THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976 - 1980)

TECHNICAL REPORT

HYDROLOGY AND METEOROLOGY

JUNE 1980

R.E. Black and J.E. Rosher

DEPARTMENT OF CONSERVATION AND ENVIRONMENT
BULLETIN No. 89

A TECHNICAL REPORT to

THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976-1980)

THE PEEL INLET AND HARVEY ESTUARY SYSTEM HYDROLOGY AND METEOROLOGY

by

R.E. Black and J.E. Rosher

Department of Physics,
Western Australian Institute of Technology

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DEPARTMENT OF CONSERVATION & ENVIRONMENT

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PUBLICATIONS:
THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976-1980)

This report is one of 14 technical reports that were presented to the Environmental Protection Authority's Estuarine and Marine Advisory Committee as part of the Peel-Harvey Estuarine System Study (1976-1980).

The publications arising from the study are listed below and are available from the Department of Conservation and Environment, 1 Mount Street, Perth WA 6000.

- The Peel-Harvey Estuarine System Study (1976-1980). A report to the Estuarine & Marine Advisory Committee December 1980. E.P. Hodgkin, P.B. Birch, R.E. Black, and R.B. Humphries, Department of Conservation and Environment, Report No. 9.
- The Peel-Harvey Estuarine System Study. A report by the Estuarine and Marine Advisory Committee to the Environmental Protection Authority, March 1981. Department of Conservation and Environment, Bulletin No. 88.

TECHNICAL REPORTS

BULLETIN No.

89 The Peel Inlet and Harvey Estuary System Hydrology and Meteorology. R.E. Black and J.E. Rosher. June 1980.

90 Sediments and Organic Detritus in the Peel-Harvey Estuarine System. R.G. Brown, J.M. Treloar and P.M. Clifton. August 1980.

91 The Ecology of *Cladophora* in the Peel-Harvey Estuarine System. D.M. Gordon, P.B. Birch and A.J. McComb. 1981.

92 The Decomposition of *Cladophora*. J.O. Gabrielson, P.B. Birch and K.S. Hamel. October 1980.

93 The Control of Phytoplankton Populations in the Peel-Harvey Estuarine System. R.J. Lukatelich and A.J. McComb. 1981.

94 Cyanobacteria and Nitrogen Fixation in the Peel-Harvey Estuarine System. A.L. Huber. October 1980.

95 Phosphatase Activities in the Peel-Harvey Estuarine System. A.L. Huber. October 1980.

96 The Sediment Contribution to Nutrient Cycling in the Peel-Harvey Estuarine System. J.O. Gabrielson. 1981.

97 Aspects of the Biology of Molluscs in the Peel-Harvey Estuarine System, Western Australia. F.E. Wells, T.J. Threlfall and B.R. Wilson. June 1980.

98 The Fish and Crab Fauna of the Peel-Harvey Estuarine System in Relation to the Presence of *Cladophora*. I.C. Potter, R.C.J. Lenanton, N. Loneragan, P. Chrystal, N. Caputi and C. Grant. 1981.

99 Phosphorus Export from Coastal Plain Catchments into the Peel-Harvey Estuarine System, Western Australia. P.B. Birch. October 1980.

100 Systems Analysis of an Estuary. R.B. Humphries, P.C. Young and T. Beer. 1981.

101 Peel-Harvey Nutrient Budget. R.B. Humphries and R.E. Black. October 1980.

102 Nutrient Relations of the Wetlands Fringing the Peel-Harvey Estuarine System. T.W. Rose and A.J. McComb. August 1980.

PREFACE

This report is the final working document of a three year study into the hydrology of the Peel Inlet and Harvey Estuary system. It has been prepared as a summary of the research,field work, computing, data collection and analysis of the authors and many assistants, for presentation to the Estuarine and Marine Advisory Committee of the Department of Conservation and Environment of Western Australia. It aims not only to present the above summary, but also to form an integral part of what has been a major interdisciplinary study.

Insofar as has been possible with data available to the authors at the time of writing, results are interpreted and fully discussed. However, because of the large amount of computer analysed data, in some instances results are presented in a summary form. The various appendices contain full data sets and copies are held by the Department of Conservation and Environment for use by those interested.

From the outset, we adopted the philosophy that wherever possible, the purchase of expensive equipment would be avoided if it was possible to utilise student assistants to perform the necessary tasks with less sophisticated instrumentation. We feel that this policy has been successful and that accuracy has in no sense been sacrificed in achieving this aim. Thus the work presented in this report owes a great deal to a large number of undergraduate and postgraduate students of the Departments of Physics (primarily), Biology and Surveying of the Western Australian Institute of Technology.

Furthermore, the co-operation and enthusiastic support of Dr. Warren Walker, Head of the Department of Physics, is gratefully acknowledged.

A number of residents of the Mandurah-Pinjarra area contributed greatly to the success of this project. In particular, those who watched over our climatological instrumentation (with such care that not a single hour's data was lost through unauthorised interference), are sincerely thanked. Mr. Merv. Christiansen of the Shire of Mandurah, who effected introductions to these people, also assisted greatly.

Officers of the Public Works Department not only made freely available their excellent hydrological and climatological records, but also treated our every request (both the reasonable and the unreasonable) with customary efficiency and care. Messrs. Keith Barrett, Ian Loh, Robert Harvey, Bill Collins, Brian Chester and Don Wallace and Dr. Bill Andrew are especially thanked in this regard.

Dr. Ross Field, secretary of EMAC and Mr. Ian Parker of the Department of Conservation and Environment are to be commended for the extraordinary efficiency with which the project in general and field exercises in particular were carried out.

We would also like to sincerely thank our fellow researchers in the other teams; notably Professor Peter Young, Drs. Bob Humphries, Tom Beer and Paul Whitehead of the CRES team; Assoc. Professor Arthur McComb and Mr. Robert Atkins of the Department of Botany, UWA; Dr. Dennis Kidby, Mr. John Gabrielson and Miss Ann Huber of the Department of Soil Science, UWA; Dr. Ray Brown and Mr. Jim Treloar of the Department of Geology, UWA; and so many others from state and commonwealth government departments who assisted in many ways.

Our "hydrological" colleagues who have helped with constructive advice and criticism throughout should be mentioned again for the way in which they have enriched the authors' experience throughout this study. In particular we have learned a great deal from Professor Peter Young of ANU, Professor George Hornberger of the University of Virginia, Professor Robert Spear of the University of California, Berkeley, Dr. Bob Humphries of ANU, Dr. Paul Whitehead of the Institute of Hydrology Wallingford, England, Dr. George Fleming of the University of Strathclyde, Glasgow, Scotland, and in the latter stages of the study, Professor Jorg Imberger of UWA.

The final analysis and writing of this report was completed by the principal investigator whilst on professional experience leave from the Western Australian Institute of Technology at the University of Strathclyde and the Institute of Hydrology. For this we are indebted to the WAIT and moreover to the Trustees of the Robert and Maude Gledden Overseas Fellowship (of the University of W.A.) who provided the principal investigator with such generous support for travel and subsistence. Without their help the finalisation of this work would have been made immeasurably more difficult.

Mrs. Glenyce Black and Miss Pat Lean who were respectively responsible for the drafting of maps and figures and the typing of the final report are especially thanked for their efforts and tolerance.

We would like to thank Mr. B. Bowen, Director of the Department of Fisheries and Wildlife and Chairman of EMAC and all other members of the committee who have done so much to help and encourage our research. We should of course acknowledge that this study was funded through the Department of Conservation and Environment and without this support it would clearly not have been possible.

Finally we would like to reserve our most sincere thanks for Dr. Ernest Hodgkin, the coordinator of the project. His ability to maintain a keen interest and informed appreciation of all aspects of a very large and complex study filled us with admiration. His patient understanding of the numerous trials and tribulations helped to make the entire project time a most stimulating and satisfying part of our research experience.

R. E. Black
June, 1980.

University of Strathclyde,
Glasgow,
Scotland.

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THE PEEL INLET-HARVEY ESTUARY STUDY

HYDROLOGY AND METEOROLOGY OF THE SYSTEM

1. INTRODUCTION

The Peel Inlet-Harvey Estuary system is a large (133 km^2), shallow (average 1m depth) waterway approximately 70 km south of Perth, Western Australia. The study described here forms but one part of a large interdisciplinary study of the water body initiated with the dual aims of:-

(a) Determining the causes of the excessive growth and accumulation of green algae in Peel Inlet and, if possible to propose methods for its control.

(b) Gaining an understanding of the working of this estuarine ecosystem so that environmental problems can be foreseen and decisions made about its management on the basis of sound knowledge.

Within the framework of these aims, the investigation reported herein had two principal objectives related to the total physical system, viz:

(i) To establish a data base of meteorological and hydrological parameters relevant to other aspects of the study.

(ii) To estimate the water balance of the system over the period of the study by accounting for all system inputs and outputs on a suitable time scale.

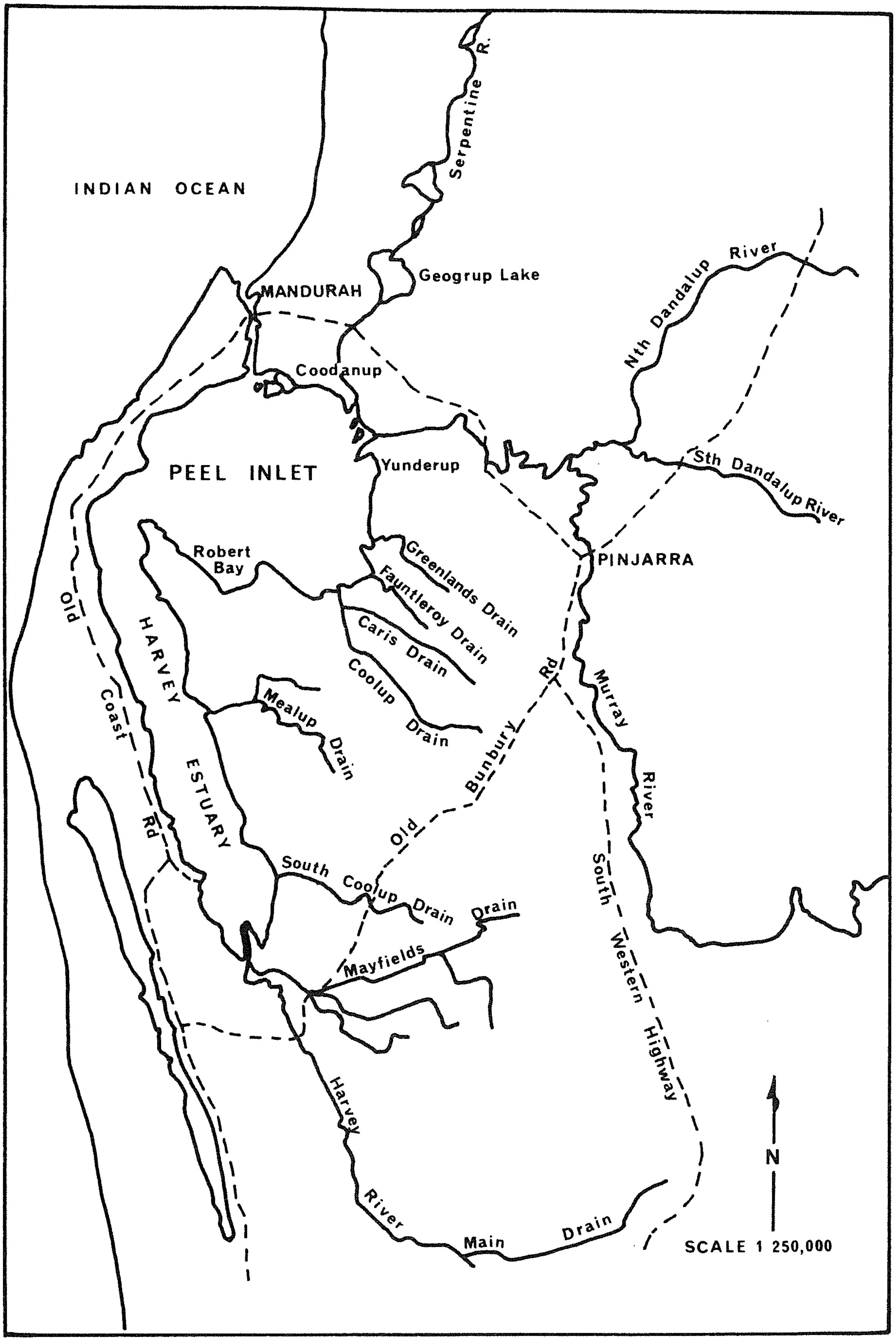


Fig. 1·1 PEEL INLET & HARVEY ESTUARY HYDROLOGICAL SYSTEM FEATURES

Hydrological inputs sampled, routinely gauged or analysed from Public Works Department flow records were confined to the three major river systems, (Murray, Serpentine and Harvey Main Drain), minor agricultural drains and groundwater estimates. In one sense, the entire catchments of these rivers was considered, but a practical upstream limitation exists on the Serpentine (the Serpentine Dam) and the Murray (the tidal weir at Pinjarra). Figure 1.1 shows the hydrological system features.

The climatology of the system was studied mainly by the establishment of a weekly visited weather station at Robert Bay (see Figure 1.1) which recorded rainfall, temperature, humidity, pan evaporation, wind speed and direction. In addition two intensive studies of lake evaporation were undertaken in January and July, 1977. Much of the climatological data collection programme was directed towards improving estimation of the evaporation from the system as this has a profound effect on the salinity of the estuary due to the limited tidal exchange experienced. Two additional pluviometers were established in June, 1977, at Mandurah and on the Harvey Estuary (see Figure 1.1). The various sensors began recording at Robert Bay as and when instruments arrived from the manufacturers, commencing with thermograph and hygrograph (October, 1976), pluviometer (January, 1977), pan evaporimeter (January, 1977), anemometer (October, 1976) and the station was closed down at the conclusion of the study on September 30th, 1979.

The hydrometeorological study commenced in late July, 1976, and following a number of visits to the area, it was decided to immediately commence gauging of the Harvey River and Harvey Estuary Drains, together with routine water sampling on, as near as possible, a weekly basis. Gauging of these drains continued until the end of 1978 when it was decided that minor drain flows could be estimated satisfactorily from Harvey River continuous flow records which became possible after the installation of a water level recorder in October, 1978.

In fact the quality and frequency of drain and river flow gaugings was progressively improved as equipment purchased from project funds became available throughout 1976 and 1977. With the development of the Department of Botany, University of Western Australia Analytical Laboratory and the addition of the Applied Systems (Water Cres) Group of the Australian National University Centre for Resource and Environmental Studies in late 1977, more intensive sampling was established. Thus two complete "water years" (October 1 to September 30) were sampled from October 1, 1977, to September 30, 1979.

Prior to the study there was no existing flow record for the Harvey River or other drains and whilst PWD records were available for both the Murray and Serpentine Rivers, gauging stations were remote from the system and there are tributaries downstream in both cases. Whilst this problem could be relieved on the Murray by routing flow to Pinjarra Weir and adding discharge measurements from the relevant tributaries, the Serpentine River remained essentially ungauged until April, 1979, when the PWD installed an automatic water level recorder just upstream of Geogrup Lakes (see Figure 2.1).

A Bureau of Meteorology daily rainfall station has existed for many years at the Mandurah Post Office but this provides only 0900 daily readings of rainfall and temperature. Thus the Robert Bay climatological station supplies the only detailed meteorological records for the other elements of the study.

As the study progressed and an understanding of the excess nutrient problem developed it became apparent that measurements of water volume and salt flux to the ocean would have to be made. Two intensive (hourly) 5 day periods of direct flow measurement at the Mandurah Bridge were made - one in February and the other in August, 1978. This enabled calculations of tidal exchange with the ocean to be made under conditions of zero river flow (summer) and maximum river flow (winter). Regrettably, the period of the study covers, in whole or in part, 3 very dry years with rainfall around 50%/60% long term average (1976, 1977 and 1979) and one average year (1978). The extent to which these atypical climatic conditions influenced all aspects of the study will be examined in some detail later.

Chapter 2 describes the climatology of the system, with particular emphasis on the estimation of evaporation and the intensive exercises carried out to relate estuary evaporation to pan evaporimeter results.

Chapter 3 gives a summary of the quantitative river and drain hydrology, including flow routing on the Murray River and the estimation of minor drain flows from Harvey River records.

Chapter 4 analyses the nutrient loadings of the input waterways and should be read in conjunction with time series plots of this information provided by the CRES team.

Chapter 5 deals with the question of tidal exchange insofar as it can be determined from Mandurah Bridge measurements previously referred to. An attempt is made to model volume fluxes from tide records in the entrance channel.

Chapter 6 briefly summarises the estimation of groundwater inputs to the system and the conclusion that this is an insignificant element in the total water balance.

Chapter 7 draws together the data and analyses from chapters 2 to 6 and attempts to solve the water balance equation for the Peel-Harvey estuarine system.

The conclusions of the study are stated in chapter 8.

Throughout this report, there is considerable integration and overlap with the systems analysis of the CRES team. This is inevitable since their role in many instances is to synthesise the field data collected by members of this study team with water quality analysis of the Department of Botany team. We have enjoyed an excellent working relationship with both teams throughout and it is thought that a little duplication here and there in our reporting will not detract greatly from the final result.

The summer and winter conditions in the estuary differ so markedly that if the thrust of this report is to be the determination of a water balance for the system, then the time scale chosen for this equation is critical. In the summer condition there is virtually no rainfall and all rivers and drains, save the Harvey, have ceased to flow. Here it might be thought that under the influence of tidal exchange the estuary would achieve equilibrium at oceanic salinity levels. However the dominant forcing function becomes evaporation and hypersaline conditions (up to 50‰ Na Cl) are reached in January or February.

In the winter condition, even before the major rivers began to flow into the system, there is a steady reduction in salinity to ocean levels (circa 35 ‰) as tidal exchange dominates over the reduced evaporation rates of April and May. Progressively throughout the winter estuarine water (which has penetrated as far as Pinjarra weir during the summer) is forced back by freshwater flow in the Murray River (circa 5‰) and there is considerable previous knowledge of this behaviour compiled by E. P. Hodgkin and R. Rippingale over a number of years in the early 1970's. Two dye injection experiments carried out by Mr. R. B. Humphries and the CRES team have added to this knowledge and will be referred to throughout this report.

Large amounts of computer analysed data have been used in the compilation of this report. This is mainly continuously recorded (strip chart) data digitised by hand or computer techniques developed during the study. This output has been progressively supplied to the other team members on demand. It is compiled separately as an Appendix and a copy held by the Department of Conservation and Environment. In most instances, the compiling or analysing programme is attached to the data for the benefit of those interested.

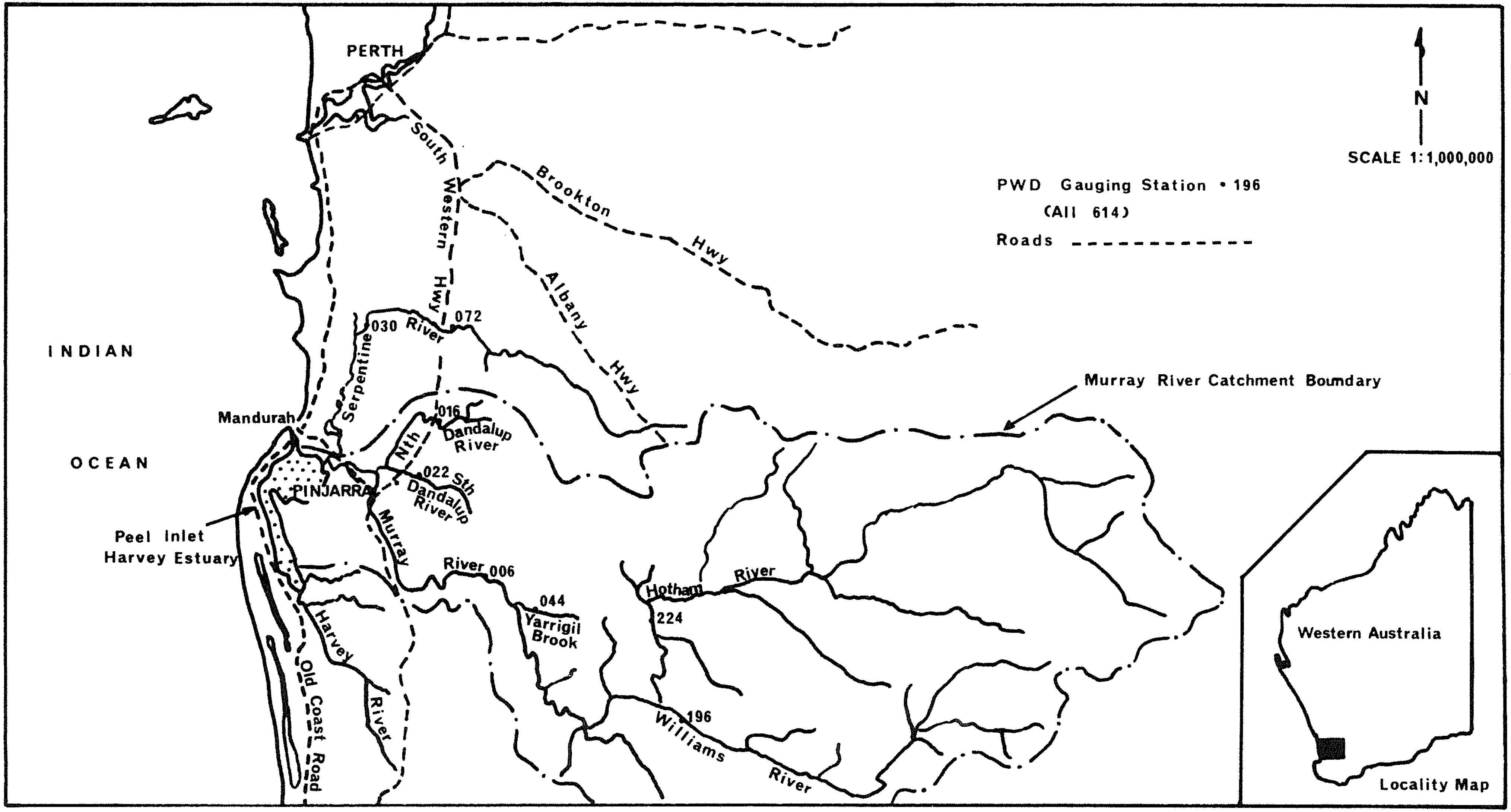


Fig. 1·2 PUBLIC WORKS DEPARTMENT MAIN STREAM GAUGING SITES

	ACTIVITY	1976						1977												1978												1979									Oct.79 onwards
		J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	
CLIMATOLOGY	RAINFALL							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	TEMPERATURE							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	HUMIDITY							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	WIND							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	EVAPORATION						●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	NET RADIATION							●						●																											●
	BAROM. PRESSURE															●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
G/W	BORE SURVEY							●						●																											
G/W	INTERCEPTORS																																				●	●	●	●	
SURFACE HYDROL.	HARVEY RIVER	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	DRAINS	●	●	●	●	●						●	●	●	●	●	●							●	●	●	●	●	●							●	●	●	●	●	●
	MURRAY RIVER																●								●	●	●												●		●
	SERPENTINE RIVER																										●														●
FLOW ROUTING-MURRAY																	●								●	●	●												●		●
WATER SAMPLING	HARVEY RIVER	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	DRAINS							●	●	●	●	●	●	●	●									●	●	●	●	●	●							●	●	●	●	●	
	RAVENSWOOD															●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●					●	●	●	●	●	
	BARRAGUP BR.															●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●					●	●	●	●	●	
TIDAL FLUX																					●						●														●
RAINFALL/R.O.MODELLING																																						●	●	●	●

TABLE 1·1: TIMETABLE of ACTIVITY

2. CLIMATOLOGY

2.1 General - Climatalogical Data Base

In the definition of a water balance for any system of this kind, it is necessary to develop a time series of those hydrometeorologic parameters that either form part of the equation directly (such as precipitation) or are necessary to calculate another (in the way that temperature and humidity are used to estimate evaporation). One would not normally expect to find such a series or data set in existence and under continuous monitoring adjacent to the study area, and such was the case here. The Sections 2.1.1 to 2.1.6 that follow define the status of climatological data up to and including 1976/77 when the Peel study commenced.

2.1.1. Rainfall

Bureau of Meteorology daily-read rainfall stations have long been established at a number of sites surrounding the estuary. As is usual in such cases, they are manned by volunteer observers or Post Office staff and are not normally read on weekends, so that the "daily" 9.00 a.m. reading on Monday is often a 72 hour total. Four such stations were suitably located (see Fig.2.1) to provide useful long-term average data for the study. The length of record varied from 15 years (now discontinued) at Waraba to 92 years at Pinjarra. However, no hourly rainfall data was available in the vicinity and it was felt that such would be useful, especially in the analysis of Harvey River flows

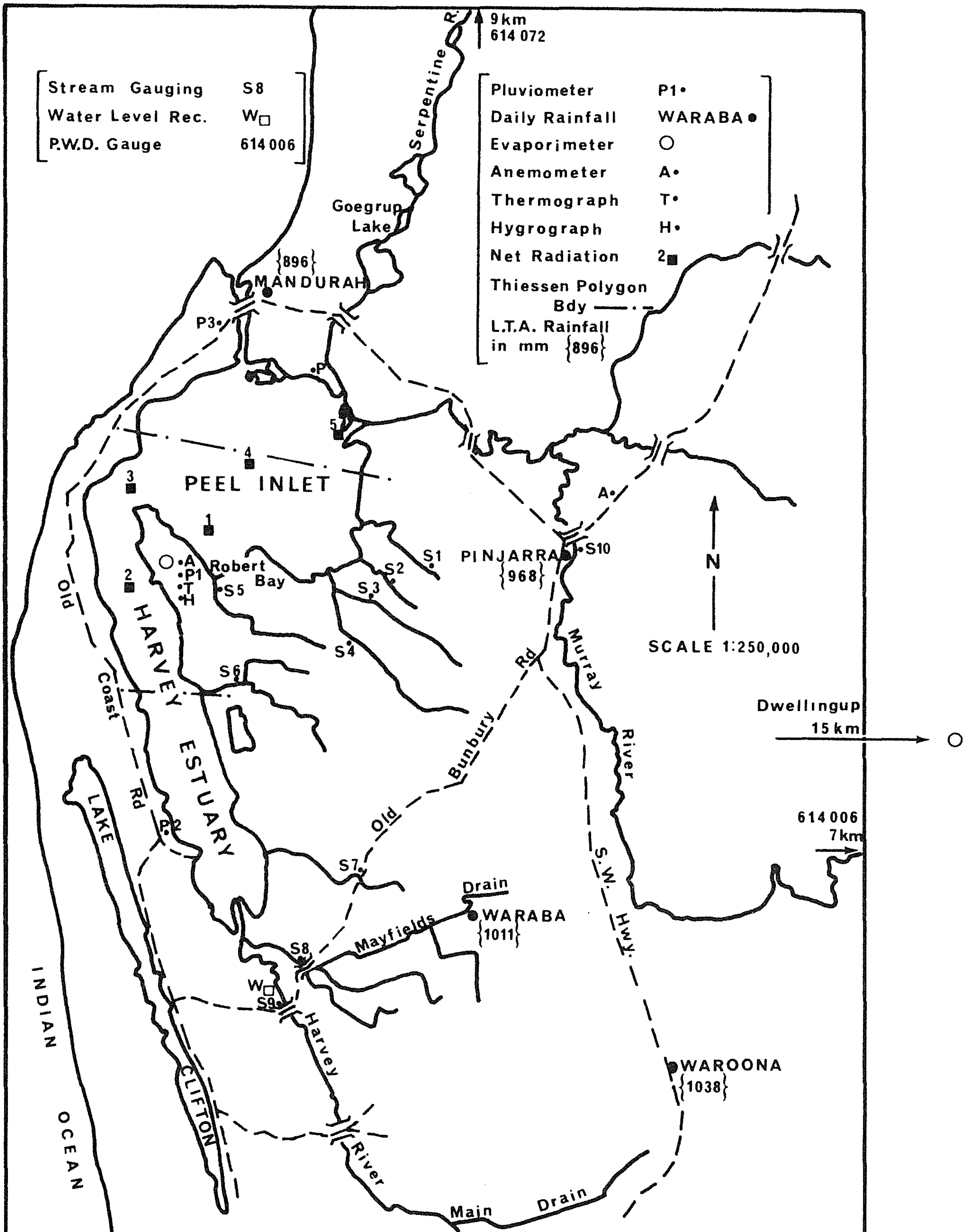


Fig. 2·1 HYDROMETEOROLOGICAL SITES

which exhibited an unusually short time-to-peak. Thus it was decided to augment the useful long-term data with a limited network of hourly pluviometers for the duration of the study. This is discussed further in 2.2.

2.1.2 Temperature and Humidity

Daily-read rainfall stations usually incorporate 9.00 a.m. readings of wet and dry bulb screen temperatures (and calculations of 9.00 a.m. dewpoint therefrom) as well as 24 hour maximum and minimum temperature. However, continuous thermograph data was not available except at Perth Weather Bureau so that it was decided to locate both a thermograph and hair hygrograph adjacent to the estuary. The necessary digitisation of the strip chart records is discussed in 2.3 and 2.4.

2.1.3 Evaporation

The Bureau of Meteorology maintains only a limited number of pan evaporimeter sites and the closest to the Peel/Harvey area is at Dwellingup (see Fig.2.1). One reason for this is probably the difficulty in providing a water supply in remote locations. This proved to be a problem in this study too. From the outset, it was considered that evaporation measurement would be a key element in the water balance determination, and thus a U.S. Class "A" pan evaporimeter should be installed. An extensive analysis of this component of the study is included in 2.5.

2.1.4 Wind

There appeared to be at least three reasons for measuring wind speeds over the estuary. Firstly it seemed likely that the estimation of evaporation would require this data. Secondly, the nuisance weed Cladophora Sp. could be seen to migrate across Peel Inlet, presumably under the influence of the dominant south-westerly winds. Thirdly, to what extent was wind-induced stirring responsible for the more or less continuously turbid state of the Harvey Estuary? The nearest wind recordings available at the start of the study were at the Alcoa Alumina Refinery at Pinjarra (see Fig.2.1), but since that time the Kwinana Air Monitoring Study (K.A.M.S.) has installed many more anemometers. A Lambrecth "Woelfle-type" strip chart anemometer was established at the estuary in late 1976. The digitising of this (monthly) data on a 4-hour time increment and its importance in estuary turbidity is discussed in 2.6.

2.1.5 Barometric Pressure

Previous studies of estuaries in the south-west of Western Australia (Hodgkin and Di Lollo 1958, Agnew and Imberger 1974) have drawn attention to the influence of meteorological conditions on tidal amplitude and flux. Indeed, in this part of Australia the normal gravitational tides are very small and the semi-diurnal component frequently too small to detect. However, barometric oscillations can cause significantly increased tidal exchange over periods ranging from 5 to 15 days and longer (Beer and Black 1979). Such oscillations have an amplitude of about 0.3 m. There would seem to be merit therefore in continuously monitoring barometric pressure in the locality and attempting to relate this to tidal flux.

A stable environment is required to house a continuously recording barograph. Since such a record was available at the author's home some 70 km. away, and in any case relative and not absolute pressure variations were required, it was decided to utilise this strip chart trace for study purposes. This chart record was subsequently digitised on a 12 hour time increment and an attempt was made to relate barometric pressures to tidal flux (see 2.7).

2.1.6 Solar Radiation (Global Radiation)

For the purposes of estimating evaporation (see 2.5), measurements of net solar radiation were made on two week-long exercises. No continuous record of solar radiation was kept at the estuary. In retrospect, since estimates of light and light penetration were needed by other members of the study team to examine various aspects of the weed growth, this was regrettable. As a substitute this data was transposed from the only available local records at Perth Airport (Guildford) and the R.A.A.F. base at Pearce Aerodrome. These sites are respectively 80 and approximately 150 km. to the north of the estuary.

2.1.7 Robert Bay Climatological Station

To make good the various deficiencies in the climatological data base referred to, it was decided to establish a weekly-visited station at Robert Bay (see Fig.2.1). Though this site was by no means ideal, it offered the following advantages:-

(i) Rainfall - good exposure; low, natural ground cover.
(ii) Temperature and Humidity - as for rainfall
(iii) Evaporation - proximity to estuary shore line.
(iv) Wind - as for evaporation

However, as with all such sites, the situation chosen was a compromise - the surrounding topography protected the station from the full effect of the dominant south-westerly winds which would probably result in reduced evaporation and wind speeds being recorded. Since the aim was to monitor the above range of meteorological variables as they would affect the estuarine environment, this was clearly less than ideal. Furthermore, the Robert Bay site situated on Western Stud Farms property proved to be quite inconvenient to service and the weekly round trip from the Western Australian Institute of Technology (which included a gauging of the Harvey River) approximated 300 km. This remoteness was however to prove a blessing - in over 3 years of data collection, not a single reading was lost or otherwise invalidated by unauthorised interference from persons or stock.

Sections 2.2 to 2.7 describe the instrumentation established at the Robert Bay station and elsewhere and Appendix I lists the full data sets recorded over varying time periods from October, 1976, to October, 1979.

2.2. Rainfall

2.2.1 Location of Pluviometers

In view of the considerable North-South extent of the estuary, it was considered from the outset that at least 3 gauging sites would be necessary to adequately determine the average precipitation over the system. Section 2.2.4 discusses the fact that in drought years, direct precipitation on the water body itself (analogous to channel precipitation in rainfall-runoff modelling) can constitute a significant proportion of total water input.

The cost of the self-recording raingauge varies considerably depending on type of collecting mechanism and method of recording, whether digital or analogue. The standard pluviometer used by rain gauging authorities in Western Australia (Bureau of Meteorology and Public Works Department) is the "RIMCO" Tipping Bucket Gauge interfaced to a continuous strip chart recorder (usually the Leopold-Stevens A35 Chart Recorder). However for the same cost as one such instrument of this type, which is capable of recording for 6 months without attention, it is possible to purchase three less sophisticated gauges and thus greatly improve the accuracy of areal representation of rainfall. This is possibly at the expense of only minimal recording accuracy. One apparent disadvantage of the latter policy decision is that weekly strip chart changing will be necessitated if hourly rainfall data is required. This was not thought to be a problem since the project site had to be visited weekly in any event for other measurements and sampling.

Consequently, three Casella Natural Siphon weekly chart self recording raingauges were purchased and located as shown on Fig.2.1 as and when they became available. The chosen locations (Robert Bay (1), Harvey Estuary (2) and Mandurah Bridge (Sutton's Farm)(3) were compromise situations with accessibility, security and representation being key factors.

After 15 March, 1979, the Robert Bay (1) pluviometer was moved to Coodanup, together with the Class A pan evaporimeter. As these were the only instruments at the Robert Bay Climatological Station requiring weekly attention, the move reduced the frequency of visits to this remote station to monthly. Fig.2.1 shows the location of the Coodanup site and reveals that the relevance of the Thiessen weight assignment to the No.1 pluviometer is still valid in this position (see 2.2.3).

2.2.2 Analysis of Rainfall Variability

(i) Seasonal variability

Peel Inlet and Harvey Estuary are subject to an essentially "Mediterranean-type" west coast margin climate having long (November to March), hot (25 °C to 40 °C maximum daily shade temperatures), dry summers and short (May to August) wet winters. In the two *"water years" examined, the following seasonal rainfall distribution reveals the typical pattern, though it must be remembered that both are below average rainfall years. (see TABLE 2.1)

(ii) Daily variability between pluviometers

Analysis of four storms provides justification for the decision to instal three pluviometers in order to adequately distribute percentages of total rainfall on an estuary-wide basis. In general, the Robert Bay gauge tended to receive lesser volumes of any particular storm

* "water year" - Oct.1 to Sept.30.

rainfall falling over the system. The variation shown from the storm analysis (see TABLE 2.2) is not unusual for such a situation where rainfall is predominantly from cyclonic (frontal) systems where precipitation from cold fronts associated with low pressure systems tends to be localised and showery. The very high standard deviations shown in TABLE 2.2 are considered adequate justification for the application of an averaging technique if a proper water balance equation is to be quantified.

2.2.3 System-wide Rainfall Averaging

A variety of averaging techniques are frequently applied in rainfall-runoff studies, the most common of which are the simple average (arithmetic mean), the Thiessen polygon method and the isohyetal method. Much more complex "derivation of rainfall surface" methods have more recently been developed with the aid of computer derived rainfall models (Lee et al 1974). However, such techniques are not suitable for a 3-gauge network. On the same grounds it is possible to dismiss the isohyetal method, whilst acknowledging however that the storm analysis of TABLE 2.2 shows that there might be some benefit in a storm by storm isohyetal distribution.

In consideration of the fact that no other water balance inputs have been derived on better than a daily time increment it would seem that the application of the Thiessen polygon averaging method provides system-wide rainfall averages with an accuracy sufficient for all practical purposes, including that of rainfall-runoff modelling. This technique consists of drawing lines connecting the three raingauges and constructing the perpendicular bisectors of these lines. The bisectors then define, along with the estuary (or catchment boundary) the area of theoretical influence of each gauge. In this case, as the three sites lie almost in a straight line (see Fig.2.1), it is necessary to subjectively adjust the bisectors as shown. The Thiessen weighting factors are then defined as the percentage of the total estuary area assigned thus to each gauge. These weights, as measured by planimeter are:-

Robert Bay (1)	=	0.58
Harvey (2)	=	0.26
Mandurah (3)	=	0.16
Total		1.00

A small computer program was then written in HPL language for the Hewlett-Packard 9825 Computer to

a) add the hourly rainfalls for each gauge to give a 24 hour daily total,
b) multiply each daily total by the Thiessen weight above,
c) sum the weighted daily totals to give a system-wide daily average,
d) sum daily total to give monthly totals.

Results are shown in TABLE 2.3

2.2.4 Direct Precipitation on Inlet

The very large surface area of the inlet as a whole (133×10^6 m^2) gives rise to the surprising fact that frequently during storms, as well as on an annual basis, direct rainfall on the water body is a considerable percentage of total input. For example, on 30 September, 1978, rainfall average over the inlet = 46.1 mm (less evaporation of 3.5 mm) which is a total volume of 5,665,800 m^3 in the day. Total daily flow for the three major rivers flowing into the estuary was:-

30 September, 1978:	1,717,800 m^3
1 October, 1978:	12,115,400 m^3

In view of the lag time for Murray River flows from the Baden Powell Water Spout gauge to Peel Inlet, it is doubtless more reasonable to relate

Year	Weighted Av. Annual Rainfall*	Weighted May, June July, August Rainfall (Winter)		Weighted Nov., Dec., Jan., Feb., March Rainfall (Summer)	
	(mm)	(mm)	% Annual	(mm)	% Annual
1977/78	745.8	518.8	69.6	24.3	3.3
1978/79	610.9	439.6	72.0	53.5	8.8

*Long term average rainfall (79 years) = 896 mm (Mandurah P.O.)

Winter % annual rainfall (79 years) = 71% (Mandurah P.O.)

TABLE 2.1 : Seasonal Distribution of Rainfall 1977/78, 1978/79 Peel Inlet/Harvey Estuary.

Pluviometer	Storm 1 17/7/77 (mm)	Storm 2 20/7/77 (mm)	Storm 3 19/5/78 (mm)	Storm 4 30/9/78 (mm)
Robert Bay (1)	15.7	21.5	20.4	38.5
Harvey (2)	26.2	21.0	27.9	56.7
Mandurah (3)	29.4	9.9	26.9	43.0
Mean; S.D.	23.8; 7.2	17.5; 6.6	25.1; 4.1	46.1; 9.5

TABLE 2.2: Daily Variability of Storm Rainfalls 1977/78, 1978/79 Peel Inlet/Harvey Estuary.

THIESSEN WEIGHTED MONTHLY TOTAL RAINFALL (mm)

YEAR	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1977	-	-	1.8*	0.5*	80.9*	86.1*	70.0	112.7	35.1	49.2	6.1	1.7
1978	0.2	6.1	10.2	10.7	150.3	185.2	141.7	41.6	142.8	18.3	22.6	12.1
1979	4.1	1.8	12.9	37.9	85.8	156.1	134.3	63.4	61.9	-	-	-

* Robert Bay gauge only installed March - July, 1977.

TABLE 2.3 : Peel Inlet/Harvey Estuary Thiessen Weighted Monthly Rainfall Data 1977/78; 1978/79.

WATER YEAR	River Discharge into Estuary ($m^3 \times 10^6$)				Rainfall on Estuary	
	Murray (at 614 006)	Serpentine (estimated)	Harvey & Drains	Total	Volume ($m^3 \times 10^6$)	% of Total Flow
1977/78	238	65	206	509	99	19.5
1978/79	62*	55*	150	267	81	30.3

*Based on incomplete September, 1979, record.

TABLE 2.4 : Rainfall on Estuary v's River Discharge 1977/78; 1978/79

the 30 September rainfall to the 1 October flow (at least) and thus direct precipitation constituted a significant percentage of total flow in this instance.

Similar comparisons can be made for the water year totals and these are shown in TABLE 2.4 It will be seen from this Table that as a % of 1977/78 rainfall and flow the 1978/79 figures vary considerably. Whilst the rainfall on the estuary figure is 82%, Serpentine River 85% and Harvey River 68%, the Murray River 1978/79 total volume is only 26% of the 1977/78 value. This in fact is the second lowest annual flow recorded in the 40 year period 1940-79 inclusive for this river and is discussed further in Chapter 3.

2.2.5 Conclusions

The most significant features of the precipitation over the Peel Inlet/Harvey Estuary system during the two water years of the study have been discussed in 2.2.1 and 2.2.4 inclusive. Finally however, it should be noted that both years were well below average rainfall periods. The 79 year average annual rainfall from the nearest daily-read gauge (Mandurah Post Office) is 896 mm. This means that the study years, at 746 and 611 mm represented respectively 83% and 68% of the long term average for the area. TABLE 2.5 together with Fig.2.1 shows the long term average rainfalls for 4 daily-read gauges surrounding the estuary. Only twice (1914 and 1940) has less rainfall been recorded in a calendar year than in the 1978/79 water year.

Raingauge	No.of years of record	Annual Rainfall Mean (mm)	Annual Rainfall Median (mm)
Mandurah P.O.	79	896	898
Pinjarra P.O.	92	968	972
Waroona	36	1038	1031
Waraba	15	1011	992
Robert Bay	2	678	-

TABLE 2.5 : Study Years Rainfall and Long Term Averages

This has an impact on river flow that is even more significant. For 1977/78, the Murray River total discharge (at Baden Powell Water Spout) was 238×10^6 m^3 compared to a long term average (40 years) of 340×10^6 m^3 which is 70%. For the entire Murray River catchment this represents an estimated yield* of 6.4% which compares with a long term average yield of 7.6% (based on a 20 station catchment wide Thiessen averaged rainfall of 650 mm (Collins 1974)). The corresponding yield for the exceptionally dry 1978/79 falls to approximately 2% (based on estimated catchment-wide rainfall average). These very low yields are typical of catchments in the south-west of Western Australia (Loh 1974, Black and Clifford 1977). Discharges and yields are discussed further in Chapter 3. Thiessen averaged daily rainfalls and hourly values for the Robert Bay, Harvey and Mandurah gauges are included in Appendix I.

* Yield is defined as (Runoff ÷ Rainfall) x 100%

2.3 Temperature

2.3.1 Thermograph Installation

At the weekly visited Robert Bay Climatological Station (see Fig.2.1) wet and dry bulb screen temperatures were recorded at the time of site inspection (usually at or about 1100 on Fridays). However, it was felt that continuous temperature measurement would be useful, especially as an input to empirical estimation of evaporation.
The instrument subsequently installed in the Stevenson Screen at the Robert Bay station was a Casella monthly chart thermograph. Its principle of operation is essentially that the change in curvature of a bi-metallic helix with air temperature variations is transmitted to a pen arm and pen which draws an ink trace on a chart wrapped around a revolving clock drum.
The analogue record produced is linear, and the instrument is calibrated from 0 °C to 50 °C. Its accuracy (manufacturer's specification) is ± 1% of full scale which gives ± 0.5 C.

2.3.2 Digitisation of Monthly Charts

The method of converting this analogue record into a monthly mean temperature was to measure the area under the curve traced by the pen arm by polar planimeter. With a monthly chart (on which 34 days is scaled to only 30 cm) this was found to be preferable to reading off individual hourly or even daily values. Thus the area under the curve in °C days is divided by the number of days in the month to yield a true monthly mean. TABLE 2.6 and Fig.2.2 depict the mean temperatures thus calculated for the period January, 1977, to September, 1979, and the water year means.

2.3.3 Extreme Events

The summer of 1977/78 (December, January, February, March) was amongst the hottest ever recorded in and about the Perth Metropolitan area. Indeed March, 1978, was the hottest March in over 100 years of Perth Weather Bureau records. The effect of such an extreme summer is of note in the estimation of evaporation using those empirical formulae which require mean air temperature as an input, notably the Meyer, Blaney-Criddle and Thornthwaite methods. (see 2.5.6 and Fig 2.5)

YEAR	Monthly Mean Air Temperature - Robert Bay Climatological Station (°C)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1977	21.6	23.6	19.8	19.5	15.2	14.2	13.2	14.0	14.2	16.5	19.6	24.1
1978	24.7	24.8	23.1	20.6	15.5	12.9	12.3	12.3	12.8	16.2	19.2	21.7
1979	22.1	23.5	22.2	17.3	15.8	14.1	12.9	10.5	12.4	-	-	-
	Water year averages: 1977/78 = 18.2 °C ; σ = 5.1 °C 1978/79 = 17.3 °C ; σ = 4.4 °C											

TABLE 2.6 : Monthly Mean Air Temperatures - Robert Bay Climatological Station 1977/78/79 (± 0.5 °C)

2.4 Relative Humidity

2.4.1 Hygrograph Installation

At the weekly visited Robert Bay Climatological Station (see Fig.2.1) determination of the dew point and relative humidity were made from the (previously mentioned) wet and dry bulb and whirling psychrometer measurements. As with air temperature however, continuous recording was necessary to facilitate evaporation estimates, notably those using the Penman formula (see 2.5.6).

The instrument installed in the Stevenson Screen at Robert Bay was a Casella Hair Hygrograph. Changes in relative humidity (R.H.) are recorded from alterations in length of specially treated human hair. These alterations are transmitted to a pen arm and pen which drives an ink trace on a chart wrapped around a revolving clock drum. The analogue record thus produced is linear, and the instrument is calibrated from 0 to 100% R.H. Its accuracy (manufacturer's specification) is $\pm$ 3% between 20 and 80% R.H. Thus the usual method of initial calibration is to cover the instrument in situ with a continuously damp cloth and adjust to 100% R.H. As this takes many hours, there was some difficulty in applying the technique at Robert Bay, so that adjustment had to be effected by comparison with a whirling psychrometer.

2.4.2 Digitisation of Monthly Charts

Digitisation was accomplished in an identical manner to that employed for the thermograph charts (see 2.3.2). TABLE 2.7 and Fig.2.2 depict the mean R.H. thus calculated for the period January, 1977, to September, 1979, and the water year means.

