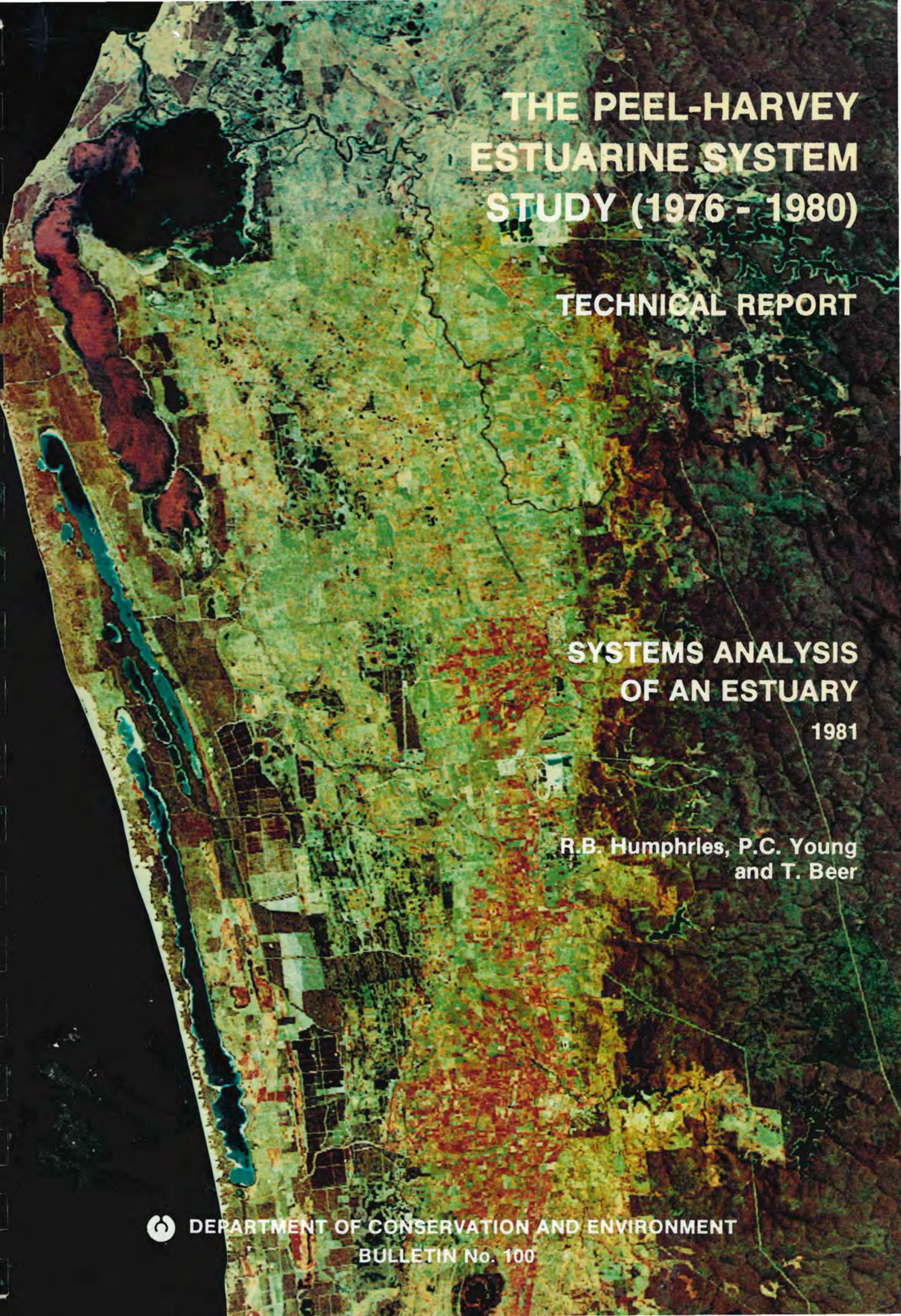


THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976 - 1980)

