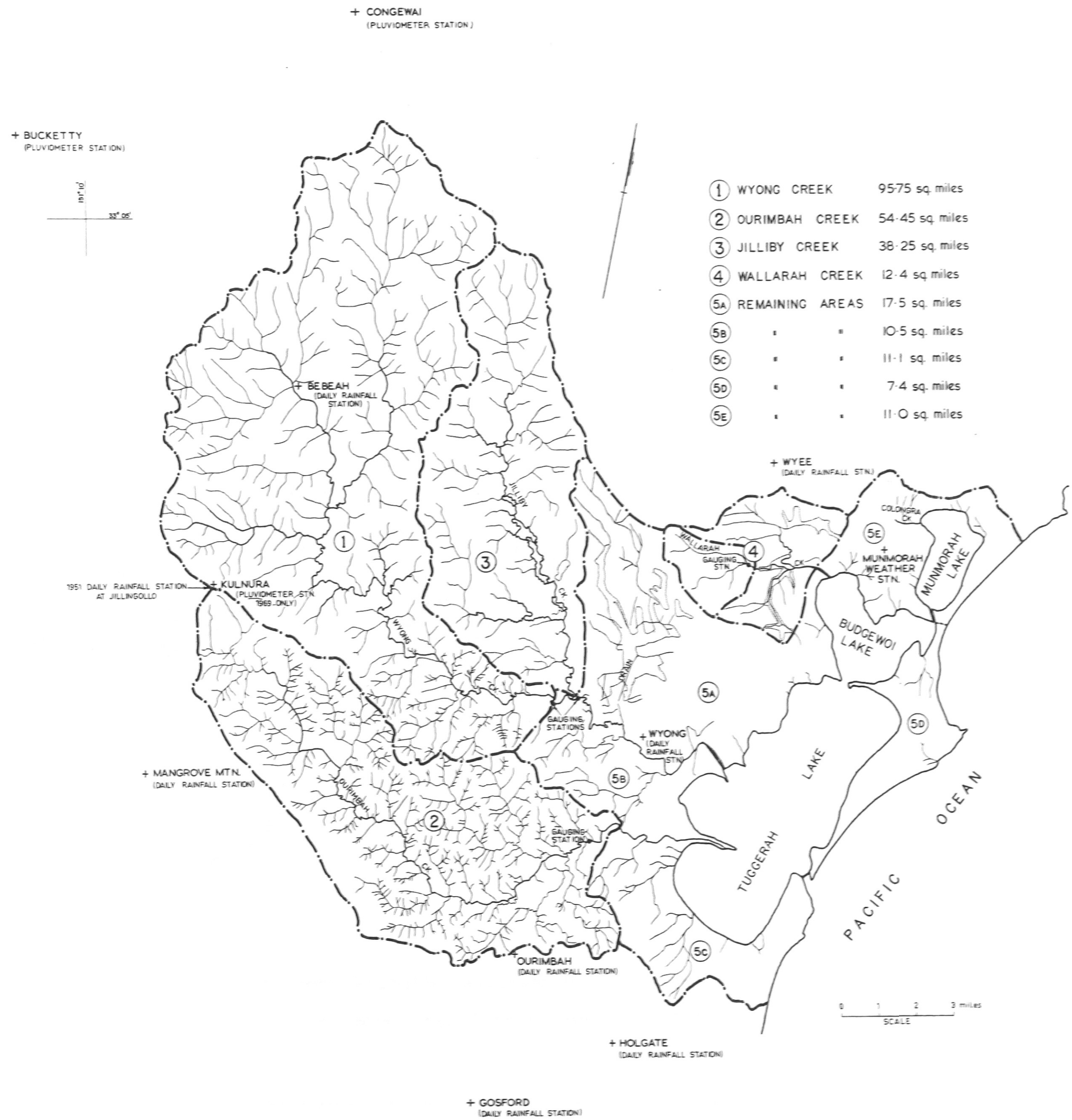

Figure 2: Location of rain gauges and gauging stations for Wyong, Ourimbah and Wallerah catchments.

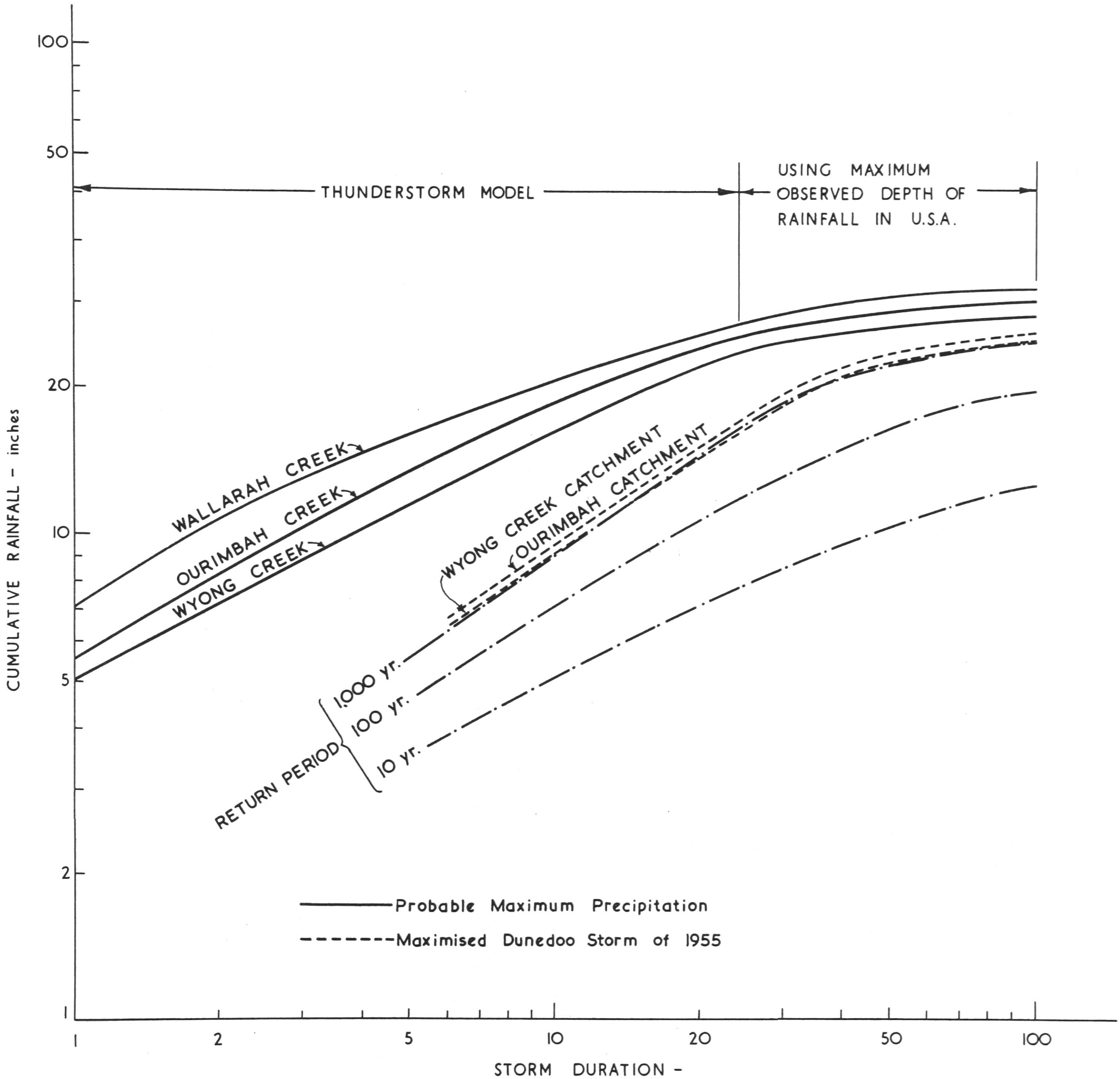

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Figure 3: Depth-area-duration curves for Wyong, Ourimbah and Wallerah catchments.