2.4.3 Errors

Regular checks were made with a whirling psychrometer and in addition it can be noted that when rain is actually falling a R.H. approaching 100% should be recorded. Despite this, it became apparent that unusually low values were being recorded from late 1977. Frequent adjustment failed to eliminate the problem and in December, 1978, a new hair set was fitted. This took some time to re-adjust in the hot summer months so that the actual digital values from July, 1978, to March/April, 1979, are highly suspect. A more reasonable approximation is shown on Fig.2.2 and this line has been used for evaporation computations. Error bars of at least $\pm$ 10% should be applied to this period.

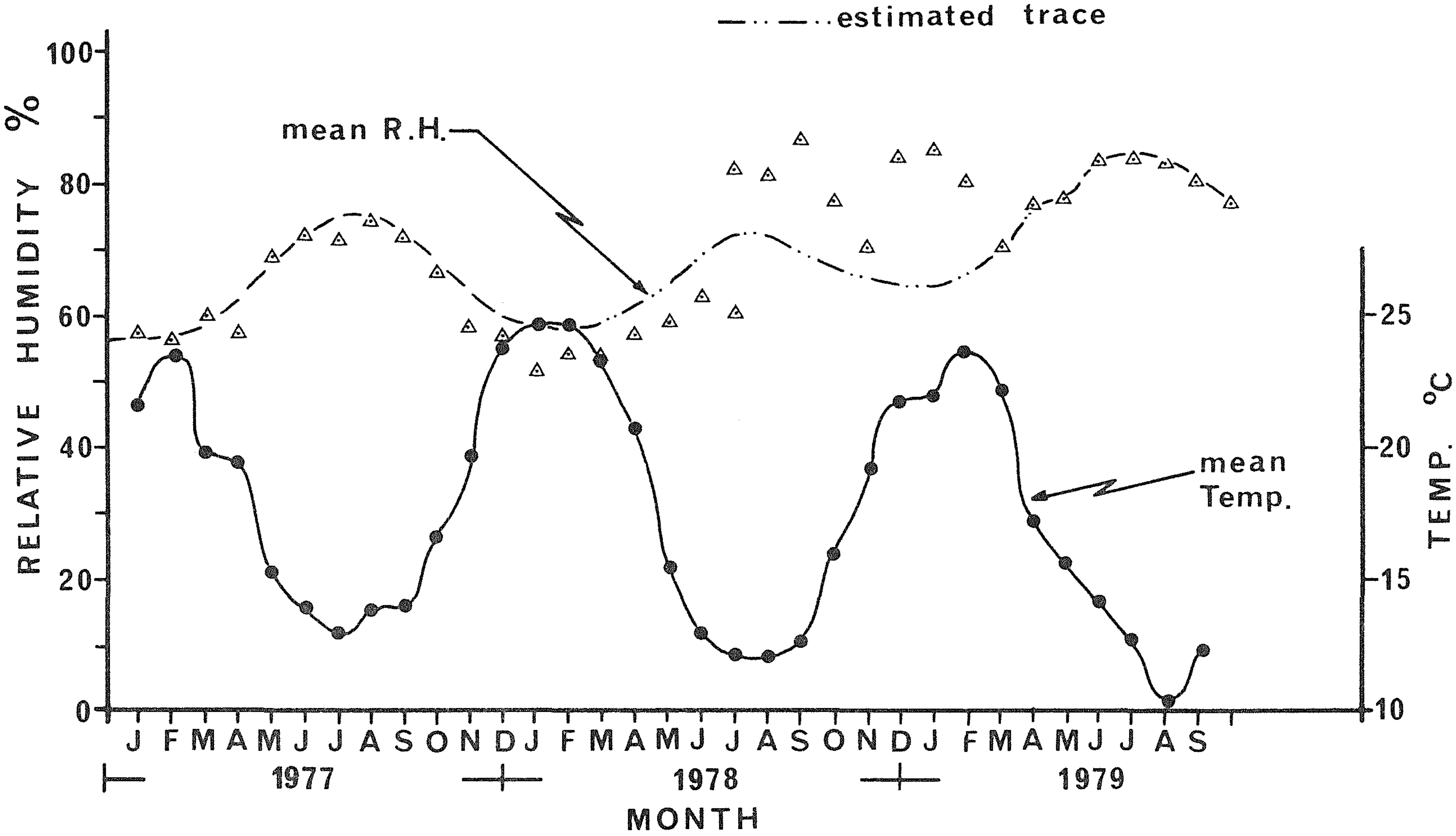


Fig. 2·2: TEMPERATURE & RELATIVE HUMIDITY — ROBERT BAY

YEAR	Monthly Mean Relative Humidity (R.H.) - Robert Bay Climatological Station (%)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1977	57	56	60	57	69	72	71	74	71	67	59	55
1978	52	53	53	57	59*	63*	*61/+ 82	82*	87*	77*	70*	84*
1979	84*	80*	71*	77*	78	85	83	81	79			
Water year averages: 1977/78 = 62%; σ = 8% 1978/79 = 73%; σ = 8%												

\+ Instrument re-calibrated

* Suspect readings - adjusted values used in water year means

TABLE 2.7 : Monthly Mean Relative Humidity - Robert Bay Climatological Station 1977/78/79 ($\pm$ 10%)

2.5 Evaporation

2.5.1 Importance

Earliest thoughts concerning the system were based on the assumption that the salinity of the estuary was likely to be predominantly influenced by tidal exchange, by river flows in the winter to a lesser degree and that evaporation could probably be neglected in view of the large area of the inlet. Indeed the salt balance equation for the Peel Inlet and for the Harvey Estuary was described by Godfrey (pers com., 1977); viz.,

$$V_1 \frac{dS_1}{dt} = -(Q_1+Q_2)S_1 + Q_o(S_o - S_1) - Q_{12}(S_1 - S_2) + Q_2S_2 \qquad (2.1)$$

and

$$V_2 \frac{dS_2}{dt} = -Q_2(t)S_2(t) + Q_{12}(S_1(t) - S_2(t)) \qquad (2.2)$$

for the Harvey Estuary

where Q_o = volume rate of exchange between Peel Inlet and ocean in m^3/sec.

Q_1 = volume rate of flow of all rivers and drains into Peel Inlet in m^3/sec.

Q_2 = volume rate of flow of all rivers and drains into Harvey Estuary in m^3/sec.

Q_{12} = volume rate of exchange between Peel Inlet and Harvey Estuary in m^3/sec.

V_1, V_2 = tidal average volume of Peel Inlet and Harvey Estuary respectively in m^3

S_1, S_2 = average salinity of Peel Inlet and Harvey Estuary respectively in mg/l.

t = time in sec.

However, these equations assume that evaporation may be neglected in the computation of the total salt content V_iS_i of either element of the system. Measurement of volume (and salt) flow through the

Mandurah channel taken in the February and August, 1978, intensive field exercises show that this assumption is invalid. Indeed, in the situation prevailing in February, where river flow (certainly into the Peel Inlet) is zero, then equation (2.1) becomes:-

$$V_1 \frac{dS_1}{dt} = Q_o S_o$$ (see also Hodgkin (1978) p. 45)

i.e. the total salt content of Peel Inlet is dependent only upon and must therefore soon become that of sea water (C.35%) and this argument also extends to the Harvey Estuary.

Salinity measurements taken on a weekly basis throughout the two complete water years (Oct.1977 - Sept.1979) clearly reveal that this is not the case and in summer 1978 salinity at site 4 (see Fig.2.1) reached nearly 50‰ . The explanation for this is that the influence of solar radiation (i.e. evaporation) dominates over that of tidal exchange during the summer months. In 1978, Peel Inlet salinity did not fall to oceanic levels until nearly June before ultimately dropping to 5‰ (approx) after significant rains had caused the Murray River to flow into the estuary.

This clearly shows the importance of evaporation on the salinity of the estuary and it will later be seen to be of similar concern in the water balance computation. For example, a typical daily pan evaporation measurement from the Robert Bay evaporimeter (January, 1977) is 8 mm. Applying a summer pan factor of 0.6 yields 0.6 x 8 = 4.8 mm lake evaporation. Over the system (area ≈ 133 km^2), this amounts to 638,400 m^3 compared to a typical daily (gravitational) tidal exchange volume of 5,770,000 m^3 or ≈ 11% which is certainly too large to neglect.

2.5.2 Methods of Estimating Evaporation

Over the last 30 years a number of workers have given attention to the various complications that arise in the evaluation of evaporation, though the broad physical principles governing evaporation from water (or flat terrain) have been well understood for many years. Since it is not really practicable to directly and continuously physically measure evaporation over the surface of a large water body such as a lake, it is usually necessary to infer daily, weekly or monthly rates from local climatic data, measurements from nearby pans or profile analysis. This means that the relationship between the measured quantities and the actual water loss from the lake in question is to some degree always in doubt. For this reason we prefer the term "estimating" rather than "measuring" evaporation, so that a higher degree of reliability than actually exists is not implied.

The following methods of estimating evaporation from large water bodies have been applied:-

(i) Empirical formulas which relate evaporation to climatic data, such as those of Meyer, Blaney - Criddle and Thornthwaite. Reviews of these formulas and their reliability have been made by Penman (1963), Ward(1967) and Black (1977).

(ii) Empirical pan factor. On an annual basis a value of 0.7 is widely accepted, i.e. lake evaporation = 0.7 x pan evaporation. Hounam (1961 and 1973), Ficke (1972), Webb (1975) and Cheng (1978) have all concluded that this can give a measure of evapotranspiration and of lake evaporation on an annual basis, but there are too many uncertainties to use the method for smaller time increments.

(iii) <u>Pan conversion</u>. Webb (1966) concluded that it was possible to estimate lake evaporation from pan evaporation on a daily basis if a numerical coefficient incorporating measured humidity and water temperatures was used. This leads to the equation:-

$$E_L = 1.50 \left\{ \frac{e_1 - e_4}{e_p - e_4} \right\} E_p \qquad (2.4)$$

where e_1, e_p are the saturation vapour pressures corresponding to water temperatures in the lake and pan respectively, taken in the afternoon (at daily maximum pan water temperature)

e_4 is the vapour pressure 4 m above the ground

E_p is pan evaporation (mm)

E_L is lake evaporation (mm)

Applying this formula to the well known Lake Hefner investigation (Kohler et al, 1955, U.S.G.S., 1954, Anderson, 1954) and utilising only days rated as Class "A" for water budget accuracy in the Lake Hefner Report, Webb compared 84 days of evaporation calculated using a simple 0.7 pan factor and his pan conversion formula above.

Results obtained from the pan conversion method are indeed excellent, being within 5% of the widely accepted heat budget results for all except 2 periods of 9 and 10 days respectively. The same cannot be said of the simple pan factor however, which showed significantly poorer agreement <u>for individual periods</u> of up to 14 days. Significantly, however, the departures from the heat budget measurements of evaporation over the period as a whole (i.e. 84 days) were very small, and very similar, being respectively + 0.8% and + 1.3% for the pan conversion and pan factor methods. This should be kept in mind when reviewing the estimates of Peel Inlet/Harvey Estuary evaporation and the instrumentation needed for each method. For the pan conversion, in addition to daily evaporimeter measurements (morning) it is necessary to determine:-

a) daily maximum water temperature (using Six's Thermometer).

b) daily (afternoon) vapour pressure at a height of 4 m above the ground, using a high quality Thermohygrograph.

c) daily lake water temperature (afternoon mean of two measurements).

For annual (or even monthly) determination of evaporative loss, it is pertinent to ask whether the greatly increased cost of instrumentation and labour to provide these measurements is warranted.

(iv) Eddy covariance or eddy correlation. Vertical vapour transport is measured in the atmosphere by sensing the turbulent fluctuations and computing the mean product of humidity and vertical velocity fluctuations. (e.g. Dyer, Hicks and King, 1967; Goltz et al 1970; Hicks and Goodman, 1971).

(v) Profile analysis. Vertical vapour flux is evaluated from measured inter-height difference of mean wind, temperature and humidity. The method as for (iv), requires significant expensive and frequently monitored instrumentation (Webb, 1965).

(vi) Bulk aerodynamic (Dalton) formula. The bulk transfer formula assumes the form:-

$$E = Cf(U_a)\ (q_s - q_a) \qquad \text{for lakes} \qquad (2.5)$$

where E = evaporation

U_a = mean wind speed at height "a" m.

q_a = saturation vapour pressure at height "a" temperature.

q_s = saturation vapour pressure at surface temperature.

Again, measurements of temperature, humidity (and in this case, wind speed as well) will have to be taken on a daily or continuous basis over the water body itself. The method is well reviewed by Cheng (1978).

(vii) Heat budget (Energy budget). This requires measurement of the difference between the amount of energy which enters and is stored in a body of water, and that which leaves it. The difference is therefore the energy used up by the evaporation of water. Again, it will be necessary to measure on a daily basis, water temperature, temperature of the evaporated water and net radiation flux at all wave lengths at the surface.

(viii) Combination approach. This method, which is initially attributed to Penman (1948), requires no introduction to agriculturalists or hydrologists. However it has been subjected to numerous variations, notably by McIlroy (1966), Slatyer and McIlroy (1961) and others. It combines the bulk aerodynamic and heat budget formulation to eliminate surface temperature and humidity. From the viewpoint of ease of measurement and expense of instrumentation this is most important. It thus means "...... that only ordinary meteorological quantities are needed (including measured or estimated net radiation); Thus evaporation can be estimated using only climatological data". (Webb, 1975).

In consideration of all of the foregoing and having in particular to keep in mind the fact that;

a) The Peel Inlet/Harvey Estuary hydrometeorological study budget would not be large enough to cover the purchase of expensive water based continuous temperature and humidity sensors;

b) Instruments located on towers on the water body itself would be liable to vandalism if located in such a popular recreational waterway;

c) Determination of this one component of the water balance on a daily basis was hardly warranted in view of the fact that nutrient (water quality) analyses could not possibly be made at more frequent intervals than weekly;

d) Climatological data would be available from the Robert Bay station on no less than a weekly basis in any case since it was required for other elements of the study;

e) Reliable, well documented estimates of lake evaporation from pan measurements were available for similar Australian sites;

it thus seemed that the best compromise would be to conduct one or more short-term intensive field exercisesto relate Robert Bay pan evaporimeter measurements to Peel Inlet lake evaporation using the well documented combination approach. That is, the thrust of the evaporation study would be to produce a field verified "pan factor" for Peel Inlet and to compare this with results reported by other workers. Additional verification could also be made by the application of one or more of the empirical formulae to Robert Bay climatological data.

2.5.3 The McIlroy Combination Method

Combining the bulk aerodynamic, (i.e. Dalton approach) and energy balance formulations avoids the difficulty of determining precise ratios such as the Bowen ratio, humidity gradients and wind profile. All of these require complex and expensive instrumentation. Thus only meteorological quantities are needed, including measured or estimated net radiation. This approach was introduced by Penman (1948) with numerous recent variations, notably Slatyer and McIlroy (1961).

(i) Theoretical Development

In the case of a large water body under constant general weather conditions, the air near the surface will be increasingly moistured as it flows along, eventually tending towards saturation. Potential evaporation will tend towards equilibrium evaporation with increasing extent of uniform fetch. This led McIlroy to the postulation of the "ideal" potential evaporation equation given as:-

$$\lambda E_p = \left(\frac{S}{S + \gamma}\right)(R - G) \tag{2.6}$$

where λ = latent heat of vapourisation of water

Ep = potential evaporation rate

S = slope of the saturation curve at mean wet bulb temperature.

γ = psychrometric constant, Cp/λ

R = net incoming radiation

G = net downward heat transfer through the surface.

Cp = specific heat of air at constant pressure.

According to circumstances, subsurface flux G may be estimated, measured or ignored (Webb 1975). Dimensional homogeniety is achieved by introducing the density of water ρ on the left hand side of Equation (2.6). This leads to (ignoring G)

$$\rho \lambda E_p = \left\{\frac{S}{S + \gamma}\right\} R \qquad (2.7)$$

with units $\rho = gm/cm^3$

$\lambda = J/gm$

$E_p = mm/sec$

$S = {}^{\circ}C^{-1}$

$\gamma = {}^{\circ}C^{-1}$

$R = mJ/sec\ cm^2$

thus we have

$$\frac{gm}{cm^3} \ \frac{J}{gm} \ \frac{mm}{sec} = \frac{{}^{\circ}C^{-1}}{{}^{\circ}C^{-1}} \ \frac{mJ}{sec\ cm^2} \times \frac{1}{100}$$

which is dimensionally balanced, and the McIlroy equation becomes:-

$$\rho E_p = \frac{1}{100\lambda} \left\{\frac{S}{S + \gamma}\right\} (R - G) \ \frac{mm}{sec} \qquad (2.8)$$

or, for direct calculations

$$\rho E_p = 0.01595 \left\{\frac{S}{S + \gamma}\right\} (R - G) \ \frac{mm}{hr} \qquad (2.9)$$

$\rho = 1\ gm/cm^3$

$\lambda = 2257.24\ J/gm$

S = slope of Specific Humidity v's Air Temperature curve.

$\gamma = 0.63A = 4.2 \times 10^{-4}\ {}^{\circ}C^{-1}$
where A is a well established empirical constant (Smithsoman Meteorological Tables, 1958).

R = net incoming radiation as measured by a net radiometer in mW/cm^2.

(ii) Measurement of G

In such a shallow water body as the Peel Inlet unacceptably high values of evaporation are calculated if the sub-surface flux G is ignored, i.e., the use of the above approach may result in estimates which exceed amounts actually measured as pan evaporation. There is little information in the literature concerning the estimation of this quantity but it would seem to be an important consideration in a water body whose average temperature can reach 30°C with little vertical stratification. Peck (pers com 1979) suggests that G can be measured/

with a modified soil flux plate usually available as a net radiometer accessory, but in the absence of such an attachment it was decided to calculate an average value for G thus:-

a) Heat absorbed by the water was calculated using the heat equation:-

$$H = mC\Delta T \qquad (2.10)$$

where H = heat in J

m = mass of water in gm

ΔT = change in temperature

C = specific heat of water

Furthermore,

$$m = V\rho$$
$$= dA\rho$$

where V = volume of water in cm^3

ρ = density in gm/cm^3

d = depth of water in cm

A = unit area ($1\ cm^2$)

$$\text{Thus } H = dA\rho C\Delta T \text{ J} \qquad (2.11)$$

$$\text{and } G = \frac{H}{At} \times 1000$$

where G = mW/cm^2

H = J

t = sec

A = unit area ($1\ cm^2$)

The field determination of an average value G for the estuary is discussed in section 2.5.4.

2.5.4 Instrumentation and Field Measurement

The "ideal" potential evaporation equation requires only three variables to be calculated or measured. These are:-

a) R - the net incoming solar radiation

b) G - net downward heat transfer near the surface

c) S - slope of the specific Humidity v's Air Temperature curve.

(i) Instrumentation

R was measured directly with a Solar Radiation Instrument (SRI) Net Radiometer output to an event recorder incorporating an integrator circuit. This recorder gives a continuous recording (trace) of net radiation. Hemi-spherical polythene covers are attached to both sides of the radiometer plates and inflated by a slow stream of nitrogen. These plates are mounted horizontally, back to back, so that one faces up, the other down, to monitor respectively downward radiation and back radiation from the water or other surface.

The whole unit is fixed to a tripod and under field conditions positioned from boat or jetty at about 0.5 m above the water surface.

G was calculated as previously explained by calculating the increase in heat content of subsurface water, i.e. by monitoring and integrating the water temperature.

S was obtained from the slope of the saturation vapour pressure curve by differentiating the specific humidity v's temperature curve equation at a given mean air temperature.

(ii) Type Example

To find a given evaporation rate in mm/hr

- average recorded value from the radiometer is 51.86 mV
- equation for slope of saturation curve is:-
- $$S = \frac{\Delta(q_{sat})}{\Delta T_w} \simeq \left\{\frac{\partial q_{sat}}{\partial T}\right\}_{T_{wA}}$$

where T_{wA} in $^{\circ}K$ and is the average wet bulb temperature

q_{sat} is the specific humidity

- q_{sat} can be approximated from $q_{sat} = 6.12 \times 10^{-3} e^{0.06T}$ where T is now in $^{\circ}C$.
- net radiation $R = 51.86 \times \dfrac{1}{0.84275} = 61.54\ mW/cm^2$

(from radiometer calibration certificate)

- mean temperature $T = 26.6\,^{\circ}C$
- $\gamma = \frac{Cp}{\lambda} = \frac{1.004 J/gm\,^{\circ}C}{2257.24\ J/gm} = 4.479 \times 10^{-4}\ {}^{\circ}C^{-1}$
- S is calculated as $1.9736 \times 10^{-3}\ C^{-1}$

$$E_p = 0.01595 \left(\frac{S}{S+\gamma} \right) R$$

$$= 0.01595(8.176 \times 10^{-1})61.54$$

$$= 0.802 \text{ mm/hr} \quad \text{pan evaporation (ignoring G)}$$

(iii) Calculation of G

Table 2.8 below gives the measurement of mean water temperature as measured in the Murray River adjacent to the estuary proper on 27.1.77.

Other relevant data:-

- depth of water $d = 50$ cm
- density of water $\rho = 1.04\ gm/cm^3$
- specific heat of water °C $= 4.18$ J/gm

Time	Temperature °C
0630 - 0730	24.3
0730 - 0830	24.3
0830 - 0930	24.6
0930 - 1030	27.2
1030 - 1130	27.4
1130 - 1230	28.1
1230 - 1330	28.6
1330 - 1430	29.5
1430 - 1530	29.7
1530 - 1630	29.6
1630 - 1730	29.8
1730 - 1830	29.4

TABLE 2.8 : Water Temperature Murray River 27.1.77

Note that the change in temperature between the hours is assumed to occur instantaneously at the end of each hour. On this assumption, the total change in water temperature is 29.4 - 24.3 = 5.1°C over the eleven hour period.

Thus $G = \frac{d\rho C\Delta T}{t}$ (see section 2.5.3)

$$= \frac{50 \times 1.04 \times 4.18 \times 5.1 \times 1000}{11 \times 3600}$$

$$= 27.99 \text{ mW/cm}^2$$

An average value of G = 28 mW/cm^2 was thus utilised for future calculations during summer periods. Table 2.9 reveals the temperature range in the Robert Bay pan evaporimeter and atmosphere (Stevenson Screen) on a daily basis over the period.

Pan Water Temperature (°C)		Screen (Air) Temperature (°C)		Date
Max.	Min.	Max.	Min.	1977
27.1	14.0	23.2	11.8	20/1
27.5	17.5	23.4	13.2	21/1
28.0	13.8	25.0	12.6	22/1
28.5	16.0	25.2	16.1	23/1
31.0	16.9	31.1	20.2	24/1
33.8	19.5	37.7	18.5	25/1
32.0	17.3	31.2	15.9	26/1
29.9	12.5	27.6	17.0	27/1
Mean Range = 13.7 Standard Deviation = 1.9		Mean Range = 12.4 Standard Deviation = 3.3		

TABLE 2.9 : Pan and Screen (Air) Temperature Range Robert Bay 20/1/77 - 27/1/77

Application of the above data to calculate G for the 26.6 cm deep pan yields a value of ≈ 40 mW/cm^2. Whilst some doubt exists as to the validity of such a high value (as the 28 mW/cm^2) for G for deeper parts of the estuary, temperature profiles taken at other times at various stations around the inlet reveal little vertical stratification and similar diurnal variations (up to 5 °C is common) (see TABLE 2.11)

(iv) Field Measurement - Summer(1977) exercise

For seven (7) consecutive days (20/1/77 - 26/1/77) five (5) stations were visited by boat and net radiation and other data measured. The stations were:-

(See Fig.2.1)	Robert Bay	1
	Centre Harvey Estuary	2
	Harvey Entrance Channel	3
	Centre Peel Inlet	4
	Murray River Entrance Channel	5

At each station the following data was recorded

a. a 15 minute continuous trace of net radiation
b. wet and dry bulb air temperature
c. wind speed
d. water conductivity
e. sub-surface water temperature

A one day continuous trace of net radiation (0630 to 1830 hours) was recorded above shallow water on the Murray River. Fig.2.3 shows the radiation curve obtained. Values were averaged to give one hourly net radiation figures, from which the hourly evaporation was determined using Equation 2.9.

These hourly values were then added to yield a total daily figure. They were then weighted and thus expressed as a fraction of the total evaporation for the day, i.e. a "Daily evaporation curve" was developed. (see TABLE 2.10)

(v) Calculating Total Evaporation

A simple computer program was written to perform the following calculations; viz.,

a) each 15 minute net radiation trace was fitted into its appropriate time slot on the daily evaporation curve, i.e. 1008 to 1023 hours was assigned the weighting factor of the 0930 - 1030 time (0.105)

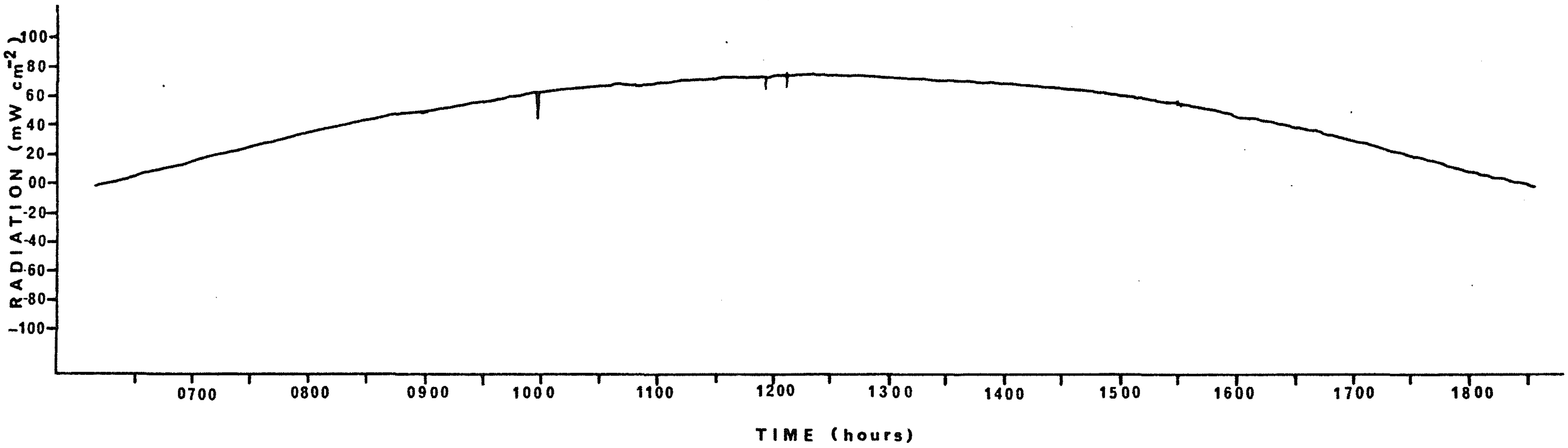


Fig. 2·3: NET RADIATION CURVE MURRAY RIVER - 27. 1. 77

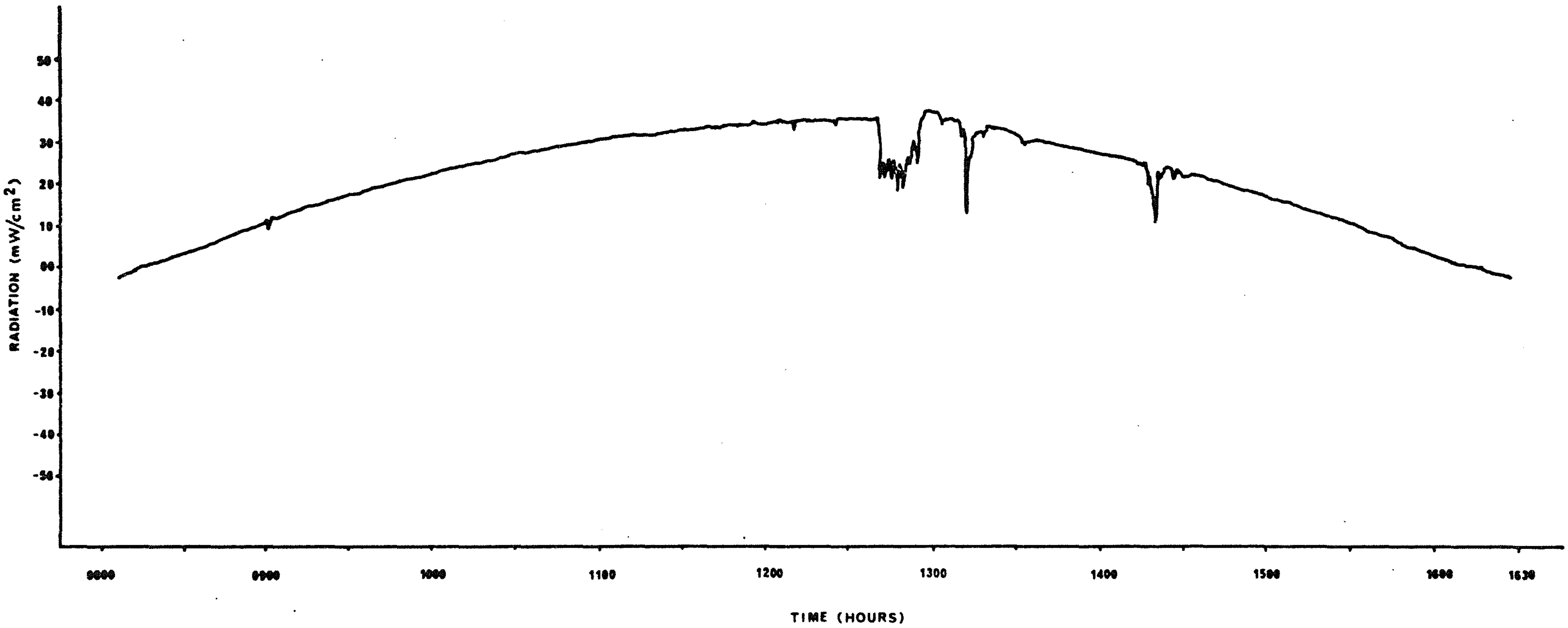


Fig. 2·4: NET RADIATION CURVE YUNDERUP CANALS - 6.7.77

(v) b) average net radiation was computed for the 15 minute intervals.

c) factor $S/(S + \gamma)$ was computed

d) evaporation (incorporating average "G") was calculated for that time slot

e) the one hourly evaporation figure was extrapolated by the use of the evaporation curve to produce a total evaporation for the day.

f) this process was repeated for the other four stations and a mean daily figure derived (see TABLE 2.11 for data sample)

The entire exercise was repeated at Yunderup Canals near the Murray River (see Figure 2.4) on 6.7.77 and TABLE 2.12 depicts the results obtained during this winter period.

(vi) <u>Justification</u>

The McIlroy "ideal" potential evaporation approach had the great virtue of simplicity and the fact that it could be utilized to derive system-wide estimates of evaporation in short intensive field exercises meant that it was not necessary to establish a semi-permanent network of water based instrumentation sites. Its use in determining a Peel Inlet Pan Factor for the Robert Bay evaporimeter is dicussed in Section 2.5.7.

Time Interval	Average Rad. $\frac{mW}{cm^2}$	Weighted Radiation Factor	Temp. (°C) Air	Water	Evaporation (ex. G) mm/hr	Weighted Evaporation Factor
0630-0730	16.78	0.024	20.0	24.3	0.197	0.022
0730-0830	41.62	0.059	22.5	24.3	0.506	0.055
0830-0930	59.25	0.084	24.4	24.6	0.737	0.081
0930-1030	73.99	0.105	28.6	27.2	0.962	0.105
1030-1130	82.72	0.117	27.2	27.4	1.060	0.116
1130-1230	87.64	0.124	28.4	28.1	1.137	0.125
1230-1330	87.64	0.124	29.2	28.6	1.146	0.126
1330-1430	81.87	0.116	30.3	29.5	1.081	0.118
1430-1530	72.21	0.102	30.3	29.7	0.954	0.105
1530-1630	56.19	0.080	29.4	29.6	0.736	0.081
1630-1730	35.09	0.050	29.4	29.8	0.460	0.050
1730-1830	11.02	0.016	27.8	29.4	0.142	0.016
Total 12 hours	Average 49.58	Total 1.00	Average 27.3	27.8	Total 9.119	Total 1.00

TABLE 2.10 : Evaporation Curve Data Murray River 27.1.77 (Summer)

Location	Site No. (Ref. Fig)	Time (hours)	Net. Rad. ($\frac{mW}{cm^2}$)	Wind Speed (m/sec)	Water Temp (°C)	Air Temp. (°C)		Calc. Evap. (per day)
						Dry	Wet	
Robert Bay	1	0930-1030	74.87	4.3	25.4	25.3	19.1	5.61
Centre Harvey	2	1030-1130	80.99	5.6	26.0	25.3	19.4	5.74
Harvey Ent.	3	1130-1230	85.51	6.7	25.5	25.1	19.9	5.77
Centre Peel	4	1230-1330	85.86	7.5	26.3	25.2	19.9	5.76
Murray Ent.	5	1230-1330	84.82	7.7	27.0	25.7	19.7	5.69

Mean Lake Evaporation using Murray River Curve = 5.71 mm

S.D. = 0.07 mm

TABLE 2.11 : Net Radiation 15 minute Traces Peel Inlet 26.1.77

Time Interval	Average Rad. ($\frac{mW}{cm^2}$)	Weighted Radiation Factor	Temp. (°c) Air	Water	Evaporation (inc G)* (mm/hr)	Weighted Evaporation Factor
0830-0930	13.05	0.060	13.2	14.6	0.091	0.045
0930-1030	26.95	0.124	15.2	15.0	0.246	0.121
1030-1130	36.12	0.166	17.1	15.5	0.357	0.175
1130-1230	41.22	0.189	16.4	16.0	0.410	0.201
1230-1330	42.12	0.193	17.2	15.9	0.426	0.209
1330-1430	32.88	0.151	17.0	15.6	0.320	0.157
1430-1530	20.52	0.094	16.9	15.2	0.181	0.089
1530-1630	5.11	0.023	16.6	15.2	0.008	0.004
Total 8 hours	Average 27.25	Total 1.00	Average 16.2	15.4	Total 2.040	Total 1.00

*Calculated average value of G(Winter) = 4.44 mW/cm^2

TABLE 2.12 : Evaporation Curve Data Yunderup Canals
6.7.77 (Winter)

2.5.5 The Pan-Lake Relationship

For a variety of reasons, evaporation from a pan is not exactly representative of that from a lake, even when the pan is located immediately adjacent to the lake (estuary) shore as is the case here. Even when such pans have been floated on rafts they yield greater evaporation than the host lake (Australian Water Resources Council, 1970). For Mundaring Reservoir, Western Australia, (some 85 km from Peel Inlet) this factor was found to be 0.93 on an annual basis, but some studies of pans floated on inland (desert) waterways have yielded pan factors as low as 0.66 (Australian Water Resources Council, 1970). In all cases the pan evaporimeter referred to is the U.S. Class "A" Pan (1219.2 mm diameter, water 243 mm deep). In common with most pans in Australia, the one established at Robert Bay in this study was fitted with a bird-guard. Such screens may affect the evaporation from the pan by amounts depending on its interference with wind and net radiation. However it is usually thought preferable to have such a systematic reduction of evaporation rather than unknown values caused by birds or animals drinking or splashing the pan water.

In general evaporation measured from a pan will be greater than that measured from a lake adjacent to it and under (as near as possible) identical atmospheric conditions. This will be mainly due to the fact that the pan is ventilated on all sides and the galvanised steel sides may cause excessive heating of the water in the pan. Furthermore, there may be excessive splashing during heavy rain and water may be blown out by strong winds. However it is generally agreed that analysis over a sufficient data set will enable a reliable relationship between pan and lake to be established. Van Dijk (1975) has shown that a Class A pan with bird-guard may be converted to equivalent Class A evaporation by multiplying by 1.07.

The empirical adjustment for the computation of daily lake evaporation from pan readings introduced by Webb (1966) (See Section 2.5.2(iii)) has been shown to give results that are not significantly better than the simple application of a pan factor for sufficiently long time periods - over a month differences appear to be as little as + 5%.

Annual lake to pan coefficients are commonly expressed as the ratio of lake (E_L) to pan (E). On the basis of a review by the Australian Water Resources Council (1970) it was concluded that a value of 0.7 ± 0.1 was appropriate based on overseas studies. A study by Hoy (1977) showed that Australian results range from 0.66 to 0.93 with a mean of 0.78 and are somewhat higher than generally assumed previously. However, in view of the wide spatial variation as between stations (latitude 15°S to 42°S; longitude 116°E to 152°E) he found it relevant to examine annual pan coefficients and climatic variables. It was found that a correlation coefficient of 0.89 was obtained from a regression analysis of the pan/lake relationship and the natural logarithm of annual rainfall; viz.,

$$\frac{E_L}{E} = 0.128 \ \mathrm{Ln}\ \overline{P} \qquad \text{where } \overline{P} = \text{mean annual rainfall} \qquad (2.12)$$

with a standard error of 6%.

Applying this result to Peel Inlet over the 2 year period of the study yields a pan factor E_L/E

of 0.83 whilst on the long term average rainfall for the region (c.900 mm) we obtain $E_L/E = 0.87$. Section 2.5.7 shows this to be in general agreement with the results obtained from the Peel Inlet study. Furthermore the analysis by Hoy (1977) also confirms that pan coefficients are generally higher in moist humid regions (coastal environments) and lower in the dry interior of the continent which is also a useful confirmation of the validity of the study result.

2.5.6 Peel Inlet Evaporation from Empirical Formulae

Since all of the climatological data necessary for the evaluation of most of the empirical formulae (and even the Penman combination method) was available from the records collected at the Robert Bay station, it was decided to compute monthly evaporation for one calendar year (1977) from each of 4 such formulae for comparison with the pan converted results. The Peel Inlet pan/lake conversion is discussed further in 2.5.7 where results for the entire study period are presented.

As all of the formulae used are well documented and numerous applications reported, details of the computation will not be given here. Summaries of the formula are reported by Wisler and Brater (1949), Criddle (1958), Chow (1964), McCulloch (1965), McIlroy (1966), Webb (1975) and Black (1977).

In all, four empirical formulae were applied to the climatological data from Robert Bay for the year 1977 and extended into 1978 (January and February) because of the unusually hot conditions that occurred during the summer of 1977/78. The results are shown on Fig. 2.5 together with the estimates of lake evaporation calculated from the Robert Bay pan measurements. On a month by month basis they can be said to be most unsatisfactory, with the possible exception of the Blaney-Criddle approach. Annual total estimates of evaporation are shown in TABLE 2.13 together with correlation coefficients derived from linear regression of each calculated monthly mean with lake evaporation derived from pan measurements.

Whilst reasonably good agreement is achieved between pan derived lake evaporation and both the Meyer and Blaney-Criddle formulae for 1977, the addition of the two very hot months (January and February, 1978) reveals a marked overestimation of E in both cases. In the Meyer formula, at least, this may be accounted for by the fact that the assumption has to be made that water surface vapour pressure is equal to saturation vapour pressure at mean air temperature. This may well become a significant error when air temperatures are very high.

It is not possible to read too much into the high correlation coefficients calculated and tabulated in TABLE 2.13. Consistent over or under estimation of evaporation will still reveal a high positive correlation.

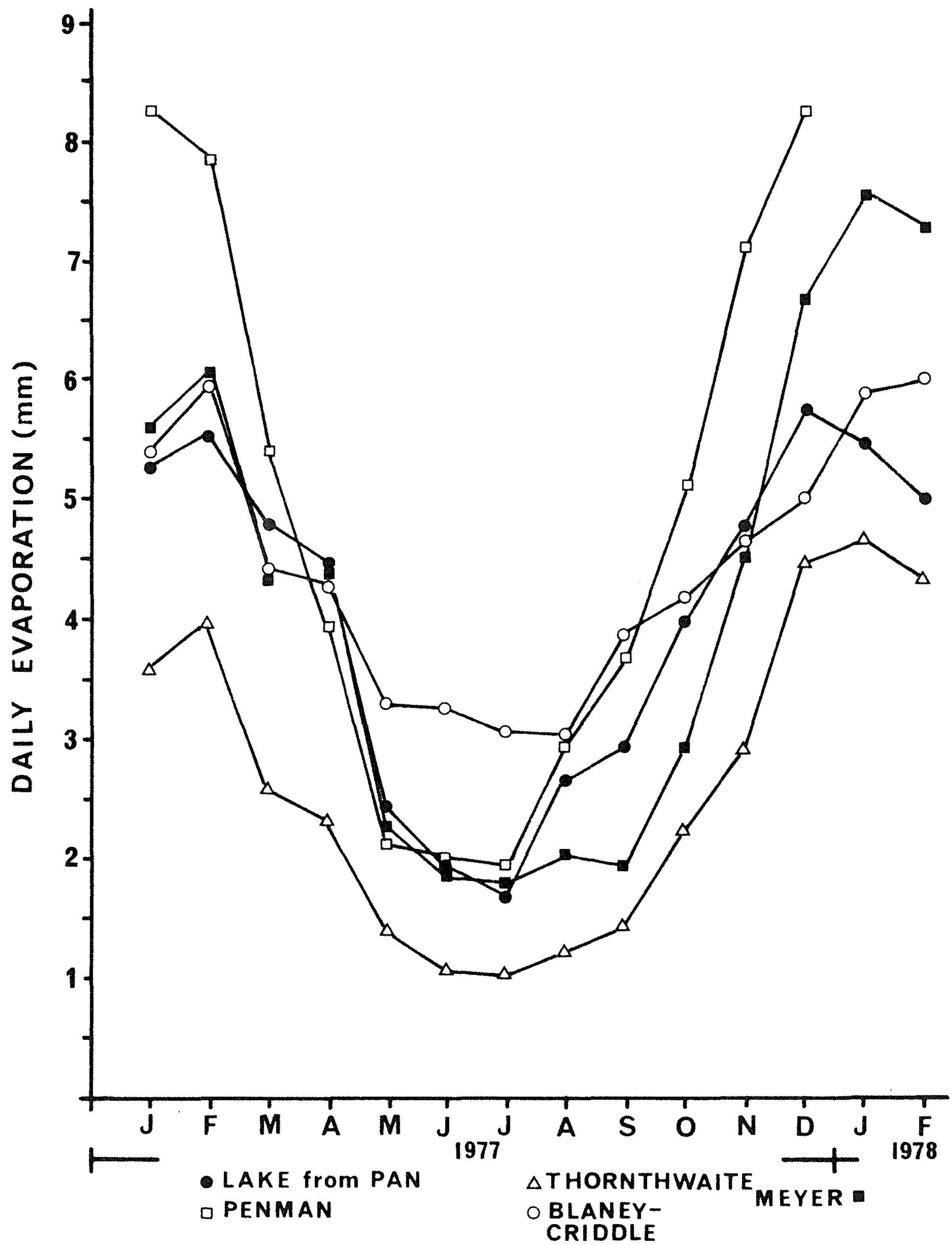


Fig. 2·5: MEAN DAILY EVAPORATION – ROBERT BAY
U.S. CLASS "A" PAN & EMPIRICAL FORMULAE

Empirical Formula	Source Reference	Annual Total Evaporation (mm) 1977	Annual Total Evaporation (mm) Robert Bay Pan	Annual Total Evaporation (mm) Lake*	Correlation Coeff. (r) (monthly means)
Blaney-Criddle	Criddle (1958)	1533	1908	1404	0.9319
Meyer	Chow (1964)	1353	1908	1404	0.9570
Thornthwaite	Criddle (1958)	809	1908	1404	0.9519
Penman	McCulloch	1768	1908	1404	0.9562

*It should be noted (see 2.5.7) that varying factors have been applied for each month. The mean of the monthly pan factors is 0.80, but varying numbers of days in the months yield an annual result of $E_L/E = 1404/1908 = 0.74$.

TABLE 2.13: Estimates of Annual Evaporation - Peel Inlet using Empirical Formulae

2.5.7 Peel Inlet Pan Factors

Mean daily evaporation values computed from the summer and winter field exercises discussed in 2.5.4 were compared with the pan evaporation measured for the corresponding day at Robert Bay and a pan factor computed thus:-

$$\text{Pan Factor (P.F.)} = \frac{\text{Lake Evaporation } (E_L)}{\text{Pan Evaporation } (E)}$$

This resulted in the following pan factors:-

Summer	(7 days)	Mean P.F.	=	0.634
Winter	(3 days)	Mean P.F.	=	1.036

It was felt that it would be useful to present monthly pan factors and that the distribution about the summer and winter figures above could be fitted by the application of mean monthly solar radiation values. Such data was available only for Perth Airport, some 85 km from the site, and is tabulated with the calculated factors. Pan factors are expressed to one significant figure only; further precision is not warranted in view of the large number of uncertainties involved in the computation of lake evaporation. (see TABLE 2.14)

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
Global Radiation (mW/cm^2*)	2700	2300	2100	1550	1250	550	550	625	1050	1150	1600	2100
Pan Factor	0.6	0.6	0.7	0.8	0.9	1.0	1.0	1.0	0.8	0.8	0.7	0.7

Annual Average P.F. = 0.8

TABLE 2.14 : Monthly Pan Factors - Peel Inlet

* Mean of 1977/78 data

2.5.8 Conclusions

(i) Comparison with other Studies

a) Lake Albert, South Australia (Cheng, 1978)

This is one of the few studies in comparable climatic regions in which monthly pan evaporation results are reported. TABLE 2.15 lists the monthly energy budget calculations and pan evaporation for Lake Albert for the year 1974-75 with those of Robert Bay for comparable periods in 1977-78 and 1978-79.

Lake Albert (Lat.35°S) is not subject to quite the same extreme summer heat as Peel Inlet (Lat. 32°S) so that the annual and monthly pan results are quite logical. Furthermore, the annual energy budget calculation of lake evaporation for Lake Albert yields a pan factor (annual) of 0.8 which is the same as that for Peel Inlet, a similar estuarine environment.

b) Lake Pretty, Indiana, U.S.A. (Ficke, 1972)

Ficke concluded that on an annual basis, lake evaporation was equal to pan evaporation multiplied by 0.76.

c) Australia (in general) (Hounam, 1961)

Houman stated that a typical annual value of lake:pan determined for Class A pans was 0.69; most values have fallen in the range 0.6 to 0.8.