TECHNICAL REPORT

SYSTEMS ANALYSIS OF AN ESTUARY

1981

R.B. Humphries, P.C. Young
and T. Beer

DEPARTMENT OF CONSERVATION AND ENVIRONMENT
BULLETIN No. 100

A TECHNICAL REPORT to
THE PEEL-HARVEY ESTUARINE SYSTEM STUDY (1976-1980)

SYSTEMS ANALYSIS OF AN ESTUARY

by

R.B. Humphries, P.C. Young and T. Beer

Centre for Resource and Environmental Studies,
Australian National University

1981.

DEPARTMENT OF CONSERVATION & ENVIRONMENT

BULLETIN No. 100

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 provides an account of the Centre for Resource and Environmental Studies (CRES) contribution to the Peel-Harvey Estuarine System Study over the period June 1977 to June 1980. The Peel-Harvey Estuarine System Study arose out of a request from the Environmental Protection Authority of Western Australia to its Estuarine and Marine Advisory Committee (EMAC) to undertake an investigation of the Peel Inlet System; and it involved other contributions from a number of research groups in Western Australia (see Hodgkin *et al.*, 1980). The report is in three parts: the first part presented in this volume outlines the various elements of the CRES research programme and reports the principal findings; the second part consists of Appendices containing more detailed descriptions of certain aspects of the work leading to that discussed in the present volume; and the final part presents all relevant numerical data in computer listed and plotted form. Note that the Appendices are not contained within this volume in order to reduce its size; the volume is, however, farily self-contained and the Appendices are available from the Western Australian Department of Conservation and Environment, if required.

The report has been prepared by Bob Humphries, Peter Young and Tom Beer on the basis of the work carried out by the CRES Applied Systems Group over the study period. Christina Sirakoff was responsible for much of the computing required in the preparation of Chapters 6 and 7; Mark Greenaway was a principal collaborator in the preparation of Chapter 9; and Ian Reynolds provided the draft of Section 10.3 of Chapter 10. Tony Jakeman, Mark Greenaway, Christina Sirakoff, and Ian Reynolds helped by reading and commenting upon the early drafts of Chapters. Alan Henderson was the principal research assistant responsible for data handling. We are indebted to Julie Cathcart and June Harries for typing the report so ably and for having so much patience with the authors.

We wish to emphasise that the CRES research programme has been a complete team effort with numerous individuals contributing in various ways. A list of CRES Team personnel and their contribution is given below.

Elizabeth Barta - illustrations
Tony Bayes - computer programming
Ruth Belin - research assistance
Julie Cathcart - secretarial, typing
Mark Greenaway - modeling, programming
Shirley Halton - research assistance
June Harries - secretarial, typing
Alan Henderson - research assistance
George Hornberger (Visiting Fellow) - speculative *Cladophora* modeling, hydrology, field assistance
Tony Jakeman - mathematics, modeling
John Kaldor - field assistance
Pat Michell - computer programming, data analysis, field assistance
Leonie Paynter - research assistance
Barbara Piper - secretarial, typing
Ian Reynolds - advice on requirements of cost-benefit analysis
Christina Sirakoff - data analysis, computer programming
David Smith - hydrology, dye tracer studies
Bob Spear (Visiting Fellow) - speculative *Cladophora* modeling, field assistance
Paul Steele - field assistance
Paul Whitehead - modeling, hydrology, field assistance

In addition to our own Team, we have greatly benefited from various joint projects with Ron Black of WAIT which have involved river dye tracing experiments, river routing models and other hydrological studies.

Peter Birch collaborated on the development of the *Cladophora* model (Chapter 9), and David Gordon, Arthur McComb and Rob Lukatelich provided data and discussions on matters biological.

Ann Huber, John Gabrielson and Dennis Kidby provided critical appraisal of biological and nutrient model proposals.

Don Wallace supplied tidal records, and collaborated on analyses of tidal data.