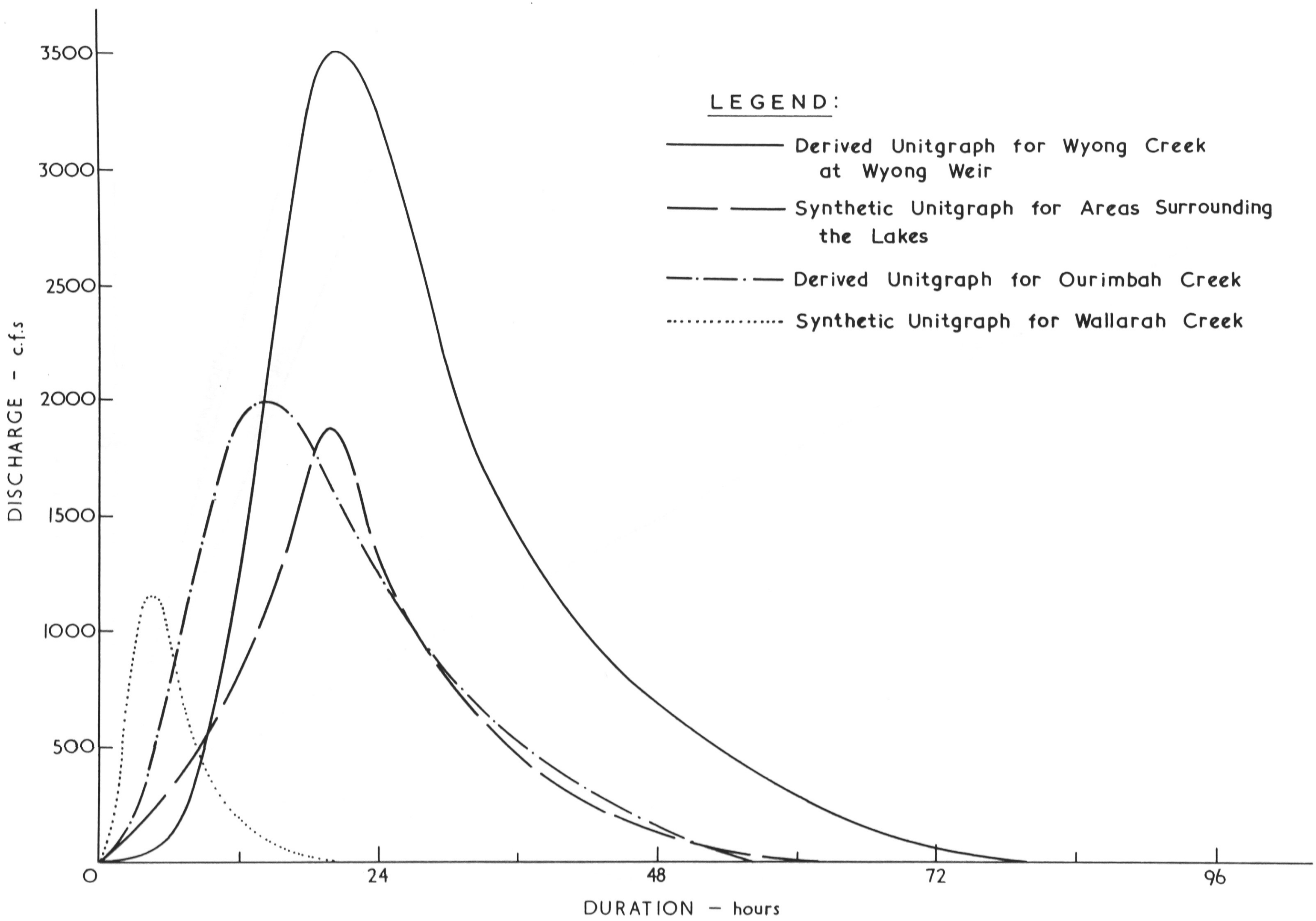


Figure 4: Summary of derived and synthetic 2-hour unitgraphs.

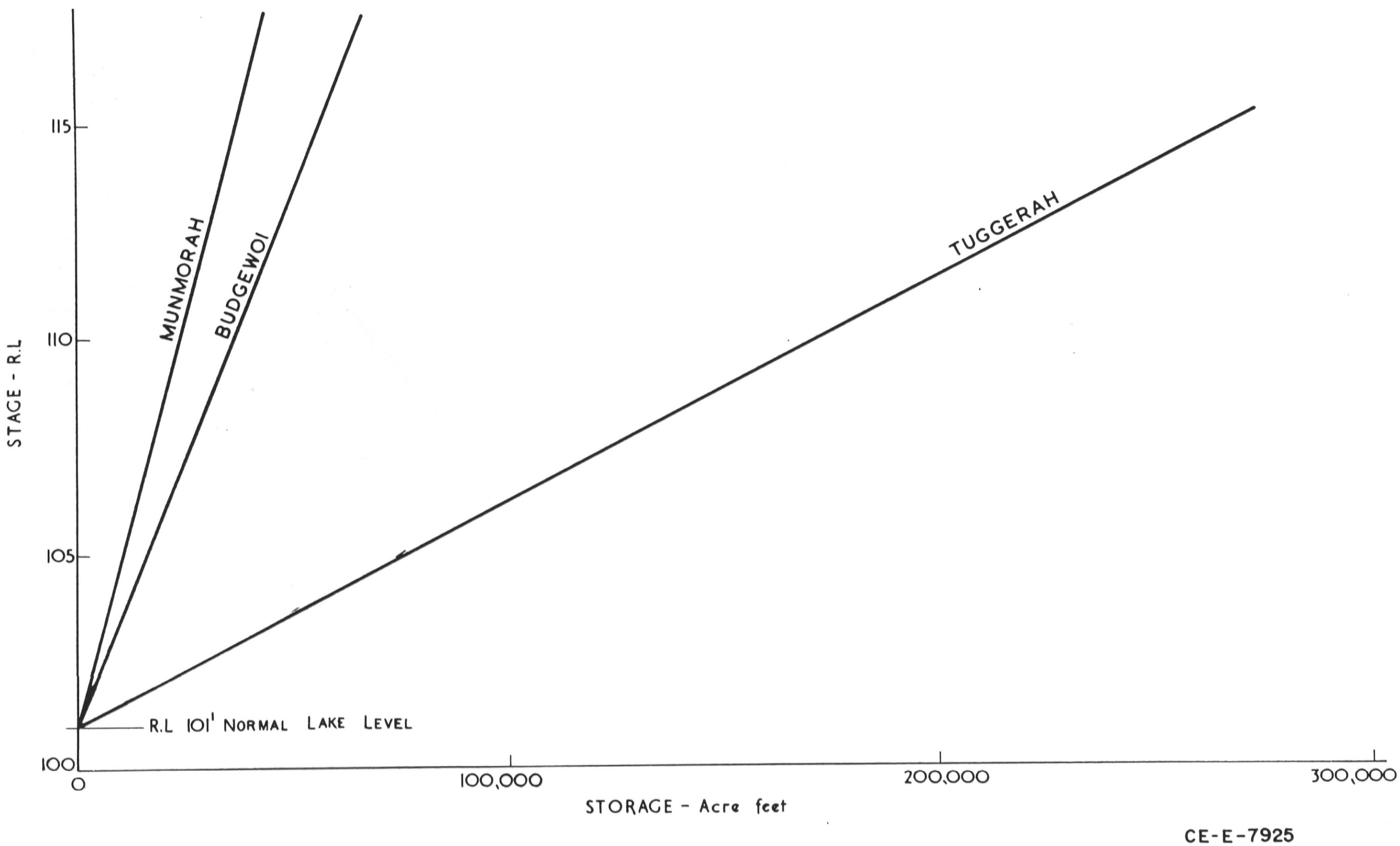


Figure 5: The storage elevation relationships for Tuggerah, Budgewoi and Munmorah Lakes.