Most useful, however, is the fact that the Lake Albert study, which involved much more extensive and complex continuous recording instrumentation, substantiates the Peel Inlet/Robert Bay monthly pan factors in general terms. From the 1974/75 data (see TABLE 2.15) we find the comparison to be, month by month, as tabulated in TABLE 2.16

MONTH	EVAPORATION (mm) (Daily mean)			
	Lake Albert (Pelican Point) (Cheng 1978) 1974-75		Robert Bay Class A Pan	
	Energy Budget	Class A Pan	1977-78	1978-79
May	1.6	1.9	2.4	3.2
June	1.9	1.8	1.8	2.5
July	1.1	2.0	1.9	2.3
Aug.	1.7	2.5	3.0	2.0
Sept.	2.4	3.3	3.5	3.1
Oct.	3.1	4.1	5.0	4.9
Nov.	5.3	6.2	6.9	7.5
Dec.	6.4	7.6	8.9	8.2
Jan.	5.0	7.8	9.3	9.4
Feb.	6.1	7.1	9.1	9.1
Mar.	4.5	5.4	7.3	6.1
April	3.4	3.5	5.0	4.9
ANNUAL	3.5	4.4 *	5.3	5.3

TABLE 2.15 : Comparison of Monthly Evaporation - Lake Albert, S.A. and Peel Inlet, W.A.

$$* \quad \text{P.F.} = E_L/E = \frac{3.5}{4.4} = 0.8$$

MONTH	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
Peel Inlet	0.6	0.6	0.7	0.8	0.9	1.0	1.0	1.0	0.8	0.8	0.7	0.7	0.8
Lake Albert	0.6	0.8	0.8	1.0	0.8	1.0	0.6	0.7	0.7	0.8	0.8	0.8	0.8

TABLE 2.16 : Monthly Pan Factors for Peel Inlet and Lake Albert.

(ii) Importance

As discussed in 2.5.1, evaporation from such a large, shallow estuary subject to ephemeral river flow and limited tidal exchange, is a key element in determining the salinity during the drought summer (November - March). Daily evaporation may account for > 10% of daily tidal exchange.

Chapter 5, which describes the question of tidal salt and volume flux, explores this question further.

It is of interest to note that for the past several years, the Public Works Department (Harbours and Rivers Branch) has routinely dredged the entrance channel to Mandurah to keep it open throughout summer when river flow ceases. One can speculate as to impact of evaporation on the depth of water in the estuary were this not done. Data exists (Hodgkin pers.comm.) as to water levels in Peel Inlet during the record drought summer of 1914-15 when the channel was closed to the ocean by a sand bar from December to the end of May.
Measured water levels over the period December 29, 1914, to April 30, 1915, showed a fall of 457 mm. The sum of lake evaporation calculated from January - April inclusive, 1979 = 600 mm. The balance of some 150 mm is presumably accounted for by seepage through the bar and the fact that neither the Serpentine nor Harvey Rivers were dammed until many years later so that some river and/or groundwater flow may have existed.

(iii) Summary of Results

Thus, we estimate the evaporation from the Peel Inlet/Harvey Estuary for the two water years 1977/78, 1978/79 to be as shown in TABLE 2.17. A complete listing of daily estimates for the study period is included in APPENDIX I.

Month	Estimated Evaporation (mm)	
	1977/78	1978/79
October	122.1	126.8
November	151.2	158.6
December	195.9	185.6
January	176.8	180.5
February	147.4	137.0
March	155.1	138.4
April	118.2	86.3
May	86.9	80.4
June	57.2	46.5
July	68.4	59.8
August	66.3	67.2
September	75.8	62.9
Total (mm)	1421.2	1330.0
Total * ($m^3 \times 10^6$)	189.9	176.9

* Based on area of 133 km^2

TABLE 2.17: Estimated Monthly Evaporation Peel Inlet/Harvey Estuary (converted from Robert Bay U.S. Class "A" pan evaporimeter).

2.6 Wind

2.6.1 Anemometer Installation

For the reasons outlined in 2.1.4, a Lambrecth "Woelfle-type" anemometer was established at the Robert Bay station on September 8, 1976, and with the exception of a period of a few days in April, 1978, recorded continuously throughout the study period.

World Meteorological Organisation (WMO) standards provide for location of anemometers at two standard heights; viz., 10 m and 2 m above the average ground surface level. The former requires a specially constructed tower and in any case provides less useful information for estimates of wind influence on the migration of Cladophora or Harvey Estuary turbidity than does the 2 m position. Thus it was decided to locate the anemometer at the 2 m position.

Wind changes continuously in direction and speed and thus is only completely specified when both are known. Instantaneous values of wind velocity are meaningless because of wind squalls and gusts which form sharp pulsations of fluctuating velocity. On continuous wind records (anemographs), the total wind run is recorded for a set time period or the time taken for a wind run of some distance is recorded. This can be done using a revolution counter counting the number of revolutions made by a cup-type anemometer or by use of a mechanical wind recorder.

The Woelfle-type mechanical recorder ascertains the wind direction as well as the wind run and records both values on wax paper. Rollers connected via worm gears to co-axial spindles themselves connected to a wind vane and cup anemometer respectively, scratch lines of wax off the wax recording paper. From these lines the wind direction can be read directly and the wind speed read off using a calibrated plastic cursor.

2.6.2 Digitisation of Chart Records

Despite the great popularity of the Woelfle-type anemograph for reasons of its reliability, portability, low cost and simplicity, digitisation of the chart record is time consuming and tedious. In fact, it normally takes one man-day to convert a month's chart into digital form.

For this reason it was decided to develop a computer-aided system to speed up direct digitising and also summarise and analyse data recorded.

Full details (including a program listing) are published (Rosher and van den Berghe (1978)) but in summary, the procedure is as follows:-

(i) Data on the anemometer rolls is digitised using a "Summagraphics" Data Tablet/ Digitizer which is linked via an interactive terminal to a computer system (D.E.C.SYSTEM 10).

(ii) Programe DIGIT analyses the digitised co-ordinates and produces the wind data which is written into a file area and printed out on the terminal.

(iii) Program ANEMOM operates on the data file furnished by DIGIT and produces a four hourly and daily mean of wind speed and modal direction in tabular form.

(iv) A sample of ANEMOM output is shown in Fig.2.6

2.6.3 Results

(i) A complete listing of the results as produced by ANEMOM is included in Appendix I. This covers the period 8.9.76 to 30.9.79. This data has been progressively supplied to other elements of the study team for the purposes outlined in 2.1.4 on demand. In this form it is too bulky to include in this report and does not readily lend itself to summary into longer time periods in any way that is particularly meaningful. However, TABLE 2.18 lists the monthly wind speeds (means) and directions (modes) for the study period 1977/78; 1978/79.

Fig. 2·6: PEEL INLET AND HARVEY ESTUARY STUDY — ANEMOMETER LISTINGS

DATE	0000 - 0400	0400 - 0800	0800 - 1200	1200 - 1600	1600 - 2000	2000 - 2400	AVERAGE DAILY
80976	-1.00 /-100	-1.00 /-100	-1.00 /-100	2.08 / 190	1.48 / 180	1.40 / 150	1.65 / 170
90976	1.24 / 160	1.28 / 120	1.44 / 70	2.24 / 190	1.17 / 190	0.98 / 190	1.39 / 190
100976	0.95 / 190	0.80 / 190	1.40 / 60	1.89 / 240	1.38 / 240	0.85 / 240	1.21 / 240
110976	1.06 / 200	1.77 / 200	2.11 / 210	2.79 / 270	1.37 / 240	0.80 / 240	1.65 / 240
120976	0.60 / 240	0.67 / 240	1.66 / 45	2.46 / 330	1.61 / 250	0.80 / 250	1.30 / 240
130976	0.85 / 60	0.86 / 60	1.05 / 0	2.00 / 240	1.13 / 210	0.81 / 240	1.12 / 240
140976	0.60 / 40	0.73 / 90	1.80 / 190	2.08 / 190	1.20 / 200	0.80 / 240	1.20 / 190
150976	0.98 / 210	1.62 / 160	1.85 / 70	2.36 / 150	2.01 / 200	1.30 / 200	1.69 / 200
160976	1.70 / 170	2.14 / 150	1.77 / 0	2.17 / 280	1.05 / 290	0.80 / 240	1.60 / 240
170976	0.80 / 10	1.25 / 10	3.70 / 330	4.76 / 340	4.73 / 270	2.94 / 270	3.03 / 10
180976	2.51 / 240	1.98 / 240	3.26 / 220	3.01 / 240	1.74 / 240	1.54 / 240	2.34 / 240
190976	1.51 / 240	0.92 / 180	1.74 / 190	2.70 / 210	1.64 / 210	1.46 / 200	1.66 / 210

(ii) Wind direction. It should be noted that the mean of wind direction is not a valid method of summary. Rather the mode, or most commonly occurring value, is required. However, on a monthly basis this statement as to the most frequent direction is to say the least, of doubtful value. It can be said that the dominant wind directions lie in the south west quadrant.

(iii) Wind speed. TABLE 2.18 also includes the monthly standard deviations (σ) for the reason that one or two extreme events can bias the means. For example, the April, 1978, monthly mean wind speed was 2.60 m/sec with σ = 1.12. This largely is due to the influence of tropical cyclone "Alby" which struck the Peel Inlet area on April 4. It gave rise to a mean wind speed on that day of 7.41 m/sec including a 4 hour mean of 15.58 m/sec (1600 - 2000 hours) and instantaneous gusts of much higher values (>100 km/hour). On no other day in that month did mean daily wind speed exceed 4 m/sec.

(iv) What TABLE 2.18 mainly serves to indicate is that over periods as long as one month, wind speeds vary from 1.58 to 3.47 m/sec with the greatest velocities in the summer months when afternoon coastal breezes are dominant.

We conclude that wind speed needs to be examined on a much smaller increment (say one day) if results and conclusions are to be meaningful.

Year	Month	Mean Wind speed* (m/sec)	Modal Wind direction (degrees)	Modal Wind direction (compass)
1977/78	Oct.	2.79 (0.93)	210	SSW
	Nov.	2.95 (0.67)	240	WSW
	Dec.	3.11 (0.36)	210	SSW
	Jan.	3.17 (0.66)	210	SSW
	Feb.	3.17 (0.74)	90/150	E/SSE
	Mar.	2.51 (0.58)	90/150	E/SSE
	Apr.	2.60 (1.12)	180/210	S/SSW
	May	2.73 (1.09)	270/330	W/NNW
	June	2.12 (0.87)	180/210	S/SSW
	July	2.75 (1.63)	270/300	W/WNW
	Aug.	1.58 (0.35)	90/150	E/ESE
	Sept.	2.32 (0.87)	180/210	S/SSW
1978/79	Oct.	2.39 (0.76)	150/210	SSE/SSW
	Nov.	2.91 (0.72)	210	SSW
	Dec.	3.32 (0.80)	180/240	S/WSW
	Jan.	3.47 (0.61)	210	SSW
	Feb.	3.45 (0.93)	90/150	E/SSE
	Mar.			
	Apr.			
	May			
	June			
	July			
	Aug.			
	Sept.			

TABLE 2.18: Monthly wind speed (mean) and direction (mode) Robert Bay 1977/78; 1978/79

* Standard deviation in parenthesis

2.7 Barometric Pressure

2.7.1 Influence on Tidal Exchange

"The most notable feature of water level movements around this part of Australia is the smallness of the astronomical (gravitational) tides, which result in variations due to non-tidal, principally meteorological, factors being of the same (or greater) order as those due to the tide generating force of sun and moon ...." (Agnew and Imberger, 1974). In the Fremantle-Mandurah area, the amplitude of the diurnal components, K_1 and O_1 is over twice that of the semi-diurnal constituents, M_2 and S_2. This results in a predominantly diurnal tide, though the perturbation brought about by the semi-diurnal component can be clearly seen on the Mandurah tide record. An analysis of the tides for all major ports on the south western coast of Western Australia has been described by Hodgkin and Di Lollo (1958).

The Mandurah tide record reveals that these small astronomical tides are superimposed upon much longer period (of from 5 to 15 days and more) variations in water level. These lower frequency components are strongly correlated with barometric pressure (Hamon 1966). Fig.2.7 shows the analysis of the mean barometric pressure and volume flux at Mandurah Bridge (as determined from water levels at the two extremes of the Mandurah entrance channel). It can be clearly seen that, in general, a period of net rising barometric pressure will be accompanied by (resulting in) a net outflowing of water from the estuary. Conversely, falling pressure will be associated with a long period, low frequency net rising water level as there is consistent positive (flood tide) volume flux for several days.

2.7.2 Instrumentation and Digitisation

Continuous recording of barometric pressure requires a stable environment for analogue or digital barograph. No instrument was located at the study area except for short periods during intensive exercises in February and August, 1978. Even on these occasions, the data was only used for short term weather forecasting and to predict a change in the net inflow-outflow status of the estuary. However, as Fig.2.7 reveals, it is change in barometric pressure that is important in producing these low frequency components of water level and hence volume flux variations. Thus it would seem that relative and not necessarily absolute barometric pressure data would suffice.

Such a record was in any event being continuously recorded on a Casella aneroid barograph at the author's home in Rossmoyne, some 70 km from the estuary. As this instrument was sea level corrected and produced a weekly chart graduated at 2 hour intervals it was felt that its trace could be used to provide the required relative pressure changes which might be read in conjunction with volume flux if necessary.

Strip charts from this instrument were digitised by hand for every 12 hours (0000 and 1200) for the period 1/10/77 to 30/9/79 inclusive. These results are included in Appendix I , and shown also in graphical form.

2.7.3 Results and Conclusions

There is considerable difficulty in attempting to derive a mathematical model capable of predicting net volume flux at Mandurah Bridge from barometric pressure variations. The chief

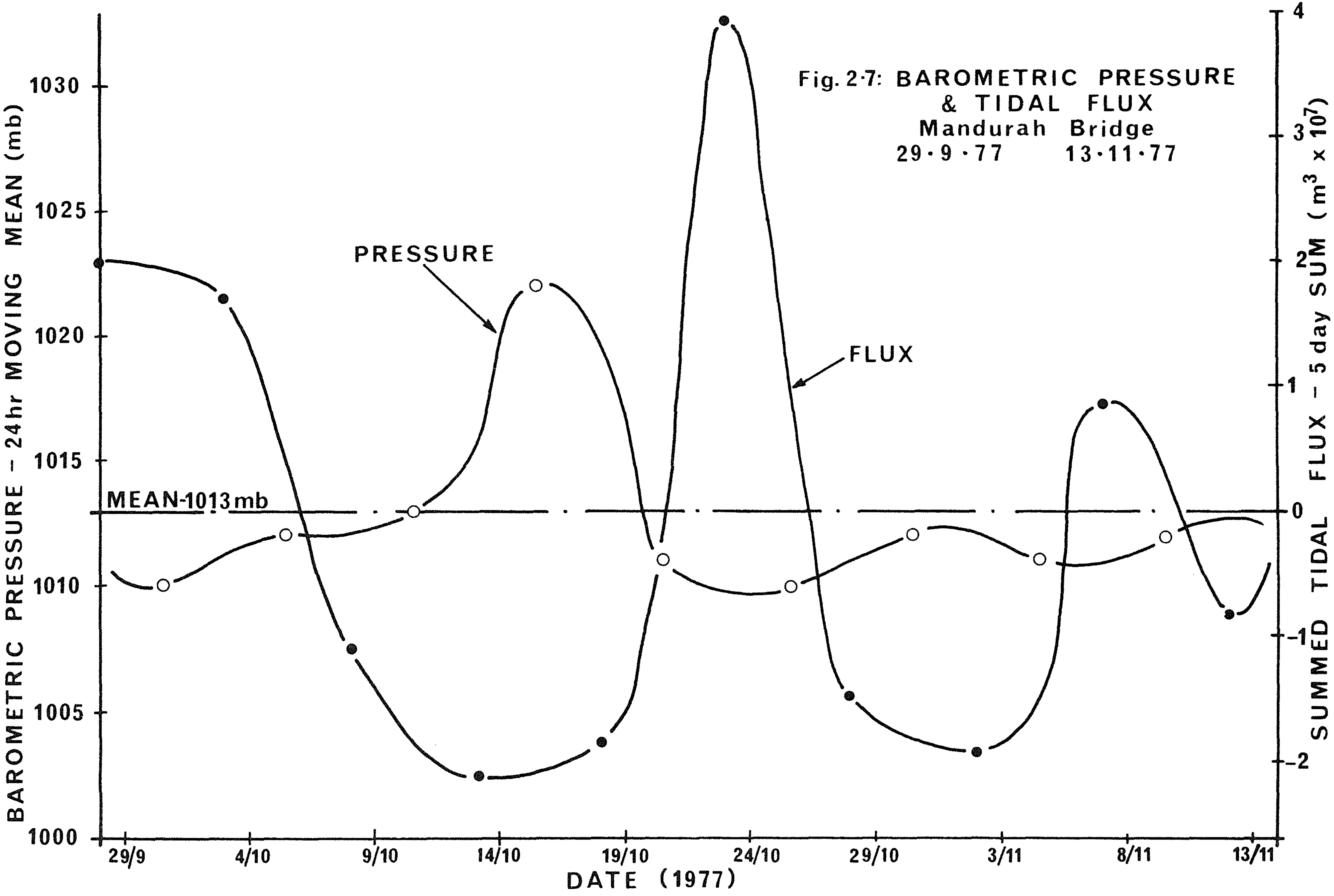


Fig. 2·7: BAROMETRIC PRESSURE & TIDAL FLUX
Mandurah Bridge
29·9·77 13·11·77

problem is in the selection of a time increment and in evaluating the lag. Furthermore, it is clearly the difference in barometric pressure (from one selected time period to the next) and not the actual pressure that is correlated with net volume flux. Analysis using a Box and Jenkins (1970) approach would probably suggest an autoregressive, differenced forecasting model though one might anticipate considerable difficulty in obtaining "stationarity" of the barometric pressure data.

In any event, since water level has been continuously recorded at both the Mandurah and Chimneys tide gauges throughout the period of the study, and as Chapter 5 reveals, this can be used to satisfactorily predict volume flux from water level differences, there seems little point in attempting the much more difficult task of modelling the pressure-flux relationship.

To demonstrate both this relationship and the difficulties in selecting a suitable time period for "differencing" the data, Fig.2.8 has been plotted using 5-day data from one continuous period (29/9/77 - 13/11/77) and 4 separate 5-day periods chosen because larger than average fluxes occurred. Linear regression of these data sets shows a correlation coefficient (r) of 0.697. This means that the coefficient of determination (r^2) ≈ 0.486. r^2_{xy} is defined as the proportion of the variance in "y" observations that is accounted for by variations in "x", i.e. in the plot of Fig. 2.8 , only 49% of the predictions of 5-day summed volume flux (ΣF_t) from changes in barometric pressure over the preceeding 5-days ($\Delta \overline{P}_{t-5}$) as calculated using the linear equation below can be relied upon. This linear equation: viz.,

$$\Sigma F_t = -0.3919 \Delta \overline{P}_{t-5} - 0.7915$$

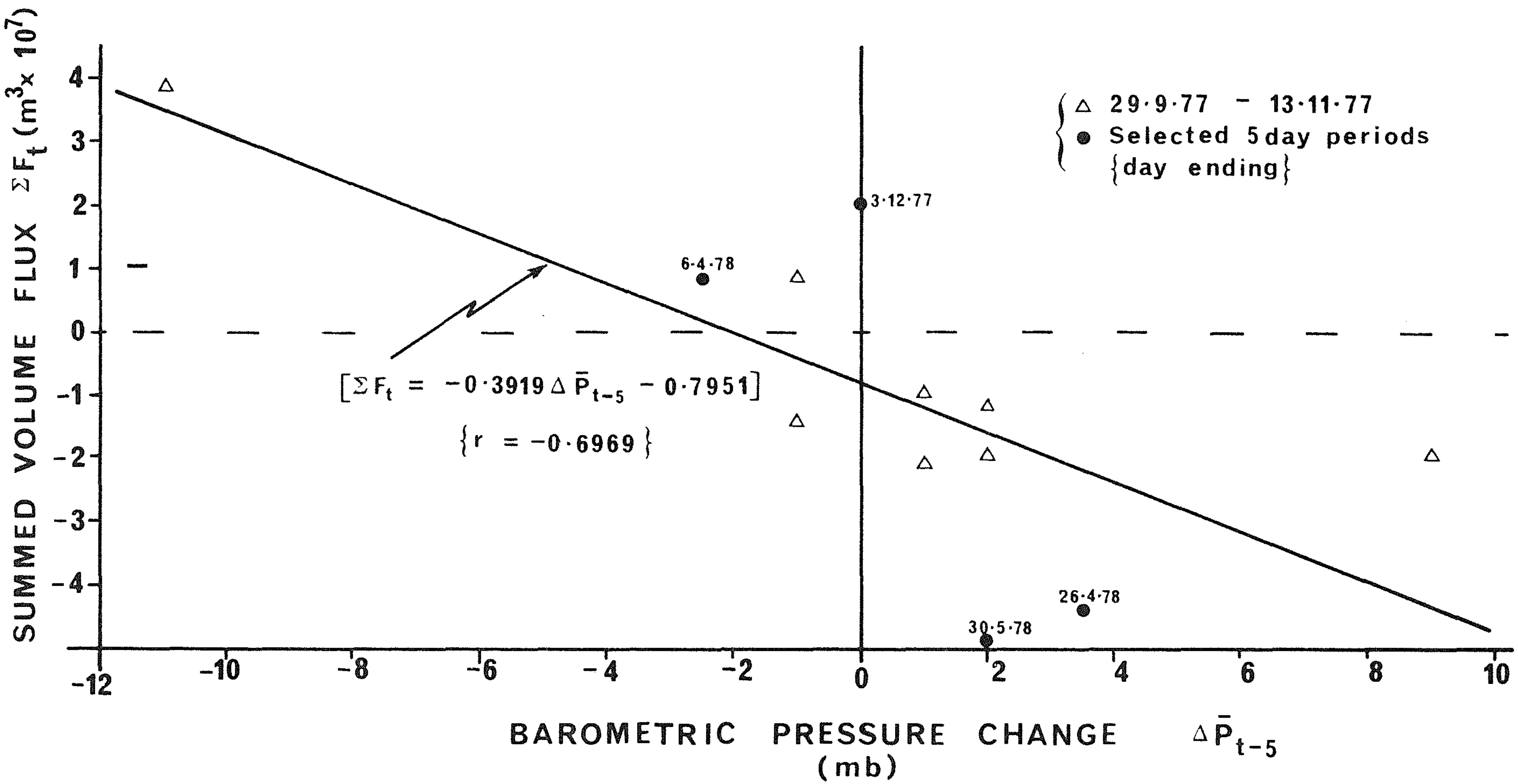


Fig. 2·8: BAROMETRIC PRESSURE v's TIDAL FLUX (Mandurah Bridge) should perhaps include a number of other factors such as channel friction. However, it seems most probable that the basic reason for the poor fit is accounted for in the selection of a suitable lag time.

We can also apply the following additional test in relation to correlation; viz.,

"Test that there is no linear correlation between ΣF_t and $\Delta\overline{P}_{t-5}$ - assume the null hypothesis, $H_o = 0$".

Find the "F" ratio

$$F = \frac{r^2(n - 2)}{1 - r^2}$$

$$= \frac{0.486(12 - 2)}{1 - 0.486}$$

$$= 9.450$$

at the 99% confidence level; $F = 10.04$ and we accept H_o and confirm that ΣF_t and $\Delta\overline{P}_{t-5}$ are not linearly related.

at the 95% confidence level; $F = 4.96$ and we reject H_o and state that ΣF_t and $\Delta\overline{P}_{t-5}$ are linearly related.

In summary, we have demonstrated that Mandurah channel volume flux and barometric pressure changes are inversely proportional and that "barometric tides" account for most of the water level fluctuations in the inlet. However it is not likely that with the data available it will be possible to use such pressure variations to adequately model tidal exchange.

3. RIVER AND DRAIN QUANTITATIVE HYDROLOGY

3.1 Introduction

The Peel Inlet - Harvey Estuary catchment comprises a total area of over 11,377 square kilometres (km^2) and the estuary system constitutes the outlet to the Indian Ocean for three major river systems and a host of minor drains. Two of the rivers, the Harvey and the Serpentine, have been dammed for periods of approximately 50 years and 20 years respectively. More recently, the two major tributaries of the Murray River, the North and South Dandalup Rivers have also been affected by storage reservoirs, as have several smaller rivers.

Thus, of the total 11,377 km^2 of possible catchment area, a total of 1,717 km^2 is dammed as follows:-

Catchment	Area (km^2)
Serpentine Dam	663
North Dandalup Pipe-head	153
South Dandalup Dam	318
Waroona Dam	47
Samson Brook Dam	65
Logue Brook Dam	39
Stirling Dam	251
Harvey Weir	181
Total catchment dammed	1717

Of this area, 373 km^2 is diverted through the Harvey River Diversion with provision for sluice gate release of up to 5.66 m^3/sec down the Harvey River Main Drain (old river course) into Harvey Estuary. Figure 3.1 shows the catchment

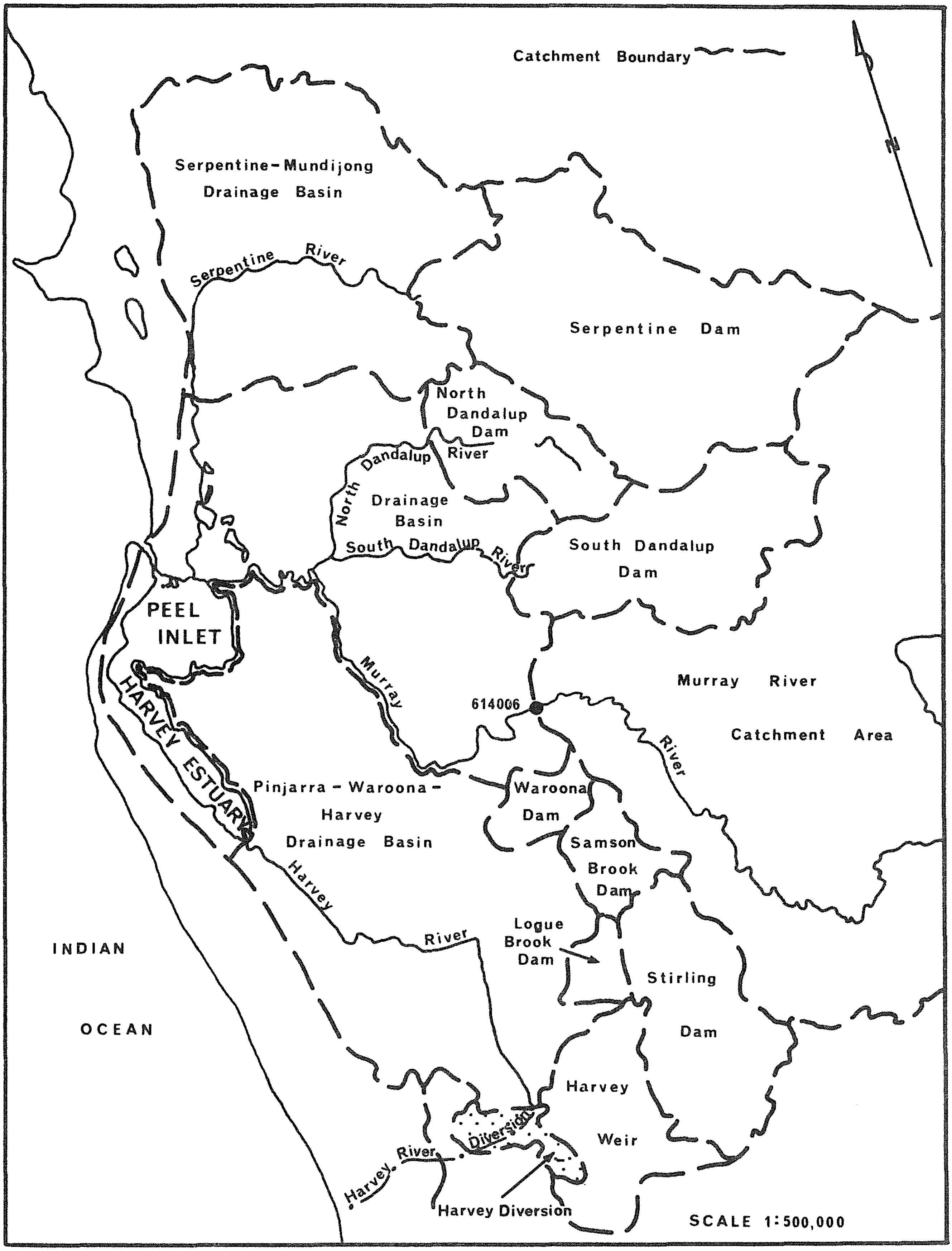


Fig. 3·1 : PEEL INLET & HARVEY ESTUARY CATCHMENTS
(after PWD 47461-1-1A)

areas and the Harvey River Diversion which was dug from the Harvey Weir to sea during the 1930's.

Drainage districts on the coastal plain comprise 1,761 km^2 as follows:-

Drainage District	Area (km^2)
Serpentine - Mundijong	725
Pinjarra - Waroona - Harvey	1036
Total drainage catchments	1761

Remaining natural catchment areas are all associated with the Murray River system. Collins (1974) describes the topography of the large basin of the Murray thus:

> " .... The Murray transects the Darling Range through a steep, rocky, fault-aligned valley, deeply incised in extensive laterite uplands drained by several small tributaries, most of which are similarly fault-aligned and have mature "upper" and "rejuvenated" lower reaches. Beyond the Darling Fault Scarp - (the western boundary of the Plateau) the Murray traverses the coastal plain sediments between natural levees to debouch into Peel Inlet. On the coastal plain, the Murray is joined by the Dandalup River, the three branches of which (North, South and Little) rise on, and drain the western slopes of the Darling Range just north of the main Murray system ...."

The "Forest", "Marginal" and "Agricultural" portions of the Murray River basin (Collins 1974) which in general cover the area upstream of the Baden Powell Water Spout gauge (Public Works

Department Station No.614 006) have an area of 6,889 km^2 whilst the coastal plain drainage segment covers some 1,010 km^2. These total 7,899 km^2.

In summary, 7,899 km^2 of the total 11,377 Peel Inlet - Harvey Estuary catchment is not dammed by either major storage works or pipehead construction and thus contributes flows more or less in response to rainfall directly, frequently ceasing to flow entirely during some or all of the summer months.

Surface drainage systems of all 3 river systems on the coastal plain were characterised, in the natural regime, by gentle gradients such that winter flows frequently exceeded channel capacity and local flooding was a regular seasonal occurrence. As a result of this, from various times from about 1910 onwards, artificial drainage works were put in hand; viz.,

> " .... However, around the 1930's, after subdivision of the colonial land grant, recognition of the role of trace elements and the general use of inorganic fertilizers, settlement of the coastal plain became more intensive, and as a consequence many of the natural waterways were canalized and water-logged areas artificially drained. Since about 1950, the Public Works Department has maintained and improved the major trunk drains into which local farmers divert their private land drainage systems ...."
>
> (Collins and Rosair 1978)

It seems likely that as a result of these improvements, the coastal plain drainage of the Harvey, Serpentine and Murray systems now carries a considerably greater volume of both surface run-off and groundwater than was the case when the land was in its pristine condition. This might, to some extent, help to redress the loss to the estuary system of water from the upland portions of rivers dammed. However as hydrographs from the Harvey River reveal, a river whose headwaters have been truncated (and diverted elsewhere or abstracted for water supply and/or irrigation) behaves in a very different fashion to one which still has an upland, midland and lowland (coastal plain) phase.

As the coastal plain is the portion of the Peel - Harvey catchment which receives by far the greatest application of phosphatic fertilizers, the fact that coastal plain drainage now constitutes a higher percentage of total river flow will be seen to be of great importance. This is discussed in Chapter 4.

3.2 The Murray River Drainage System

3.2.1 Catchment Characteristics

The Murray River basin (Australian Water Resources Council Basin No.614) is of such size and diversity of landform, climate and vegetation that it is difficult to describe it in general terms. A water resources survey of the Murray by the Public Works Department of Western Australia (Collins 1974) provides a most complete analysis of the basin carried out for the purposes of establishing a base-line study for water resources planning. The most useful subdivision of the catchment for the Peel Inlet study purposes is one based upon water quality considerations and this (see Fig.3.2) divides the basin into the following regions:-

(i) Agricultural Region - in the far eastern portion of the catchment. Here the water quality is saline (>3000 mg/1) with few exceptions. In this area the landscape has been subjected to widespread clearing for agriculture. Annual average rainfall isohyets range from only 430 mm to 630 mm and land use is almost exclusively for cereal production (wheat/sheep) to the east and sheep (wool) and lambs on improved pasture to the west.

(ii) Marginal Region - runs in an arc through Bannister, Boddington and Williams adjacent to the Agricultural region and water quality varies from marginal (500 - 1000 mg/l) to saline (>3000 mg/l). The less saline water comes from a few timber logging areas and the very high salinity water from extensively cleared valleys. The brackish (intermediate quality - 1000 - 3000 mg/1) water comes from the sub-catchments which still have a considerable cover of forest on their divides. Rainfall varies from 630 mm to approximately 850 mm per annum.

(iii) Forest Region - mainly forested and indigenous species. Water quality is generally fresh (100 - 500 mg/1) but some sub-catchments to the east are only of marginal quality. Rainfall annual averages range from 850 mm to upwards of 1100 mm.

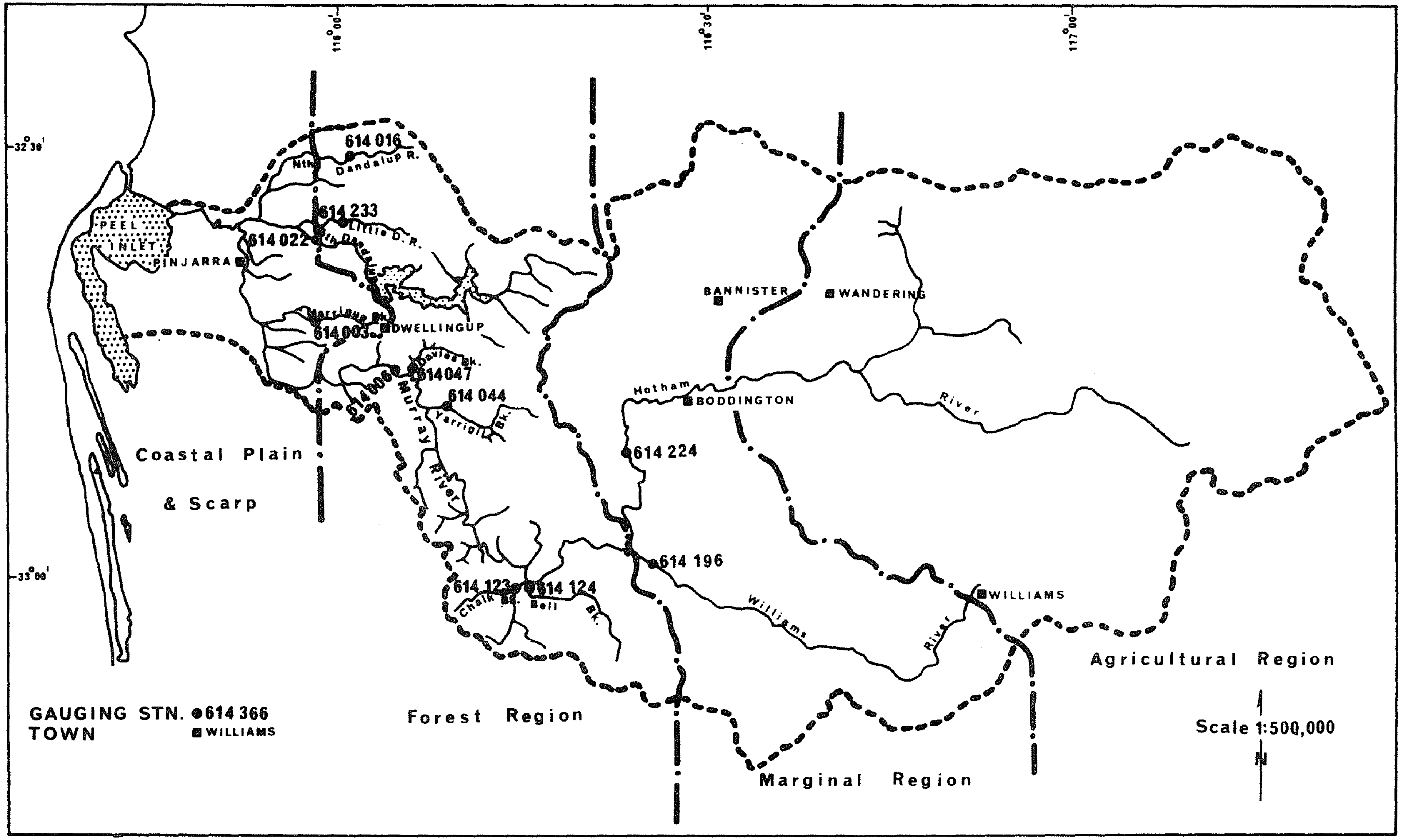


Fig. 3 2: MURRAY RIVER BASIN (after Collins 1974)

(iv) Coastal Plan and Scarp - west of the Darling fault scarp where the basement rocks are overlain by considerable depths of sedimentary material " ...... hydrogeological investigations indicate that there is an appreciable discharge of groundwater westwards to the sea ...." (Collins 1974). Rainfall in this region tails off from the peak of over 1200 mm on the edge of the scarp to about 900 mm at Mandurah at the entrance to the sea. Water quality is fresh (100 - 500 mg/l) but this is not relevant beyond Pinjarra towards the Peel Inlet, from where the Murray is a tidal river. A small timber and rock weir at Pinjarra provides an upstream limitation for tidal (sea-water) intrusion. There is rarely flow over this weir in the summer months so that the Murray River is merely an extension of the Peel Inlet from about December to late April/early May when river flow downstream of Pinjarra re-commences. The coastal plain has been extensively cleared and used for dairying on improved pastures with some irrigated cultivation in certain localities.

3.2.2 Catchment Rainfall

It is difficult to describe rainfall "averages" for the Murray River Basin either in areal or seasonal terms. Such a large catchment (6840 km^2 at the last downstream river gauging station) with a variation in rainfall from east to west of 430 mm to over 1200 mm annual cannot be assigned a single rainfall figure that has much significance. Moreover, the seasonal variation is from zero (January, February, March) to 80% to 90% (June, July, August).

However, in order to estimate the yield of the catchment, it is necessary to define a single weighted average annual rainfall for the basin area at the Baden Powell Water Spout gauge. Collins (1974) used Thiessen weightings of 20 rainfall stations to determine the mean annual catchment rainfall for the 30 year period 1940 - 1970 of 650 mm.

Fig.3.3 (after Collins (1974)) shows the histogram of catchment rainfall and the variation enpressed as a departure from the mean.

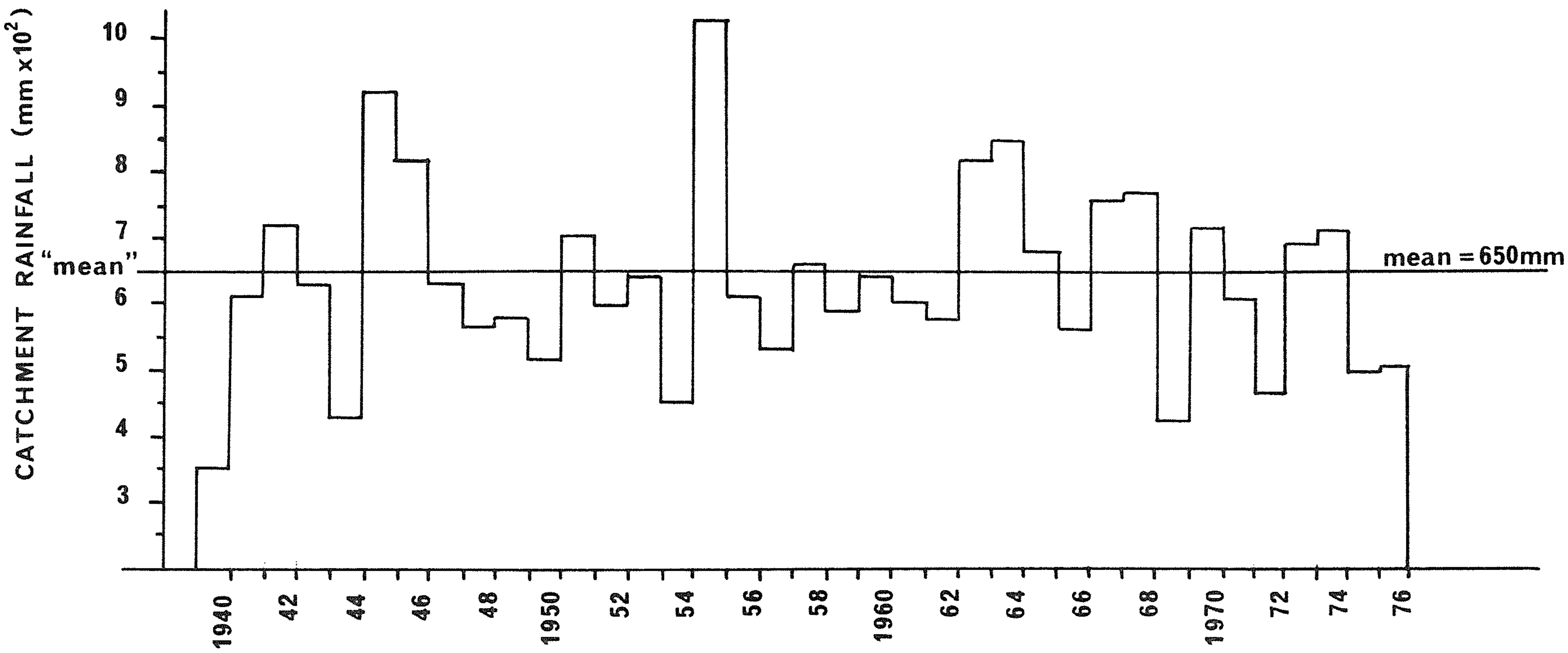


Fig. 3·3 : MURRAY RIVER BASIN RAINFALL (after Collins 1974)

Catchment & A.W.R.C. No.	Catchment Rainfall, Runoff & Characteristics				
	Catchment Area (km^2)	Mean Rainfall (mm)	Mean Runoff ($m^3 \times 10^6$)	Period of Record	Catchment Characteristics
Marrinup Bk. 614 003	46.1	1190	9	1971 to date	Coastal plain and scarp Mainly cleared - pasture
North Dandalup R. 614 016	153	1190	30	1939 to date	Scarp and Laterite plateau Forest and W/S catchment
Little Dandalup R. 614 233	39.6	1170	10	1967 to date	Scarp and laterite plateau Forest and W/S catchment
South Dandalup R. (Main Dam)	313	1090	34	1963 - 71	Laterite plateau & incised valley Forest and W/S catchment
Murray River 614 006	6840	650	327	1939 to date	Laterite plateau, dissected slopes 40% forest, 60% agricultural
Davies Brook 614 047	67.3	1270	10	1954 to date	Laterite plateau & incised valley 80% forest, 20% orchards
Yarragil Brook 614 044	73	1010	5.1	1951 to date	Laterite plateau & incised valley 100% forest
Chalk Brook 614 123	104.9	960	11.4	1959 to date	Laterite plateau & incised valley 100% forest
Bell Brook 614 124	200	770	6.0	1959 - 65 1967 - 72	Laterite plateau & incised valley 100% forest
Hotham River 614 224	4015	590	145	1966 to date	Laterite plateau, dissected slopes 20% forest, 80% cleared
Williams R. 614 196	1437	610	72	1966 to date	Incised wide valleys, laterite divides, Mainly cleared

TABLE 3.1 : Murray River Basin Gauging Stations (after Collins 1974; Black 1976)

3.2.3 Runoff

Fig.3.2 shows the location of eleven (11) operating river gauging stations in the Murray Basin. These cover many types of sub-catchment as shown. TABLE 3.1 lists these stations and the relevant catchment characteristics and period of record. A complete list of all Murray River Basin gauging stations is recorded by Collins (1974).

It should be borne in mind that the Dandalup stations are located adjacent to water utilization schemes and the rivers are subjected to abstractions or storage for Perth Metropolitan Water Supplies. This means that recorded flows at 614 016 and 614 022 (especially in the summer months) do not necessarily reflect the response of the catchment to rainfall, but include controlled releases of water (compensation flows).

Initially it was felt that the Public Works Department gauging station 614 006 (Baden Powell Water Spout; formerly Hughes Bridge) could provide a reasonable estimate of Murray River flows into Peel Inlet. However, as 3.4.2 shows, there is an approximate "gain" of 15% from 614 006 to Pinjarra Weir, the limit of tidal intrusion. This reach of the Murray River incorporates the contributions of such minor tributaries as Marrinup Brook (gauged at 614 033), Oakley Brook, and Barrett Brook (both ungauged).

Downstream of Pinjarra Weir, the Dandalup Rivers, whose confluence is just west of the South Western Highway join the Murray River main channel and flow into Peel Inlet. These include:-

North Dandalup River (gauged at 614 016)
South Dandalup River (gauged at 614 022)
Little Dandalup River (gauged at 614 233)

Collins (1974) reports that the North and South Dandalup Rivers have been developed for use by the Metropolitan Water Board and the Public Works Department, viz.,

	Yield ($m^3 \times 10^6$)
North Dandalup Pipe Head Dam (M.W.B.)	6.6
South Dandalup Reservoir (M.W.B.)	27.0
South Dandalup Pipe Head Dam (P.W.D.)	7.3

It is envisaged that future development entails "................. a storage reservoir on the North Dandalup and possibly a pipe head or diversion structure on the Little Dandalup ...." (Collins, 1974).

Estimates of long term average annual flows have been obtained by correlation for these rivers and it is useful to compare them with the Murray River record. We find that:-

River	Average Annual Runoff ($m^3 \times 10^6$)
Murray (at 614 006)	340
Murray (inc.15% gain)	391
North Dandalup	30
South Dandalup	34
Little Dandalup	10

This suggests that on an annual basis, the Little Dandalup River, which is not dammed, supplies approximately 2% of the Murray Basin input to Peel Inlet. However if we compare its flows to the total input in the key winter months (when by far the greatest part of the nutrient input is provided) we find that the Little Dandalup contributes < 1% and can probably be neglected. Such a figure is in any event well outside the limits of accuracy of either gauging or flow estimation.

It would however seem unwise to similarly neglect the contribution of the North and South Dandalup Rivers since compensation releases can on occasions represent a high percentage of total Peel Inlet inputs; e.g., for the high flow months June, July and August, 1978, we find that the combined North and South Dandalup flows were respectively 16%, 15% and 21% of the Murray River flow at Pinjarra Weir.

Thus TABLE 3.2 lists the monthly inputs to Peel Inlet from the Murray River, the North Dandalup River and the South Dandalup River for 1977/78 and 1978/79. A complete listing of daily flow volumes from these rivers for the study period is supplied in Appendix II.

The very low flow in 1978/79 has previously been discussed in 2.2.5 and the catchment yield is examined further in 3.2.5.