Finally, our special thanks must go to Ernest Hodgkin and Ross Field, for their stalwart efforts in project co-ordination, and to EMAC for funding our participation. We are also grateful to Professor Frank Fenner, the former Director of CRES, and to Professor Geoff Taylor, the present Director, for their help and encouragement.

VOLUME 1

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

VOLUME 2

APPENDICES

(Available from the Western Australian Department of Conservation and Environment and the Centre for Resource and Environmental Studies, Australian National University)

Appendix 1. Historical Analyses of Eutrophication in the Peel-Harvey Estuarine System

(AS/WP15 - Humphries and Henderson)

2. The CAPTAIN Package

(Young and Jakeman)

3. A Discussion of Badly Defined Systems

(P.C. Young manuscript)

4. *Cladophora* Simulation Modeling

(AS/R18 - Hornberger and Spear;
AS/WP9 - Humphries;
Humphries and Greenaway;
Greenaway, Humphries and Birch)

5. Murray River Flow Routing

(AS/R25 - Whitehead, Hornberger and Black)

6. Intensive Dye Experiments

(AS/WP1 - Humphries and Michell;
AS/WP6 - Humphries and Bayes)

7. Speculative Management Analyses

(Humphries, Beer and Young - IFAC paper, Weed Management)

VOLUME 3

Time Series Plots of the Weekly Sampled Data

(Available from the Western Australian Department of Conservation and Environment and the Centre for Resource and Environmental Studies, Australian National University)

1. INTRODUCTION

1.1 History and Aims of the Study

Accumulation of algae on the beaches of Peel Inlet (see Figure 1.1, Plate 1.1) became a noticeable problem in 1969-70 (Cross 1974, Hodgkin 1979, Hodgkin and Lenanton 1980). In 1976, the Environmental Protection Authority of Western Australia asked its Estuarine and Marine Advisory Committee (EMAC) to undertake an investigation of Peel Inlet, partly to:

(i) define the causes of green algal accumulation on the shores of Peel Inlet;

(ii) suggest possible methods for the control of these algae.

(iii) gain an understanding of the estuarine system so that environmental problems can be foreseen, and management decisions made on the basis of sound knowledge.

The principal nuisance alga in the Peel-Harvey System is a benthic *Cladophora* species, which grows as spherical clumps or balls, typically forming extensive beds in some areas of Peel Inlet. (Atkins *et al*, 1977). The *Cladophora* beds vary in thickness, usually from 1-10cm deep, though they may reach 40-50cm deep in places. During high rates of photosynthesis, the filamentous balls entrap oxygen bubbles, and some superficial *Cladophora* balls become positively buoyant, and then rise into the water column. The floating balls are transported by water movement, and either sink elsewhere within the estuarine system, or accumulate in large banks on the beaches, where their decomposition affects the amenity of the beach. The Peel Inlet Management Authority periodically