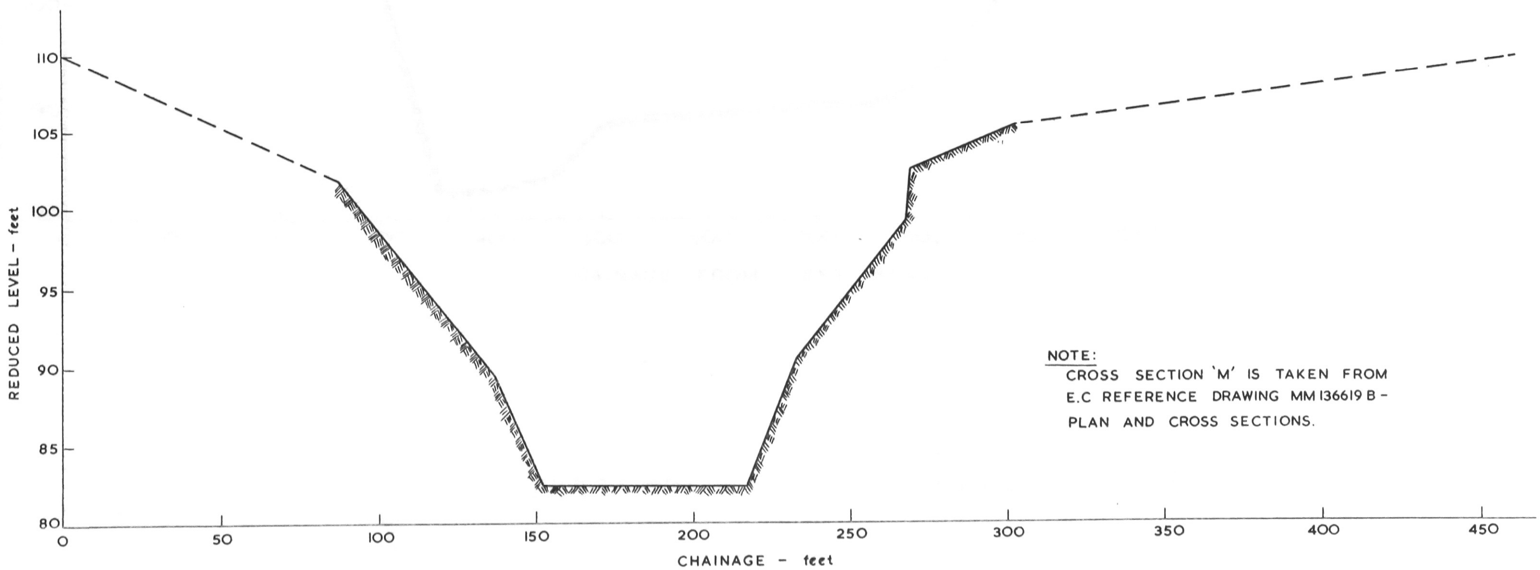
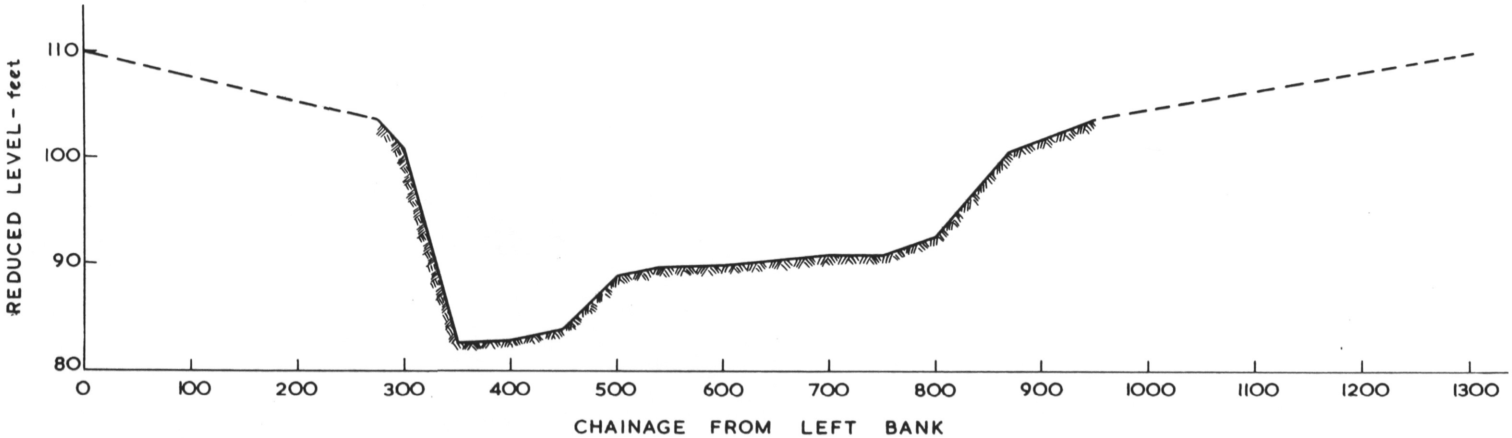


Figure 6: Cross section 'M' at Budgewoi Channel.



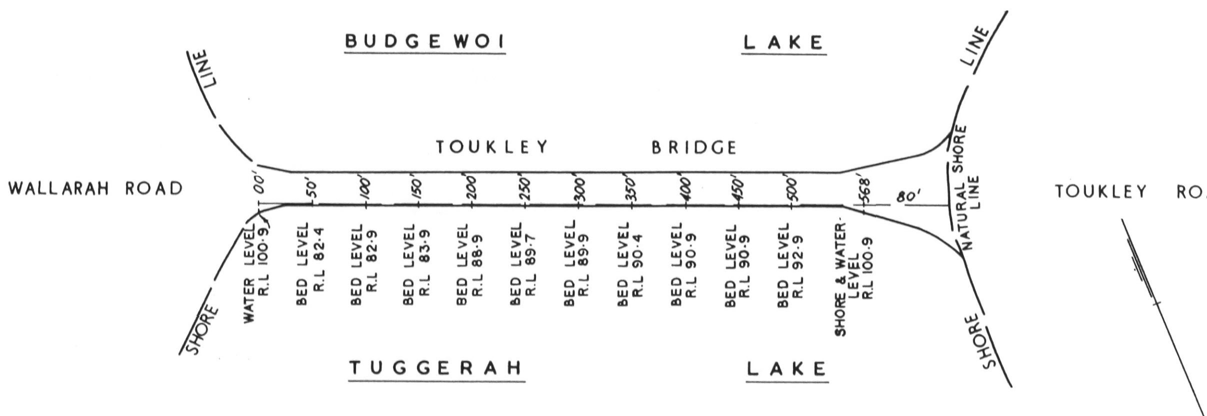


Figure 7: Cross Section at Toukley Bridge.

Figure 8: Contour plan of the Entrance area.

Figure 9: Photograph of the Entrance area.