RIVER	YEAR	MONTHLY FLOW VOLUMES ($m^3 \times 10^6$) Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual Total	
Murray (Pinjarra)	1977 -78	9.0	6.4	1.0	0.2	0.1	0.1	0.1	1.6	14.0	180.0	42.7	18.1	273.3	
North Dandalup (614 016)	1977 -78	1.7	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.8	6.2	1.5	2.1	12.7	
South Dandalup (614 022)	1977 -78	0.2	0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.5	1.3	0.1	0.5	3.2	
TOTAL	1977 -78	10.9	6.8	1.1	0.2	0.2	0.2	0.2	1.8	15.3	187.5	44.3	20.7	289.2	*
Murray (Pinjarra)	1978 -79	18.9	2.3	1.1	0.5	0.2	0.1	0.1	0.8	3.8	18.0	13.3	12.7+	71.8	
North Dandalup (614 016)	1978 -79	2.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.9	2.3	2.5+	13.7	
South Dandalup (614 022)	1978 -79	1.4	0.1	0.1	0.0	0.0	0.1	0.1	0.2	0.4	0.8	0.6			
TOTAL	1978 -79	23.1	2.6	1.2	0.5	0.2	0.2	0.2	1.0	4.4	20.7	16.2	15.2+	85.5	*

TABLE 3.2 : MURRAY RIVER SYSTEM - Monthly Inputs to Peel Inlet; 1977/78, 1978/79

* The inclusion of flows from Little Dandalup River (614 233) adds approx. 1% to total flow.

\+ Estimated only from gauged flows to 11/9/79.

3.2.4 Flow Routing

As Figs.3.1 and 3.2 reveal, the first permanent flow record of the Murray River main channel is from PWD station 614 006 at Baden Powell Water Spout (hitherto "Hughes Bridge") some 36 km upstream from the Pinjarra Weir. This station has a record variously quality tagged as "good" to "estimated" and dating from 1940.

Furthermore, the uncertainties of simply using this record as an indication of Murray River contribution to the estuarine water balance are exacerbated by the fact that the Murray River flow at this point has ranged from 56 to 1143 x 10^6 m^3 per year. Gauging, even on a temporary basis of the Murray River below the Pinjarra Weir is not practicable, as has been previously stated, due to the tidal nature of the river below this point. Conventional, current metering immediately upstream of the weir would be very difficult, if not impossible, given the financial and manpower constraints of the study.

One solution to the problem of estimating the "gain" or enhancement of flow on the reach of the river between 614 006 and Pinjarra Weir is offered by the application of dye dilution gauging described by Wilson (1968). This approach was used successfully in a hydrological study of the Murrumbidgee River (Whitehead et al., 1978) to determine velocity and discharge for a number of flow levels. This enabled the computation of the coefficients "a" and "b" in the equation

$$U = aQ^b \qquad (3.1)$$

where U is the mean flow velocity (m/sec)

Q is the average discharge (m^3/sec)

With regard to the problem of determining a reliable estimate of river inflow into the Peel Inlet, it was felt that a series of such dye gauging experiments could be used to evaluate "a" and "b" in (3.1)(above) and also to calculate the gain from 614 006 to Pinjarra weir. Full details of the flow routing model are reported by Whitehead, Hornberger and Black (1979).

(i) Dye Gauging Technique

Tracing using fluorescent dyes was first carried out as early as the late 1950's, as a result of a desire to use something other than radiosotopes such as Tritium which caused both handling problems and public disquiet. The procedures were first adapted to measurement of stream discharge by the United States Geological Survey (U.S.G.S.) in 1967.

In brief, the technique consists of the "slug" injection of a specific amount of fluorescent dye into the river and the measurement of its concentration (dilution) at some point downstream. Analysis of the "difference" in concentration at the two sites can be used to give a measure of the discharge volume (l/sec or m^3/sec).

Mandatory requirements for successful gauging are:-

a) Injection and detection site must be sufficiently far apart to ensure adequate mixing.
b) Flow must be sufficiently turbulent to ensure mixing (the technique is suspect at low flows).
c) Natural abundances of the chosen dye in the river (background) must be (i) low and (ii) measured.

The quantity of dye required for successful measurement is a function of the river discharge, length of reach, concentration of dye used, velocity of river and detection limits of chosen instrument. Kilpatrick (1970) suggests that for one widely used dye, Rhodamine WT, the dosage formula is:-

$$\text{(20\% solution)}\quad V_d = \frac{2 \times 10^{-4}(Q_m\ L)}{U}\ C_p \qquad (3.2)$$

where V_d = volume of dye in gallons of solution
Q_m = mean discharge of reach in ft^3/sec
L = length of reach in miles
U = mean velocity in ft/sec
C_p = peak concentration required in µgm/ at the measurement point

The S.I.(metric) version of this formula becomes:-

$$V_d = \frac{6 \times 10^{-3}(Q_m\ L)}{U}\ C_p \qquad (3.3)$$

where V_d is in litres (l)
Q_m is in m^3/sec
L is in km
C_p is in µgm/l

Thus, for example, if we require a peak concentration of 10 µgm/l; estimated discharge is 20 m^3/sec; length of reach is 2 km; estimated velocity is 0.5 m/sec; then -

$$V_d = \frac{6 \times 10^{-3}(20 \times 2)}{0.5} \times 10$$

$$= 4.8 \text{ litres}$$

In practice, suitable hydrographs can be derived from much lower values of C_p, so that 2 - 3 litres would suffice in the above case.

All that is required is to empty a "slug" of the dye into the upstream site and sample (or continuously record) the flow of the stream at sufficiently short time intervals to define the concentration of dye curve as it passes the downstream station. A plot of dye concentration versus time (μgm/l v's sec.) yields a curve, the area beneath which is the "dilution" in (μgm/l) sec. Thus if we divide the injected <u>mass</u> of dye (in μgm) by this figure, we have:-

$$\frac{\mu gm}{\mu gm} \times \frac{1}{sec} = \frac{1}{sec}$$ which is the mean discharge of the stream

Concentration of the dye is determined using a fluorometer; i.e., an instrument which measures the fluorescence or relative intensity of light emitted by the fluorescent dye when excited by a lamp, suitably filtered. Details of the technique are described by Wilson (1968).

As an alternative to the collection of samples for later laboratory analysis of their fluorescence, it is possible to obtain a continuous trace of the passage of the dye by setting up the fluorometer in "flow-through" mode. This requires an intake pump and hose, outlet pipe and strip chart recorder. Both techniques were used on the Murray River study. The great advantage of the latter method is that the arrival of dye will be directly observed and a complete dye-concentration curve obtained.

(ii) Gaugings at Pinjarra Weir

The dye gauging of the Murray River at Pinjarra Weir and its correlation with flows measured at Baden Powell Water Spout (36 km upstream) was a joint project of the authors and the C.R.E.S. team of Professor Young which included Drs. Whitehead, Hornberger and Spear, Dr. Humphries and Ms. Michele. Two gaugings were carried out by each team. Of the four gaugings, regrettably none even approach the mean July flow (39 years) of approximately 40 m^3/sec. Indeed, due to the very dry period encompassed by the study, only two of the gaugings took place at "reasonable" flows; i.e., above 10 m^3/sec.

Fig.3.4 shows the dye concentration curve obtained from the gauging of the highest flow recorded on the 30th June, 1978. TABLE 3.3 lists the relevant data measured in the computation of the "gain" from 614 006 to Pinjarra Weir and subsequently used to enhance flows from the PWD station to Peel Inlet. Fig.3.5 is a logarithmic plot of velocity versus discharge at Pinjarra used to establish the travel time parameters "a" and "b".

Length of reach from injection to detection site varied. Three of the gaugings were made over a reach of 1.3 km. The fourth, at a very low flow was made over a length of more than 3 km to try to provide a sufficient mixing time.

(iii) Analysis of Results

TABLE 3.3: shows that estimates of the gain from 614 006 to Pinjarra range from 1.03 to 1.25. It should be acknowledged that low flow gaugings using this technique are suspect. This is due to the fact that mixing may not be complete and that some dye may become trapped temporarily in back-waters. This will, in general, lead to overestimation of discharges. We are led to conclude that a gain of 1.15 $\pm$ 0.15 is applicable, even on the basis of so small a sample.

Thus, for the purposes of computing Murray River flows subsequently to be used as a water balance element or to determine nutrient loads, we have allowed the following:-

PWD STATION 614 006 - Mean Daily Flow

x 1.15

= PINJARRA FLOW

\+ NORTH DANDALUP FLOW
614 016

\+ SOUTH DANDALUP FLOW
614 022

= PEEL INLET INPUT

Other minor tributaries such as Oakley Brook and Marrinup Brook are included in the gain of 1.15 at Pinjarra Weir.

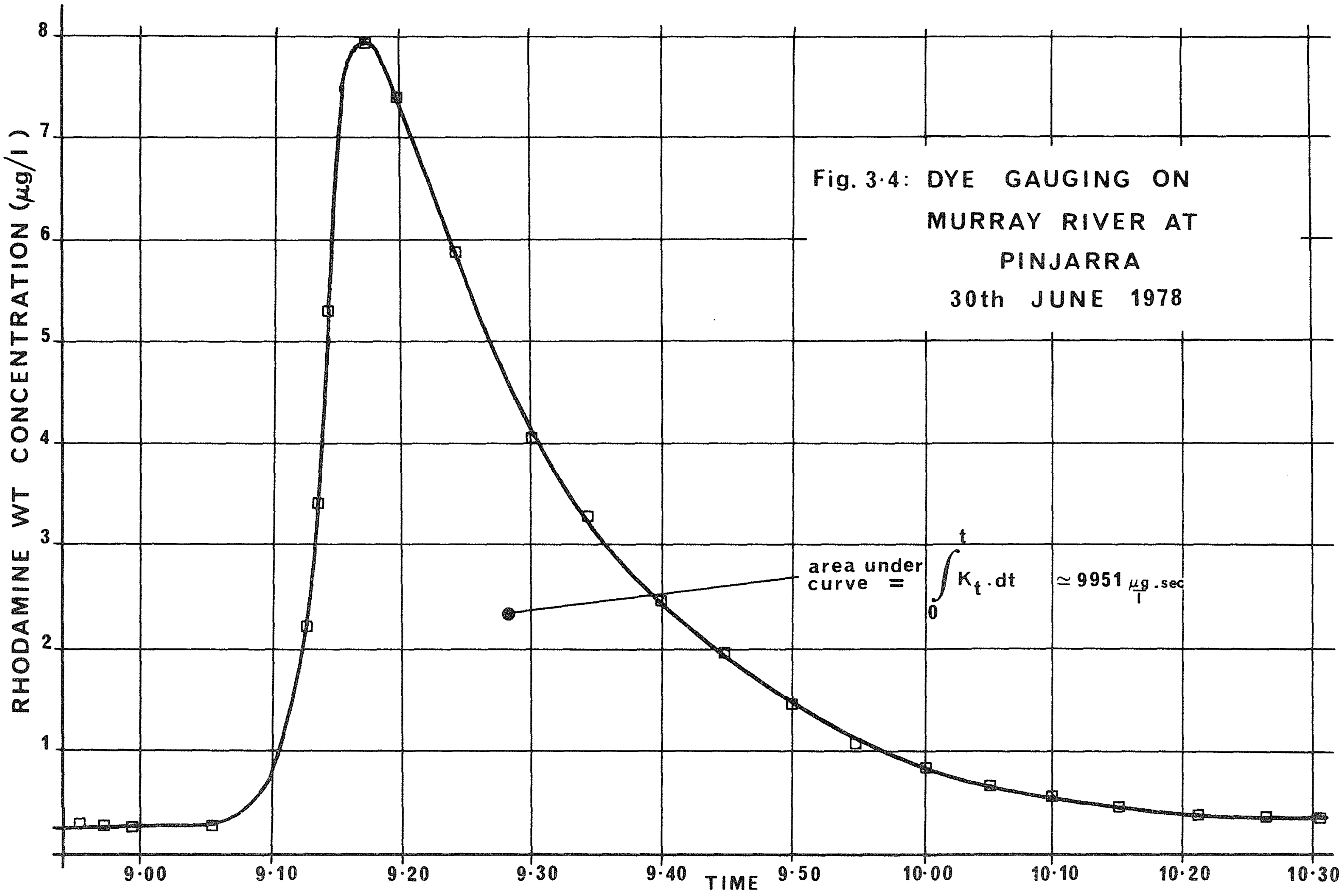


Fig. 3·4: DYE GAUGING ON MURRAY RIVER AT PINJARRA 30th JUNE 1978

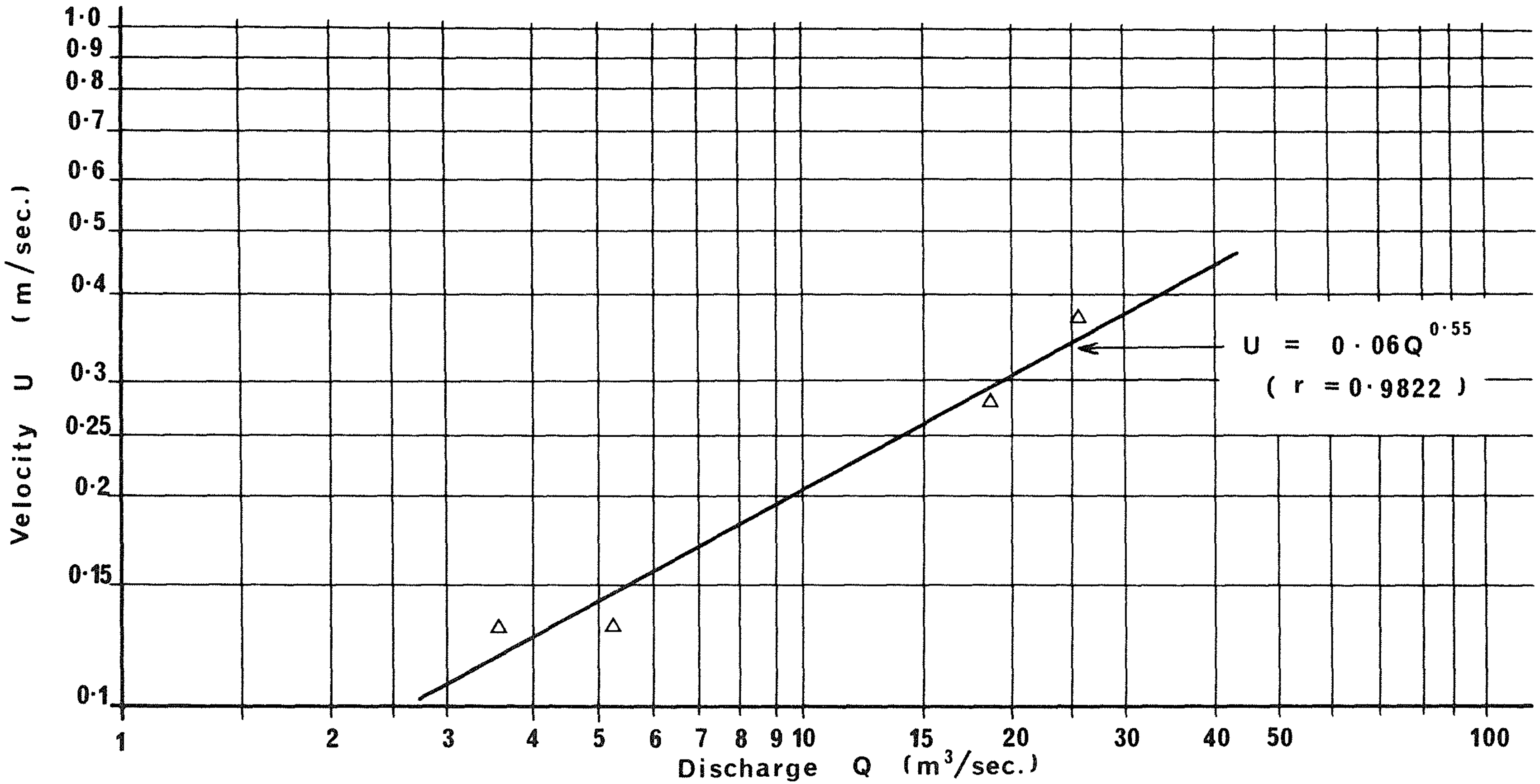


Fig. 3·5: MURRAY RIVER - VELOCITY & DISCHARGE AT PINJARRA

Date of Gauging	Estimated Velocity (m/sec)	Lag Time 614 006 to Pinjarra (hours)	Calculated Discharge at Pinjarra ± 10% (m^3/sec)	Mean Daily Flow at 614 006 ± 10% (m^3/sec)	Gain Over 36 km plus Tributaries ± 20%
6.10.77	0.13	78	5.2	4.1	1.25
30. 6.78	0.37	27	25.1	20.9	1.20
12. 8.78	0.28	36	18.6	16.1	1.16
22. 8.79	0.13	78	3.5	3.4	1.03

TABLE 3.3 : Routing flows from Baden Powell Water Spout (614 006) to Pinjarra Weir.

3.2.5. Catchment Yield

Collins (1974) estimates the long term average (L.T.A.) rainfall for the Murray Basin to be 650 mm (see also 2.2.5). Rainfall figures for 20 stations were used to calculate this Thiessen weighted average for the 30 year period 1940 - 1969. Data necessary to compute the catchment mean for the 1977/78 and 1978/79 water years are not yet available. However reasonable approximations can be made by multiplying the L.T.A. figure of 650 mm by the ratio Peel Inlet/Harvey Estuary Thiessen Weighted Mean: Mandurah P.O. L.T.A. (896 mm).

This produces the following result:

Year	Gauged Flow at 614 006 (mm)	Est.Catchment Rain (mm)
1977/78	34.8	540
1978/79	9.1	443

Public Works Department flow records for 614 006 show that in the period of record 1940 to date, on only one occasion (calendar year 1940) has less flow occurred than in the water year 1978/79. It seems likely that the figures, when available, will show that the 1979 calendar year flow was very close to the 1940 figure of 8.2 mm.

L.T.A. yield for the Murray Basin is given by:

$$\frac{\text{L.T.A. flow}}{\text{L.T.A. rain}} \times 100\%$$

$$\text{and} = \frac{49.7}{650} \times 100 = 7.6\% \ *$$

For the study years we have:

$$1977/78 \quad \text{Yield} = \frac{34.8}{540} \times 100 = 6.4\% \ *$$

$$1978/79 \quad \text{Yield} = \frac{9.1}{443} \times 100 = 2.0\% \ *$$

The impact of the very low soil moisture storage levels resulting from 4 years of below average rainfall (1975, 76, 77, 78) is clearly seen on the 1978/79 flow when rainfall equal to approximately 68% L.T.A. produces runoff equal to only 18% L.T.A., i.e., there is a 73% reduction in yield which falls from 7.6% to 2.0%.

3.3 The Serpentine River Drainage System

3.3.1 General - Catchment Characteristics

Despite the fact that both a pipe-head and main (earth fill) dam have existed for some years on the valley of the Serpentine River as it crosses the Darling Scarp, sufficient drainage has existed on the coastal plain to warrant investigation by the Public Works Department (on behalf of the Metropolitan Water Supply, Sewerage and Drainage Board) with a view to long term future exploitation. This has been reported on by Collins and Rosair (1978).

> "The major stream .... is the Serpentine River, which rises on the Darling Plateau and traverses the Scarp in a deeply incised valley that provides the sites for the present storage structures .... only those parts of the catchment downstream of the Reservoir and Pipehead Dam contributed flow to the lower reaches except for some releases of compensation water in the summer months. From the foot of the Scarp, the Serpentine flows in a westerly direction for about 15 km to where it is apparently deflected southwards by the coastal limestone formations, and from whence it follows an ancient "shoreline", featured by a chain of shallow lakes and wetlands, for a further 20 km before entering Peel Inlet.
>
> Along the western edge of the Darling Plateau, seven small streams arise and flow westwards across the alluvial

> plain ...., but ....
> turn, either north or south and join the Serpentine. Under the natural regime the winter flows frequently exceeded the capacity of these channels to contain them on such gentle gradients, and local inundation was a seasonal occurrence ...."
>
> (Collins and Rosair 1978)

This survey provides the best (indeed, almost the only) estimates of the contribution of the Serpentine River and its coastal plain drainage to the Peel Inlet. Sampling and spot gauging was carried out between April, 1976, and September, 1977, at a number of sites on the six (6) sub-systems identified; viz.,

(i) The Serpentine Sub-system (main river and drain from Pipehead dam to Peel Inlet).
(ii) The Peel Drain Sub-system.
(iii) The Birrega Drain Sub-system.
(iv) The Oaklands Drain Sub-system.
(v) The Dirk/Punrak Sub-system.
(vi) The Balgobin/Nambellup Sub-system.

Fig. 3.6 shows the drainage system and sampling points used in the Public Works Department survey. These were used to supplement the records from the three (3) PWD gauging stations 614 005, Dirk Brook; 614 013, Peel Drain; and 614 072, Serpentine River (Falls).
Subsequently (April, 1979) another gauge was installed on the Serpentine Sub-system near Karnup (614 030) and on Dirk Brook adjacent to Hopelands Road (614 028).

3.3.2 Rainfall

As with the climate of the entire south west region, the normal pattern is one of hot, dry summers and cool, wet winters. Rainfall

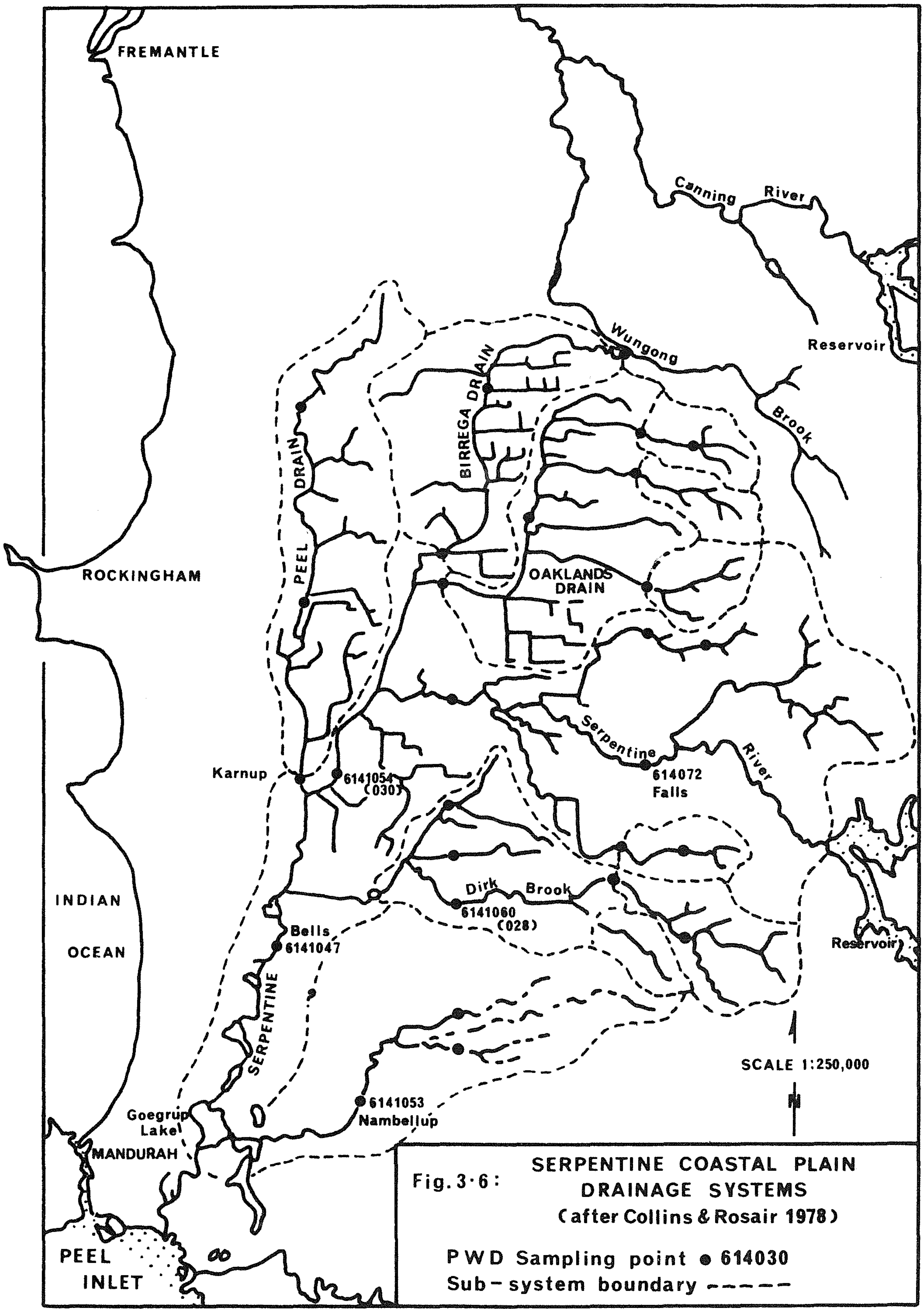


Fig. 3·6: SERPENTINE COASTAL PLAIN DRAINAGE SYSTEMS (after Collins & Rosair 1978) averages over the Serpentine system downstream of the Pipehead Dam range from 850 mm per annum on the coastal zone to about 1200 to 1300 mm on the Darling Scarp. Both the PWD survey period (April, 1976, to September, 1977) and the Peel Inlet study period (October, 1977, to September, 1979) encompass a significant drought - some months in both instances are amongst the lowest rainfall months on record. To this extent, the estimates of flow made in the survey can be used with some confidence in defining the Serpentine River drainage system contribution to Peel Inlet during 1977/78/79.

3.3.3 Runoff

As has been previously mentioned, the only continuous records of flow available at the start of the PWD survey were as follows:-

614 005 Dirk Brook (1971 to date)
614 013 Peel Drain
614 072 Serpentine River ("Falls") (1958 to date)

To these were correlated a number of instantaneous flow estimates. These approximate measurements were made by calculating the stream's cross-sectional area and finding surface velocity with a float. Thus " .... The reliability of these estimates tends to vary with the nature of the site, and are probably least accurate in deep, slow moving sections. Generally the flows are a slight over estimate of the actual discharge when compared with the recorded flows at nearby gauging stations". (Collins and Rosair 1978).

From this data has been calculated the average daily flow in m^3/sec and $m^3 \times 10^3$ for both winter and summer, and these are listed in TABLE 3.4 . From the standpoint of estimating flows into Peel Inlet throughout the study period (October, 1977 - September, 1979), a

PWD Sampling Station (A.W.R.C. Number)	Estimated Average Daily Flow from April 76 to Sept.77 ($m^3 \times 10^3$)	Estimated Average Daily Flow (Winter) ($m^3 \times 10^3$)	Estimated Average Daily Flow (Summer) ($m^3 \times 10^3$)
"Bells" (614 1047)	172	238 (from totals)	35.9 (from totals)
"Nambellup" (614 1053)	2.16	2.16	- (assumed)
Serpentine (Falls) (614 072)*	25.9	34.0	8.2
*continuous record			
Estimated "gain" from 614 072 to (614 1053 + 614 1047)	Annual	Winter	Summer
	6.72	7.00	4.38

TABLE 3.4 : Estimated Daily Flows and Gain - Serpentine Water Resources Survey (after Collins and Rosair, 1978)

number of points need to be made; viz.,

(i) Between 614 1047 and 614 1053 and the Peel Inlet lies Goegrup Lake and a number of smaller lakes and wetlands.

(ii) The effect of these on flows into Peel Inlet is unknown but it seems likely that such an increase in flow section will result in greatly reduced velocity and a marked increase in evaporative loss. Thus it seems reasonable to assume that average flow into Peel Inlet will be less than the sum of the flows recorded or estimated at 614 1047 and 614 1053.

(iii) In the absence of a continuous recording station close to the lakes, the best estimates of Serpentine River drainage flows into Peel Inlet must be made by making use of the calculated "gain" obtained from the PWD study, discounted as outlined in (ii) to allow for losses in the lakes and wetlands.

(iv) TABLE 3.4 shows that estimated gain varies from 6.7 (Annual) to 7.00 (Winter) and 4.38 (Summer) based on the 1976-77 survey. However as Collins and Rosair (1978) point out " .... These volumes are only estimates and should be accepted as such. They probably represent the order of flow to be expected during a similar dry period, although the calculations do appear to over-estimate summer flows to a degree ...."

For all these reasons, we have decided that a figure of 6.0 should be used as a gain multiplier to estimate Serpentine River Drainage system input to Peel Inlet from Serpentine River (Falls) gauge 614 072, i.e.,

$$\left.\begin{array}{l}\text{Serpentine River Drainage}\\ \text{System Input } (Q_S)\end{array}\right\} = \left\{\begin{array}{l}\text{Mean Daily}\\ \text{Flow at 614 072}\end{array}\right\} \times 6$$

In April, 1979, a continuous recording gauging station was established at Karnup (614 030) near the site of 614 1054 sampling point on the Serpentine Sub-system. As estimated flows at this point represent approximately 65% of total flow into Peel Inlet, data from this gauge, when available, will provide important corroboration of the above estimated gain. Regrettably, at the time of writing, no flow records are yet available from 614 030.

3.3.4 Flow Estimation

On the basis of the 6 times gain from Serpentine River (Serpentine Falls) gauge (614 072), TABLE 3.5 lists the probable inputs of Q_S to Peel Inlet. There is little doubt that summer flows are over-estimated to a degree, but in terms of nutrient loads and total annual flow, they are so small that this is not significant. Furthermore, flows recorded at 614 072 throughout the summer months are a result of releases of compensation water and those in the other drainage sub-systems are attributed to outflow of irrigation water or private land drainage systems to major trunk drains.

A hydrograph for the Serpentine River at 614 072 is included in the report of the C.R.E.S. group of Professor Peter Young.

Water Year	Serpentine Drainage System - Estimated Flows into Peel Inlet ($m^3 \times 10^6$)												
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1977/78	5.2	1.2	0.7	1.0	1.2	1.4	1.1	2.0	7.7	26.6	7.3	9.5	64.9
1978/79	12.5	1.9	0.9	1.0	0.8	0.9*	0.9*	1.4	4.4	9.5	11.6	9.0*	54.8*

*Based on incomplete record at 614 072

Water Year	Seasonality - Statistics of Flow			
	Summer (Nov, Dec, Jan, Feb, Mar.)		Winter (June, July, Aug, Sept.)	
	$\Sigma(m^3 \times 10^6)$	% of Annual	$\Sigma(m^3 \times 10^6)$	% of Annual
1977/78	5.5	8.5	51.1	78.7
1978/79	5.5	10.0	34.5	63.0

TABLE 3.5 : Serpentine Drainage System - Statistics of Flow

3.4 The Harvey River Main Drain and Minor Drains

3.4.1 General - Catchment Characteristics

The 1036 km^2 Pinjarra-Waroona-Harvey drainage catchment area constitutes the largest single unit of the coastal plain drainage into the estuarine system. The major watercourse of this drainage area is the old Harvey River, now more accurately referred to as the Harvey River Main Drain. In addition, a large number of minor drains also contribute to discharge into the Harvey Estuary on the south side of Peel Inlet. Some of these are so small (and dry for the greater part of the year) that gauging their flow seemed neither worthwhile nor practicable. Those selected for gauging and sampling were: (see Fig.2.1)

001	Greenlands Drain
002	Fauntleroy Drain
003	Caris Drain
004	Coolup Drain
005	Robert Bay Drain
006	Mealup Drain
007	South Coolup Drain
008	Mayfields Drain ("Little Harvey River")

Of these, two were soon found to have an insignificant input; viz., 001 Greenlands Drain had a flow that never exceeded 0.1 m^3/sec or 8.6 x 10^3 m^3/day; and 005 Robert Bay Drain was constructed on a gradient so flat that it was never possible to record a flow into Peel Inlet. Indeed at times of high inlet water level, such movement as existed in this drain appeared to be away from the estuary.

The most significant feature of hydrographs from all drains, and especially the Harvey River Main Drain, was the uncharacteristic short time to peak. This was hardly surprising as the effect of the construction of the Harvey Weir and subsequent diversion of the Harvey River to the sea (see 3.1) is to deny the downstream segment of the river the attenuation provided by the upper reaches. Thus the effect of storm rainfall is to produce a hydrograph with a time to peak that varied between 6 and 24 hours, an unusually short time for Western Australia (south west) catchments (Loh 1974).

To the west of the South Western Highway, the basin is exclusively on the coastal plain (see Fig.3.1) and it is almost impossible to separate out the catchments of individual drains due to the very flat nature of the terrain. From a quantitative point of view, there is little point in trying to do so and attention was focused on the correlation of flows in each of the drains with the much larger Harvey River Main Drain. Subsequently, mathematical modelling using both deterministic and stochastic methods conceptualised the flow from the catchment into Harvey Estuary as occurring at a single gauging point. This is examined in 3.4.4.

3.4.2 Rainfall

Fig.2.1 shows the existing daily-read rainfall stations in the vicinity of the Harvey catchment. No single gauge could be considered truly representative of the basin rainfall, though the Warraba site is certainly centrally located on Mayfields Drain and the Waroona rainfalls might be considered relevant to the eastern portion of this large catchment.

Of the three pluviometers installed for the study, the Harvey estuary site is the only one relevant to this basin. As it is only 15 km from the Waraba gauge (now closed) and the topography is so flat that variations due to the orographic effect would be negligible, this pluviometer might be expected to have a long term average not much different from Waraba. For the study period we find that:

Harvey Pluviometer (2)

1977/78	Annual total	=	845 mm
1978/79	Annual total	=	630 mm

Waraba Daily Gauge (closed August, 1937)

Long term average (LTA) 15 years	=	1011 mm
Minimum annual total (1919)	=	844 mm

Waroona Daily Gauge

Long term average (LTA) 36 years	=	1038 mm
Minimum annual total (1940)	=	559 mm

Thus we find that, in all probability, in the last sixty years, lower rainfall than 1978/79 has only occurred on one occasion, namely 1940. The 1977/78 rainfall total is also amongst the lowest recorded.

In the rainfall-runoff modelling for the Harvey catchment (see 3.4.4), hourly values from the Harvey pluviometer are used for the Stanford Watershed Model runs, and system-wide Thiessen averaged daily totals for the time series modelling.

3.4.3 Runoff

(i) Gauging Harvey River Main Drain

From July, 1976, spot gauging of the Harvey River Main Drain were carried out using an A.Ott propellor-type current meter at the old railway bridge immediately south of the Harvey Estuary (see Fig.2.1). On each occasion the metering was related to a measurement of river height taken from the top of the soffit over the central span of the bridge. Subsequently a gauging pole was permanently affixed to one of the bridge piers to facilitate this measurement.

The aim of these gaugings, which were made at flows ranging from 0.55 m^3/sec to 5.82 m^3/sec, was to establish a rating curve or curves for the gauging point which would relate river height to discharge. Such a relationship is usually logarithmic, and it was found in this instance that the curve plotted on Fig. 3.7 provided the best fit over the range of discharges measured.

As is usually the case, some difficulties were encountered with the rating curve and these can be summarised as follows:

(a) High flows. As it was not feasible to establish a semi-permanent cable way, gaugings were made by wading (only feasible at flows up to about 5 m^3/sec) and by rubber dinghy above this. This reduced the number of "sections" that it was possible to measure.

(b) Bank-full stage. When flows were such that the river overlapped its banks, gauging was virtually impossible as the area flooded on either bank increased the river width by a factor of 2 to 3. Thus the estimation of such flows from the extrapolated rating curve is highly suspect.

(c) Throughout the 1977/78 water year, measurements of river stage (and hence estimates of instantaneous discharge) were made weekly. Mean daily flows could thus only be interpolated from these estimates. In view of the previously mentioned rapid response of the river to storm rainfall (see 3.4.1), this is highly suspect, and requires verification.

(d) To help overcome the problems encountered by weekly spot gauging or stage measurement, it was decided to establish a Leopold-Stevens A35 Water Level Recorder at a site just downstream of the bridge. This instrument thus provided continuous measurement of stage throughout the 1978/79 water year. The physical task of sinking a float well and connecting intake pipes

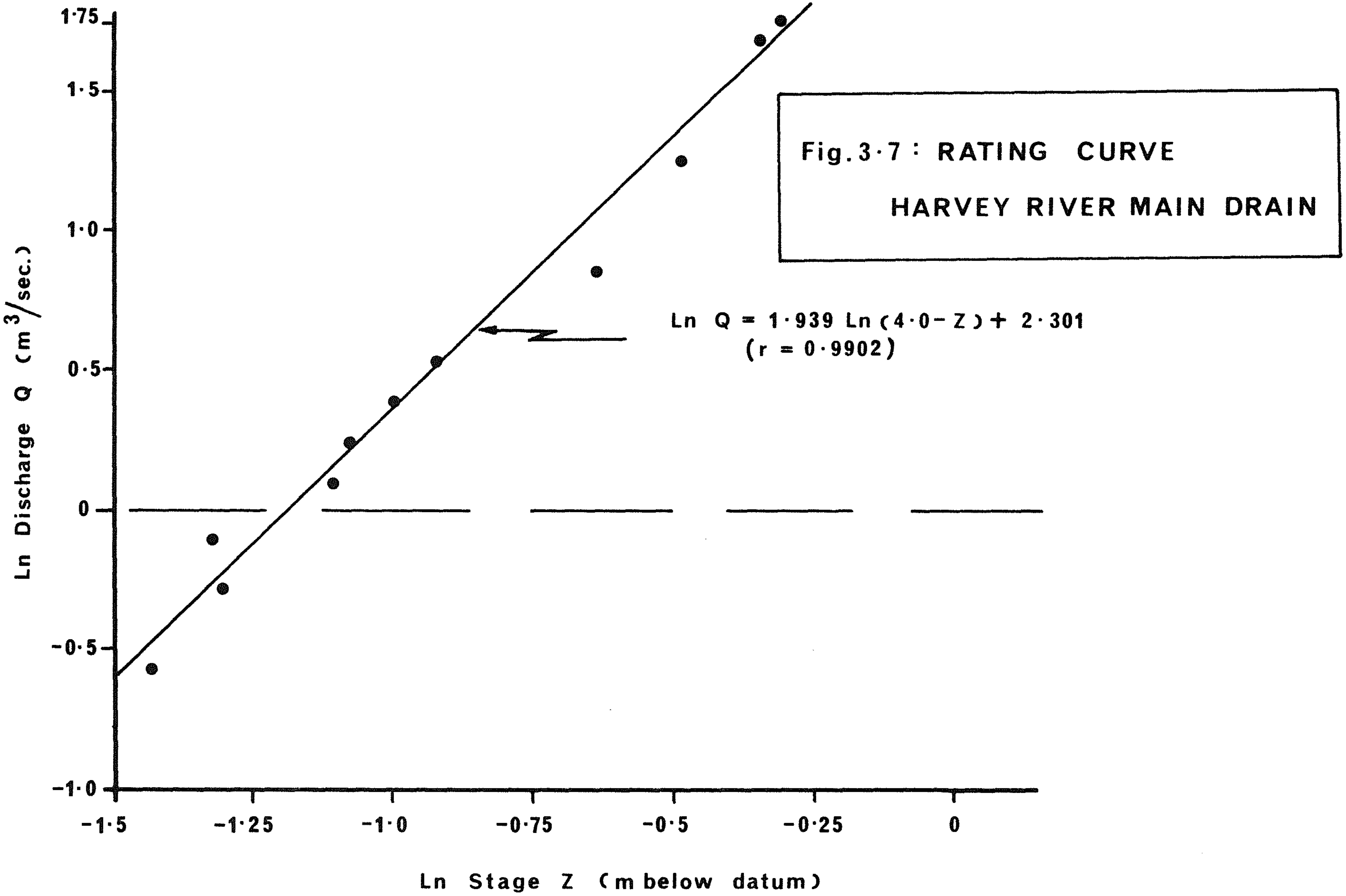


Fig. 3·7: RATING CURVE
HARVEY RIVER MAIN DRAIN

from it to the main river channel, proved to be very difficult indeed. However, the successful establishment of the water level recorder meant that a continuous flow record (of a reliability no less than that of the rating curve) was now available.

(e) The rainfall-runoff relationship for 1978/79 could now be examined and used to verify the accuracy of the previously estimated 1977/78 flows. This is discussed in some detail in 3.4.4.

(ii) Gauging other drains

From July, 1976, until the end of the summer of 1978/79 (April, 1979) spot gauging using current meter and wading rod were made of flows in the drains listed in 3.4.1. In the case of those with larger flows and more stable controls (Coolup, South Coolup, Mealup, Mayfields) an attempt to relate flow to stage was also made so that weekly estimates would be possible.
It proved physically impossible to gauge all drains in one day as well as carrying out weekly maintenance on the Robert Bay Climatological Station.
However it seemed reasonable to assume that drain flow would be strongly correlated with Harvey River Main Drain discharge and thus it was decided in November, 1978, to discontinue gauging of minor drains. From that time on, flow estimates were made solely from Harvey flows determined from continuous stage measurements. The relationship between Harvey River stage and the stage of drains 002 to 008 inclusive (except 005) is shown in TABLE 3.6.

Though the relationship appears somewhat less than satisfactory, especially for the Mealup Drain/Harvey River correlation, it must be remembered that the magnitude of Harvey flows is very much greater than that of drain flows.

	FAUNTLEROY 002	CARIS 003	COOLUP 004	MEALUP 006	STH.COOLUP 007	MAYFIELDS 008	HARVEY 009
FAUNTLEROY 002	1.0000	0.9670	0.8728	0.6900	0.8491	0.7950	0.8940
CARIS 003	0.9670	1.0000	0.9065	0.7282	0.8509	0.8676	0.9259
COOLUP 004	0.8728	0.9065	1.0000	0.8830	0.9692	0.9396	0.9547
MEALUP 006	0.6900	0.7282	0.8830	1.0000	0.8630	0.7944	0.7385
STH.COOLUP 007	0.8491	0.8509	0.9692	0.8630	1.0000	0.8865	0.9173
MAYFIELDS 008	0.7950	0.8676	0.9396	0.7944	0.8865	1.0000	0.9320
HARVEY 009	0.8940	0.9259	0.9547	0.7385	0.9173	0.9320	1.0000

TABLE 3.6 : Pinjarra - Waroona - Harvey Drainage Basin
Correlation coefficients from natural logarithm (ln) of drain stage (arbitrary datum)

Indeed we can state a general rule that:-

	Harvey River	:	Mayfields Drain	:	All other drains
as	100	:	15	:	10

(iii) Hydrographs

For all these reasons and the fact that nutrient concentrations in minor drains vary very little from those in the Harvey River (see Chapter 4), we have decided to consider, for the purposes of rainfall-runoff modelling and nutrient loads, the Harvey River Main Drain and minor drains as a single input. It is realised that this will not enable us to say a great deal about individual point or areal sources of nutrient input to the system via the drains. This question is examined in greater detail in Chapter 4. However, as Fig.3.1 shows, all the aforementioned channels drain the one catchment, namely the Pinjarra-Waroona and Harvey drainage basin, and may reasonably be thought of as a single input to Harvey Estuary for quantitative purposes at least.

Figures 3.8 and 3.9 plot the composite hydrographs of the Harvey River Main Drain and minor drains (called "Harvey Drains") for the water years 1977/78 and 1978/79 respectively. TABLE 3.7 lists the monthly total flows for the same period. The fact that flow continues throughout the drought summer should be noted and the following points made:-

(a) For the months November, December (1977); January, February, March, April, May (1 - 15 inc.)(1978); flows recorded occur in the Harvey River Main Drain only.

(b) For the months November, December (1978); January, February, March, April, May; June (1 - 3)(1979); flows recorded occur in the Harvey River Main Drain only.

(c) i.e., Minor drains cease to flow in late October and measurable discharges do not begin again until late May/early June after significant rains.

(d) The sustained summer flow in the Harvey River Main Drain is probably a result of "drainage" irrigation water supplied from one or more of the irrigation dams, e.g., Harvey Weir. It should not be thought of as a groundwater component of flow from upstream sources.

(iii) Estimating minor drain flows

Stage poles were established in each drain and throughout 1979 (as well as on prior occasions when metering was not practicable) flows were estimated using a rating curve for each drain. Details of these curves are to be found in Appendix II. We have found the relationship between Harvey River stage and drain stage to be as shown in TABLE 3.8 A similar relationship was also developed for Harvey River discharge and drain discharge and this is shown in TABLE 3.8 also.

The correlations between drain stage and Harvey River stage previously referred to are tabulated in TABLE 3.6. As an example only of the calculation, application of the estimating equations to Harvey flows of 10 and 50 m^3/sec respectively leads to the estimate shown in TABLE 3.9.