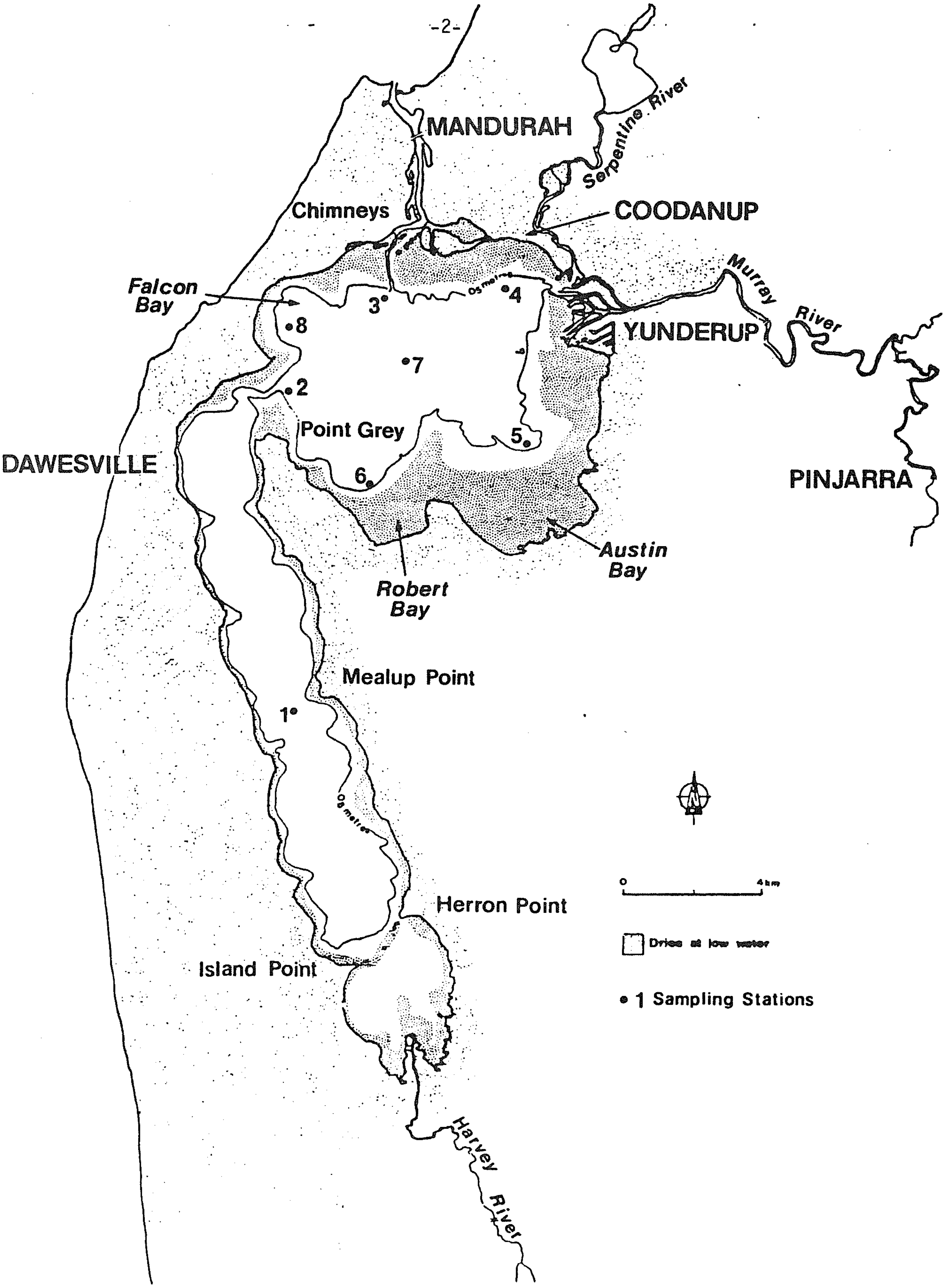


FIGURE 1.1 Weekly Sampling Sites

clears the beached algae with bulldozers, and carts the weed away (Plate 1.2).

This flotation and transport mechanism facilitates "migration" of *Cladophora* balls to all parts of the estuarine system (see Chapter 9), although the major viable benthic populations of the alga are restricted to Peel Inlet. Other benthic algal species occurring in the estuaries do not possess these peculiar mechanical properties of *Cladophora*, and so are not transported to the same degree, and do not form a major fraction of the accumulated algal drift on the beaches.

The predominance of *Cladophora* as the major nuisance organism in the system, together with the complexity of both the biology of *Cladophora* and of the estuaries and their catchments led EMAC to contract research on various aspects of the estuarine system to different groups, both in Western Australia and, in mid-1977 to the Applied Systems Group of the Centre for Resource and Environmental Studies, Australian National University, Canberra. The major role of CRES has been to provide a "systems component" to the estuarine study, as discussed in detail in Chapter 2.

Our ongoing role has been one of broad integration among the component groups in this study, and particularly a systematic appraisal of the available data, both contemporary and historical. This document reports on this contribution.