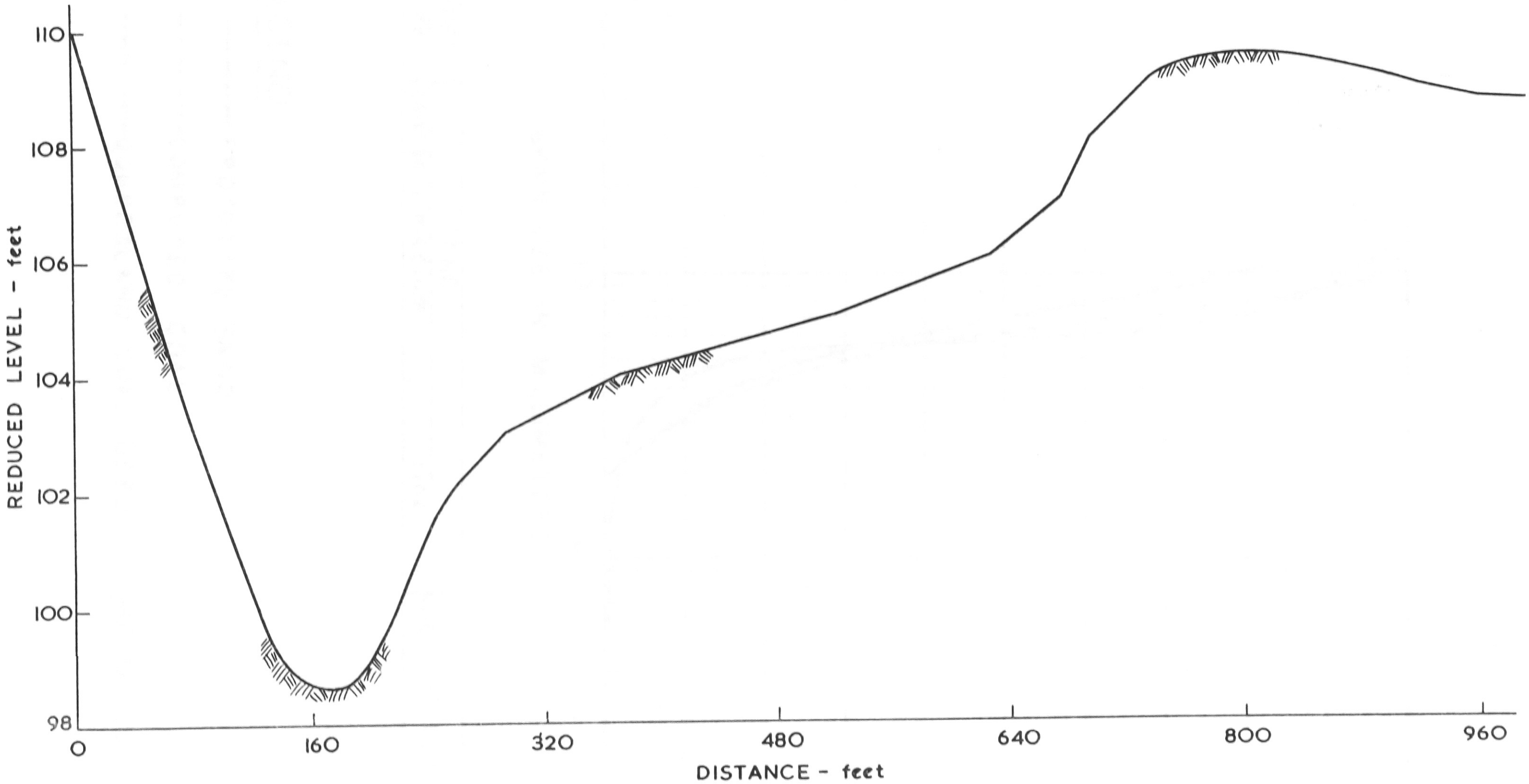


Figure 10: Cross Section C-C at Entrance.

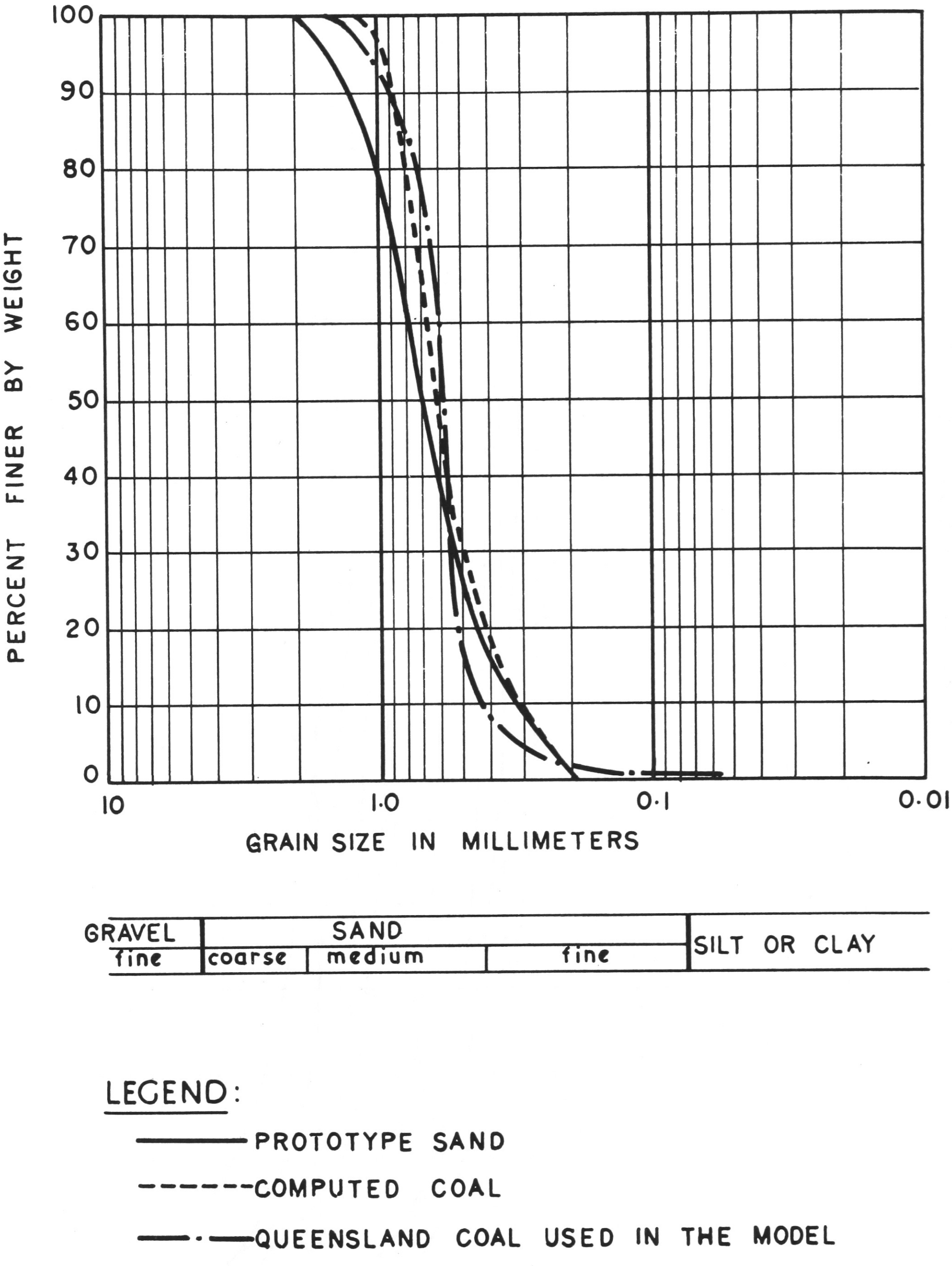


Figure 11: Particle size distribution curves.