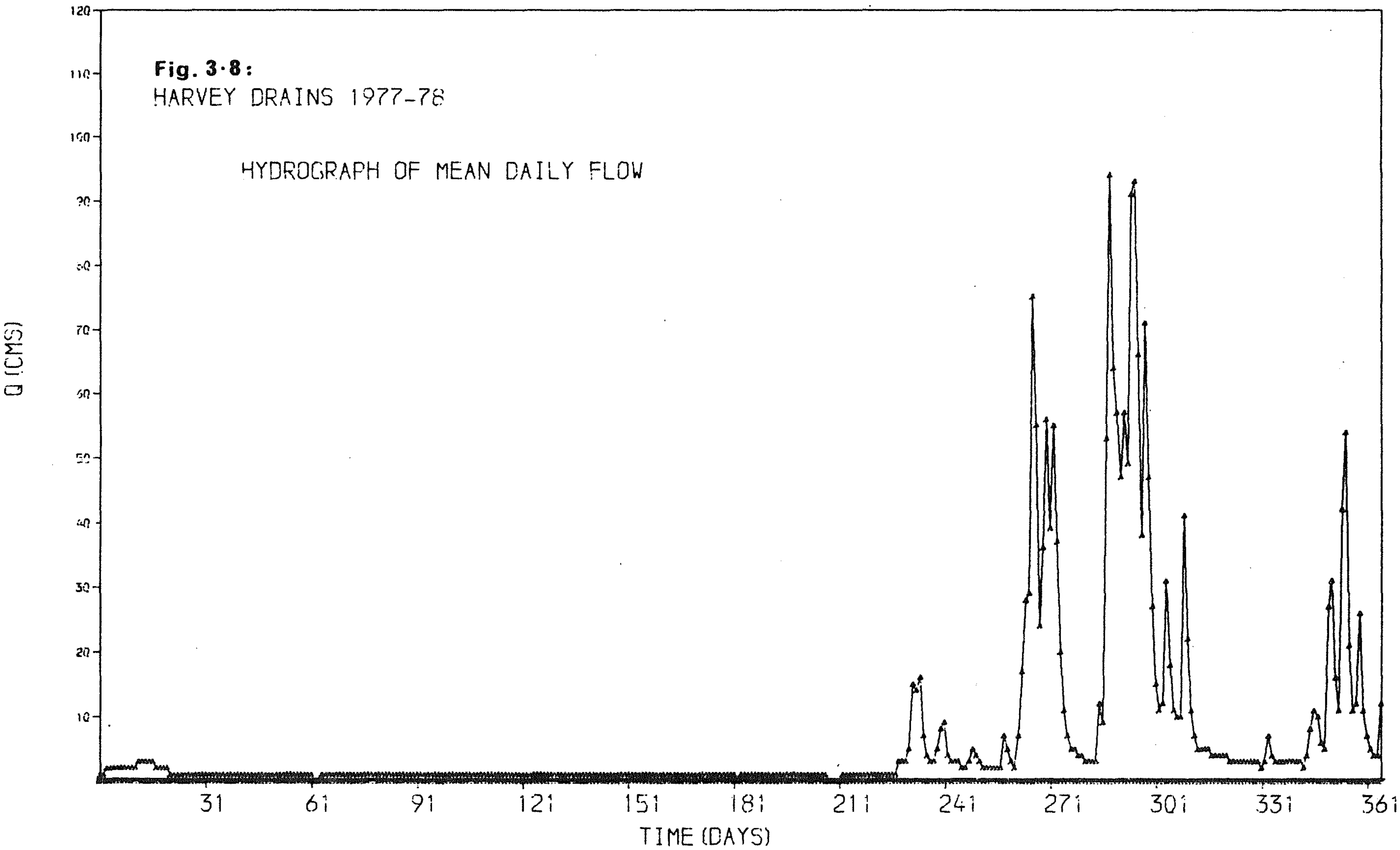


Fig. 3·8:
HARVEY DRAINS 1977-78

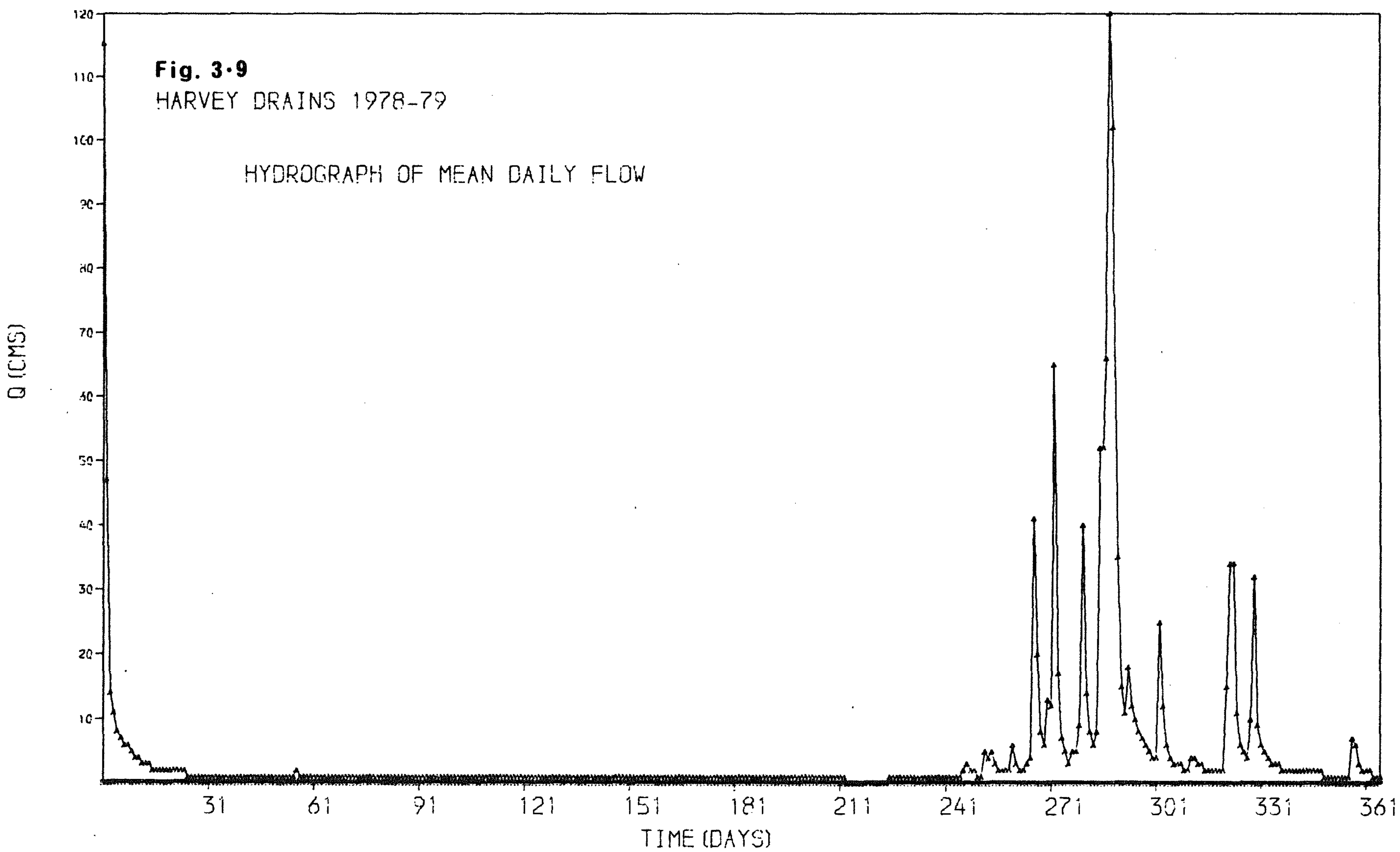


Fig. 3·9
HARVEY DRAINS 1978-79
HYDROGRAPH OF MEAN DAILY FLOW
Q (CMS)
120
110
100
90
80
70
60
50
40
30
20
10
31
61
91
121
151
181
211
241
271
301
331
361
TIME (DAYS)

WATER YEAR	TOTAL DRAIN FLOW TO HARVEY ESTUARY ($m^3 \times 10^6$)												
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1977/78	4.5	1.7	1.8	1.6	1.4	1.8	1.6	10.4	43.9	87.4	18.9	30.9	205.9
1978/79	25.9	3.1	2.1	1.9	1.8	2.9	2.3	2.8	22.2	58.9	20.6	6.0	150.5

TABLE 3.7 : Monthly flows Harvey River Main Drain and minor drains* (1977/78; 1978/79)

* Includes 002 Fauntleroy Drain
003 Caris Drain
004 Coolup Drain
006 Mealup Drain
007 South Coolup Drain
008 Mayfields Drain

DRAIN	STAGE EQUATION *	DISCHARGE EQUATION **
Fauntleroy 002	$H_2 = e^{-2.05} H_H^{1.066}$	$Q_2 = e^{-5.56} Q_H^{1.23}$
Caris 003	$H_3 = e^{-1.60} H_H^{1.220}$	$Q_3 = e^{-4.23} Q_H^{1.17}$
Coolup 004	$H_4 = e^{-1.25} H_H^{1.190}$	$Q_4 = e^{-3.19} Q_H^{0.86}$
Mealup 006	$H_6 = e^{-1.42} H_H^{0.600}$	$Q_5 = e^{-2.258} Q_H^{0.44}$
South Coolup 007	$H_7 = e^{-1.21} H_H^{1.060}$	$Q_6 = e^{-4.27} Q_H^{1.20}$
Mayfields 008	$H_8 = e^{-0.366} H_H^{0.898}$	$Q_7 = e^{-1.80} Q_H^{0.95}$

TABLE 3.8: HARVEY DRAINS - relationship in stage and discharge between Harvey River Main Drain and minor drains.

* H_H = stage below datum of Harvey River (m)

** Q_H = discharge of Harvey River (m^3/sec)

Case No.	Harvey River gauged flow (m^3/sec)	ESTIMATED DRAIN FLOW (m^3/sec)						
		Fauntleroy 002	Caris 003	Coolup 004	Mealup 006	South Coolup 007	Total "others"	Mayfields 008
1	10	0.065	0.215	0.300	0.290	0.220	1.090	1.480
2	50	0.470	1.410	1.200	0.590	1.530	5.200	6.880

Case 1: Harvey : Mayfields : "Others"
100 : 15 : 11

Case 2: Harvey : Mayfields : "Others"
100 : 14 : 10

TABLE 3.9 : HARVEY DRAINS - Estimated minor drain flows from Harvey River Main Drain gauged flow.

3.4.4. Mathematical Modelling

In 3.4.3 we discussed the difficulties in estimating weekly flow volumes on the Harvey River Main Drain from once weekly spot gaugings and/or stage measurement. This problem is exacerbated by the (previously mentioned) unusually short time to peak of Harvey River hydrographs.

Loh (1974) revealed that the south west catchments in Western Australia have extremely long lag times. He found that the lag time L_c (defined as the time between the centroids of rainfall excess and direct runoff) was " .... insignificantly dependent on rainfall excess duration ...." and that " .... all observed time parameters were high in value, indicating the exceptionally sluggish response of streams in the south west". Loh found the relationship between main stream length (km) and L_c to be logarithmic and on the basis of his calculations, the Harvey River Main Drain length of approx. 40 km suggests a lag time of not less than 40 hours is appropriate.

However, Loh's data related to 11 forested or partly cleared catchments which could be expected to produce far more attenuated hydrographs than the Harvey River Main Drain which flows entirely over coastal plain predominantly cleared for pasture. Examination of lag times for Harvey hydrographs is necessarily confined to the 1978/79 water year when continuous flow measurement was possible.

For the six biggest flood events of 1978/79, this yielded the following result:-

Date	Instantaneous Peak (m^3/sec)	Approx.Lag Time (hours)
October 1	121.2	12
June 23	49.5	15
June 29	61.7	17
July 7	40.7	16
July 15	110.7	24
August 18	33.8	15

What these results reveal is that it will not be possible to estimate mean daily flows from once weekly gaugings of such a river with any degree of reliability. Thus, any "testing" of the accuracy of representation of 1977/78 flows, before continuous water level data was available, should be confined to longer periods, say weekly or preferably monthly.

Two distinctly different mathematical modelling approaches were employed, details of which follow.

(i) Deterministic modelling - the Stanford Watershed Model IV

Research at Stanford University into rainfall runoff modelling culminated in the publication of a report on the Stanford Watershed Model IV by Crawford and Linsley (1966). This model, which has been widely used throughout the world is classed as a "general purpose model" - a comprehensive representation of the hydrological cycle which can be used to represent a wide range of catchment regimes. Results of simulation of flows using the model under Australian conditions have been published by Fleming and Black (1974), Black and Clifford (1977) and Weeks and Hebbert (1980). The latter two publications used data from the south-west of Western Australia.

The Stanford model uses hourly rainfall data, mean daily streamflow and average daily potential evaporation for its input data. Keeping in mind that what was required in this case was a model capable of estimating total flow from the Pinjarra - Waroona - Harvey drainage basin into Harvey Estuary, the following procedure was adopted.

1. The 1978/79 water year was used to "calibrate" the model; i.e., to set the parameters defining catchment conditions and hydrograph characteristics to levels such that the model would simulate mean daily flows (from rainfall and evaporation data) that closely matched the actual recorded discharges.

2. Input data sets were:
   Hourly rainfall - Harvey (2) Pluviometer
   Daily evaporation potential - Robert Bay pan evaporation x pan factor
   Mean daily flow - Harvey River Main Drain + Minor Drain flows *

3. Catchment area - 1036 km^2

4. Using the "trial and error" method of optimisation of model parameters (Fleming 1975), those parameters which did not have physical significance; (i.e., are not fixed by nature, such as % forest cover, etc.) were adjusted until a reasonable fit between recorded and simulated flows was achieved. "Perfect" fitting is neither reasonable nor practicable for a variety of reasons. Apart from the fact that all input data is to a greater or lesser degree "noisy" due to measurement errors, assignment of point source data to an area, etc., special problems existed in this case; viz.,

* See 3.4.3 (iii)

a) Rainfall data. The Harvey pluviometer may be taken as reasonably representative of catchment wide rainfall, but clearly for larger storms, the effect of lack of uniformity of rainfall distribution (partial area storm) on such a large catchment may be critical.

b) Flow data. As has been previously discussed, input mean daily flows are not (as they should be) from a single point source, but from the aggregate of all drains.

c) Summer flows. The persistence of flow in the Harvey River Main Drain throughout summer is not attributed to groundwater flow throughout the drought period. Rather it is a result of irrigation drainage water and sluice gate release down the Harvey River old course from the Harvey Weir (up to 5.663 m^3/sec). For this period, there can be no rainfall-runoff relationship, and <u>no flow should be simulated</u> by the model.

Given all these difficulties, however, it was nonetheless possible to achieve reasonable fit between actual and simulated flows as Fig. 3.11 reveals. TABLE 3.10summarises the monthly recorded and simulated volumes for 1978/79.

With the parameters of the Stanford model set as determined by the 1978/79 calibration, the model was run with 1977/78 data. The aim of this"production run" was to test the accuracy of flow estimates made from the aforementioned weekly gaugings. These monthly recorded and simulated volumes are also tabulated in TABLE 3.10 and plotted on Fig. 3.10.
In general, and excluding the summer months for the reasons outlined above, the water balance achieved for 1977/78 is only fair.
On an annual basis, volumes are overestimated

by about 11%. (Remember that if the model is adopted, "recorded" flows estimated from once weekly gaugings are being tested). The key winter months which carry the bulk of the total nutrient load are respectively in "error" by:-

+ 10% (June)
+ 13% (July)
- 68% (August)

Thus there can be little cause for satisfaction in the overall result. There are two obvious possibilities for error; viz.,

1. Poor estimation of flows from weekly gaugings.
2. Poor model calibration.

The latter hypothesis at least can be tested by simply using another modelling approach (see(ii)). From this it will be possible to see if refinement of 1977/78 Harvey Drains flows can be achieved so that, at the very least, the same rainfall/runoff relationshp can be seen to apply in both water years.

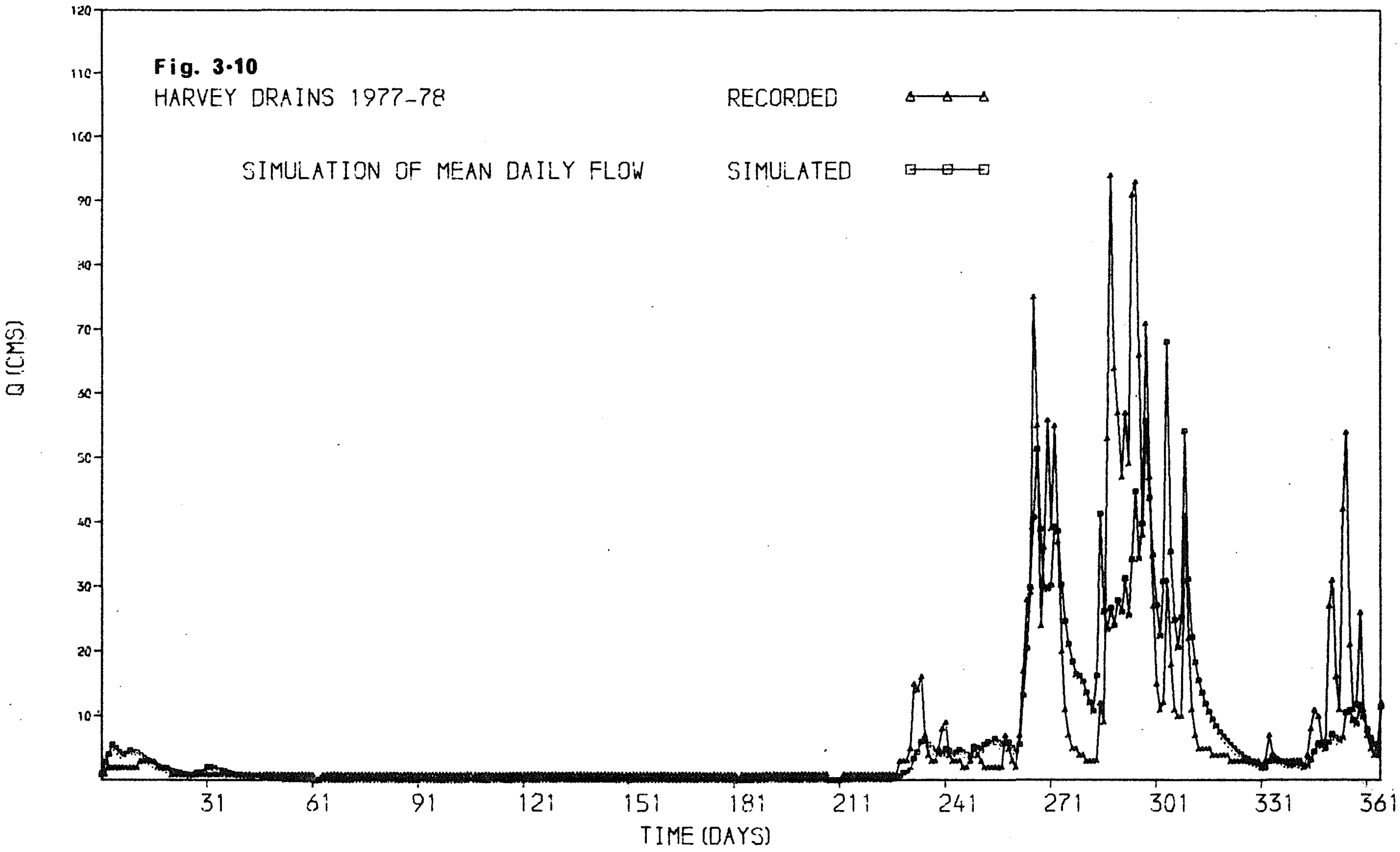


Fig. 3·10
HARVEY DRAINS 1977-78
SIMULATION OF MEAN DAILY FLOW
RECORDED
SIMULATED
Q (CMS)
TIME (DAYS)
120
110
100
90
80
70
60
50
40
30
20
10
31
61
91
121
151
181
211
241
271
301
331
361

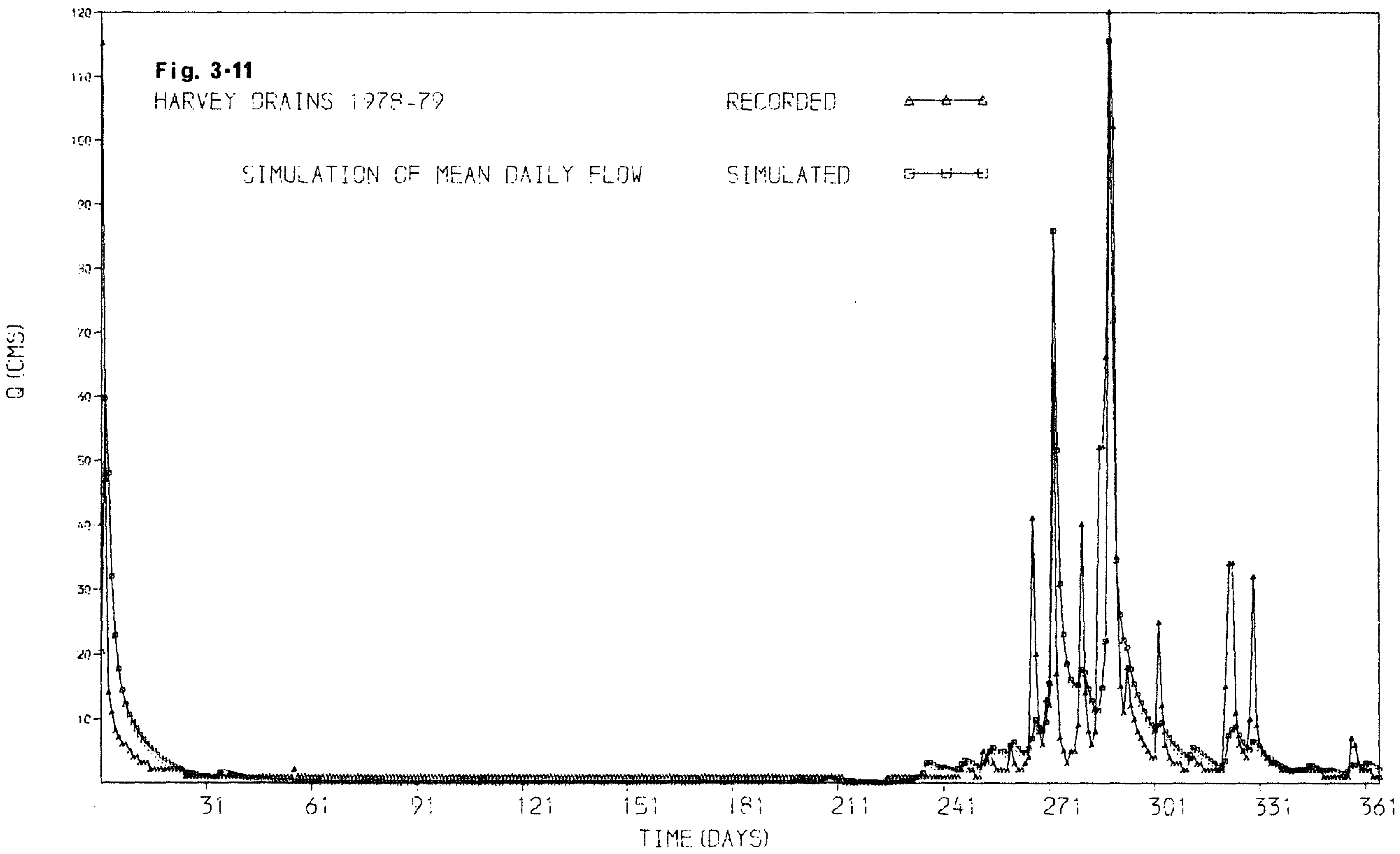


Fig. 3·11
HARVEY DRAINS 1978-79
SIMULATION OF MEAN DAILY FLOW
RECORDED
SIMULATED
Q (CMS)
TIME (DAYS)
120
110
100
90
80
70
60
50
40
30
20
10
31
61
91
121
151
181
211
241
271
301
331
361

YEAR		MONTHLY FLOW VOLUME ($m^3 \times 10^6$)													
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual 1	Annual 2 *
1977	Recorded	4.5	1.7	1.8	1.6	1.4	1.8	1.6	10.4	43.9	87.4	18.9	30.9	206	198
-78	Simulated	6.8	1.6	0.0	0.0	0.0	0.0	0.0	5.4	39.6	76.1	31.8	15.1	177	177
1978	Recorded	25.9	3.1	2.1	1.9	1.8	2.9	2.3	2.8	22.2	58.9	20.6	6.0	150	138
-79	Simulated	27.4	1.6	0.1	0.0	0.0	0.0	0.2	2.3	24.7	56.6	13.8	6.0	133	133

TABLE 3.10: HARVEY DRAINS.
Recorded and Simulated Flows 1977/78 and 1978/79 using Stanford Watershed Model IV

* Annual 2 excludes Recorded summer flows

(ii) Time Series Analysis - the CAPTAIN package

Estimates of the 1977/78 flows were also tested with the CAPTAIN suite of time series analysis programs. This was done during the principal investigator's study in the U.K., using the CAPTAIN package available at the Institute of Hydrology, Wallingford, Oxon. The CAPTAIN package, i.e. "Computer Aided Procedure for Time-Series Analysis and Identification of Noisy Processes" used is described by Venn and Day (1977), who state:-

> "The original CAPTAIN package consisted of a suite of ALGOL programs developed by Professor Peter Young and Dr. Stuart Shellswell at the Department of Control Engineering, University of Cambridge, (Young, Shellswell and Neethling, 1971, Shellswell, 1972) on the basis of core programs which Professor Young had originated at the Naval Weapons Centre, California, and at Cambridge during the period 1964-70. The original package was improved by Dr. Paul Whitehead and Professor Young at Cambridge in the period 1973-74 and was acquired by the Water Resources Board in 1974. " ....". This suite (of programs) has been re-written and extended to form the integrated, interactive package described in this report".

The access to this version of the package, so freely given by the Institute of Hydrology, is gratefully acknowledged, as is the assistance and most helpful advice of Dr. Paul Whitehead.

Venn and Day (1977) describe the problem thus:

"One approach to the modelling of time series data is to attempt to analyse the internal mechanics that govern the operation of a stochastic system. This may be termed the mechanistic approach. An alternative approach, and the one adopted here, is to represent the overall characteristics of a system with a simple input-output or "black-box" model. In this case, the internal descriptions are avoided and the overall input-output relationship is inferred directly from the data........................"

"The types of model that can be examined by the package are stochastic models and transfer functions with superimposed noise, both of which are discussed in depth by Box and Jenkins (1970), ..."

For the Harvey Drains flow data, the following procedure was adopted:-

1. The wet season period 22.6.79 to 5.9.79 (Sequence numbers 0-75 on Fig.3.12) was used to estimate a rainfall-flow model with input data from the Harvey (2) pluviometer and Harvey Drains flow records, estimated from the rating curve of Fig.3.7.
2. The model thus estimated had the following structure:

   No. of autoregressive parameters(AR) = 1
   No. of moving average parameters(MA) = 1
   Time delay = 1
   Estimated parameters: a = -0.526 (0.056)
   b = 1.826 (0.132)
   (values in parenthesis are standard errors)

Thus the model is of the form:-

$$F_k = 0.526\ F_{k-1} + 1.82\ R_{k-1}$$

where F_k is estimated mean daily flow in m^3/sec. on day k.

R_{k-1} is rainfall in mm on day k-1.

3. The observed series and model output is shown on Fig.3.12. Whilst the fit is, for the most part, reasonable, mention must be made of the conspicuous under-estimation on days 23 and 24 (15 and 16 July, 1979). Somewhat less than 75 m^3/sec. mean daily is estimated by the model when extrapolation of the rating curve has suggested that a flow of 120 m^3/sec. is applicable.*

It is clear that we must doubt the rating curve's ability to define such large flows which occur when the bankful stage is reached and it seems that we have overestimated the discharge on such occasions. However only five such events occurred in the 1977/78 water year and two in the 1978/79 year, so that without gaugings at such high flows (which is obviously very difficult) we are not able to improve our estimates of flow from stage with existing data.

One should, however, be conscious of the probable over-estimation of flows on the following dates:-

Fig.No.	Sequence No.	Date
3.12	23	15.7.79
3.12	24	16.7.79
3.13	38	23.6.78
3.13	60	15.7.78
3.13	66	21.7.78
3.13	67	22.7.78
3.13	138	1.10.78

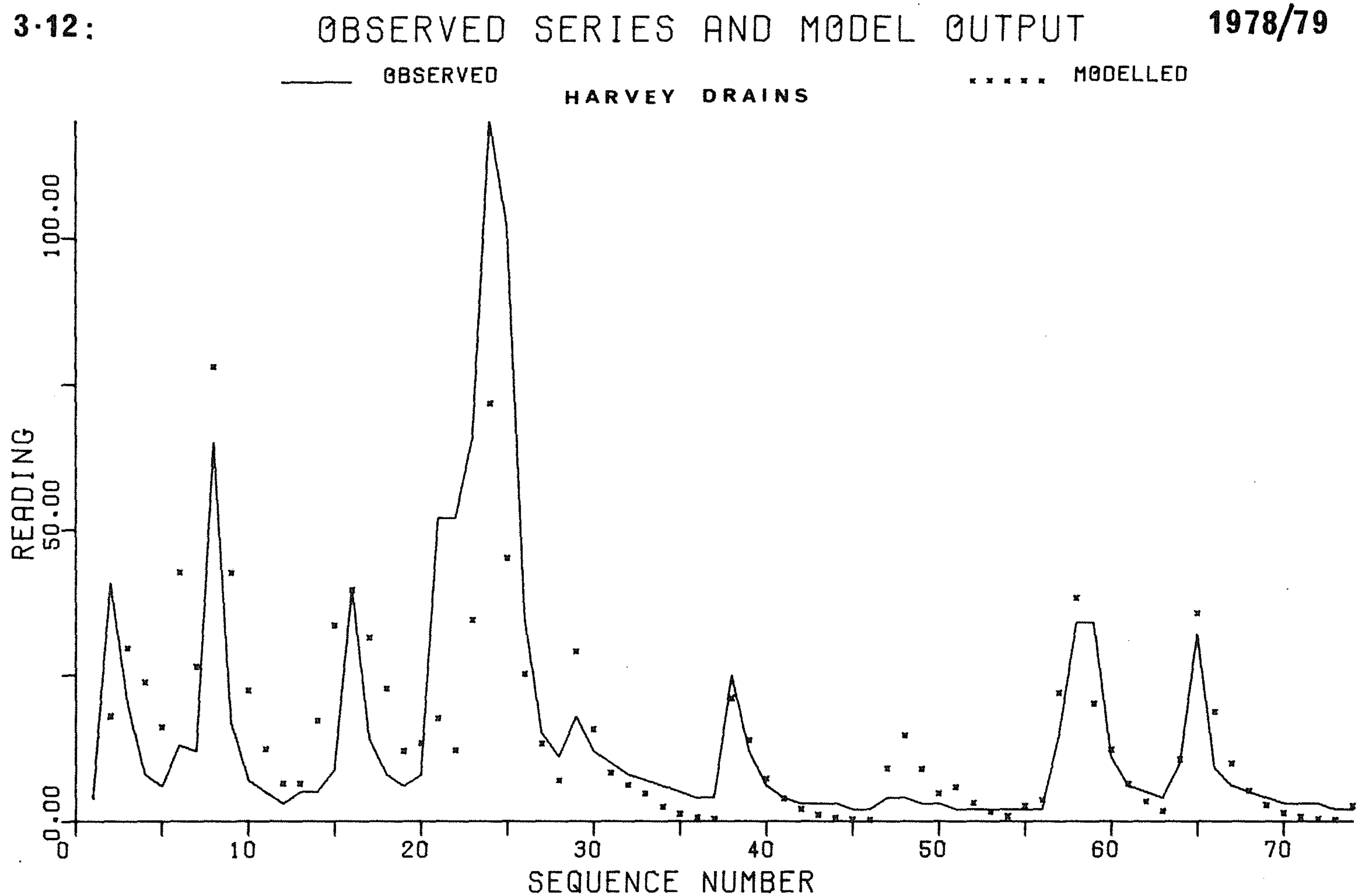
* Note however, that the soil moisture computation available on the A.N.U. version of the CAPTAIN package would doubtless improve the fit in the earlier months (Whitehead et al (1978)).

4. The model thus developed was then used with Harvey (2) rainfall data to forecast flows for the wet season period 16.5.78 to 24.10.78 (Sequence numbers 0 - 162 on Fig.3.13). In general, the model verifies that flow estimates made, as previously described, from weekly gaugings and/or stage measurement are reasonable. The notable exceptions are of course contained within the period 15.7.78 to 25.7.78 (Day numbers 60 - 70 on Fig.3.13). The same poor estimation is apparent from the SWM IV simulation shown on Fig.3.10 (Day numbers 288 - 298 on Fig.3.10)

5. TABLE 3.11 compares the monthly flow volume forecasts made with the two different modelling approaches and further highlights the problem in July, 1978, when the really significant period of bankful flow occurred.

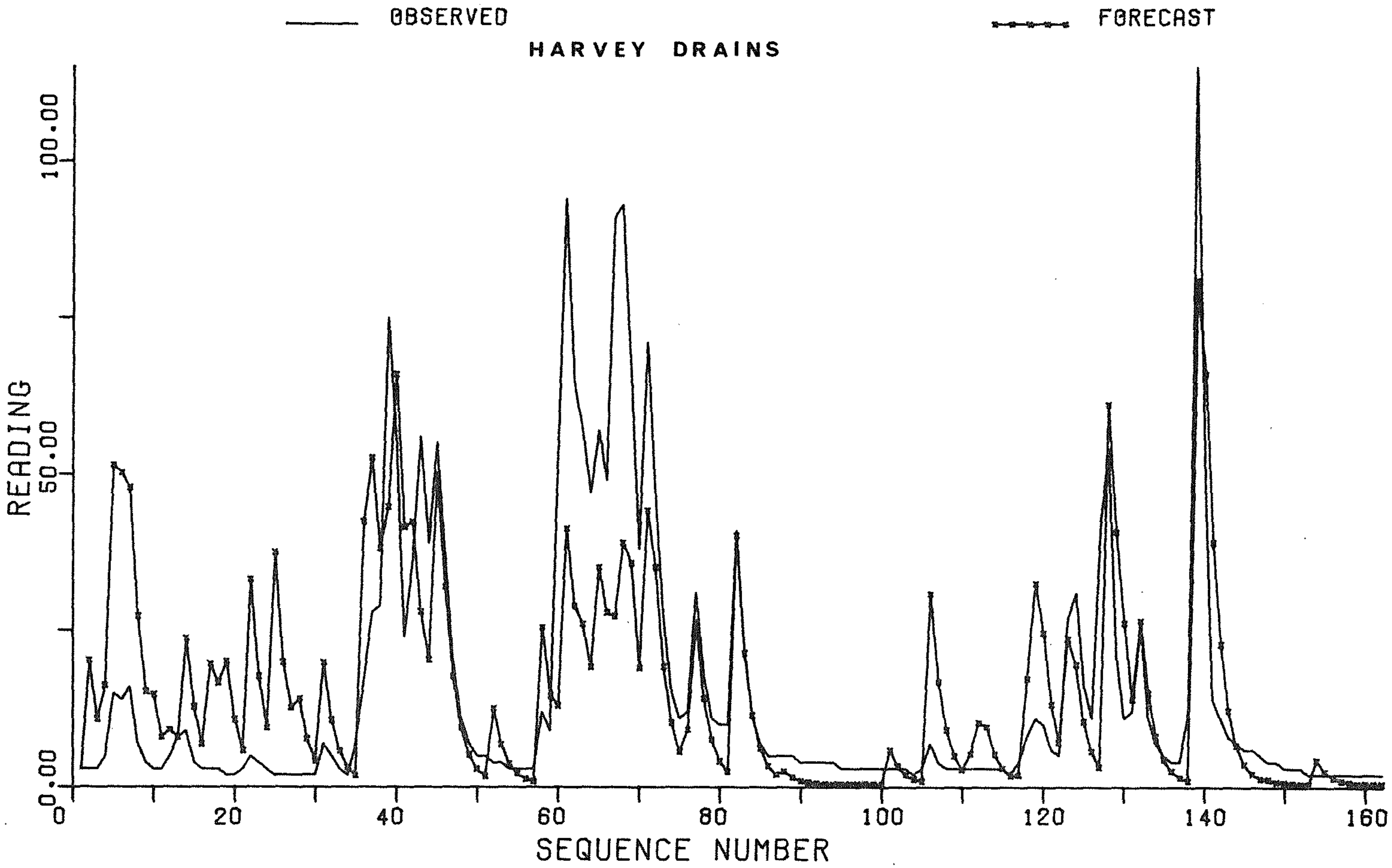
Finally it should be stated again that both mathematical models suggest that our estimates of very large flows are almost certainly too large, but that (with the exception of July, 1978) most monthly volumes estimated are probably fairly accurate. In view of the very peaky nature of Harvey River hydrographs which reveal that over bankful flow is of relatively short duration, this problem of over-estimation is not too serious.

Fig. 3·12:



Day 630 – 705 (22.6.79 to 5.9.79)

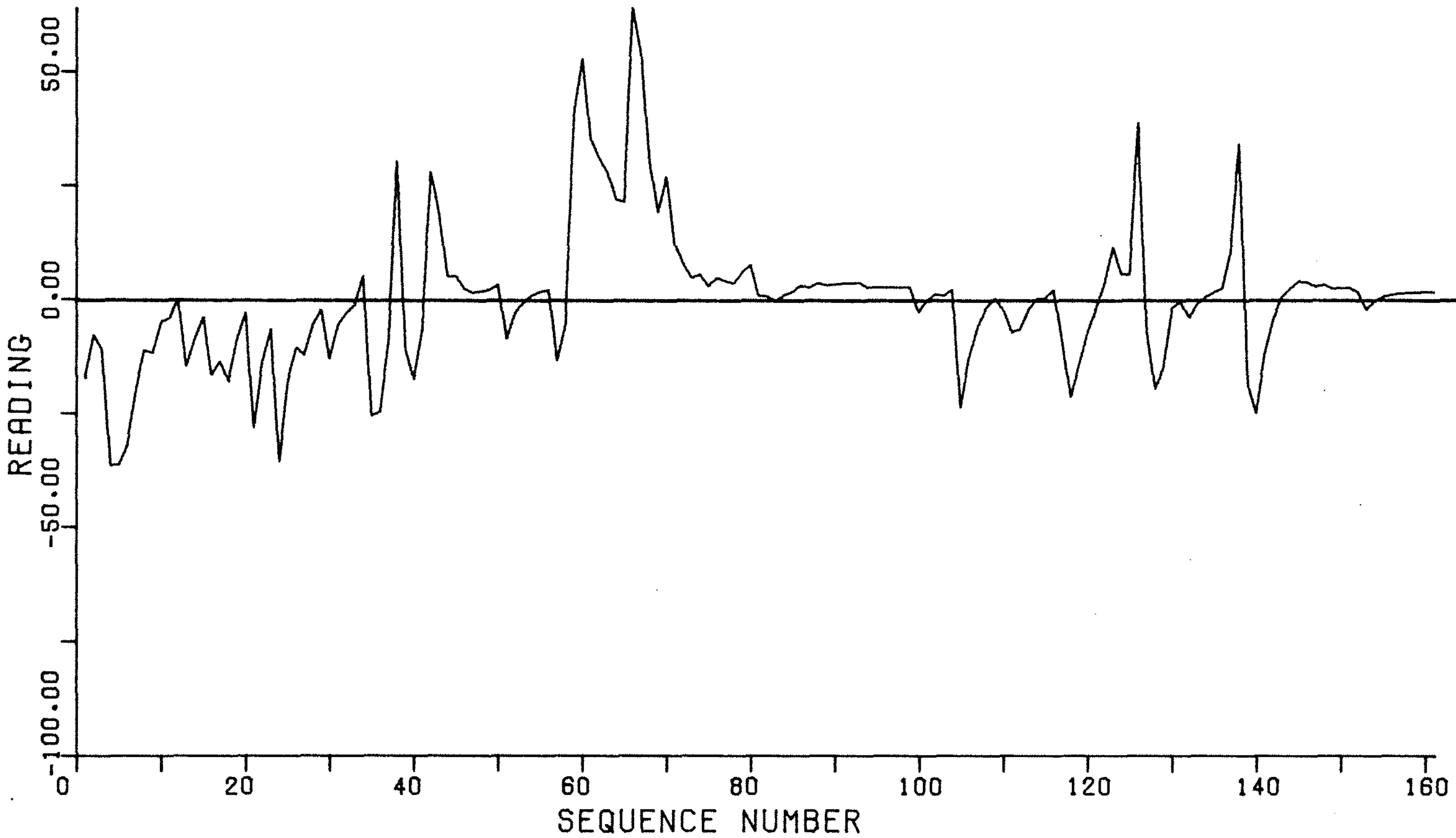
Fig. 3·13: FORECAST OF SERIES F **1977/78**



Day 228 - 389 (16.5.78 to 24.10.78)

Fig. 3·14: PLOT OF N1 **1977/78**

HARVEY DRAINS



Day 228 - 389 (16.5.78 to 24.10.78)

DATA SOURCE	1978 MONTHLY FLOW VOLUME ($m^3 \times 10^6$)			
	JUNE	JULY	AUGUST	SEPTEMBER
Recorded	43.9	87.4	18.9	30.9
"CAPTAIN" Forecast	57.6	48.5	17.1	36.7
SWM IV Simulation	39.6	76.1	31.8	15.1

TABLE 3.11: HARVEY DRAINS
Comparison of Flow Forecasts using CAPTAIN package and Stanford Watershed Model IV - 1977/78 Wet Season.

3.5 Conclusions

The three major river systems contributing to the Peel Inlet and Harvey Estuary water balance all presented special problems with respect to flow estimation and/or measurement. Only the Murray River was gauged at a point upstream of which most of its Peel Inlet flow occurred, and we are satisfied that the flow routing to Pinjarra plus the addition of (gauged) tributary flow has provided a reliable record for the two water years of the study. As the Murray system is by far the biggest, this is indeed fortunate.

The Harvey River and its associated drains (Harvey Drains) were not gauged prior to this study and special difficulties have been overcome to some extent by mathematical modelling techniques. We cannot, however, be particularly confident of the few (approx.7) major floods which were estimated from the rating curve, but are likely to be over-estimates for at least part of the time. The effect of this problem on both water balance and nutrient load is mitigated however, by the fact that such events are of very short duration.

By far the least reliance must be placed on Serpentine River input estimates, which are based solely on the gauged record from 614 072, a station which records probably only about one-sixth of the total estuarine contribution from this system, the balance coming from a number of ungauged coastal plain drainage systems. Nevertheless, as a result of the work reported by Collins and Rosair (1978) we are able to approximate the total flow of the Serpentine system. This will also be greatly improved when records from the new station 614 030 become available.

4. RIVER & DRAIN QUALITATIVE HYDROLOGY NUTRIENT LOADINGS

4.1 Introduction

At various times prior to the commencement of the Peel Inlet and Harvey Estuary study proper sampling and analysis of input rivers had been carried out, notably by the CSIRO (1951-56), PWD (1974-present) and Government Chemical Laboratories (1972-78). The purposes of these analytical programmes varied, as did the locations of sampling points. The list below summarises the position prior to October, 1977, when the Peel study data collection programme commenced in earnest.

Authority	Sampling Interval	Location of Sample Points on Input Rivers	
CSIRO	3 monthly	Murray River mouth	
		Murray River Ravenswood	
		Murray River Pinjarra	
PWD	monthly	Harvey River Doman's Bridge	
		Mayfield Drain	Old
		South Coolup Drain	Bunbury
		Coolup Drain	Road
GCL	3 monthly	Murray River Ravenswood	
		Murray River Pinjarra	
		Murray River Yunderup	
		Harvey River Doman's Bridge	
		Serpentine River Barragup Bridge	

Schulz (1979) summarises the data collection programme of the GCL and CSIRO.

However, from the standpoint of computing short-term nutrient inputs to the Peel Inlet and Harvey Estuary from the 3 major river systems, it will be seen that there is considerable difficulty in using this data for the following reasons:-

(i) Flow variability. We have seen in Chapter 3 that all 3 systems are subject to unusually large fluctuations in flow so that there is no such thing as an "average" monthly flow that can be simply multiplied by a nutrient concentration in order to compute a nutrient input.
For example, the Murray River in June, 1978, recorded gauged flows at Baden Powell Water Spout (614 006) that ranged from daily totals of 116.1 to 1962.0 $m^3 \times 10^3$ about a mean of 405.3 $m^3 \times 10^3$. Clearly, to use this latter figure to represent average flow conditions for the month could be very misleading indeed.

(ii) Nutrient concentration variability. Even greater variations in nutrient concentrations are recorded, especially during the critical winter period. As will be seen in 4.3, concentration is quite well correlated with flow, but gross errors occur if one simply multiplies monthly flow volumes by "average" concentration to compute input loads. The problem is best illustrated by reference to the data below from the Murray River for the month of June, 1978.

MURRAY RIVER AT RAVENSWOOD BRIDGE - JUNE,1978.

Discharge* ($m^3 \times 10^3$)	N_T (µg/l)	P_T (µg/l)	N_T Load (kg)	P_T Load (kg)	Date (June)
176	659	-	116	-	2
158	748	40	118	6.3	9
157	987	47	155	7.4	16
488	1741	207	850	101	23
1903	2352	155	4476	295	30

* Flow includes 15% "gain" + N.& S. Dandalup Rivers.

Thus we have adopted the policy that a sample must be associated with a simultaneous gauging of flow if it is to have meaning insofar as inputs to the estuary system is concerned. Clearly, from the data above, it would be desirable to sample as often as it is possible to express flows; i.e., as a daily mean (m^3/sec) or daily total ($m^3 \times 10^3$). As samples were to be analysed for the following constituents:-

Nitrogen	Phosphorous
Ammonia	Orthophosphate
Nitrate-Nitrite	Organic
Organic	Total (P_T)
Total (N_T)	

The volume of samples required (100 ml for each constituent) would be quite prohibitive for daily collection, and manpower requirements difficult, to say the least.
For this reason, a weekly collection programme was selected as a compromise since samples could in any case be collected during normal gaugings of rivers and drains.

Analysis of the samples was carried out by the Department of Botany, University of Western Australia (Mr. R. Atkins under the supervision of Assoc. Prof. A. J. McComb) and their report covers the implications for weed growth and management of the relative contributions of the various constituents previously mentioned. <u>For the purposes of this chapter</u>, i.e., to estimate (i) the relative nutrient loads of the various waterways; (ii) the seasonal variations in load; (iii) the correlation between load and discharge; and (iv) the impact of the "first flush" of winter rains, it will suffice to consider merely the total Nitrogen load and concentration (N_T) and the total Phosphorous load and concentration (P_T).

4.2 Routine (Weekly) Sampling

4.2.1 Murray River (Ravenswood Bridge)

Sampling of the Murray River at Ravenswood Bridge began in October, 1977, and continued without interruption until late 1978. At this time it was decided that there was little point in sampling throughout the drought summer period as little or no flow into Peel Inlet existed. Sampling then re-commenced when flow over the Pinjarra Weir was observed at a weekly inspection.
Groups of six samples were taken for analysis for the 5 constituents (see 4.1) with one spare and were field frozen in a portable car-freezer. They remained in that state until thawed for analysis at the Department of Botany.

TABLE 3.2 (Section 3.2.3) shows that some flow is recorded into Peel Inlet in the summer months. However, only 3.6% of the 1977/78 Murray River system flow occurred in the months November, 1977, to May, 1978, inclusive and 7% of the 1978/79 flow in the months November, 1978, to May, 1979. Furthermore, average nutrient concentrations were much lower in the low flow months also; viz.,

Summer N_T < 1000 μg/l c.f. Winter N_T up to 7000 μg/l
Summer P_T < 100 μg/l c.f. Winter P_T up to 300 μg/l

This results in a nutrient load for the summer months that is probably <3% of the total annual load.

TABLE 4.1 lists the monthly flow, N_T and P_T concentrations and load from the water years 1977/78, 1978/79, with the low flow months of 1978/79 omitted. It is a table that should be read with some caution. For example, it is not possible to simply multiply monthly nutrient concentration by total monthly flow in June, July,

Year	Month	Discharge ($m^3 \times 10^6$)	Average Nutrient Conc. (μg/l)		Estimated Nutrient Load (tonnes)		
			Nitrogen N_T	Phosphorous P_T	N_T	P_T	
1977/78	Oct.	10.9	388	20	4.23	0.218	
	Nov.	6.8	318	20	2.16	0.136	
	Dec.	1.1	444	24	0.488	0.026	
	Jan.	0.2	729	58	0.146	0.012	
	Feb.	0.2	922	78	0.184	0.016	
	Mar.	0.2	934	91	0.187	0.018	
	Apr.	0.2	910	288	0.182	0.058	
	May	1.8	752	280	1.35	0.069	*
	June	15.3	1297	112	26.20	1.96	*
	July	187.5	4488	72	846.10	18.36	*
	Aug.	44.3	3648	37	244.60	2.74	*
	Sept.	20.7	1313	74	27.18	1.53	*
Total	1977/78	289.2			1153.01	25.14	
1978/79	Oct.	23.1	1199	63	27.70	1.46	
	Nov.	2.6	619	25	1.61	0.065	
	Dec.	1.2	not sampled	not sampled	-	-	
	Jan.	0.5			-	-	
	Feb.	0.2	"	"	-	-	
	Mar.	0.2	"	"	-	-	
	Apr.	0.2	"	"	-	-	
	May	1.0	"	"	-	-	
	June	4.4	1579	120	6.95	0.528	
	July	20.7	1656	58	33.82	1.07	*
	Aug.	16.2	1289	33	22.79	0.440	*
	Sept.	15.2*	1142	20	17.36	0.304	*
Total	1978/79	85.5			110.23	3.87	

TABLE 4.1 : MURRAY RIVER (at Ravenswood) - Nutrient Loadings 1977/78; 1978/79

* summed from weekly totals

Year	Week ending Friday	Discharge (m^3 x 10^3)	Nutrient Conc. (μg/1)		Nutrient Load (tonnes)	
			N_T	P_T	N_T	P_T
1978	23/6	1,601	1741	207	2.79	0.331
	30/6	9,837	2352	155	23.14	1.52
	7/7	10,676	4220	36	45.05	0.384
	14/7	5,075	4266	37	21.65	0.188
	21/7	58,378	3851	83	224.81	4.85
	28/7	98,764	5615	131	554.56	12.94
	4/8	25,544	7274	41	185.81	1.05
	11/8	16,813	≃ 1500	≃ 65	25.22	1.09
	18/8	7,985	2428	44	19.39	0.351
	25/8	5,062	1243	25	6.29	0.126
Total	1978	239,735			1109	22.8
Percentage of water year total					96%	91%
1979	29/6	1,556	2405	201	3.74	0.313
	6/7	1,878	1292	49	2.43	0.092
	13/7	2,910	≃ 2000	105	5.82	0.305
	20/7	9,594	1385	56	13.29	0.537
	27/7	4,706	2290	21	10.78	0.098
	3/8	3,248	918	24	2.98	0.078
	10/8	2,376	1288	18	3.06	0.043
	17/8	2,036	1954	89	3.98	0.181
	24/8	5,325	1583	18	8.43	0.096
	31/8	5,163	1128	16	5.82	0.083
Total	1979	38,792			60.3	1.8
Percentage of water year total					55%	47%

TABLE 4.2 : MURRAY RIVER - Nutrient Loads from Winter Flushing 1977/78; 1978/79

August and September to calculate monthly loads. This is due to the extreme variability in both daily flow and weekly nutrient concentrations referred to in 4.1. However, it may serve as a reasonably useful summary. For reasons of economy of space, a full weekly nutrient load table for input rivers is included in Appendix III.