1.2 Eutrophication of the Estuarine System

Excessive plant growth in natural waters is usually due to an oversupply of the major plant nutrients, nitrogen and phosphorus, from the catchment of the water body. (Likens 1972, Wetzel 1975, Vollenweider 1968). Human activities within catchments, particularly clearing, agriculture and sewage production, increase the nutrient content of runoff entering the receiving water body. In the Peel-Harvey estuarine system's case, several mechanisms have been proposed to account for increasing eutrophication of the water bodies. These include (from Hodgkin, 1979):

- Clearing and cultivation of the coastal plain, mainly for cattle grazing, and the associated drainage of land to the estuary (the first drains were dug to Harvey Estuary in 1906 and others were not constructed until 1918).

- The increased application of artificial fertilizers.

- Construction of hills reservoirs and consequent reduced direct river runoff to the estuary and irrigation of the coastal plain.

- Growth of the resident Mandurah population (1,687 in 1954 to 8,800 in 1977), the enormous growth in the holiday population, and associated changes in water usage and sewage disposal.

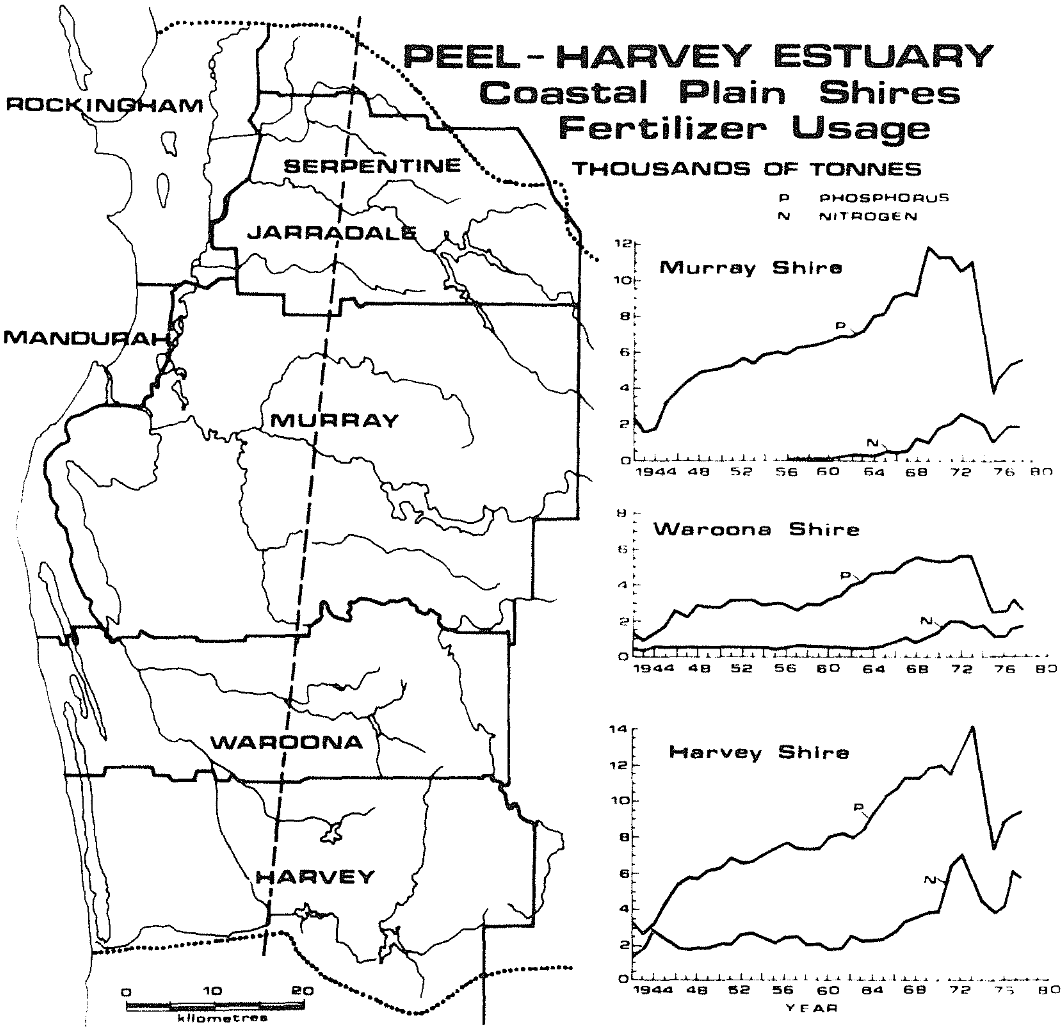
- Construction of training walls at Mandurah (1967). Before this the bar occasionally closed completely in summer and frequently was so shallow as to greatly restrict exchange with the seas. The last complete closure appears to have been December 1957 to May 1958.