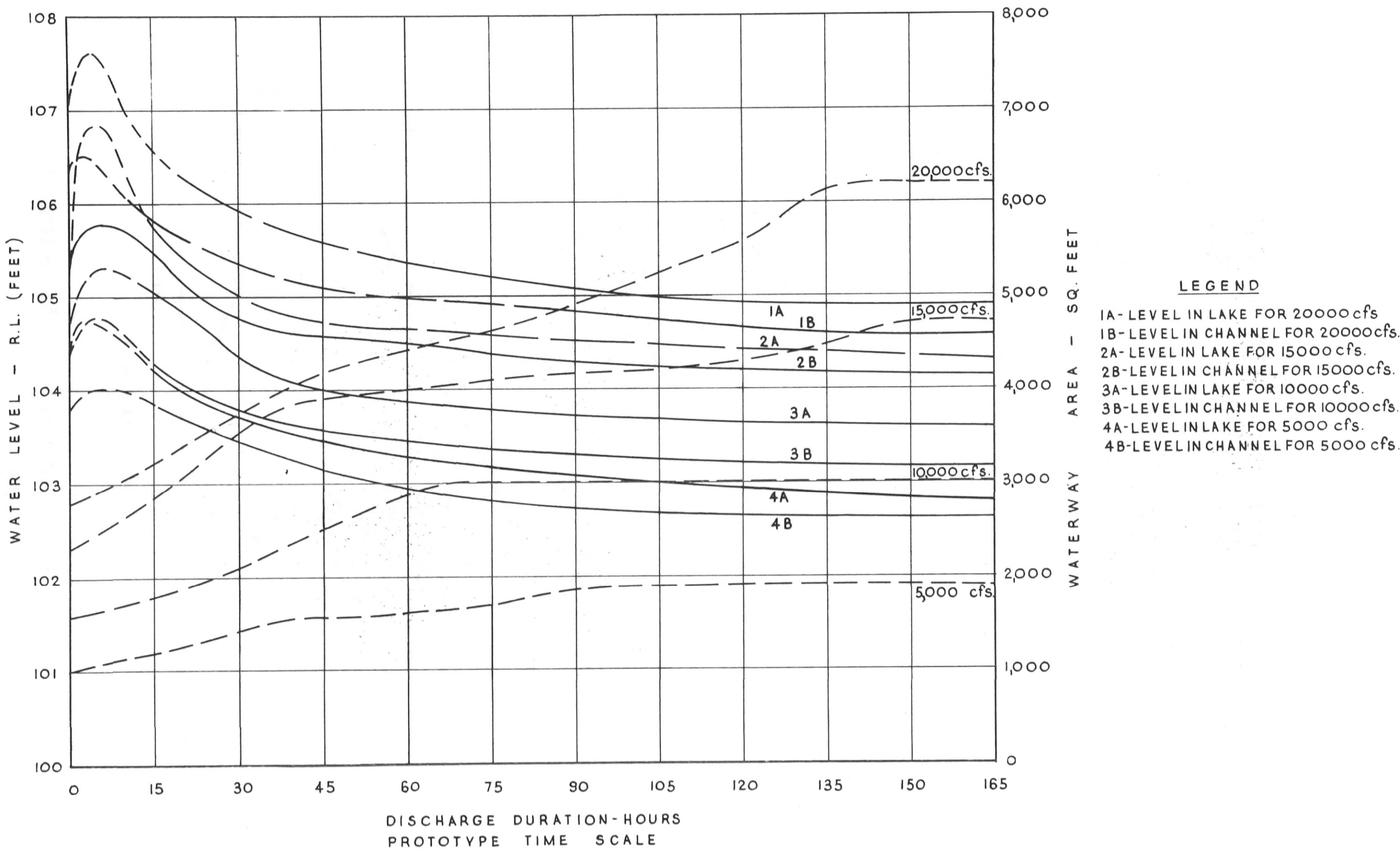


Figure 12: The Entrance - lake level and waterway area.

CE-E-8277

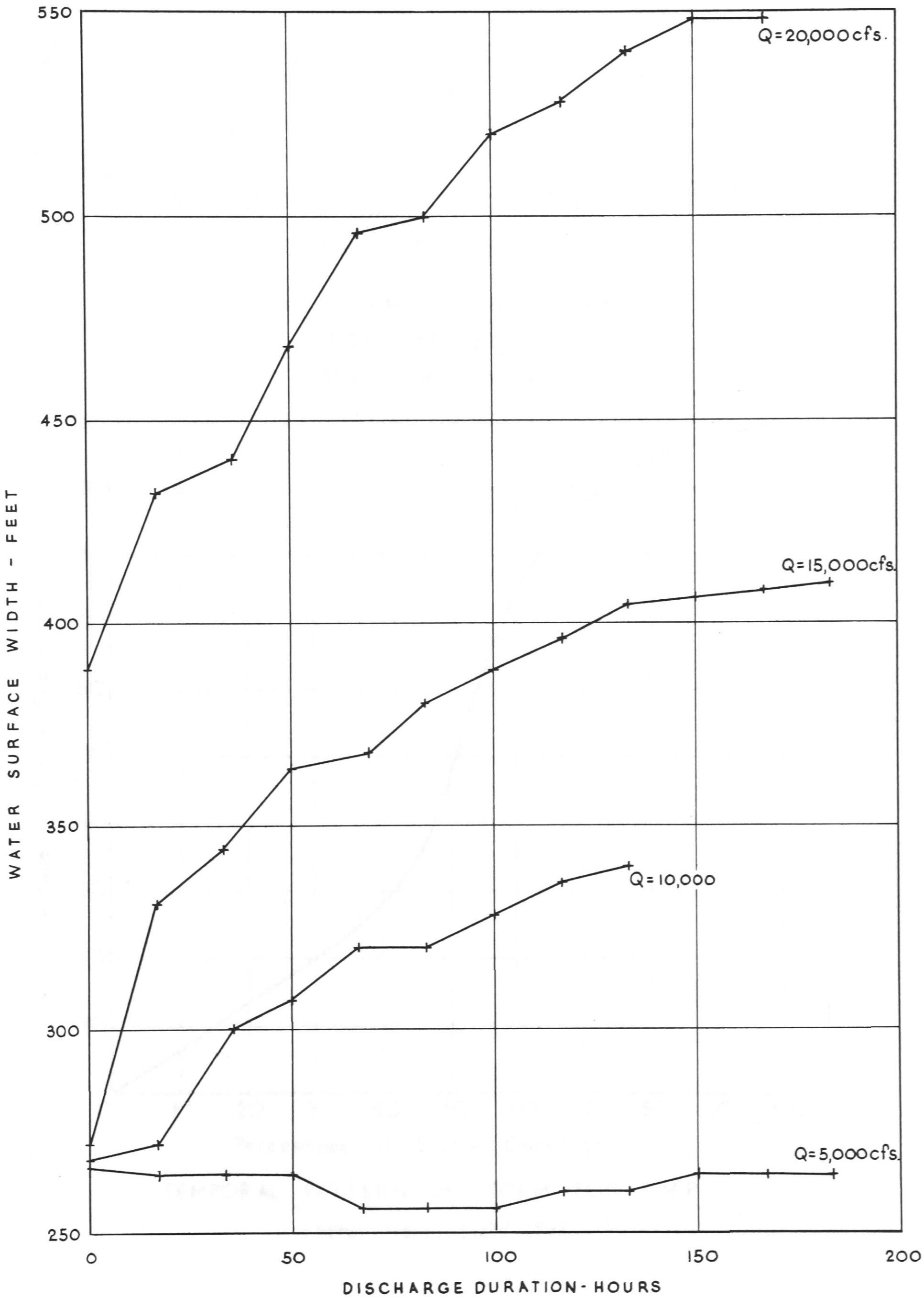
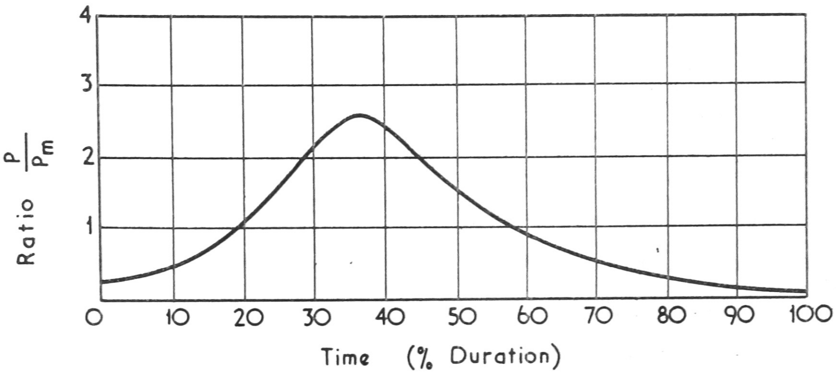
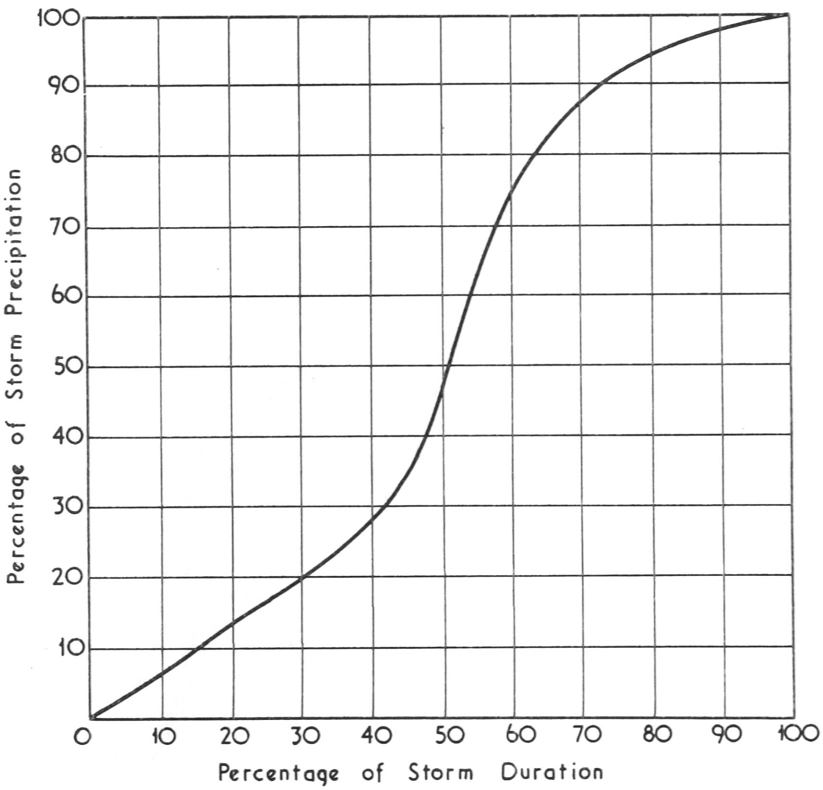