However, the key winter months when the "first flush" of nutrients from the catchment is recorded are especially noteworthy and these (23/6 to 25/8, 1978 and 29/6 to 31/8, 1979) are tabulated in TABLE 4.2.

The very low flow of the Murray River in 1978/79 has resulted in a greatly reduced impact of the "first flush" in the winter of 1979. In 1977/78, 83% of the annual flow occurred in the 10 weeks 23/6 to 25/8; c.f. 45% in the 10 weeks 29/6 to 31/8, 1979. The huge N_T peak that results from this flush which lifts the N/P ratio from ≈ 5 in the summer to >150, so evident in 1978, is much reduced in 1979 (c.100). P_T fluctuates very much less than does N_T in the Murray system. Indeed, Schulz (1979) quotes a dry season mean of 56 µg/l and a wet season mean of 59 µg/l for the Murray River at Ravenswood. It is the massive Nitrogen "pulse" in the first weeks of flow that is the striking feature of the Murray, contributing over 95% of its total annual input to the system in that short time period.

4.2.2 Serpentine River (Barragup Bridge)

Sampling of the Serpentine River at Barragup Bridge followed the same routine as that for the Murray River described in 4.2.1. Here it is necessary to reiterate the quality of flow estimates for this river. In TABLE 3.5 (3.3.4) we defined the Peel Inlet input from the Serpentine River (plus drainage system) to be

6 x Flow at 614 072. This crude estimate will have to be used in making nutrient load estimates and the results should thus be used with caution.

TABLE 4.3 lists the monthly flow, N_T and P_T concentrations and load for the water years 1977/78, 1978/79, with the low flow months of 1979 omitted. Note however that the extreme variability of the Murray system is not a feature of the Serpentine which is of course dammed above 614 072. Thus the impact of compensation flows and abstractions is to smooth out the seasonal fluctuations to some extent.

Total Phosphorous concentrations are in general 4 to 8 times higher than those of the Murray River. Nitrogen concentrations, whilst generally similar, lack the impact of the "first flush" phenomenon of the undammed Murray.

At the time of the February, 1979, seminar (Hodgkin, 1979), the authors considerably over-estimated the contribution of the Serpentine River. This was due to the fact that, in the absence of other estimators, the Serpentine flow was determined as a fixed percentage of the Murray River flow. Subsequently, data provided by Collins (1978) has enabled us to make hopefully improved estimates based on gaugings at 614 072. In the event of data from the new (April, 1979) gauge 614 030 on Peel Drain becoming available, further refinement may be possible.

The key winter months during which the river contributes the great bulk of the nutrient load are separately listed on a weekly load basis in TABLE 4.4. As with the Murray system it can be seen that P_T <u>concentrations</u>, though generally higher in times of high flow, are not strongly correlated with discharge and neither are N_T <u>concentrations</u>. Furthermore, the impact of the "first flush" on Nitrogen loads is greatly reduced as evidenced by an N/P ratio which varies

Year	Month	Discharge ($m^3 \times 10^6$)	Average Nutrient Conc. (µg/l) Nitrogen N_T	Phosphorous P_T	Estimated Nutrient Load (tonnes) N_T	P_T
1977/78	Oct.	5.2	860	178	4.47	0.926
	Nov.	1.2	756	278	0.907	0.334
	Dec.	0.7	894	232	0.626	0.162
	Jan.	1.0	1108	187	1.11	0.187
	Feb.	1.2	1237	234	1.48	0.281
	Mar.	1.4	1466	256	2.05	0.358
	Apr.	1.1	814	202	0.895	0.222
	May	2.0	1098	298	2.196	0.596
	June	7.7	1796	179	13.83	1.38
	July	26.6	2195	460	58.39	12.24
	Aug.	7.3	2155	455	15.73	3.32
	Sept.	9.5	1549	272	14.72	2.58
Total	1977/78	64.9			116.40	22.59
1978/79	Oct.	12.5	1809	252	22.61	3.15
	Nov.	1.9	1228	181	2.33	0.344
	Dec.	0.9	not sampled	not sampled	-	-
	Jan.	1.0			-	-
	Feb.	0.8	"	"	-	-
	Mar.	0.9	"	"	-	-
	Apr.	0.9	"	"	-	-
	May	1.4	"	"	-	-
	June	4.4	2083	97	9.16	0.427
	July	9.5	2878	373	27.34	3.54
	Aug.	11.6	2398	242	27.82	2.81
	Sept.	9.0	2122	154	19.10	1.39
Total	1978/79	54.8			108.36	11.66

TABLE 4.3 : SERPENTINE RIVER (at Barragup) - Nutrient Loadings 1977/78; 1978/79

Year	Week ending Friday	Discharge ($m^3 \times 10^3$)	Nutrient Conc. ($\mu g/L$)		Nutrient Load (tonnes)	
			N_T	P_T	N_T	P_T
	23/6	1,632	1128	100	1.84	0.163
	30/6	4,980	3601	445	17.93	2.22
	7/7	1,782	2717	550	4.84	0.98
	14/7	1,818	2169	232	3.94	0.42
1978	21/7	15,580	1915	459	29.84	7.15
	28/7	6,030	1977	597	11.92	3.60
	4/8	2,886	2339	545	6.75	1.57
	11/8	1,980	≈3200	≈530	6.34	1.05
	18/8	1,398	2393	543	3.34	0.760
	25/8	1,170	1733	276	2.03	0.323
Total	1978	39,256			88.77	18.23
Percentage of water year total					76%	81%
	29/6	1,765	2083	97	3.68	0.171
	6/7	1,181	2833	215	3.35	0.253
	13/7	1,620	2378	539	3.85	0.873
	20/7	4,203	3022	454	12.70	1.91
1979	27/7	1,596	2780	449	4.44	0.717
	3/8	1,692	2962	281	5.01	0.475
	10/8	1,020	2220	206	2.26	0.210
	17/8	1,260	1646	91	2.07	0.115
	24/8	6,252	2634	389	16.47	2.43
	31/8	2,538	2529	241	6.42	0.611
Total	1979	23,127			60.25	7.76
Percentage of water year total					56%	67%

TABLE 4.4 : SERPENTINE RIVER - Nutrient Loads from Winter Flushing 1977/78; 1978/79

about an annual mean of 5.1 (σ = 1.8); this ratio rises to only 6.2(σ = 2.6) in the 10 key weeks of winter flow.

4.2.3 Harvey River Main Drain and Minor Drains

(i) Relative contribution of minor drains

When, at the end of 1978, it was realised that the relative flow contribution of minor drains with respect to the Harvey River Main Drain was

	HARVEY	:	MAYFIELDS	:	"OTHERS"
as	100	:	15	:	10

(see 3.4.3(ii))

it was decided to estimate minor drain flows from Harvey River gaugings thereafter. Similarly, an analysis of nutrient concentrations of minor drains showed that whilst in general, they were marginally above Harvey River concentrations, in view of the greater flow and hence greater load of the latter, they too could be estimated from Harvey analyses in 1979.

Since we do not have continuous flow records for drains, but merely weekly spot gaugings (and/or stage measurements) throughout 1978, total nutrient loads will have to be determined from Harvey River records, though it might be possible to make allowance for higher concentrations prevailing in certain minor drains.

As an example, nutrient concentrations and loads for 21st July, 1978, are shown in TABLE 4.5 together with the relevant statistics. This particular day was chosen as having one of the highest flows recorded in 1978.

Drain		Nutrient Conc. (μg/1)		Nutrient Load (gm/sec)	
		N_T	P_T	N_T	P_T
Fauntleroy	002	1810	422	2.98	0.70
Caris	003	1610	357	7.54	1.67
Coolup	004	1705	557	4.32	1.41
Mealup	006	2447	921	2.83	1.06
South Coolup	007	1758	566	6.99	2.25
Mayfields	008	1315	438	25.44	8.47
Harvey	009	1591	394	129.79	32.14
Total	Σ	-	-	179.89	47.70

Statistics (i) N/P Ratios

Drain No.	002	003	004	006	007	008	009
N/P	4.3	4.5	3.1	2.7	3.1	2.9	4.1

(ii) Load Ratios

	Harvey	:	Mayfields	:	Others
N_T -	100	:	20	:	19
P_T -	100	:	29	:	22

(iii) Nutrient Concentrations (μg/1)

	Harvey	Mean (all)	Standard Deviation (all)
N_T -	1591	1738	354
P_T -	394	522	193

TABLE 4.5 : HARVEY DRAINS - Nutrient Data 21.07.78

This suggests that the estimate of Harvey Drains total loads based as it is upon <u>total drain flow</u> and Harvey River Main Drain nutrient concentrations, <u>might very well be slightly underestimated</u>. However, day by day examination of the nutrient statistics show that they vary considerably, and that concentrations in the Harvey are by no means always less than those in other drains. We are thus led to conclude that in general, loads obtained as previously described constitute the best available estimates.

However it is worth noting that certain characteristically high concentrations exist in one or two drains. Whilst <u>volumetrically</u> they are insufficient to greatly alter load estimates, they nonetheless seem worthy of further investigation. Of special interest are:

1. <u>South Coolup Drain</u>. This drain records uniformly high Phosphorous concentrations (and very high N_T concentrations at times as well).
   The mean of 30 samples (from 10.9.76 to 17.11.78) is 580 μg/l P_T (σ = 167 μg/l)
2. <u>Mealup Drain</u>. The gauging and sampling site for this drain is situated within a dairy farm, so it is not surprising to record very high N_T concentrations; viz., Mean (22 samples from 24.9.76 to 20.10.78) = 2169 μg/l N_T (σ = 899 μg/l).

(ii) TABLE 4.6 lists the annual loadings of N_T and P_T on a monthly basis for the 1977/78 and 1978/79 water years. These are derived as previously described from "Harvey Drains" flows and Harvey River Main Drain concentrations.

(iii) TABLE 4.7 lists the contributions to total nutrient load that occurred in the key first few weeks of winter rains (23.6.78 to 25.8.78 and 29.6.79 to 31.8.79). For both N_T and P_T some

Year	Month	Discharge ($m^3 \times 10^6$)	Average * Nutrient Conc. (µg/L)		Estimated Nutrient Load (tonnes)	
			Nitrogen N_T	Phosphorous P_T	N_T	P_T
1977/78	Oct.	4.5	538	121	2.42	0.544
	Nov.	1.7	499	122	0.848	0.207
	Dec.	1.8	1057	225	1.90	0.405
	Jan.	1.6	850	248	1.36	0.397
	Feb.	1.4	742	212	1.04	0.297
	Mar.	1.8	1554	187	2.80	0.337
	Apr.	1.6	992	92	1.59	0.147
	May	10.4	766	153	7.97	1.59
	June	43.9	1756	361	77.09	15.85
	July	87.4	1716	432	149.98	37.76
	Aug.	18.9	1420	260	26.84	4.91
	Sept.	30.9	1397	355	43.17	10.97
Total	1977/78	205.9			317.01	73.41
1978/79	Oct.	25.9	928	187	24.04	4.84
	Nov.	3.1	1196	215	3.71	0.666
	Dec.	2.1	1116	235	2.34	0.494
	Jan.	1.9	1979	256	3.76	0.486
	Feb.	1.8	971	222	1.75	0.400
	Mar.	2.9	1350	186	3.91	0.539
	Apr.	2.3	1028	144	2.36	0.331
	May	2.8	981	106	2.75	0.297
	June	22.2	2062	383	45.78	8.50
	July	58.9	2468	407	145.36	23.97
	Aug.	20.6	2222	418	45.77	8.61
	Sept.	6.0	1772	281	10.63	1.69
Total	1978/79	150.5			292.16	50.82

TABLE 4.6 : HARVEY DRAINS (Harvey River Main Drain and Minor Drains) - Nutrient Loadings 1977/78; 1978/79

* from Harvey River Main Drain

Year	Week ending Friday	Discharge ($m^3 \times 10^3$)	Nutrient Conc.* (μg/l)		Nutrient Load (tonnes)	
			N_T	P_T	N_T	P_T
1978	23/6	13,812	2355	426	32.53	5.88
	30/6	26,046	2275	545	59.25	14.20
	7/7	4,831	1572	379	7.59	1.83
	14/7	7,450	1782	468	13.28	3.49
	21/7	39,570	1591	394	62.96	15.59
	28/7	30,931	1917	489	59.29	15.12
	4/8	8,998	2294	424	20.64	3.82
	11/8	8,353	1088	207	9.09	1.73
	18/8	2,429	958	182	2.33	0.44
	25/8	1,833	1341	228	2.46	0.42
Total	1978	144,253			269.4	62.5
Percentage of water year total					85%	85%
1979	29/6	14,241	3384	771	48.19	10.98
	6/7	3,089	2163	364	6.68	1.12
	13/7	15,558	3283	568	51.07	8.84
	20/7	26,080	2663	398	69.45	10.38
	27/7	4,416	1763	298	7.78	1.32
	3/8	5,176	2111	357	10.93	1.85
	10/8	2,353	1506	509	3.54	1.20
	17/8	2,681	3221	477	8.64	1.28
	24/8	9,084	2456	413	22.31	3.75
	31/8	5,301	1814	335	9.62	1.77
Total	1979	87,979			238.21	42.49
Percentage of water year total					82 %	84 %

TABLE 4.7 : HARVEY DRAINS - Nutrient Loads from Winter Flushing 1977/78; 1978/79

* Concentrations quoted are from Harvey River analyses

85% of the 1977/78 load and 84% of the 1978/79 load entered the Harvey Estuary during the first ten weeks of significant winter flow. That these percentages are less than the Murray is of course due to the fact that the river is dammed at Harvey Weir (and much of the upstream flow diverted to the sea). Compensation releases and drainage from the coastal plain account for the sustained flow of the river (drain) downstream of the weir throughout the year.

The impact of the "first flush" phenomenon is discussed further in 4.3.1.

(iv) Other relevant data. Schulz (1979) records P_T and N_T loadings for the period April, 1972 to March, 1978, on a 3 monthly basis that are broadly in agreement with those analysed during the study, subject of course to the quite large fluctuations occurring apparently randomly. Public Works Department monthly analyses from the Doman's Bridge site are listed in Appendix III.

4.2.4 Relative Contribution of Major River Systems

TABLE 4.8 shows the percentage of flow, N_T and P_T contributed to the Peel Inlet and Harvey Estuary by the Murray, Serpentine and Harvey Drains system respectively. As previously mentioned, these differ in respect of the Serpentine and Harvey systems from those reported in February, 1979 (Hodgkin, 1979) for the 1977/78 water year. This is due to the (now) improved flow estimates for these rivers.

In the 1977/78 water year which was of nearly average flow, we find that though the Murray River system contributed just over 50% of the flow to the estuary, it accounted for some 73% of the total Nitrogen input but only 21% of the total Phosphorous input. This may be

YEAR	DATA		RIVER SYSTEMS - % of TOTAL INPUT			
			Murray	Serpentine	Harvey	Total
1977/78	Discharge	$m^3 \times 10^6$	289	65	206	560
		% total	51	12	37	100%
	N_T	tonnes	1153	116	317	1586
		% total	73	7	20	100%
	P_T	tonnes	25	23	73	121
		% total	21	19	60	100%
1978/79	Discharge	$m^3 \times 10^6$	86	55	150	291
		% total	29	19	52	100%
	N_T	tonnes	110	108	292	510
		% total	22	21	57	100%
	P_T	tonnes	4	12	51	67
		% total	6	18	76	100%

TABLE 4.8: PEEL INLET AND HARVEY ESTUARY - Relative Contribution of Input Waterways 1977/78; 1978/79

accounted for by the fact that the Serpentine and Harvey systems drain coastal plain with improved pastures subject to annual agricultural fertilizer dosage. Birch (1979) discusses the question of fertilizer runoff with particular reference to these three river systems in detail.

The very dry 1978/79 water year has resulted in a Murray River flow that we estimated to be exceeded about 97% of the time; i.e., only once in 40 years would we expect so low a flow.

Flows in the Serpentine and Harvey channels are nowhere near as low, due of course to compensation flows and (in the case of the Harvey), a much higher yield resulting from the "peaky" hydrographs that are a characteristic of this truncated catchment. Thus, in this year, the Harvey system contributes an atypical percentage of total river flow; i.e., over 50%. Similarly its N_T contribution rises to 57% and P_T to 76%.

We therefore regard the whole system as having been particularly "starved" of Nitrogen in 1978/79, lacking as it did the impact of a few weeks of very high Murray River flow which might normally contribute up to 70% of the total N input from all rivers.

TABLES 4.9 and 4.10 set out the statistics of flow and nutrient load for all three systems for the water years 1977/78, 1978/79; in particular the contribution of the first few weeks of winter flow is highlighted.

YEAR	DATA		RIVER SYSTEMS Murray	Serpentine	Harvey
1977/78	Annual discharge ($m^3 \times 10^6$)		289	65	206
	Discharge 23/6 to 25/8 *	$m^3 \times 10^6$	240	39	144
		% annual	83	60	70
	Annual N_T load (tonnes)		1153	116	317
	N_T load 23/6 to 25/8 *	tonnes	1109	89	269
		% annual	96	77	85
	Annual P_T load (tonnes)		25	22	73
	P_T load 23/6 to 25/8 *	tonnes	23	18	62
		% annual	92	82	85

TABLE 4.9 : PEEL INLET AND HARVEY ESTUARY
Statistics of Nutrient Load for Input Rivers 1977/78

* Differences from % values on TABLES {4.2 and 4.4} are due to "rounding off" errors.

YEAR	DATA		RIVER SYSTEMS		
			Murray	Serpentine	Harvey
1978/79	Annual discharge ($m^3 \times 10^6$)		86	55	150
	Discharge 29/6 to 31/8	$m^3 \times 10^6$	39	23	88
	*	% annual	45	42	59
	Annual N_T load (tonnes)		110	108	292
	N_T load 29/6 to 31/8	tonnes	60	60	238
	*	% annual	55	56	82
	Annual P_T load (tonnes)		4	12	51
	P_T load 29/6 to 31/8	tonnes	2	8	42
	*	% annual	50	67	82

TABLE 4.10 : PEEL INLET AND HARVEY ESTUARY

Statistics of Nutrient Load for Input River 1978/79

* Difference from % value on TABLES {4.2, 4.4, 4.7} are due to "rounding off" errors.

4.3 Intensive Sampling.

4.3.1 Harvey River Main Drain - "First Flush" June 28/29, 1979.

(i) Rationale and methodology

Weekly data reveals that in general terms, the highest nutrient concentrations are associated with the highest (winter) discharges. Linear regression on the 52 data points in 1977/78 for Harvey River Main Drain flow (Q) on N_T show only a relatively low correlation ($r = 0.48$) mainly due to fluctuations in N_T concentrations during low flow periods. Throughout the winter, N_T levels are consistently high at values > 1100 µg/l. P_T levels are similarly high (> 250 µg/l).

Thus it was felt desirable to sample the river flow up the rising limb of the first major flood hydrograph of 1979.

This was achieved by installing an automatic water sampler set to a sampling interval of 2 hours. The first samples were taken at 1200 hours on June 27, 1979, when discharge had been steadily falling for some hours, but the synoptic weather chart indicated the strong possibility of significant rains within a few hours. Unfortunately, the water level in the Harvey River Main Drain continued to fall for the next 24 hours to the extent that the sampler intake was exposed from 0400 to 1800 on June 28. This meant that no samples were taken during this period of falling discharge.

However, from 1200 on June 28 until 0100 on June 29, 44.5 mm of rain was recorded at the adjacent Harvey (2) pluviometer. The Hyetograph of this precipitation is plotted with the resultant Harvey River hydrograph on Fig.4.1.

Discharge rose from 1200 on June 28 to a peak of 61.7 m^3/sec at 1000 on June 29, and automatic sampling re-commenced at 1800 on June 28 when the flow had risen from a low of 5.1 m^3/sec to 9.6 m^3/sec. Sampling then continued without difficulty throughout the time of rise of the river and was halted after the recession had begun at 1400 on June 29.

Water samples were packed and field frozen and subsequently analysed at the Department of Botany, University of Western Australia for Ortho and Organic Phosphate and total P; Ammonia, Nitrate-Nitrite and Organic Nitrogen and Total N. For convenience only N_T and P_T are plotted on Fig.4.1.

All analyses are tabulated in Appendix III.

(ii) <u>Results and discussion</u>

Fig.4.1 reveals, there is no apparent correlation between nutrient concentrations and discharge up the rising limb of the hydrograph ($r = 0.299$). Small, random fluctuations in N_T and P_T occur but do not appear to relate in any meaningful way to discharge <u>with the chosen sampling interval</u>. Concentrations are uniformly very high throughout the flood. The "peaky" nature of the Harvey River Main Drain hydrograph (a 13 hour storm produced a flood with a time to peak of 18 hours) means that it is likely that all similar pulses pass high concentrations of nutrients which cannot be effectively related to discharge over small time increments.

It could be that the concentrations of N_T and P_T are more likely to be related to the origin of surface run-off for a particular sample, though turbulent mixing (which would be most effective at high discharge) makes this improbable.

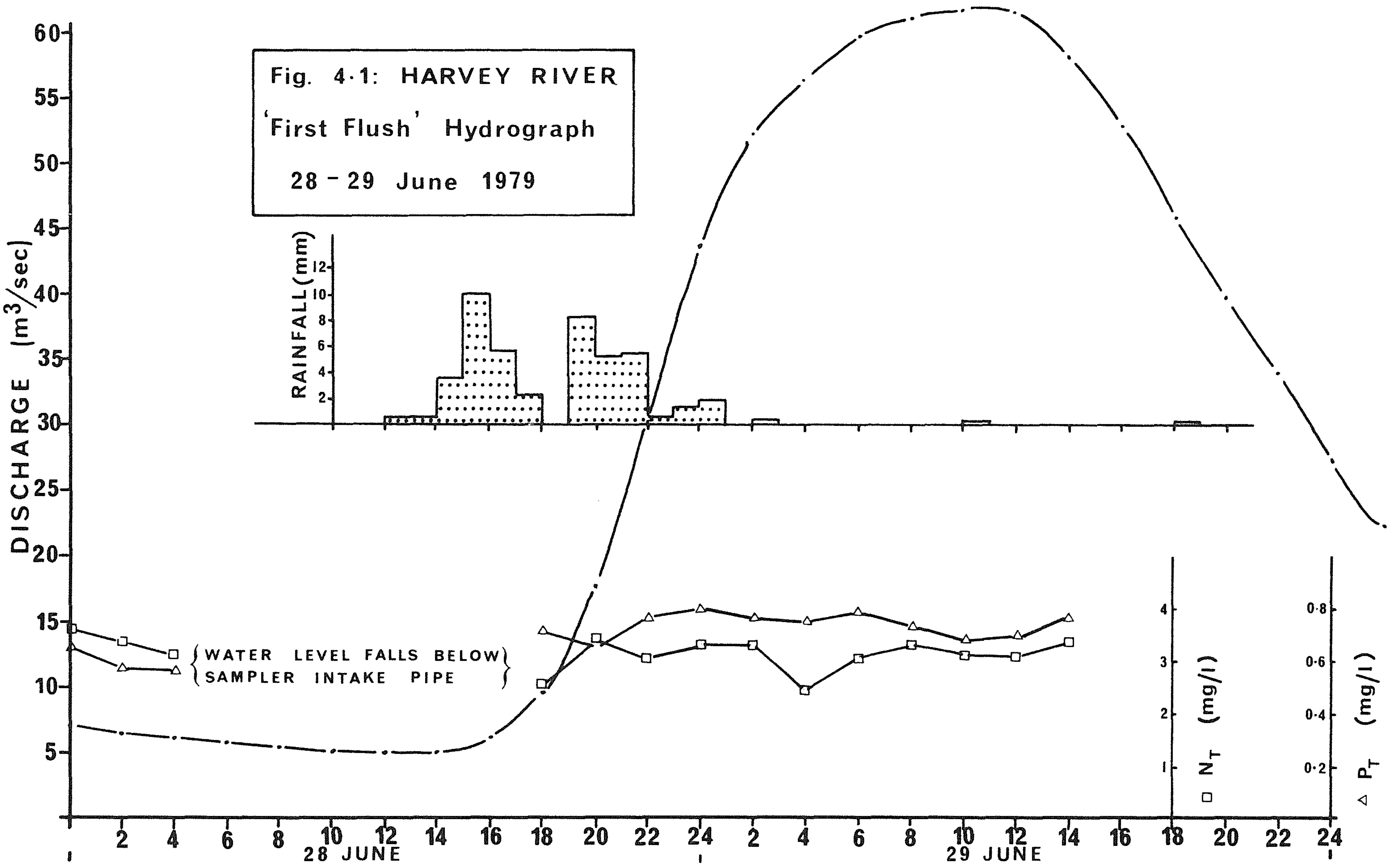


Fig. 4·1: HARVEY RIVER 'First Flush' Hydrograph 28 – 29 June 1979

4.3.2 Murray River and Tributaries - "First Flush" July 9/13, 1979.

For the reasons outlined in 4.3.1 it was decided to undertake a one-week intensive sampling of the Murray River and its major tributaries at the time of the first significant flows in the winter of 1979. Further, it was hoped that this would also help to identify specific sources of nutrient input contributing to the very high "pulses" of N_T recorded in 1978.

The following sampling sites were selected and samples taken on each of the five (5) days July 9 - 13 inclusive and analysed as reported in 4.3.1.

	River	Location
Murray River Basin: (see Fig.3.2 for locations)	Murray River	614 006
	Murray River	Ravenswood
	Murray River	Pinjarra
	Yarragil Brook	614 044
	Williams River	614 196
	Hotham River	614 244
Serpentine River Basin: (see Fig.3.6 for locations)	Peel Drain	614 030
	Dirk Brook	614 028

In addition, sampling and analyses were carried out by the Public Works Department and Forests Department at these and a number of other tributaries at 3 or 7 day intervals. Complete results of both exercises are tabulated in Appendix III.

PWD and Forests Dept. Sampling

(June - August, 1979)

Murray River Basin
(see Fig.3.2 for locations)

River	Location	Period of Sampling & Interval
Murray River	614 006	01.06.79 to 08.08.79 (3 days)
Warren Brook	614 017	01.06.79 to 06.08.79 (3 days)
Yarragil Brook	614 044	25.06.79 to 06.08.79 (2-3 days)
Hotham River	614 224	06.06.79 to 08.08.79 (7 days)
Williams River	614 196	06.06.79 to 08.08.79 (7 days)
L.Dandalup R.	614 233	01.06.79 to 06.08.79 (3 days)
Marrinup Brook	614 025	01.06.79 to 08.08.79 (3 days)

Serpentine River Basin
(see Fig.3.6 for locations)

River	Location	Period of Sampling & Interval
Serpentine (Peel) Drain	614 030	06.06.79 to 08.08.79 (7 days)
Dirk Brook	614 028	06.06.79 to 08.08.79 (7 days)

Regrettably, the very low flows of the Murray River system in the winter of 1979 meant that we were unable to record in detail (as was hoped) the "first flush" phenomenon so apparent in the 1978 data. Indeed during the week of July 9 - 13, flows were so low in most rivers sampled that it must be said that the intensive sampling added little new information. However, (i) and (ii) below summarises the data collected.

(i) Intensive (daily) sampling - July 9/13, 1979.
Fig.4.2 plots the N_T concentrations recorded at the sampling sites on the Murray Basin rivers. Flows recorded at 614 006 on the five (5) days were:-

July 9	269.3	$m^3 \times 10^3$
10	356.4	$m^3 \times 10^3$
11	312.7	$m^3 \times 10^3$
12	375.5	$m^3 \times 10^3$
13	394.3	$m^3 \times 10^3$

These compare unfavourably with the mean daily July flow (39 years) of 3,470 $m^3 \times 10^3$. Indeed the minimum daily July flow is 236 $m^3 \times 10^3$. (39 years).
Under such conditions we are hardly likely to see dramatic evidence of a first flush of nutrients. In retrospect, delaying the exercise by another week would have sampled a peak winter flow of 1640 $m^3 \times 10^3$ (July 17). However, examination of the PWD/Forests Department samples shows that even this increased flow (which is still only one third LTA July daily flow) failed to produce any noticeable increase in nutrient concentration.
P_T concentrations were generally far too low (<90 µg/1) to warrant plotting. The exception to this was at the Ravenswood sampling site, where sufficient flow off the coastal plain occurred to lift P_T concentrations to a peak of 238 µg/l.

Fig.4.3 plots P_T concentrations for the Serpentine River Basin tributaries (Peel Drain 614 030 and Dirk Brook 614 028). These two channels drain predominantly coastal plain and might be expected to record high P_T values. Loh (pers. comm.1979) suggests that the low concentrations for Dirk Brook are due to a high percentage of its flow actually running off the largely uncleared upland portion of the catchment.

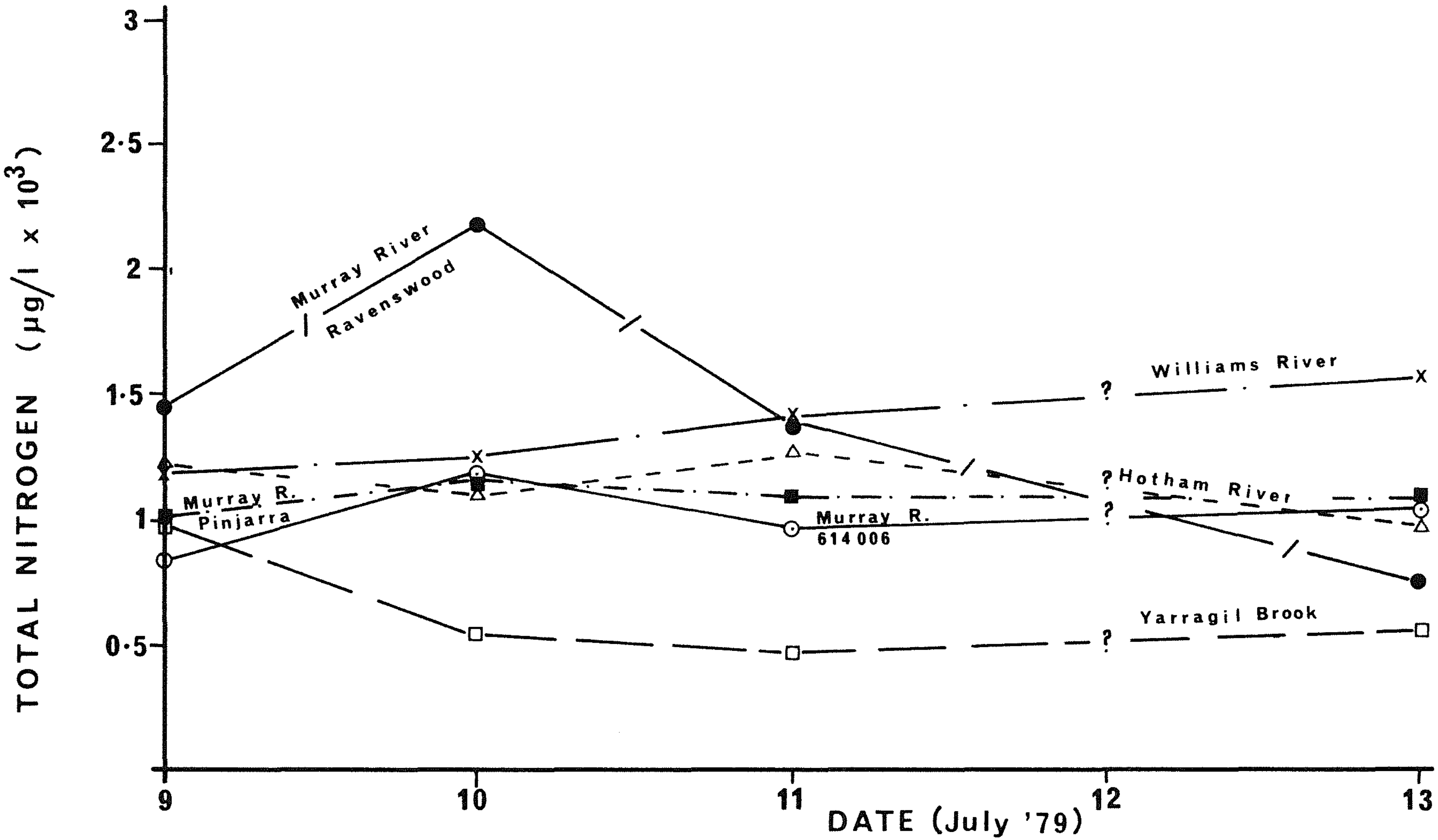


Fig. 4·2 : N_T CONCENTRATION – MURRAY RIVER BASIN; JULY, 1979

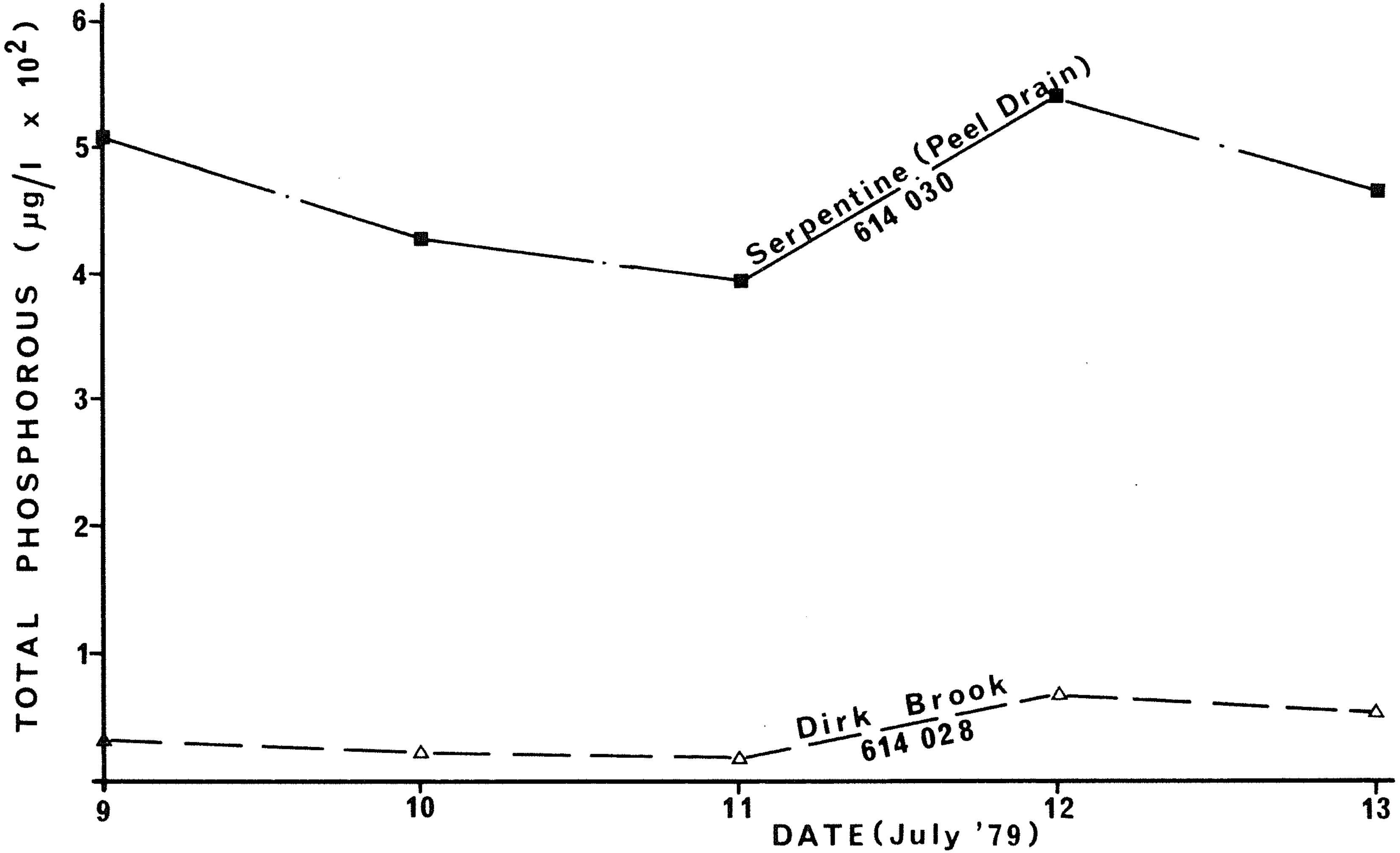


Fig. 4·3: P_T CONCENTRATION – SERPENTINE BASIN, JULY, 1979

(ii) PWD/Forests Department Sampling
June 1 - August 8, 1979.

Fig.4.4 plots the $NO_3 + NO_2$ as N concentrations recorded for Murray River tributaries as shown. The only really noteworthy features of this plot are:-

1. Williams River. As expected the Williams River catchment which is 100% cleared and largely under exotic pasture species recorded the great majority of $NO_3 + NO_2$ as N input (peak concentration 2900 μg/l on July 18).

2. Marrinup Brook. A surprising feature was the very high $NO_3 + NO_2$ as N concentrations recorded in this stream. However Loh (pers. comm.1979) suggests that this is due to presence of a working piggery immediately upstream of the gauge/sampling point.

Figs.4.5 and 4.6 are plots of P_T and N_T concentrations of note for this period (Murray and Serpentine systems).

4.4 Conclusions

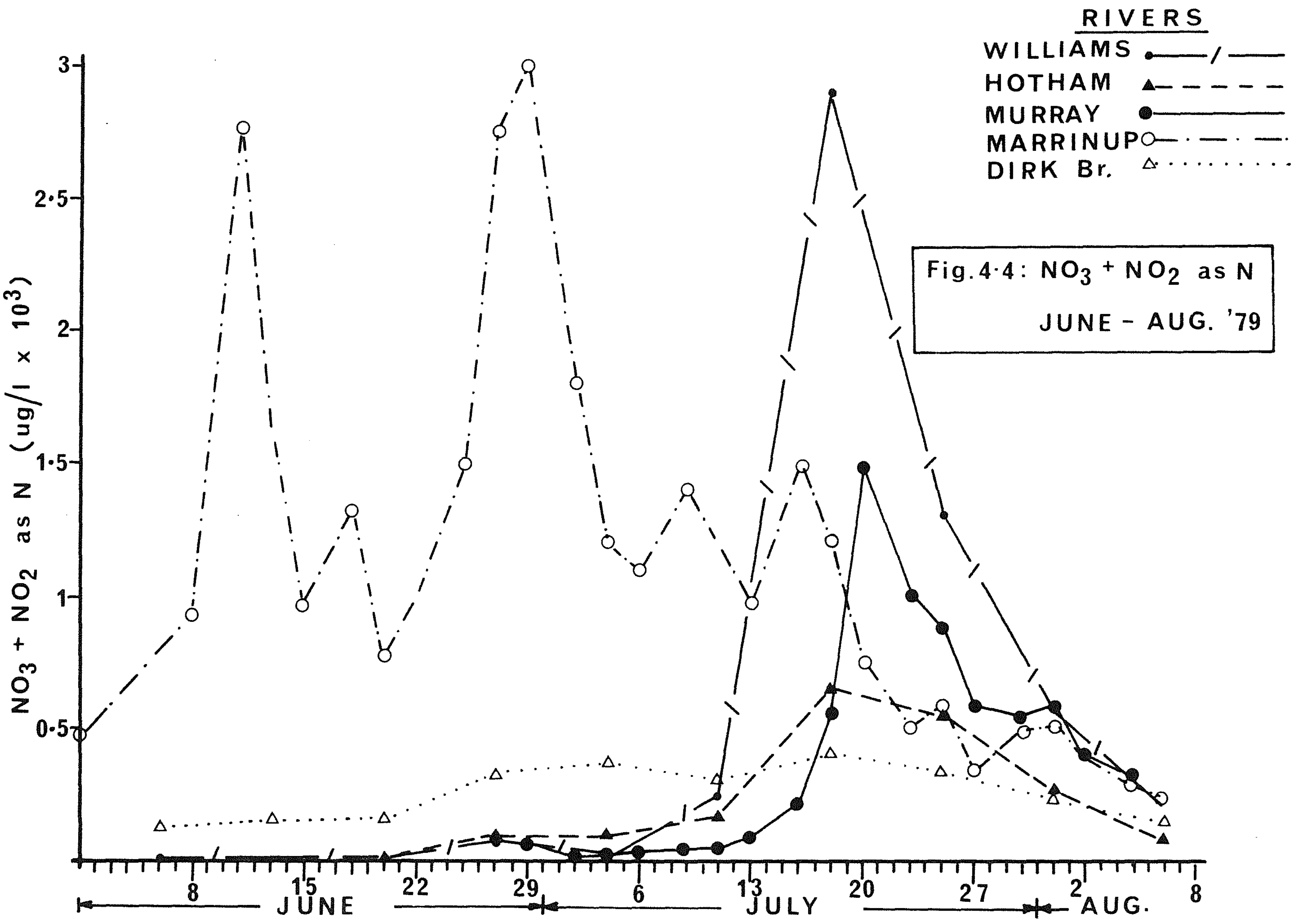
Strongly seasonal fluctuations in N_T concentrations have been widely reported elsewhere (National Water Council U.K. 1979), and given our experience in 1978 it was hoped to closely monitor the first flush in the winter of 1979. This would have provided information that should have improved the nutrient load estimates and (hopefully) more precisely identified the sources of N. Regrettably, the abnormally low flow conditions of 1979 made this exercise largely a waste of time and effort.

We have been able to identify the Murray River and its tributaries as the principal source of N. Similarly, the Harvey River and minor drains contributes most of the P to the system. The Serpentine system is more notably a contributor to P than to N which is in keeping with its largely coastal plain catchment (downstream of the Serpentine Dam).

The very high concentrations of P in certain minor drains suggests that identification of the source of these inputs to the South Coolup, Coolup and Mealup Drains may be worthwhile. However, volumetrically they are much less important than the Harvey River Main Drain (whose P_T concentrations are only a little lower). It should also be noted that the Murray River contributed a significant load of P in 1977/78 ($\simeq$ 20%) and the source of this input bears investigation.

NOTE:

Throughout this chapter, minor differences in nutrient loads estimated and those quoted in the CRES report, are due to small variations in the estimation of missing data.


RIVERS
WILLIAMS
HOTHAM
MURRAY
MARRINUP
DIRK Br.
Fig. 4·4: $NO_3 + NO_2$ as N
JUNE – AUG. '79
$NO_3 + NO_2$ as N (ug/l × 10^3)
3
2·5
2
1·5
1
0·5
8
15
22
29
6
13
20
27
2
8
JUNE
JULY
AUG.

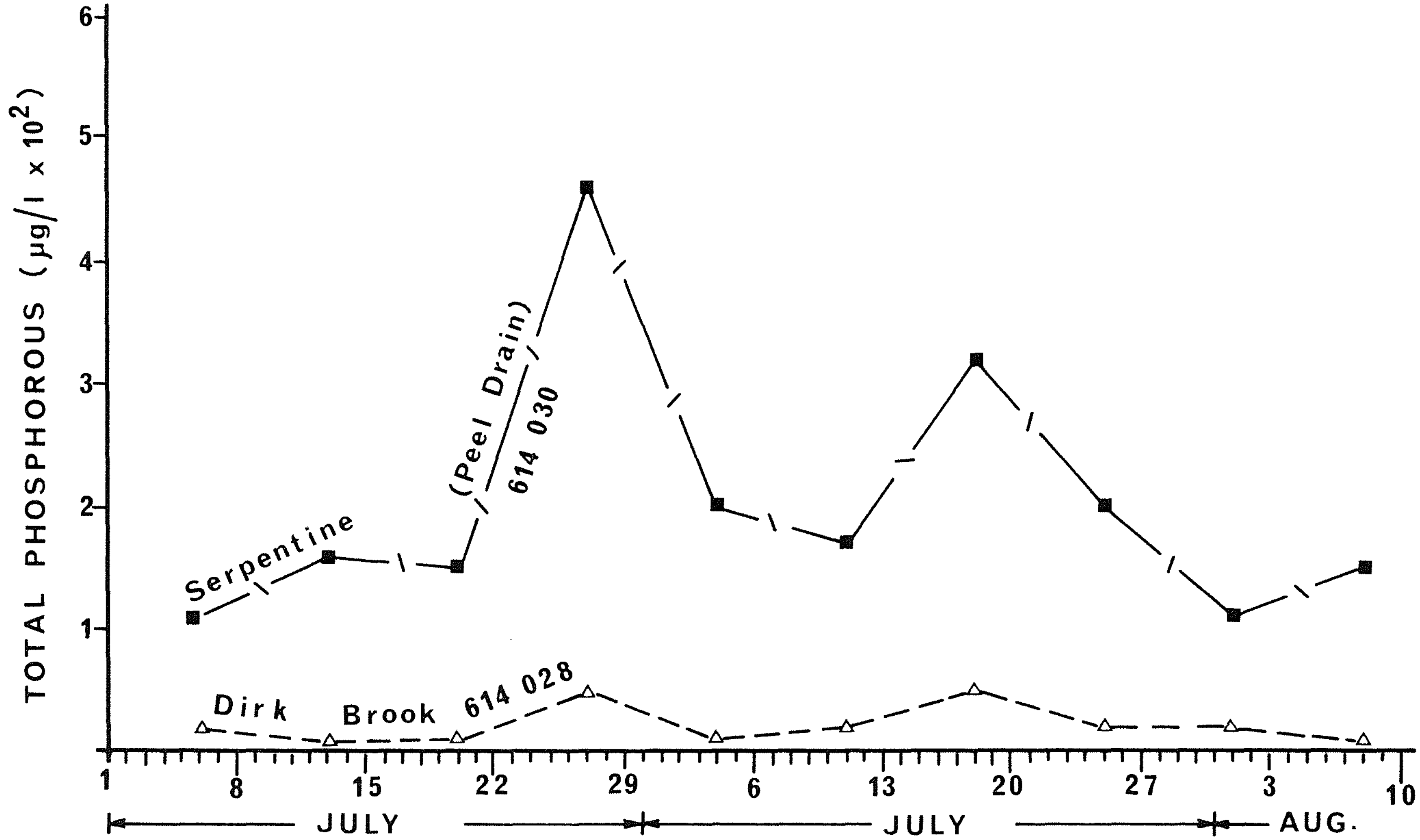


Fig. 4·5: P_T CONCENTRATIONS JUNE – AUGUST 1979; Serpentine Basin

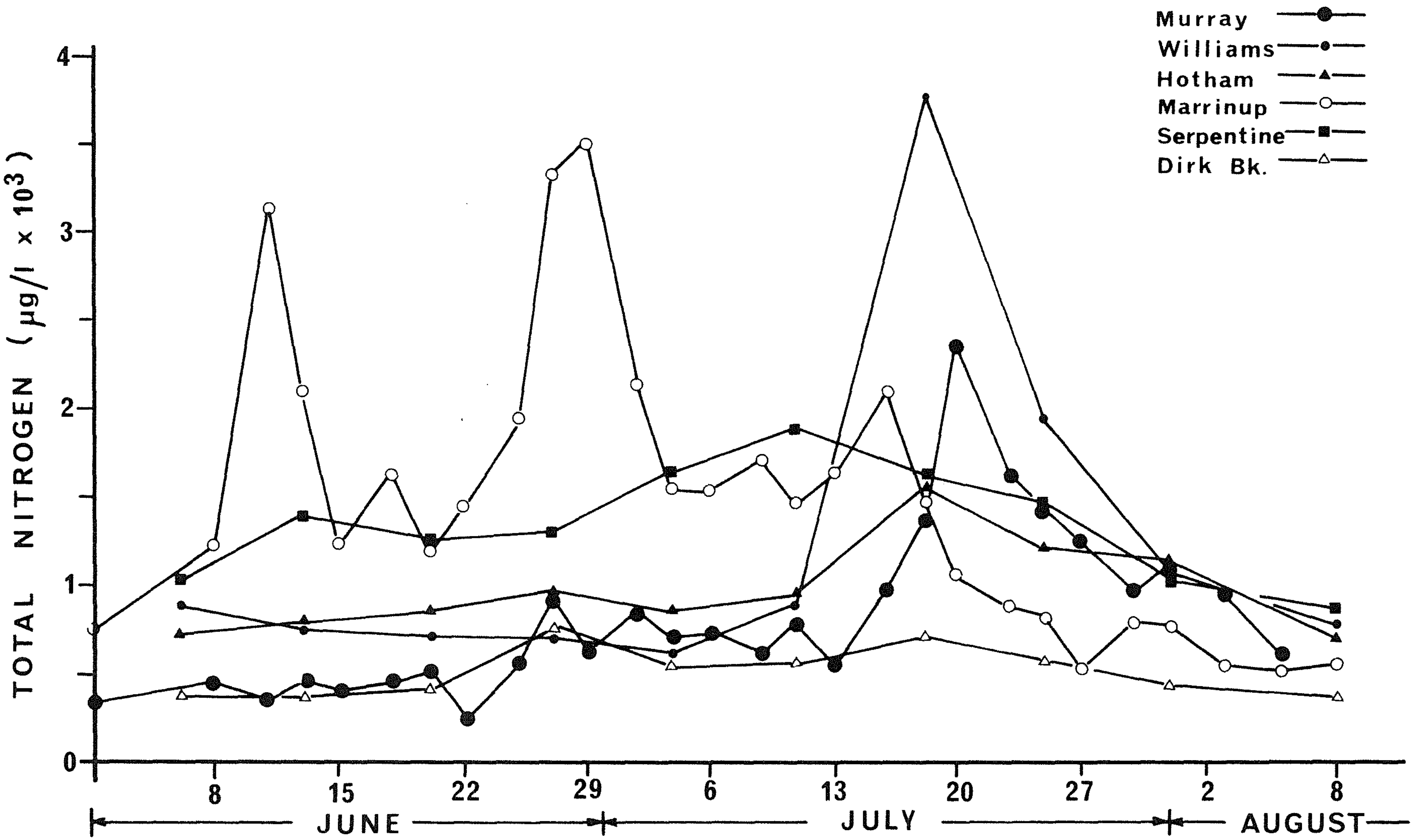


Fig. 4·6: N_T CONCENTRATIONS JUNE - AUGUST 1979; PEEL INLET RIVERS

5. TIDAL EXCHANGE

5.1 Introduction

In his analysis of the influence of atmospheric pressure change on mean sea level variations, Hamon (1966) states that " .... In theory, the level of deep oceans should respond as an inverse barometer to atmospheric pressure changes whose space and time scales are appropriate to normal weather systems ...." The regression of summed 5-day volume flux (calculated for Mandurah Bridge) on 5-day changes in mean atmospheric pressure (see 2.7) shows that such a response clearly exists for the Mandurah entrance channel and hence Peel Inlet.

Hamon used the regression of daily mean sea level on daily mean atmospheric pressure in an examination of the main features of the variation in barometer factor (regression coefficient) around Australia. He showed that on the west coast, the barometer factor is about twice the isostatic value at Fremantle (about 65 km north of Peel Inlet). Abnormally high values on this coast are shown by an examination of graphs of daily sea level and pressure at Fremantle, Geraldton and Bunbury. For one period of 58 days at Fremantle (starting June 26th, 1960) the barometric factor is nearly twice the isostatic value and there is an exceptionally high degree of correlation between sea level and pressure. He concluded that 85% of the sea level variance could be accounted for by regression on atmospheric pressure in this instance. Furthermore, he concluded that " .... it is not possible to say definitely on the basis of multiple regression studies alone if the nonisostatic barometer factors are due to omission of wind stress. But when other factors are taken into account, it seems most unlikely that the wind stress effect is large enough ...." (Hamon, 1966).

Observations suggest that the presence of travelling continental shelf waves on the west coast, moving in a southerly direction, appear to increase the response of sea level to atmospheric pressure. The wave velocity appears to be of the order of 3 to 6 m/sec; highest correlation coefficients were found at a velocity of approximately 4.5 m/sec which results in a lag of about 1½ days in observed sea levels between Geraldton and Fremantle.

Whatever the reason, these variations in mean sea level give rise to considerable difficulties in determining the volume of water exchanged on a tidal cycle at Mandurah from differences in water level as observed at gauges located at the seaward (Mandurah) and Peel Inlet side (Chimneys) respectively of the Mandurah entrance channel. As will be seen in 5.4, a difference of only 1 mm in the choice of "mean" sea level, would result in an error equal to the entire volume of Peel Inlet over one year.

5.2 Measurement of Tidal Exchange - Field Exercises

From the start of the 1977/78 water year, routine weekly sampling (for nutrient analysis) and salinity measurements (in situ) were made throughout the Peel Inlet and Harvey Estuary as well as on all input rivers and drains. However it soon became apparent that some hard data on volumes and nature of water exchanged with the ocean was needed to estimate:-

(i) nutrient loss to the ocean
(ii) the influence of tidal exchange on estuarine salinity levels
(iii) the relationship between water level and exchange volume
(iv) the "flushing time" of the estuary

Once again, the strong seasonal differences are important; i.e. in summer, river flow into the estuary and hence to the sea effectively ceases; ocean and estuarine water are exchanged on each flood and ebb tide with the latter gradually equalling, then exceeding oceanic salinity as the influence of evaporation dominates. This is discussed further in 5.3. In winter, river water effectively flows out to sea "over the top" of tidal exchange. Vertical salinity profiles can be expected to show the growth and decay of a pronounced salt wedge in the entrance channel on each flood and ebb tide respectively.

For these reasons, two field exercises were undertaken, one in February, 1978, and the other in August, 1978, and the current speed and direction as well as temperature and salinity profiles measured at Mandurah Bridge for a continuous 5-day period in each case. The following procedure was adopted:-

(i) A Braystoke Multi-Parameter meter was set up on the platform beneath the Mandurah Road Bridge (see Fig.5.1).
(ii) Every hour, on the hour, measurements of current speed and direction, temperature and salinity at surface, 1.0 m, 2.0 m, 3.0 m, 4.0 m, and 5.0 m (bottom at approximately 5 m) were made. Measurements were taken every 0.5 m at times of significant differences in salinity from top to bottom to locate the halocline.
(iii) Cross sectional measurements for depth and velocity were taken across the full channel width to determine the "representativeness" of the above single point velocity

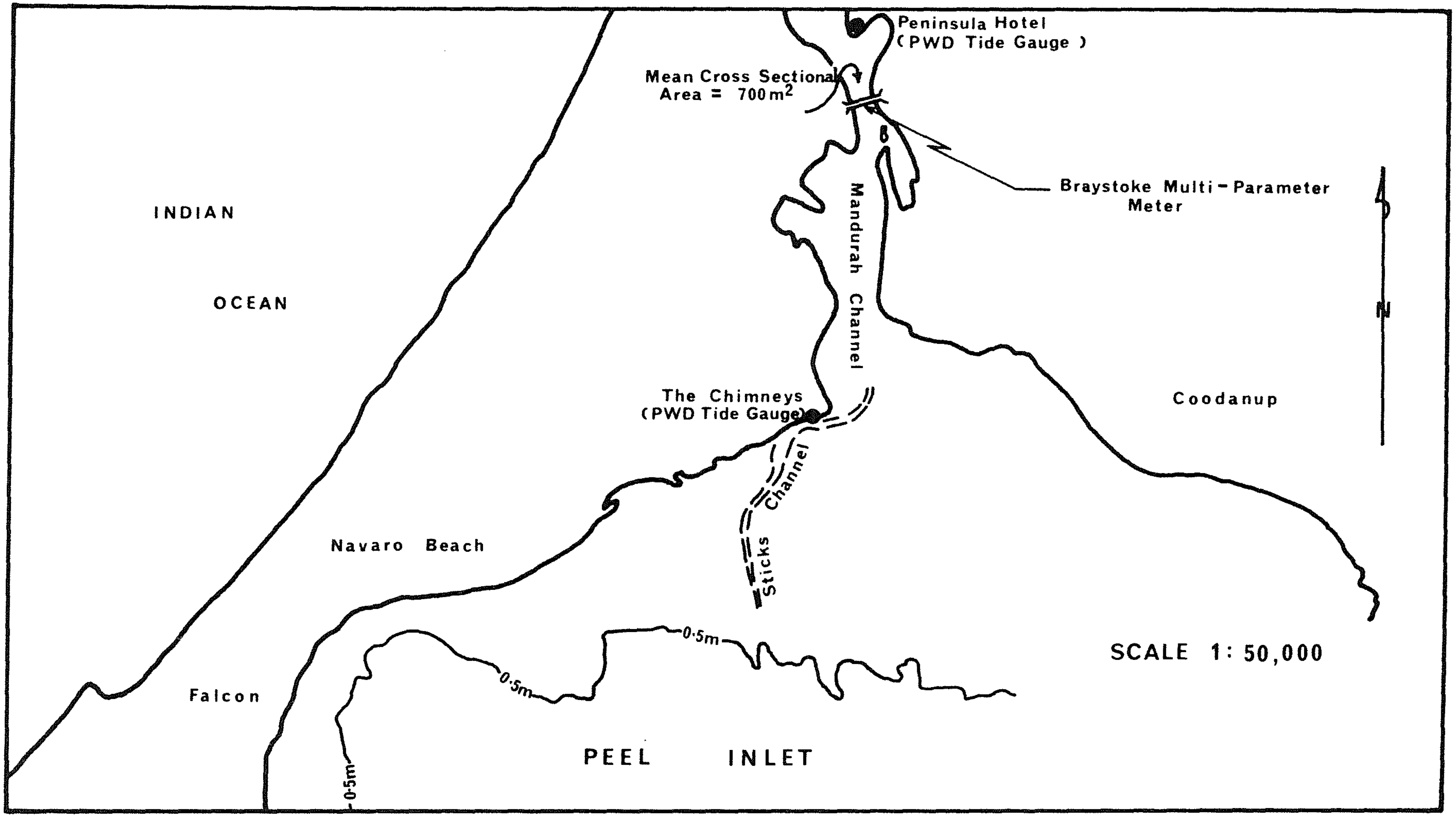


Fig. 5·1: TIDAL EXCHANGE - MANDURAH CHANNEL

(iii) measurements. (Because of the size and weight of the Braystoke meter, it was not possible to move this instrument and a hand-held A.Ott meter was used for this exercise.

(iv) A program ("Flux") was written to calculate the mean velocity and discharge of the channel section. Using the sign convention flood tide (+), ebb tide (-), the summed tidal flux in m^3 was estimated therefrom. Summed salt flux in kg was similarly approximated. A complete listing of hourly results for both exercises is included in Appendix IV.

5.2.1 Summer Exercise, February 12 - 17, 1978.

Fig.5.2 shows the calculated salt and volume fluxes for the period 12th February (1800 hours) to 17th February (1800 hours) 1978. Appendix IV gives a complete listing of all hourly measurements of current speed and direction, water temperature and salinity and an arbitrary datum tide height.

Two features of this summer tidal exchange data require amplification.

(i) Net volume flux. As TABLE 5.1 shows, there was a net gain of 4.562×10^7 m^3 over the 120 hours of the exercise. This compares with an average estuary volume (Peel Inlet and Harvey Estuary shoreline combined) of 13.3×10^7 m^3. This is of course due to the fact that the 5 day period sampled was too short to record one complete "barometric" cycle and Fig.5.2 shows that the comparatively small diurnal flood and ebb tides are merely superimposed on the much larger water level variation due to meteorological effects.

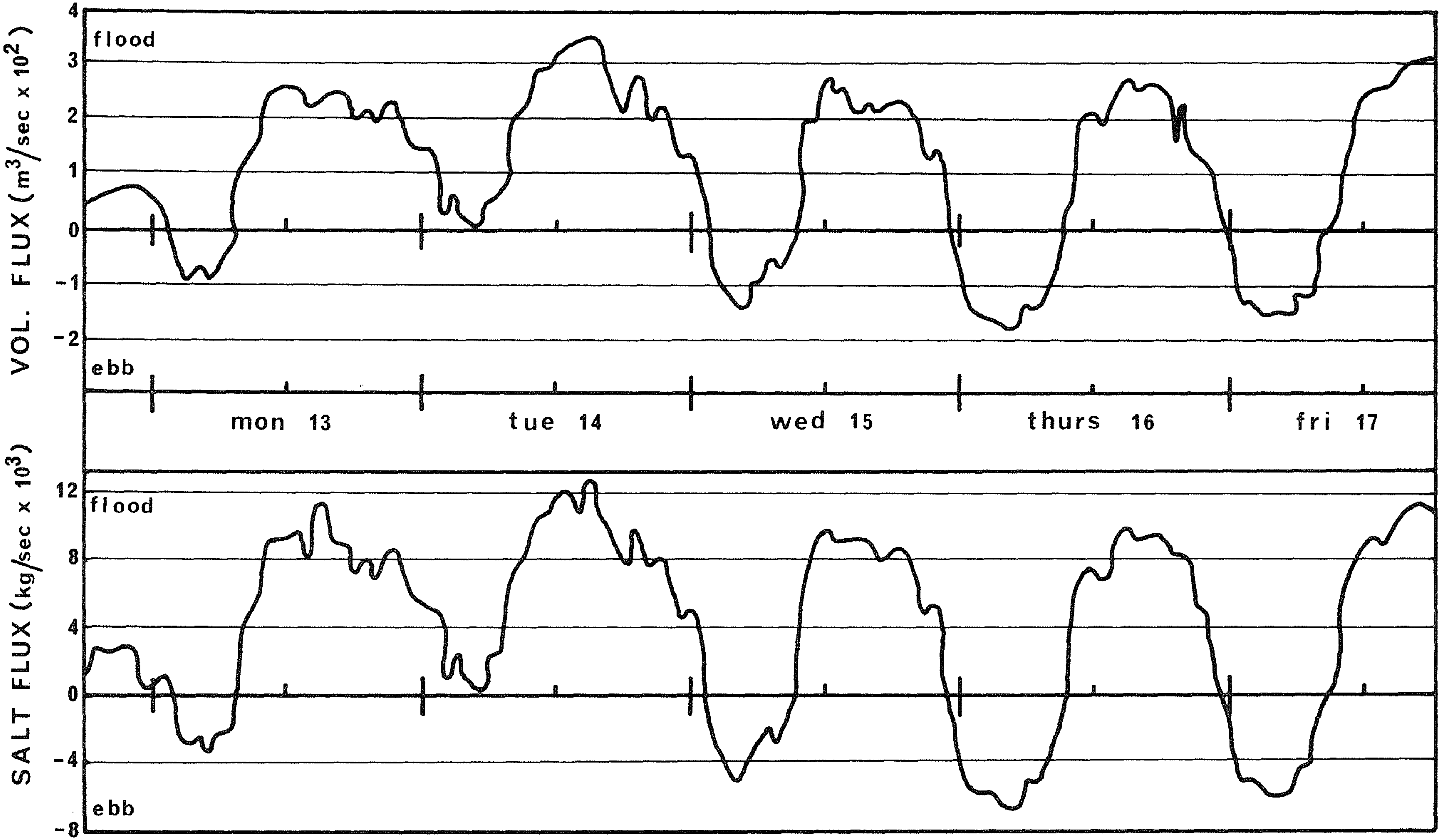


Fig. 5·2: SALT & VOLUME FLUXES – Mandurah Channel – February 1978

Date (1978)	Hour	Salinity (p.p.t.)		Net Volume Flux ($m^3 \times 10^7$)
		Top	5.0m	
12/2	1800	37.0	37.0	0.019
12/2	2400	37.0	37.2	0.153
13/2	1200	37.1	37.1	0.362
13/2	2400	37.1	37.1	1.311
14/2	1200	37.0	37.1	1.906
14/2	2400	36.8	36.8	2.950
15/2	1200	36.9	36.9	2.943
15/2	2400	37.0	37.0	3.657
16/2	1200	37.2	37.1	3.372
16/2	2400	37.0	37.1	4.144
17/2	1200	37.1	37.1	3.949
17/2	1800	37.1	37.1	4.563

TABLE 5.1 : Tidal Exchange Measurements
Mandurah Bridge 12 - 17 February, 1978.

(ii) Salinity profiles. Throughout the exercise virtually no stratification of the tidal prism was observed as it moved in and out of the Mandurah channel. The range of salinites shown in TABLE 5.1 is from 36.8 to 37.0 parts per thousand (p.p.t.). This occurred despite the fact that hypersaline conditions existed within the Peel Inlet and Harvey Estuary (as high as 45 p.p.t. at the Coodanup area) and that oceanic salinities of the order of 35.5 p.p.t. prevailed along the coastline. Thus it seems that a pool of dilute estuarine water merely oscillated back and forth through the Mandurah channel, having only a marginal influence on Peel and Harvey salinity. This is discussed further in 5.3.

5.2.2 Winter Exercise, August 13 - 18, 1978.

Fig.5.3 shows the calculated volume fluxes for the period 13th August (1800 hours) to 18th August (1600 hours) 1978. Appendix IV gives a complete listing of all hourly measurements of current speed and direction, water temperature and salinity and an arbitrary datum tide height. In addition, because of the marked stratification observed on many occasions, linearly interpolated values of temperature and salinity are listed and graphs of salinity versus depth drawn.

(i) Salinity and salt flux. By this time, winter rains in June and July and subsequent Murray River flow in particular had lowered the Peel and Harvey salinity to a system average of 11.5 p.p.t. There was however wide variation across the system (S.D. = 8.7) and measured salinities ranged from 7.3 (top) to 29.9 (bottom) indicating the existence of a pronounced salt wedge.

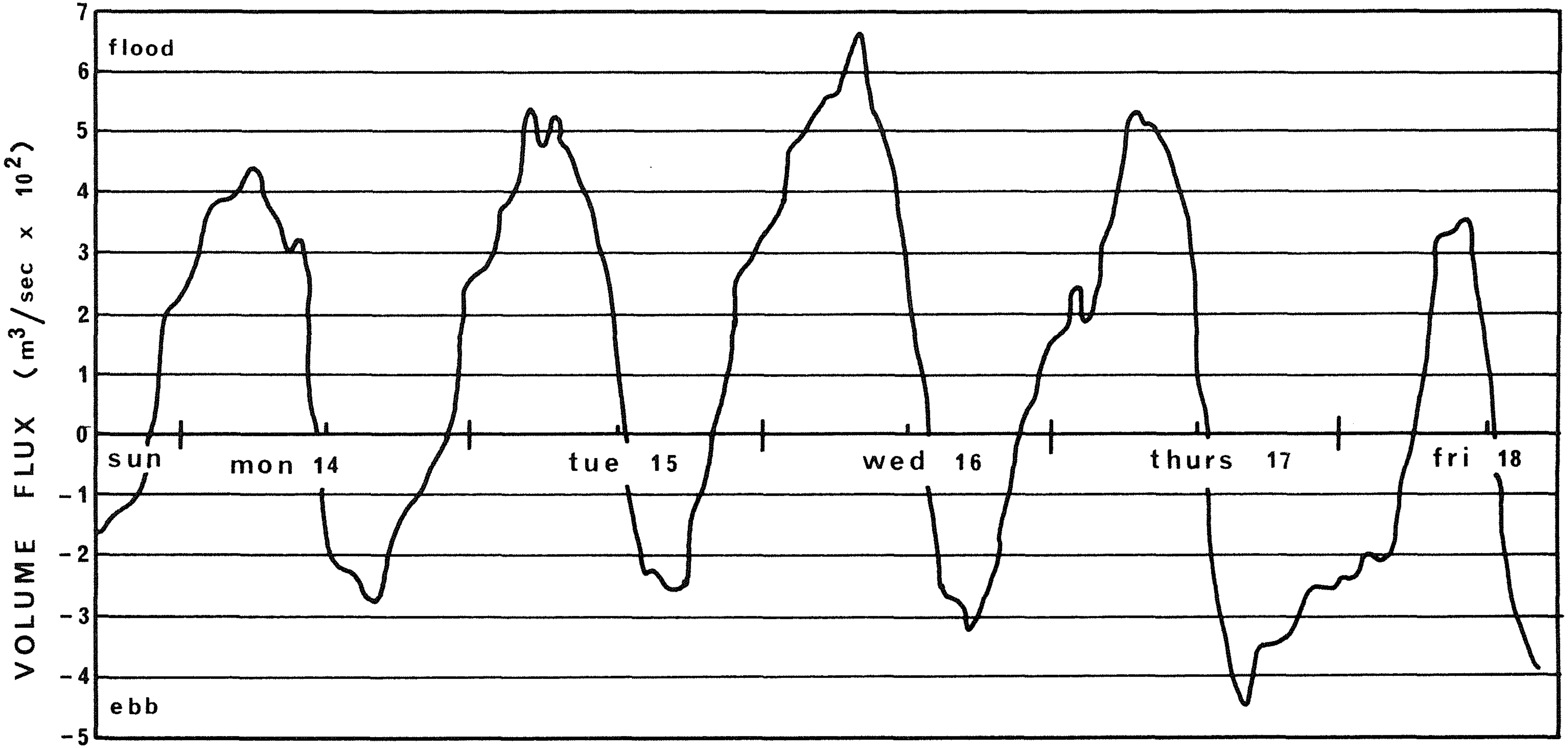


Fig. 5·3: VOLUME FLUXES - Mandurah Channel - August 1978

(i) This greatly complicated the determination of salt flux at the Mandurah Bridge where clearly defined haloclines were observed. Indeed, it is only really possible to estimate mean values for salt input and export under these conditions so that net salt flux determinations probably have little meaning. Fig.5.4 provides a much more useful picture in that surface and bottom salinities are plotted against time for the duration of the exercise.

In general, it can be seen from this plot that an ebb tide takes from 3½ to 4 hours after slack water to flush the inlet channel of oceanic water brought in on the previous flood tide. However, as the measurement point beneath the Mandurah Bridge is only 1 km from the ocean, the corresponding time taken for the flood tide to produce homogeneous ocean water at the bridge is less than 3 hours.

From this we conclude that under these conditions, most of the estuarine water leaving during the previous ebb tide will not return to the system.

(ii) Volume flux. Regrettably, as TABLE 5.2 shows, a similar period of net water gain to the Peel Inlet and Harvey Estuary was encountered. This time the gain over 118 hours was 3.848×10^7 m^3 or roughly 30% of the system mean shoreline volume. It will be noted, however, if Figs.5.2 and 5.3 are compared, that much greater fluxes occur under winter conditions.

(iii) Nutrient flux. Samples taken every 3 hours from 0600 on 14/8/78 to 0600 on 18/8/78 (33 sample points) provide additional support for the hypothesis that little estuarine water leaving the

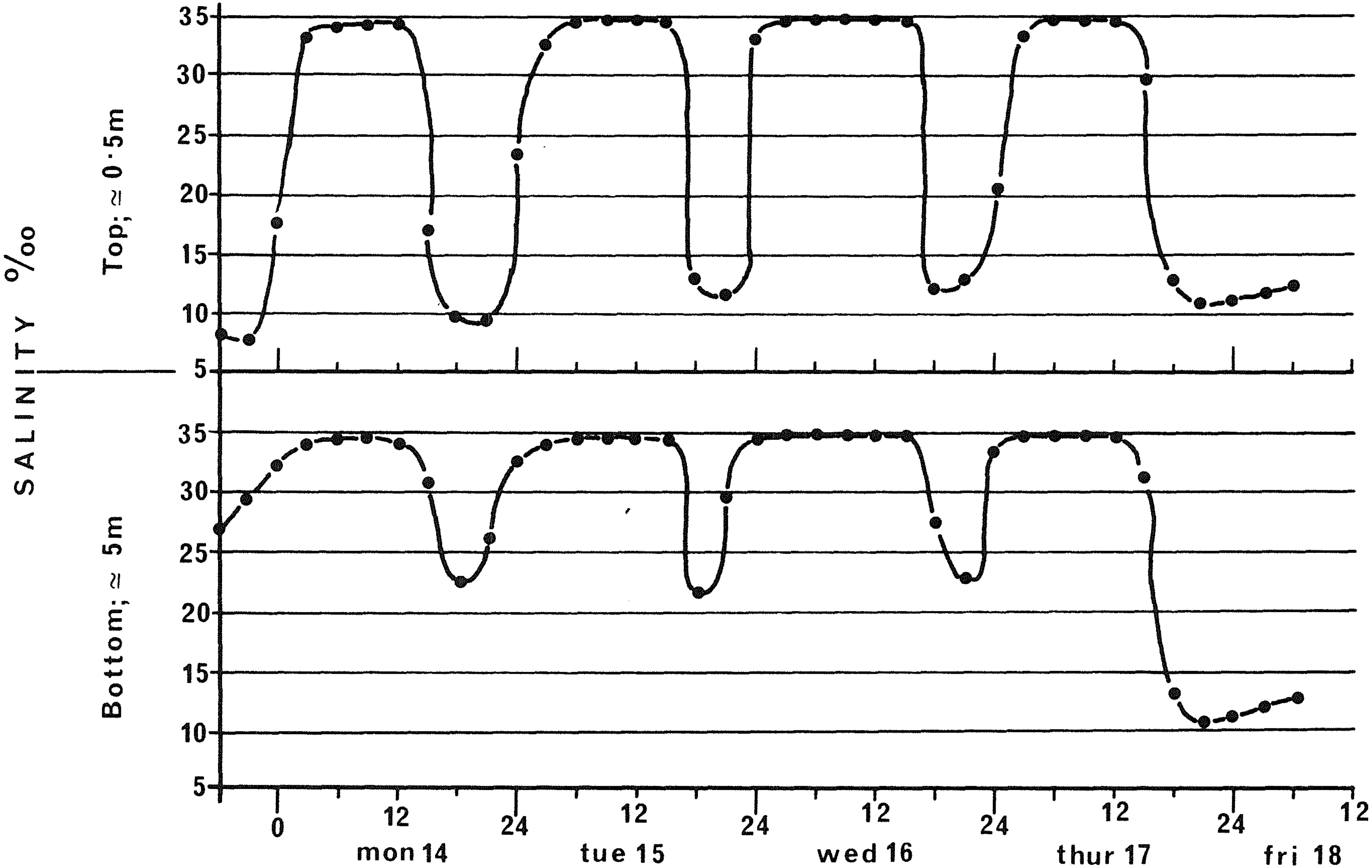


Fig. 5·4: MANDURAH CHANNEL – SALINITY; August 1978

Date (1978)	Hour	Salinity (p.p.t.)		Net Volume Flux ($m^3 \times 10^7$)	State of Tide
		Top	5.0m		
13/8	1800	8.2	26.4	-0.057	Ebb
13/8	2400	17.5	32.5	-0.008	Flood
14/8	1200	33.9	34.3	1.236	Ebb
14/8	2400	23.0	32.4	0.759	Flood
15/8	1200	34.1	34.6	2.420	Flood
15/8	2400	32.9	34.2	2.238	Flood
16/8	1200	34.5	34.5	4.333	Flood
16/8	2400	20.9	33.3	3.853	Flood
17/8	1200	34.7	34.7	5.366	Flood
17/8	2400	11.5	11.6	4.004	Ebb
18/8	1200	34.0	34.6	4.221	Flood
18/8	1600	21.0	26.1	3.848	Ebb

TABLE 5.2 : Tidal Exchange Measurements
Mandurah Bridge 13 - 18 August, 1978.

Mandurah channel on an ebb tide returns on the next flood tide. Fig.5.5 plots NO_3 - N and salinity for both top and bottom samples at the bridge against time. If we use salinity as a measure of the status of tidal exchange (whether flood or ebb), then it can be seen that the considerable difference between estuarine levels of NO_3 - N (≈ 400 to 600 μg/l) and oceanic levels (<5 μg/l) make it clear that when a flood (positive, incoming) tide turns, after approximately 3 hours (time to flush Mandurah and Sticks channels) NO_3 - N levels reach the high estuarine concentrations.

There is a similar, though more rapid return to low oceanic concentrations of NO_3 - N when an ebb (negative, outflowing) tide turns. Less than 3 hours is needed to flush the Mandurah channel between bridge and ocean before low oceanic concentrations are recorded.

We are indebted to Assoc. Prof. Arthur McComb and his staff (Messrs. R. Atkins and R. Lukatelich) for the NO_3 - N analyses.

Linear regression for both surface (1.0 m) and bottom (5.0 m) salinity on NO_3- N concentration at the same points shows:-

$r = -0.8906$ (surface) and

$r = -0.8995$ (bottom)

The negative sign indicates that salinity increases as NO_3- N decreases for the winter condition.

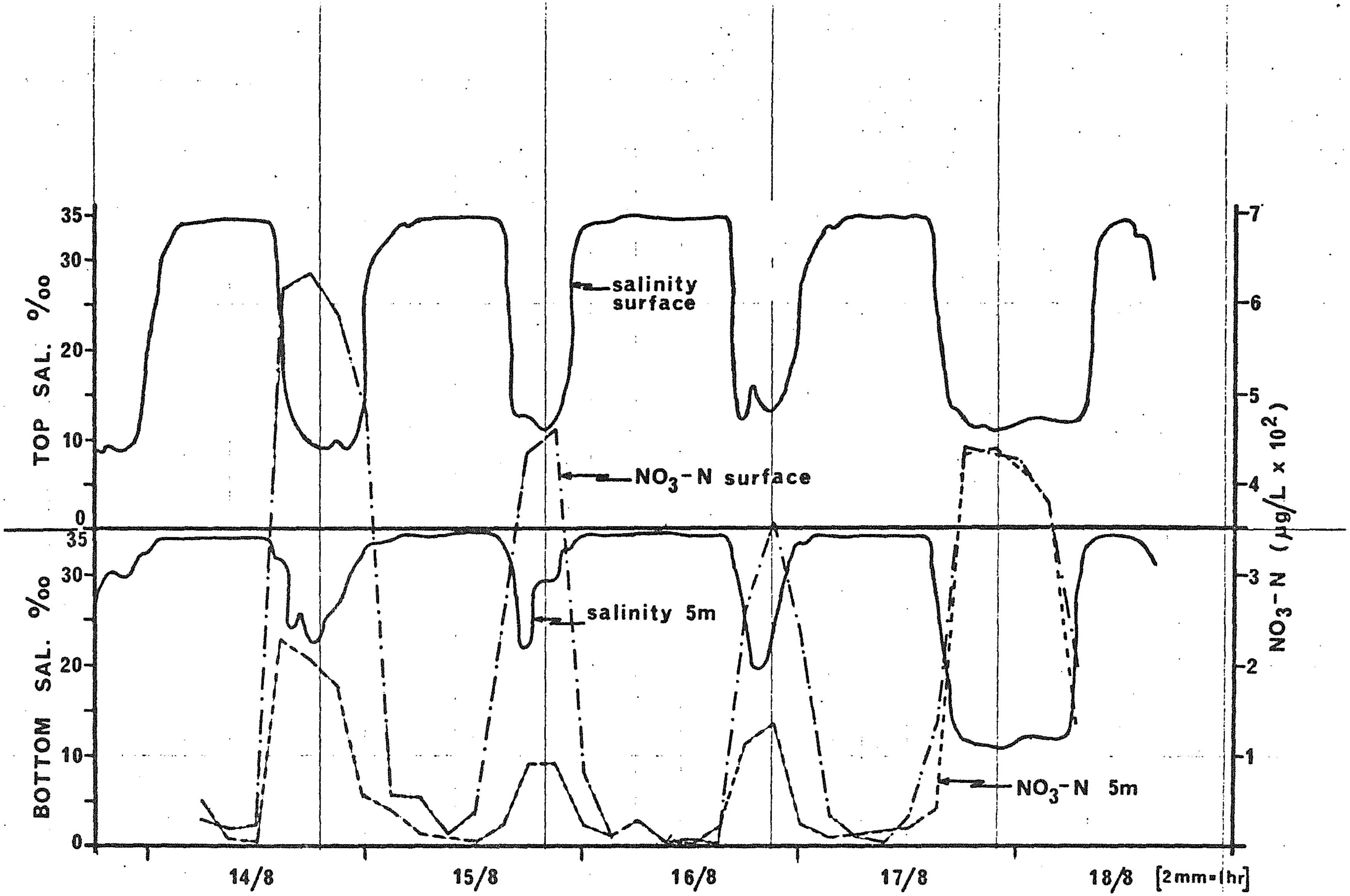


Fig. 5·5: MANDURAH CHANNEL - SALINITY & NO_3-N, August 1978

5.3 Estuarine Salinity/Tidal Exchange/Evaporation/River Flow

Fig.5.6 shows mean salinity for the Peel and Harvey together with Robert Bay pan evaporation, Robert Bay rainfall and Murray River flow (at station 614 006) for the two water years 1977/78, 1978/79. The shapes of the salinity and evaporation curves are in close agreement which in itself is hardly surprising. However several points can be made:-

(i) From the beginning of the water year (1st October) only negligible rain falls on the Peel and Harvey and river flow virtually ceases by the end of October. Thus we would expect that tidal exchange via the Sticks and Mandurah channels would gradually bring estuarine water up to ocean salinity levels (approx. 35 p.p.t.). As there are no other inputs (except small groundwater seepage) it might be imagined that this would constitute an upper limit to salinity of the system.

(ii) However under the twin handicap of a very narrow (and tortuous) inlet channel and very low amplitude tides (<0.5 m), the exchange with the ocean is very restricted and flushing time for site 7 in the middle of Peel Inlet is estimated to be in excess of 6 weeks (Hodgkin 1978). At site 1 in Harvey Estuary, the corresponding time may be as high as 23 weeks.

(iii) For the period of minimal rainfall and river flow; i.e. October to May, the salinity and evaporation curves closely match and indeed it is possible to write:-

$$\frac{dS}{dt} + aS = bS_o \qquad (5.1)$$

where S_o is salinity of water entering on a flood tide

t is time

S is salinity of water leaving on an ebb tide

$\left.\begin{matrix} a \\ b \end{matrix}\right\}$ are dependent parameters

It appears that evaporation is incorporated into the "a" parameter and that b/a is the steady state gain (Beer pers.comm.1979)

(iv) As net solar radiation, and hence evaporation increases, so salinity rises to a peak of 47 p.p.t., on March 28, 1978. The highest value recorded as a system average in 1978/79 was 43.8 p.p.t., on March 20, 1979. The higher value recorded in 1977/78 is probably a natural response to the fact that March, 1978, was the hottest March on record in the area. (see 2.3)

More detailed analysis of the flushing and circulation in the Peel Inlet and Harvey Estuary is contained in the report of the C.R.E.S. group.

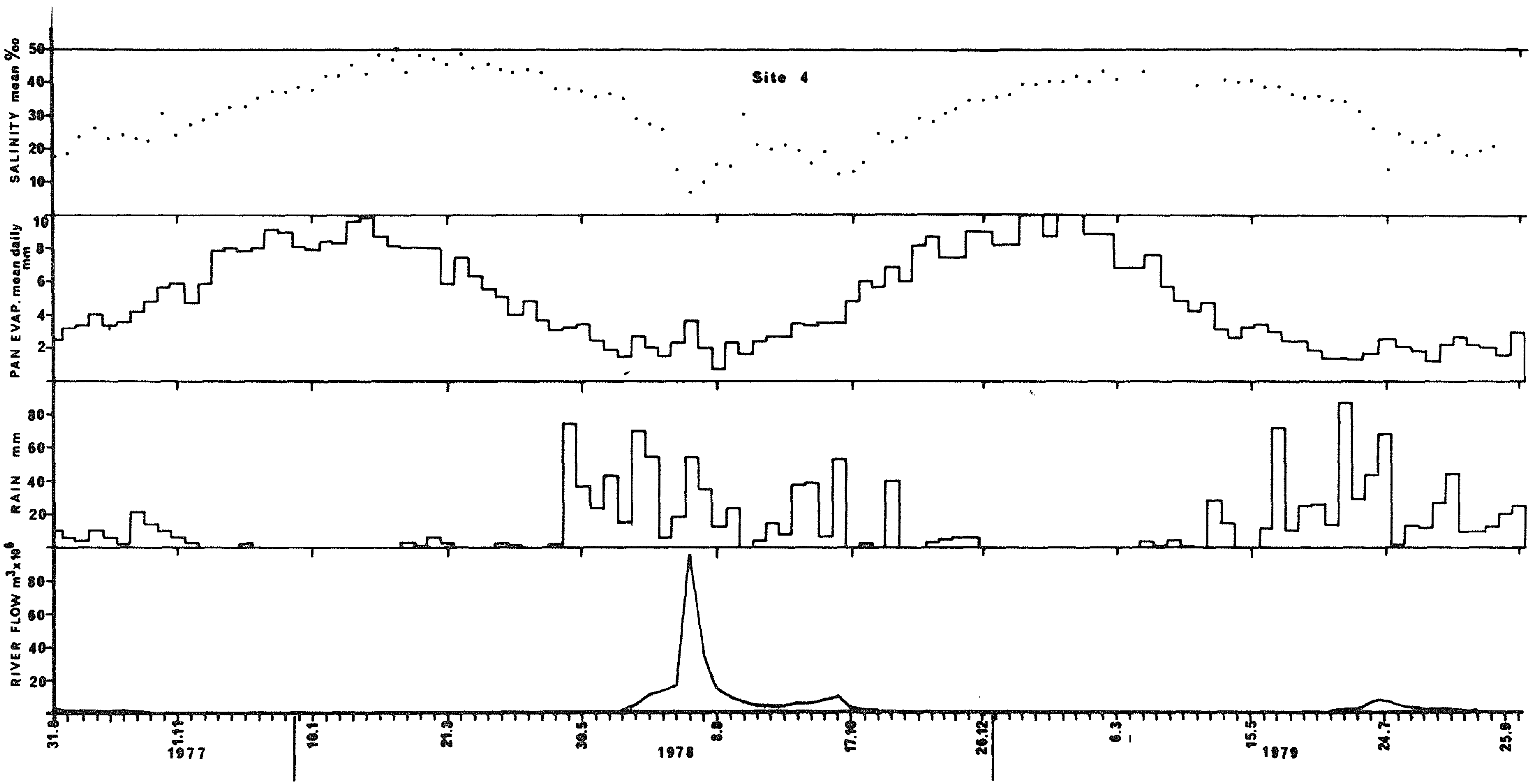


Fig. 5·6: PEEL INLET - WEEKLY SALINITY, EVAPORATION, RAINFALL & MURRAY RIVER FLOW

5.4 Modelling Volume Flux from Water Level - Mandurah and Chimneys Tide Gauges

Throughout the duration of the study, a Public Works Department (Harbours and Rivers Branch) tide gauge (water level recorder) has been continuously operating in the Mandurah Channel, just downstream of the Mandurah Bridge at Mandurah Jetty. In addition, other gauges were located at various sites within the Peel Inlet and Harvey Estuary for the period of the February, 1978, intensive study and beyond. They were:-

Dawesville Ford (opp. Heron Point)	Harvey Estuary
Robert Bay Coodanup Falcon	Peel Inlet
Chimneys	Mandurah Channel

The Chimneys gauge operated throughout 1978 and 1979 and with the Mandurah gauge, provided data as to the state of the tide in the channel on a continuous basis. It was therefore decided to attempt to model volume flux through the Mandurah channel into and out of the Peel Inlet from these water levels available at either end of the channel and the 2 separate week's direct measurement of flux at the Mandurah Bridge (see 5.2).

The method used to model the process was a time-series approach employing an empirical input-output (black box) model by methods of statistical inference directly from the two sets of observed data (water level difference Mandurah - Chimneys and volume flux measured at Mandurah Bridge). We were indebted to Professor Young and his team (especially

Dr. Paul Whitehead) for making available on magnetic tape the "CAPTAIN" package suite of programs. This version of the package (which we shall call the "ANU version" for simplicity) is reported in detail by Mutch & Whitehead (1976), Whitehead (pers.comm.1980) and its broader philosophy described by Young (1974), Young (1976), Young et al (1978) and Young and Jakeman (1979). The package is extremely simple to use and indeed was designed for use by the "non-programming" scientist. No particular difficulty was experienced in fitting a model to the February, 1978, data or the August, 1978, data. Fig.5.7 shows predicted volume flux at Mandurah Bridge from height difference Mandurah - Chimneys for the period 12.2.78 - 17.2.78; i.e. the February exercise. An equally good "fit" can easily be obtained for the August exercise if treated as an entirely separate entity. However it was very soon realised that the idea of fitting a model to the February data and then using the same model to synthesise a year's data (to include the August exercise period) presented a vastly different problem. Predicted volume flows for the period August 13 - 18, 1978, were found to be widely different from those actually measured at Mandurah Bridge. Similar, and indeed greater problems are encountered if the model is fitted to the August data and then used to predict February flows. The poorer fit in this latter example is almost certainly due to the "noise" created by fluctuations in river flow in August. In February, all water movement through the channel is a result of tidal exchange.

Basically the cause of the inadequacy of the model as a predictor of volume flux lies in the selection of a mean water level; i.e.,

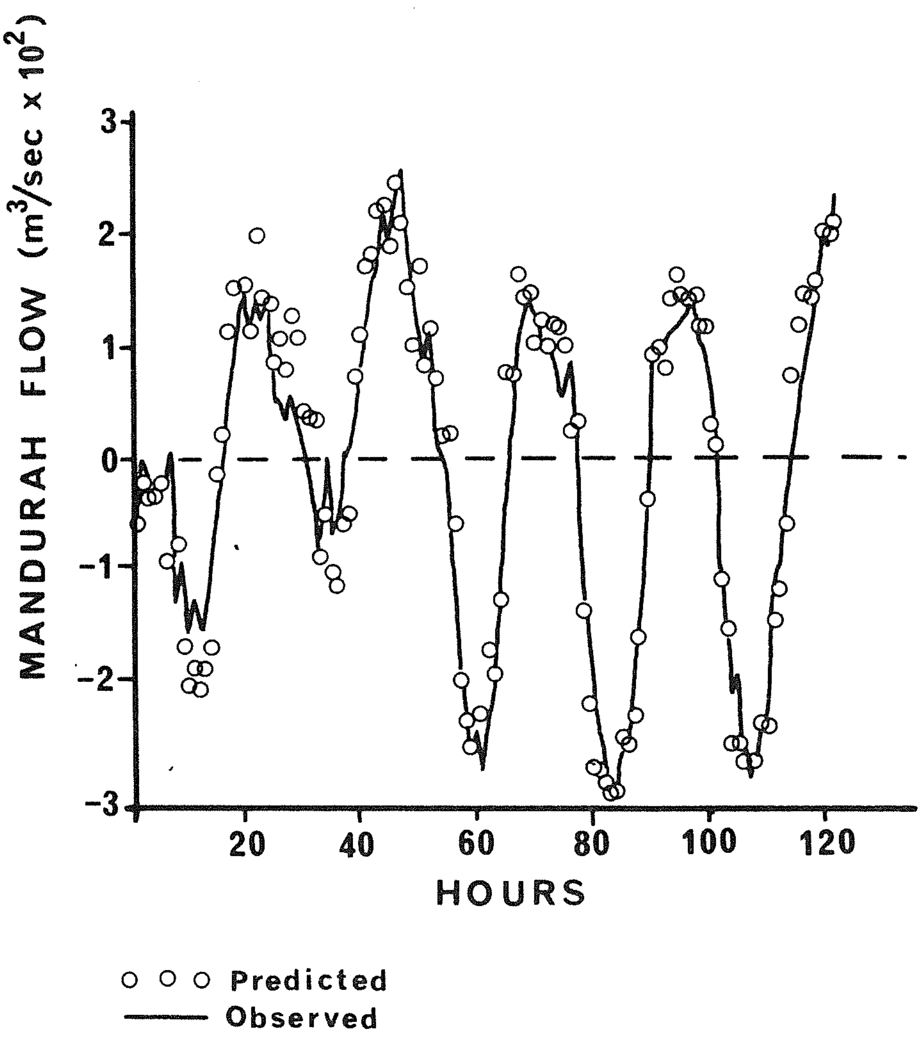


Fig. 5·7 : PREDICTED FLOW AT MANDURAH FROM HEIGHT DIFF. MANDURAH – CHIMNEYS the establishment of a suitable datum for the Mandurah and Chimneys gauges. On the model derived by the CAPTAIN package on the data sets (i) $(\text{Mandurah} - \text{Chimneys})^{\frac{1}{2}}$ $(\text{in cm})^{\frac{1}{2}}$ and (ii) Volume Flux (in m^3/sec) we find that the sensitivity is such that an "error" in the establishment of mean water level of only 1 mm will generate a volume "error" in prediction equal to the entire Peel Inlet and Harvey Estuary volume in one year; i.e.,

Mean water level error = 1 mm → Volume flux error $\simeq 130 \times 10^6 \ m^3$ * in one year's predicted flows

The form of the ANU version of the CAPTAIN package is the discrete time-series or pulse transfer function representation of a linear stochastic dynamic system. In the model, the output from a discrete dynamic system is considered to result from a deterministic input, which causes most of the output variation, and a stochastic input attributed to unavoidable uncertainties in the relationship; e.g., those arising from additional disturbances and measurement "noise". The difficulty is to derive a model from one data set that is able to adequately fit the other and this is due to non-linearity - parameters will vary from one "starting point" to another. i.e., using a February-derived model to predict August volume fluxes and hence the balance of the year(s) for which only tide heights are available. These problems may be summarised as follows:-

1. "Noise" in the volume flux measurements attributed to:-
   (a) errors resulting from use of one current metering site to represent the entire cross section at Mandurah Bridge.