Figure 13: The Entrance - channel water surface width.

CE-E-8278



TYPICAL STORM INTENSITY PATTERN
FOR SYDNEY
(After Laurenson (Ref. 1.))



TEMPORAL PATTERN OF STORM FOR P.M.P
(After Herschfield (Ref. 7.))

Figure 14: Temporal storm patterns.

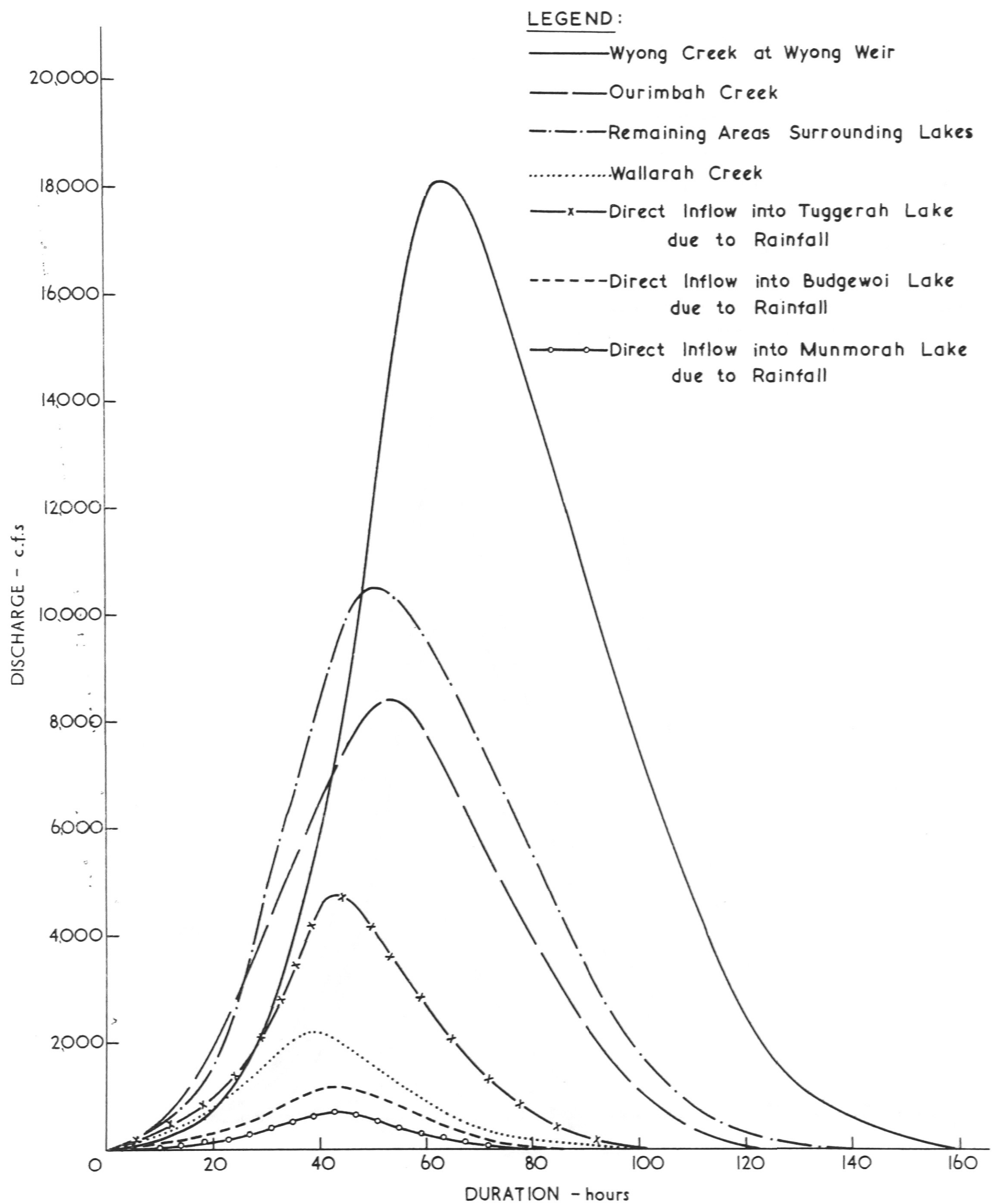


Figure 15: Inflow hydrographs for 1 in 10 year return period storm of duration 96 hours.