* Assuming mean system depth of 1 m.

1. (b) perturbations resulting from significant river flow as well as tidal exchange in the August data set (or any other winter data).

2. Difficulties in establishing a suitable mean for water level measurements at Mandurah and Chimneys.

3. Non-stationarity of the volume flux data set due principally to 1(b) above.

5.5. Conclusions

The measurement of tidal exchange by direct current measurement at Mandurah Bridge has enabled us to determine not only volume and salt fluxes throughout the period of the two field exercises (February 12 - 17; August 13 - 18; 1978), but also nutrient losses from the system. This latter information was only really of value in August when estuarine concentrations of nutrients were two orders of magnitude above ocean levels.

Regrettably, however, we are not able at this stage to produce a total nutrient budget for Peel Inlet and Harvey Estuary on this basis because we are unable to generate a complete weekly volume flux estimate from a data set of only two weeks duration.* At the time of writing only one year's (1978) water level measurements for Mandurah and Chimneys was available. Further work on this is proceeding, notably by the CRES team, with the aim of estimating nutrient loss to the ocean. Indeed the "flux model" is only of value insofar as it assists in achieving this goal.

Loss to the ocean might conceivably be estimated by using the aforementioned "flux model" to estimate flow, summing flows on say a 5 day increment, then multiplying these sums by nutrient concentrations measured weekly in the Sticks Channel. However it seems likely that variations in the "spot" nutrient concentrations might be so great that applying such measurement to a period as long as one week could lead to gross over or under estimation of loss to the ocean.

* However, two linear models (summer, winter) may have produced better results.

6. GROUNDWATER INPUTS

6.1 Previous Studies

A large number of bores and wells extract water from the shallow, unconsolidated quartenary sediments surrounding Peel Inlet and Harvey Estuary, chiefly in the south-eastern region. These are used to supplement scheme water for farm storages and are of widely varying yield and quality. McArthur and Bettenay (1960) and Morgan (1969) have described both the soils and hydrogeology of the area.

In April, 1977, approximate levelling was carried out on 64 such bores using Paulin (aneroid) altimeters, and from these altitudes contour trend lines were sketched by the Geological Survey of Western Australia (Black et al 1975). However without precise determinations of levels of bore hole collars and measurement of depth to standing water over short time intervals, it was apparent that insufficient data existed to even roughly compute groundwater flow rates. Furthermore, such data as existed on nutrient and salinity levels in these bores was scattered and not inter-related.

The general topography of the coastal plain (which is approximately 22 km wide) has been described by Woolnough (1920) and McArthur and Bettenay (1960). As the plain rises gently from the Inlet to the foot of the Darling Scarp it would be expected that water table contours in the unconsolidated sediment would be very flat. From the Serpentine River at Barragup to Pinjarra, a distance of some 12 km., the topography rises only 7 to 8 metres or about 1 in 1500. Beyond Pinjarra to the east, the rise to the foot of the scarp is much steeper.

6.2 Bore Hole and Well Survey - January, 1977.

In order to quantify the size and nature of groundwater inputs to the total estuarine water balance equation, it was decided to accurately determine the altitude (reduced to Australian Height Datum (A.H.D.)) of as many bores and wells as possible, as well as measuring the depth to standing water. As most bores were in more or less continuous use by local farmers, this was to be supplemented by one or more east-west transects to determine the level (A.H.D.) of water in the bore over as short a time period as possible. In this way it was hoped to avoid errors due to recent abstractions of water.

6.2.1 Water Levels

In all, 117 bores or wells had the elevation of their collar determined to A.H.D. and depth to water measured. This was done with a small probe consisting of a PVC float which rose to close an electric circuit when water was reached. This caused a lamp to burn at the surface and depth was read off on the graduated cable. This simple instrument was designed specifically for the task, being only 1 cm in diameter and thus capable of penetrating even the narrowest bore casing. A large scale (approx. 1:32000) map showing the A.H.D. of bores and water is included in Appendix V Fig.6.1 shows water table contours interpreted from these levels, principally to the east of Harvey Estuary. Along the northern shore line of Peel Inlet, water table levels are only a centimeter or so above A.H.D. so that it is reasonable to deduce that little, if any ground-water flow into the estuary can occur. Indeed, to the west of both Peel Inlet and Harvey Estuary

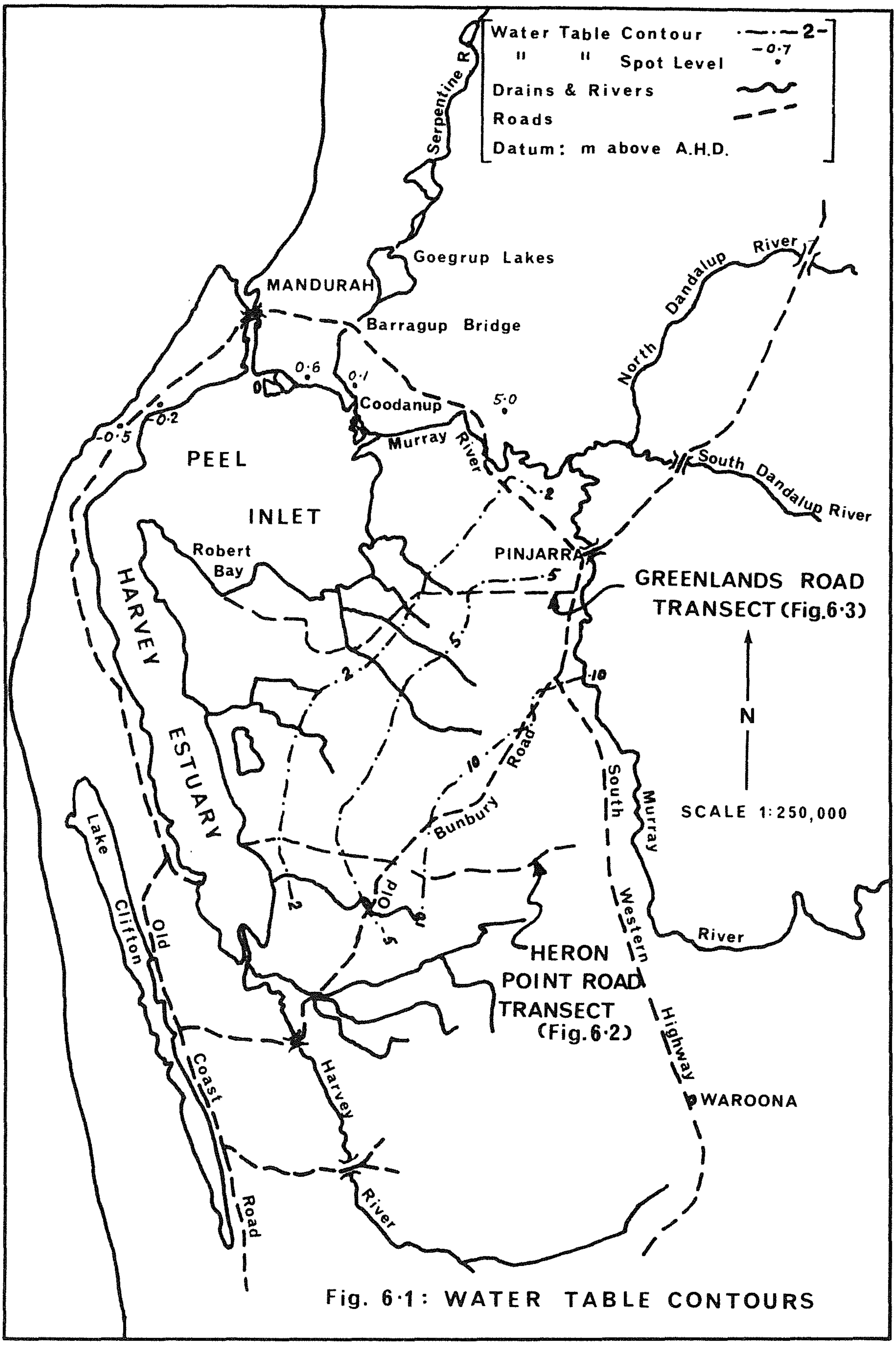


Fig. 6·1: WATER TABLE CONTOURS

those few shallow bores which exist encounter water at depths marginally below A.H.D. From this we can conclude that <u>in this area</u> the direction of groundwater flow is away from the estuary and towards the coast. Evidence from the Geological Survey of Western Australia (Lord, pers.comm.1975) seems to support this.

6.2.2 Water Quality Analyses

Samples from some 36 of these bores, more or less uniformly distributed about the area surveyed (see Fig.6.1) were analysed for the following water quality parameters:-

pH
turbidity
colour
odour
conductivity (mS/cm)
Na Cl (mg/l)
total nitrogen (N_T) (mg/l)
total phosphorous (P_T) (mg/l)

At that time (January, 1977) it was felt that groundwater could constitute a significant source of nutrient (N_T and P_T) input to the estuary, even though it was already suspected that groundwater was not likely to be a high percentage of total water inputs. As 6.3.2 shows, the latter hypothesis proved to be substantially correct.

The results of these analyses appear in full in Appendix V . A wide range of salinities for the various bores conforms in general to the advice of Lord (pers.comm.1975) and with the Geological Survey of W.A. criteria of:-

< 1000 mg/l - potable
$1000 - 5000$ mg/l - brackish
> 5000 mg/l - saline

as shown on their plans of the hydrogeology of the area.

For the 36 bores sampled, Na Cl ranged from 91 to 4220 mg/l about a mean of 879 and a huge standard deviation of 960 mg/l. Similarly the mean value of N_T was 0.21 mg/l with an S.D. of 0.19 mg/L and a number of samples had nitrogen content that was undetectable.

Much more uniform however was the P_T level which was a high mean of 0.48 mg/l and an S.D. of only 0.16 mg/l. This very high figure for the groundwaters of the Harvey - Waroona - Pinjarra Drainage district is in general agreement with the analyses from samples taken from the drains in the area and the Harvey River (see Chapter 4). There are 13 bores along the east-west transect adjacent to Fisherman's Road and Heron Point Road and these have a P_T mean of 0.50 mg/l and an S.D. of only 0.11 mg/l. This compares favourably with the nearest drain, South Coolup which is only 1-2 km to the south. Not surprisingly its mean P_T determination is 0.58 mg/l.

6.2.3 Groundwater Slope (i) Summer (ii) Winter

In order to assess the groundwater slope towards the estuary from the Darling Scarp, two East-West transects were established along the general lines of Heron Point Road and Greenlands Road (see Fig.6.1). There was a large number of well spaced bores along these roads (11 on the Heron Point Road - Fisherman's Road line and 8 on the Greenlands Road). Levels to A.H.D. of the bore hole collars or other reference point having previously been taken, checked and the level circuit closed, the water level was determined in each case over as short a time period as possible (< 2 hours for the full transect). This was done to obviate the possibility of errors due to recent pumping or other abstractions.

The exercise was repeated in July, 1977, and the resultant cross sections are plotted as Figs.6.2 and 6.3. Though in general, the water table rose in July as would be expected, the overall water level closely follows the surface slope and is reasonably uniform throughout.

Given the approximations inherent in other elements of the groundwater flow computation, it suffices to express the general slope from the scarp to the estuary as approximately 1 in 1000 for both the summer and winter condition. It should be noted however that the winter of 1977 was exceptionally dry and that greater slope might be anticipated under wetter conditions.

6.3 Groundwater Flow Rates

6.3.1 Geology - Estimation of Hydraulic Conductivity

The quaternary sediments of the region (mainly river alluvium, delta mud and leached sand) are shown by G.S.W.A. bore hole logs to have a thickness of approximately 10 metres, though clearly the depth varies from bore to bore. Hydraulic conductivities have not been widely determined from pumping tests, but it is suggested (Allen, pers.comm.1978) that a figure of 5 $m^3/day/m^2$ applicable to the high yielding Gnangara Mound to the North could be used as an extreme value.

6.3.2 D'arcy Flow

The eastern shore line of Harvey Estuary together with the north eastern portion of Peel Inlet to the Murray River delta has a perimeter of approximately 40 km. This means that application of the D'arcy equation; viz.,

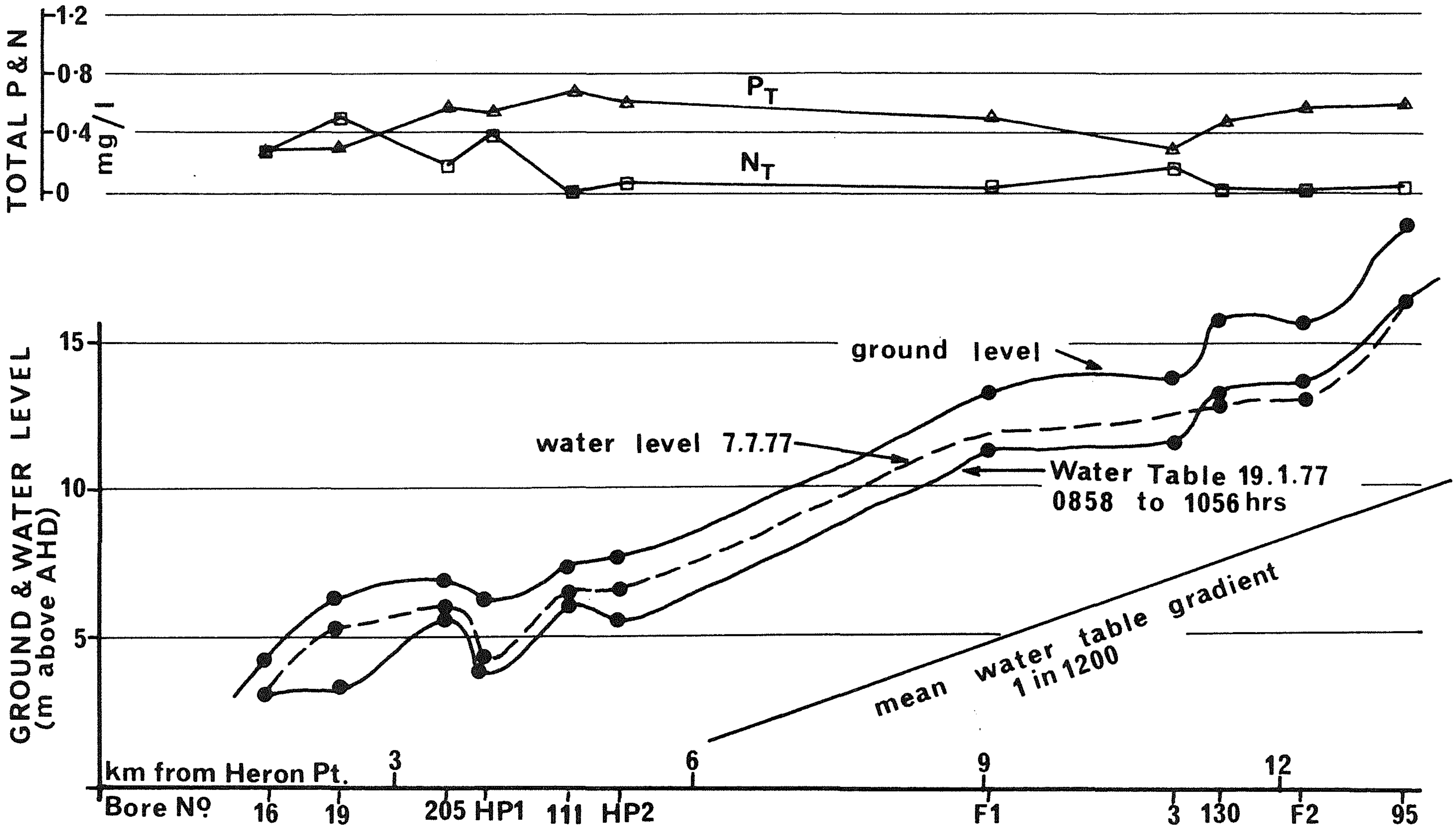


Fig. 6·2: GROUND WATER SURVEY - Heron Point Road Transect

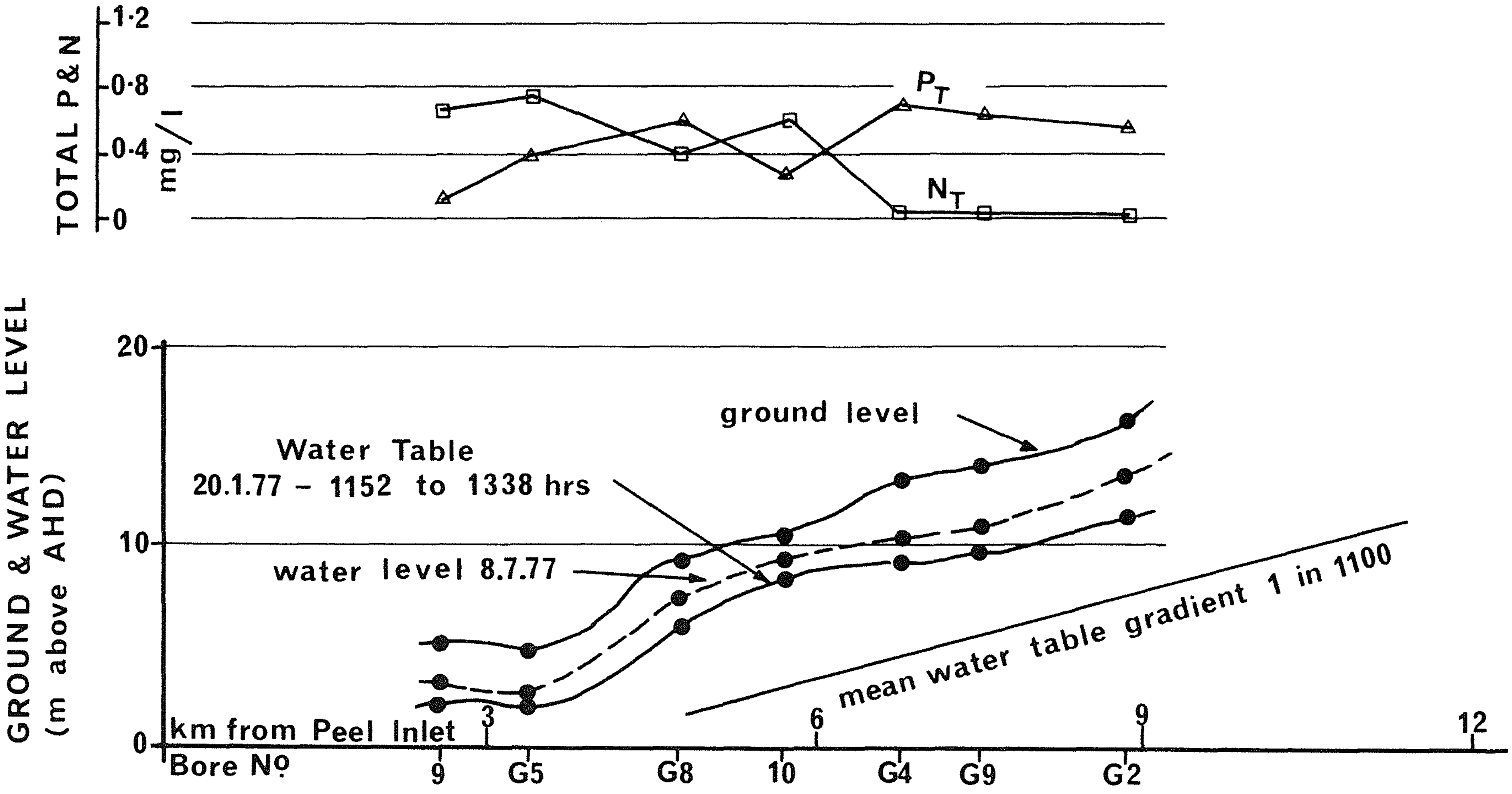


Fig. 6·3: GROUND WATER SURVEY - Greenlands Road Transect

$$Q = KAS$$

where Q = groundwater flow in m^3/day

A = cross sectional area in m^2

S = groundwater slope (dimensionless)

K = hydraulic conductivity in m^3/day/m^2

yields $Q = 5 \times (10 \times 40 \times 10^3) \times 0.0001$

$= 2000$ m^3/day

If the assumption is made that a similar groundwater slope exists around the entire estuary perimeter (Peel + Harvey) and, as the January, 1977, borehole survey and Fig.6.1 reveal, this is unlikely, then the perimeter involved is roughly doubled to 80 km. Thus an extreme upper bound for groundwater flow would then be:-

$Q = 4000$ m^3/day

Groundwater flow rates are very much less than surface water discharges. Thus the groundwater contribution to total flow is much higher in a very dry year than in an average or wet one. The estimate of total river and drain flow plus direct precipitation on the estuary for the exceptionally dry 1978/79 water year was 357×10^6 m^3. On the basis of the above calculations we have:

River, drain and direct precipitation $\simeq 357 \times 10^6$ m^3
Groundwater (365 x 4000 m^3/day) $\simeq 1.5 \times 10^6$ m^3
(or 0.4%)

Of greater concern might be that despite the fact that groundwater constitutes < 1% of total water input to the estuary, its nutrient concentration is so much greater than that of surface waters that its flow is still significant. However (see 6.2.2) mean P_T for the bores samples was 0.48 mg/l. A mean value for the Harvey River from quarterly sampling (April, 1972 - March, 1978) done by the Government Chemical Laboratories (Schulz 1979) is given as 0.22 mg/l with very much higher concentrations (up to 0.65 mg/l) in winter.

Thus we could hypothesise that the nutrient concentration of groundwaters might be (in the case of P_T) about twice that of the Harvey River and Serpentine River and ten times that of the Murray River. In 1978/79 this would enhance its contribution to the nutrient input by a factor of approximately 2, so that:-
Groundwater nutrient contribution ≃ 1% of total.

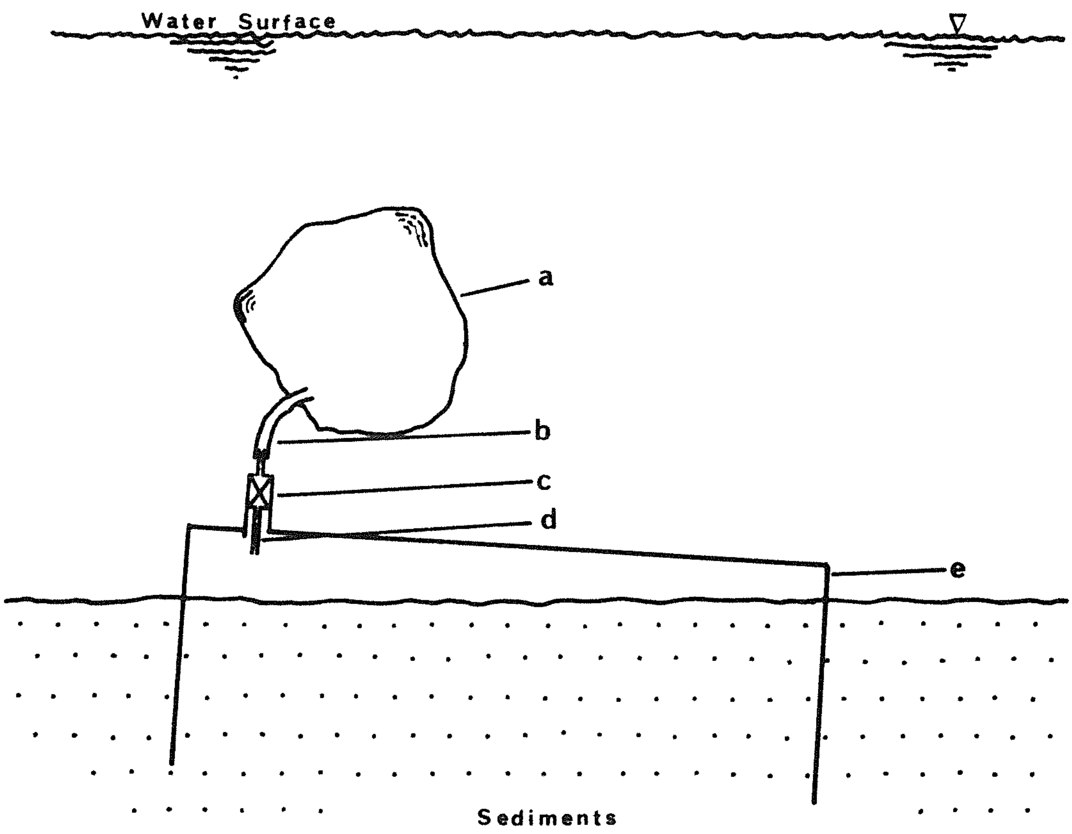
As was seen in Chapter 4, the principal source of N_T is the Murray River and N_T concentrations of groundwater samples are little if any greater than those found in the Harvey and Serpentine Rivers. It would therefore seem reasonable to regard 1% as an extreme upper bound for groundwater nutrient contribution in the absence of any direct evidence to the contrary.

6.4 Measurement of Seepage Flux

6.4.1 Methodology

To supplement the work described in 6.2 and 6.3 which provides largely indirect or inferred estimates of groundwater flux, it was decided to carry out a series of direct measurements of seepage flux using a technique described by Lee (1977). The great advantage of the method is that it does not require measurements or estimates of permeability of the sediments normally determined during pumping tests.

In essence, the technique consists of enclosing a small area of the estuary bottom with a cylinder vented to a plastic bag. Fig.6.4 shows diagrammatically the arrangement used. The cylinder or "groundwater interceptor" (G.W.I.) is turned slowly, open-end down into the sediment until its top is about 2 cm above the sediment surface. After a short time,



a – plastic bag
b – pvc tube
c – valve
d – copper pipe
e – $0{\cdot}292\,m^2$ G.I. cylinder

Fig. 6·4: SECTIONAL VIEW of GROUNDWATER INTERCEPTOR
[after Lee [1977]]

a plastic bag connected to a short length of small bore tubing is attached to the end of the opening and the top opened. The bag, in this study, was replaced weekly, its contents measured and temperature and conductivity recorded. Temperature and conductivity of the adjacent estuary water was likewise recorded.

If there is any positive groundwater seepage <u>into</u> the estuary this water will collect in the bag since -

(a) the prevailing groundwater head (slope) will cause a net upward velocity component, and

(b) the estuary is denser water than the seepage water (see TABLE 6.1)

Lee proposes a formula:-

$$v = \frac{1.075V}{t}$$

where V is litres of water entering (+) or leaving (-) the bag,

t is hours of elapsed time

v is seepage velocity in micrometers per second (μm/sec)

The factor 1.075 converts units of volume, time and area covered by the cylinder (0.255 m^2) to equivalent units of velocity (μm/sec).

Some small problems were predictably encountered with the device. If the cylinder was not positioned with its hole near the highest point, the accumulation of gas from the sediment tended to reduce seepage. Occasionally blowouts were experienced and from time to time excessive wave action removed the plastic bag. A small quantity (< 10 ml) of water unavoidably entered the bag during replacement each week.

Two cylinders were constructed of galvanised steel (to minimise corrosion) of diameter 0.6096 m which gave a surface area of 0.292 m^2 as opposed to the 0.255 m^2 described by Lee (1977). One was installed at Robert Bay, the other at Coodanup (see Fig.6.1) and measurements taken weekly from 1/6/79 to 21/9/79.

6.4.2 Results

TABLE 6.1 lists the volumes collected and temperature and conductivity of seepage and surrounding estuarine water. Volumes collected were very small indeed; so small in the case of the Robert Bay G.W.I. that it was lifted after one month and moved to a second site at Coodanup. Where conductivity of estuarine and collected water is similar (given slight variations due to temperature differences), we can postulate that the "seepage water" is in fact estuarine water forced into the plastic bag under increased tidal head.

At best it might be said that an average of < 100 mL was collected at Coodanup each week though it is doubtful that much of this water is in fact groundwater seepage. More often, the volume collected was much less than that, and we know that at Robert Bay, for example, little or no water was collected. However, for the purposes of calculation, use 100 ml/week and:-

Surface area covered by G.W.I. $= 0.292\ m^2$
and this area yields 0.1 l/week $= 0.1 \times 10^{-3}\ m^3$/week
Area of Harvey Estuary/Peel Inlet $\simeq 133 \times 10^6\ m^2$
So that $133 \times 10^6\ m^2$ yields $= \dfrac{133 \times 10^6 \times 0.1 \times 10^{-3}}{0.292}$
$\simeq 45,000\ m^3$/week
$\simeq 6,500\ m^3$/day

c.f. 4000 m^3/day (6.3.2.)

The microscopic amounts of water collected and the uncertainty as to its origin (whether groundwater or tidal) make the aforementioned computation unreliable to say the least. However, it does at least confirm the assumption of 6.3.2, that groundwater flow constitutes but a tiny percentage of total input to the estuary.

Date	COODANUP (1)			ROBERT BAY		
	Volume (ml)	G.W.I. Temp/Cond*	Bottom Temp/Cond	Volume (ml)	G.W.I. Temp/Cond	Bottom Temp/Cond
1.6.79			25/56.2			25/55.0
8.6.79	≃ 40	25/54.6	25/54.4	-	-	25/53.2
15.6.79	≃ 200	19/48.9	17.7/43.9	≃ 40	18.8/48.8	16.6/42.9
		25/52.3				
22.6.79	≃ 40	26.2/54.6	25.4/53.2	≃ 40	25.4/56.1	25.4/50.4
		25.6/55.5				
29.6.79	105	17.1/44.5	17.1/28.6	46	17.1/36.7	-
6.7.79	87	19/42.8	17.9/42.1		lifted	
13.7.79	115	21.2/37.3	21.4/41.7			
20.7.79	125	23.8/43.2	24.1/11.9	COODANUP (2)		
27.7.79	80	19.9/24.8	19.5/24.9			
3.8.79	230	22.9/23.5	25.7/25.6			
10.8.79	40	-	13.6/23.2	291	16/20.1	15/19.2
17.8.79	≃ 5	-	16/27.0	320	20/21.7	16.1/30.7
24.8.79	62	20/24.9	19.3/5.3	wash away	-	19.4/12.3
31.8.79	170	21.1/25.9	20.4/28.5	30	19.8/27.0	20.4/26.2
7.9.79	20	22.0/17.6	20.8/12.9	wash away	-	20.4/16.0
14.9.79	15	-	20.8/19.0	25	20.1/18.7	20.9/24.0
21.9.79	40	21.7/24.6	21.4/36.1	30	21.9/27.3	21.5/33.9
21.9.79		lifted			lifted	

Temp. in °C: Conductivity in mS/cm.

TABLE 6.1 : Seepage Flux as determined from Groundwater Interceptors, Peel Inlet.

6.5 Conclusions

6.5.1 Groundwater as a Water Balance Input

Groundwater seepage flux was determined, so far as available funds permitted, from existing bore hole water table contours using the well-known D'arcy equation for flow in porous media at very low Reynolds Numbers. The contours thus estimated confirmed the hypothesis that the very flat surface terrain would be reflected in a similarly flat unconfined aquifer in the quaternary sedimentsof the Pinjarra plain to the east and north-east of the system. This view was reinforced by the results obtained using the method of groundwater "interceptors". It might reasonably be argued that the siting of these devices is critical - significant groundwater flux might very well occur along specific "preferred paths" having unusually high or unrepresentative permeabilities. There seems little doubt that insufficient head exists around the estuary to significantly alter the value of "S" in the D'arcy computation Q = KAS for the local unconfined aquifer system.

This means that a very much higher value of hydraulic conductivity "K" is required than that postulated. There seems little geological evidence to support this possibility. In his study of the hydrogeology of the Swan Coastal Plan, Kwinana - Pinjarra area, Morgan (1969) describes the sediments surrounding the estuary as "Coastal limestone (upper unit), alluvium, marly estuarine beds, drift sand, delta mud and contemporary river alluvium ...." Permeabilities vary from "low" to "good" but there is no evidence that the value of $K = 5\ m^3/day/m^2$ is other than a high estimate.

One cannot discount the possibility of one or more pressure aquifer systems discharging higher volumes of groundwater into the estuary, but we have no hard evidence of this, and conclude that the probable maximum groundwater seepage flux is < 1% of the total water input.

6.5.2 Groundwater Nutrient Input

As discussed in 6.3.2, given the higher concentrations of both total nitrogen and total phosphorous in bore hole sample analyses, the total nutrient input to the estuary from this source will be a greater percentage of the total nutrient balance than that suggested by volumetric considerations alone. However, even under the dry conditions prevailing throughout the study this is unlikely to exceed 1% of the total input. As was revealed in Chapter 4, the overwhelming majority of both N_T and P_T enters the system during a few weeks of high winter river flow.

7. WATER BALANCE

7.1 General

The simplest application of the continuity equation to any quantitative study of water occurrence, distribution and movement in a specific area takes the form of the water balance equation:

$$\text{Inflow} = \text{Outflow} \pm \Delta\text{Storage} \quad (7.1)$$

In the Peel Inlet and Harvey Estuary, if every possible sub-term of this equation can be quantified it will theoretically enable us assess the overall measurement errors in the hydrology and meteorology. As in most hydrological studies, this is not really an achievable aim and one or more of the terms (e.g., change in soil moisture storage) usually proves difficult to assess on a system-wide basis.

The time period over which the equation is applied must necessarily be quite large and in this study, at least two of the terms were not measured or were not measurable. Thus one term must become a residual in the equation, and the subjective assessment of errors in the measured quantities is critical in the evaluation of the accuracy of this residual.

7.2 The Peel Inlet & Harvey Estuary Water Balance Equation

For this system we may expand equation 7.1 thus:

$$Q_M + Q_S + Q_H + G_W + P_I \pm \Delta S = Q_O + E \quad (7.2)$$

Fig.7.1 depicts this equation graphically where:

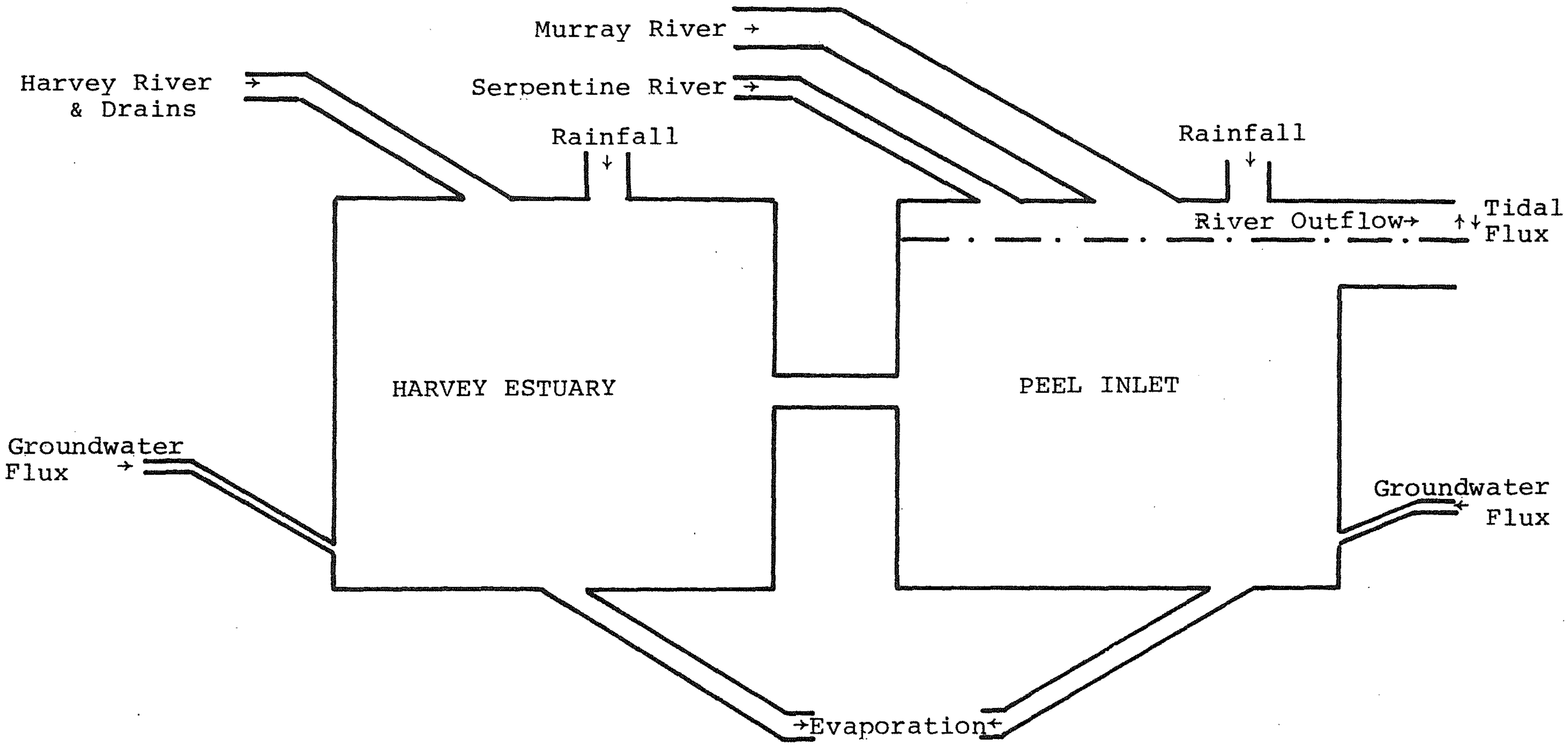


Fig. 7.1 : Peel Inlet/Harvey Estuary: Water Balance Model

Q_M is Murray River flow volume
Q_S is Serpentine River flow volume
Q_H is Harvey River flow volume
G_W is Groundwater flow volume
P_I is Thiessen averaged rainfall volume directly occurring on the estuary
ΔS is Change in storage volume
Q_O is River outflow to sea volume
E is Estuary-wide evaporation volume

(units are $m^3 \times 10^6$ throughout)

If we examine the individual terms, we find that

1. River flow terms Q_M, Q_S, and Q_H have been expressed on a daily, weekly, monthly or annual basis.
2. The groundwater term G_W has been shown (Chapter 6) to be very small (<1% of the surface inflow components).
3. Rainfall occurring directly on the estuary itself (P_I) has been measured at 3 point sources and assessed on an areal basis by the use of the Thiessen polygon technique.
4. Evaporation, E, often used as a residual term in water balance studies (Mann & McBride, 1972) has been the subject of considerable attention in this project. Despite the usual uncertainties in evaporation estimation it is felt that this term is evaluated (on an annual basis at least) to an accuracy of no worse than $\pm$ 20%.
5. We are thus left with the joint problems of change in storage ΔS (i.e., change in water level due to either (i) tidal status, or (ii) river inflow) and river outflow to the sea Q_O. What we have is not a closed, but an open dynamic system. The chosen time increment for water balance evaluation must therefore effectively eliminate the term ΔS. This increment, which

is the period over which net volume exchange between estuary and ocean is zero, varies in the short term randomly from about 5 to 15 days. Thus, even if mean estuary water level were available on a daily basis throughout the study period (and it is not) we would be confronted with the additional problem of a variable time increment.

6. This leads to the inevitable conclusion that we must choose a time interval of sufficient length to ensure that $\Delta S = 0$ or is insignificant in terms of the other components if we are to estimate river outflow to the sea; i.e., over a period of 1 year $\Delta S \simeq 0$ and it is possible to quantify the inflow/outflow terms as follows:-

YEAR 1977/78 (Volumes in $m^3 \times 10^6$)

Inflow		=	Outflow	
Q_M	289		E	190
Q_S	65		Q_O	≃ 471*
Q_H	206			
G_W	2			
P_I	99			
ΣInflow =	661		ΣOutflow =	661

*Q_O is the residual term and is ≃ 84% of 1977/78 river inflow.

YEAR 1978/79 (Volumes in $m^3 \times 10^6$)

Inflow		=	Outflow	
Q_M	86		E	177
Q_S	55		Q_O	≃ 197
Q_H	150			
G_W	2			
P_I	81			
ΣInflow =	374		ΣOutflow =	374

*Q_O is the residual term and is ≃ 67% of 1978/79 river inflow.

It might be thought feasible to repeat the above calculations on a seasonal basis, since there is such a great difference between the summer and winter condition; e.g., in 1977/78 < 5% of the river flow occurred in the "summer" months November, December, 1977; January, February, March and April, 1978.

This leads to the result that:

1. Summer 1977/78 (November - April)

ΣInflow = 30.8

E = 125.8

if ΣOutflow = 30.8; then $Q_O \simeq - 95.0$

Since over this period, mean estuary water level would not change significantly, the explanation for this obviously spurious result is that the huge evaporative losses (which easily accommodate the small inputs with a considerable residual loss as demonstrated by the hypersaline condition*) are made up by tidal exchange with the infinite ocean reservoir.

Furthermore, for the "winter" months of the same water year (October, 1977; May, June, July, August and September, 1978) we find that:

2. Winter 1977/78 (October 1977; May - September, 1978)

ΣInflow = 630.2

E = 64.2

if ΣOutflow = 630.2, then $Q_O \simeq 566.0$

---

* The surplus of E over Q_O of approximately 25% suggests that estuarine salinity in summer should exceed oceanic salinity by roughly that amount. If we assume ocean salinity $\simeq$ 35 ppt., then estuarine salinity should $\rightarrow$ 45 ppt., which is confirmed by the results.

This rather curious result suggests that more river water is lost to the sea over the winter months than has actually entered the estuary ($\simeq 535m^3 \times 10^6$). The explanation must be that once again ΔS has $\rightarrow 0$ because river outflow and tidal exchange water are indistinguishable; i.e., the additional loss term, over and above river input and evaporative loss has been provided by tidal exchange.
Thus we conclude that only over a time period of one year is it possible to balance equation (7.2) in any meaningful way.

7.3 Error Estimates

It is clearly very difficult to objectively determine relative or absolute errors in the water balance equation terms. Errors in gauging flow by current metering and subsequently from rating curves are dependent upon such variables as the number of sections measured, number of gaugings used in establishing the rating curve, quality of the river control and the necessity to frequently estimate flows from a extrapolation of the stage - discharge curve. For the Murray River, which has a reliable PWD long term flow record, we must add the errors in dye dilution gauging used to route flows from 614 006 to Pinjarra Weir (see 3.2.4).

Percentage errors in the groundwater flow estimate are certainly large, but flow volumes are so small that this is not of great concern.
The accuracy of rainfall measurement is a function of the density of the pluviometer network and thus the extent to which partial area storms bias the averaging technique.
Evaporation estimates will always be subject to considerable errors as has been discussed at length in 2.5. However, as with the other terms, the selection of a large time increment will tend to minimise percentage errors.

Finally, however, the estimate of errors is to a large extent, subjective, and based upon the field interpretation of the observer. We therefore suggest the following errors as applicable to this study:-

Inflow		Outflow	
Q_M	$\pm$ 20%	E	$\pm$ 20%
Q_S	$\pm$ 30%	Q_O	$\pm$?
Q_H	$\pm$ 20%		
G_W	$\pm$ 20%		
P_I	$\pm$ 15%		

We can estimate the error in river outflow thus:

% error in Q_O (f_O)

let e_i = absolute error; f_i = fractional (%) error

$$f_O = \frac{e_M + e_S + e_H + e_G + e_P + e_E}{Q_M + Q_S + Q_H + G_W + P_I - E} \tag{7.3}$$

(maximum possible error)

for 1977/78

$$f_O = \frac{57.8 + 19.5 + 41.2 + 0.4 + 14.8 + 38.0}{268 + 65 + 206 + 2 + 99 - 190}$$

$= 0.364$

i.e., % error in $Q_O \simeq 36\%$ (max. possible error)

for 1978/79

$$f_O = \frac{17.2 + 16.5 + 30.0 + 0.4 + 12.2 + 35.4}{86 + 55 + 150 + 2 + 81 - 177}$$

$= 0.567$

i.e., % error in $Q_O \simeq 57\%$ (max. possible error)

These are, of course, maximum possible errors and reach frightening proportions. However, it is much more reasonable to state the most probable error in Q_O, (MPE) which is calculated from:-

$$\text{MPE in } Q_O = \frac{(e_M^2 + e_S^2 + e_H^2 + e_G^2 + e_P^2 + e_E^2)^{\frac{1}{2}}}{Q_M + Q_S + Q_H + G_W + P_I - E}$$

and we find:

<u>1977/78</u> MPE in $Q_O \approx 18\%$

<u>1978/79</u> MPE in $Q_O \approx 27\%$

8. CONCLUSIONS

The brief and tentative conclusions summarised below are strictly confined to the hydrology and meteorology of the Peel Inlet and Harvey Estuary system study. They relate solely to the "aims" outlined in the Introduction. Final conclusions must await the integration of all aspects of the total environmental study.

It would perhaps be more accurate to describe the somewhat negative list that follows as <u>problems</u> of a hydrological/meteorological nature inherent in the system during this period at least, rather than conclusions. No particular order of importance is implied.

1. The atypical climatic conditions encountered over the main period of the study (October, 1977, to September, 1979) make it difficult to extrapolate from the data base acquired. In particular, the very dry calendar year 1979 has added little new information.
2. Partly as a result of 1.(above) we find that for a large part of the year, evaporation is the dominant feature of the system and that the limited tidal exchange has a role that is even further diminished in consequence. We were also surprised to note that in the below average rainfall conditions encountered, precipitation directly on the water body of the estuary was such a high percentage of total inflow (see 2.2.4).

   As another result of 1., the Murray River recorded its second lowest annual discharge in 40 years of record. As this river system is (a) the biggest and (b) the only one adequately gauged prior to and throughout the study, this is particularly unfortunate in terms of extrapolating data such as nutrient loads.

3. The entire system is strongly seasonal in nature - < 5% of river flow occurs in the six summer months. Thus the "first flush" of nitrogen in winter (especially from the Murray River basin) is of great importance. It is to be regretted that the abnormal winter of 1979 prevented us from adequately recording this phenomenon in the final winter of the study.
4. The influence of compensation releases and coastal plain drainage on the principal source of phosphorous, the Harvey River Main Drain, is considerable. It alone, of all systems, continues to flow into the estuary throughout the year.
5. Our inability to more precisely evaluate the contribution of the Serpentine River is a matter of some concern. However, results from the new (April, 1979) gauging station on Serpentine Drain (614 030) may yet provide useful data before the final integrated report is completed.
6. In view of the probable errors in flow estimates for the Harvey River in June, 1978 (as revealed by the mathematical modelling), we would like to re-examine this work during the next few months to see if better estimates can be provided for the final report.
7. The nutrient flux/salinity data from the August, 1978, exercise at Mandurah bridge warrants closer examination to see whether estimates of nutrient loss to the ocean can be estimated on an annual basis. The principal investigator intends to explore this possibility at a water quality workshop at the Institute of Hydrology, Wallingford, Oxon, in early July, 1980.

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