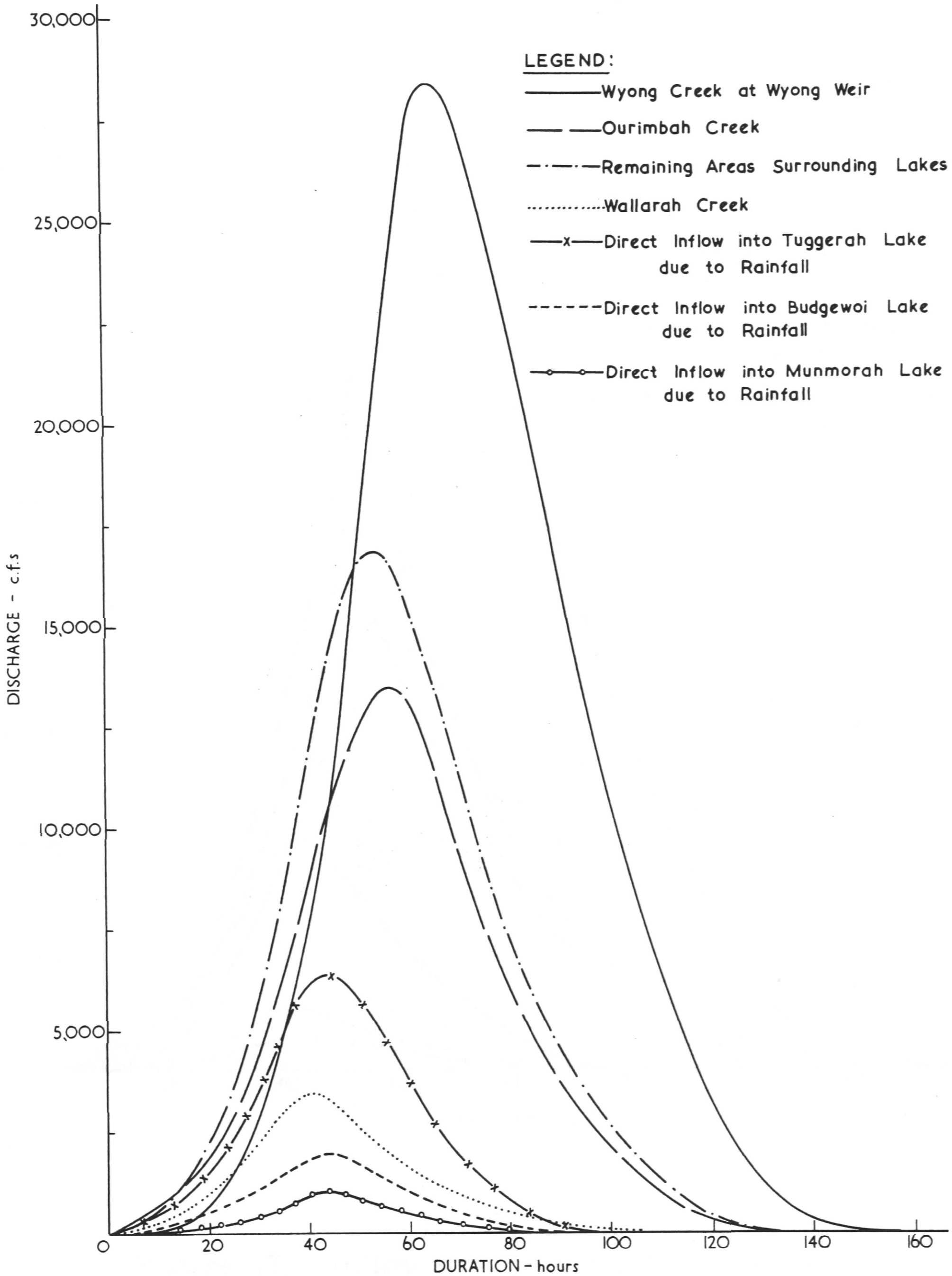


Figure 16: Inflow hydrographs for 1 in 100 years return period storm of duration 96 hours.

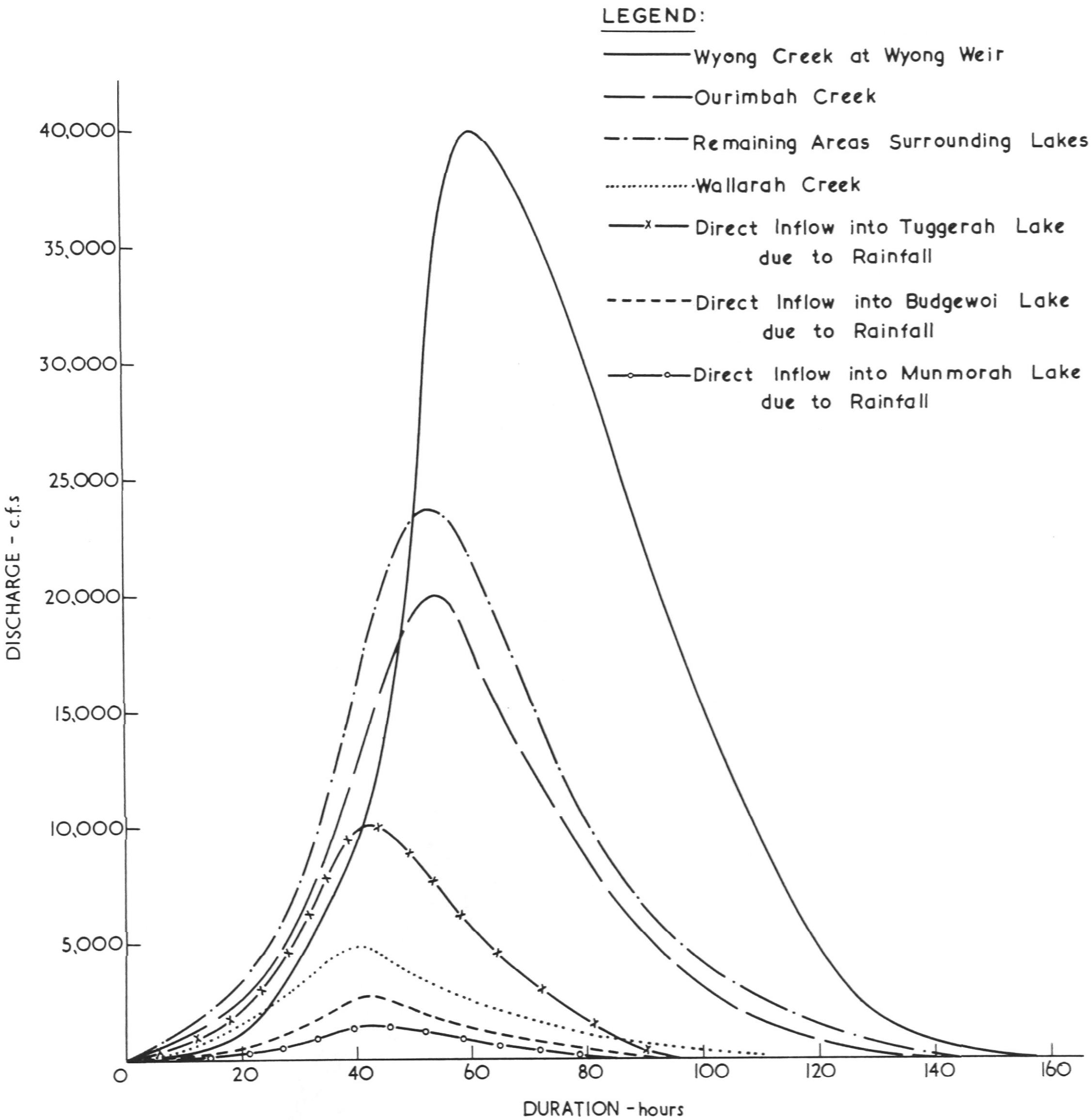


Figure 17: Inflow hydrographs for 1 in 1000 years return period storm of duration 96 hours.

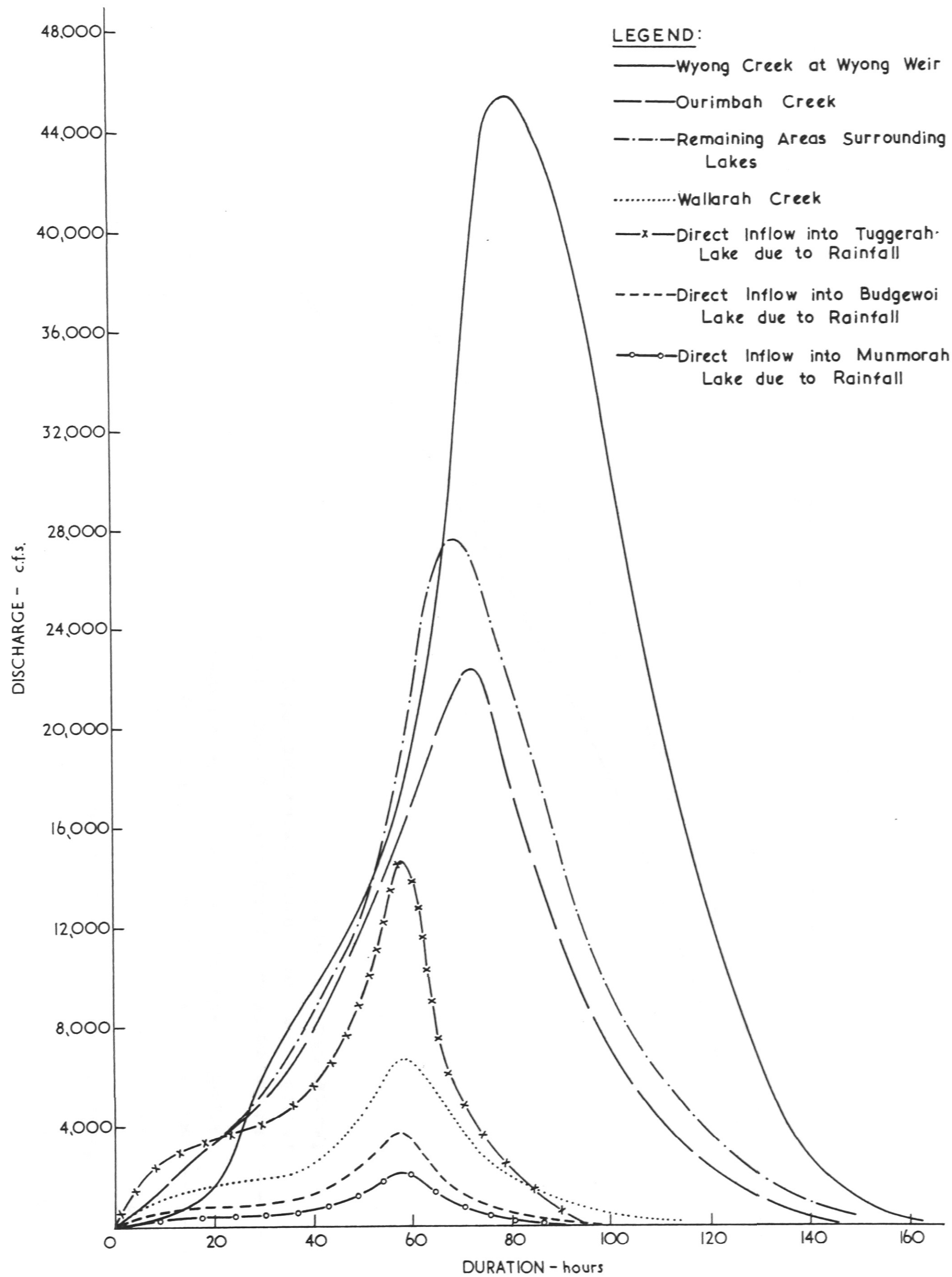


Figure 18: Inflow hydrographs for the probable maximum precipitation (P.M.P.) of duration 96 hours.

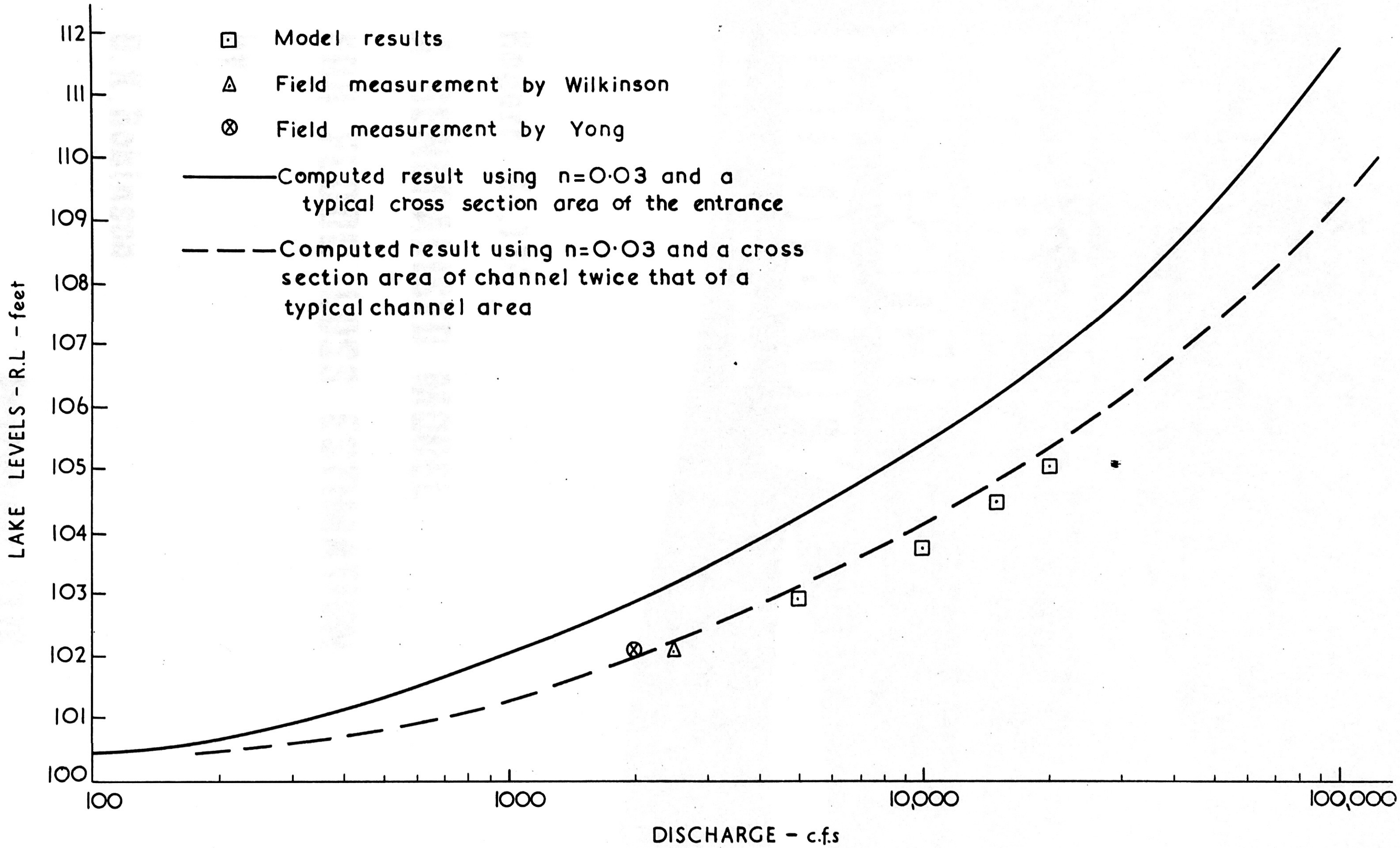


Figure 19: Discharge characteristics of the Entrance channel.