- A great increase in boat usage and consequent disturbance of sediments by boats.

These suggestions require systematic evaluation, so that the major source(s) of nutrient input can be accurately identified and then, if possible, managed to reduce nutrient loadings into the system.

As a first step in such an evaluation, it is valuable to analyse historical data sets and compare them with contemporary data to establish whether eutrophication is actually increasing. Two approaches have been used to assess the likelihood of worsening eutrophication. Figure 1.2 shows the geographic relationships of the coastal plain shires to the estuaries together with time series plots of phosphorus and nitrogen-based fertilizer usage since 1942. Steady increases in usage are apparent between 1942

FIGURE 1.2


PEEL-HARVEY ESTUARY
Coastal Plain Shires
Fertilizer Usage
THOUSANDS OF TONNES
P PHOSPHORUS
N NITROGEN
ROCKINGHAM
SERPENTINE
JARRADALE
MANDURAH
MURRAY
WAROONA
HARVEY
0 10 20
kilometres
Murray Shire
0 2 4 6 8 10 12
P
N
1944 48 52 56 60 64 68 72 76 80
Waroona Shire
0 2 4 6 8
P
N
1944 48 52 56 60 64 68 72 76 80
Harvey Shire
0 2 4 6 8 10 12 14
P
N
1944 48 52 56 60 64 68 72 76 80
YEAR

and 1964. In 1964 the rate of usage increased dramatically until about 1968, then plateaued until 1973, when a cut in Federal Government subsidy payments to farmers provided an effective disincentive. It is interesting to note that the "*Cladophora* problem" in Peel Inlet dates from 1969-70, during the period of maximum fertilizer usage.

Other evidence of worsening eutrophication is obtained from the analysis of water chemistry and flow data collected between 1949 and the present. Water chemistry measurements were made by the CSIRO Division of Fisheries and Oceanography between 1949-56 (at irregular intervals, Rochford 1951); the Peel Inlet Management Authority (at quarterly intervals between 1972 and the present); and the current Peel-Harvey Estuarine System Study (between 31 August 1977 until 30 September 1979) (Humphries 1980). The Public Works Department of Western Australia provided the river flow data for analysis.

These historical and contemporary data sets have been used in two ways. First, Humphries (1980) (see Appendix 1) has examined the relationships between river flow and river nutrient load in the Murray and Serpentine Rivers, comparing the data available for 1949-56 with that from 1972-79. Figure 1.3 shows the relationships of $\log_{10}$ NO_2/NO_3-N and phosphorus loads to $\log_{10}$ instantaneous flow. Statistical analysis of these data indicate that the rivers now carry significantly more nitrogen and phosphorus per unit flow than they did in the 1949-56 period, and that eutrophication is worsening.

Second, Humphries and Henderson (1980) (Appendix 1) have compared the relationships between salinity and nutrients in Peel Inlet for the 1949-56 and 1972-79 periods. Salinity must be considered because it is known from observations on the Peel-Harvey system and other south-western estuaries that winter river flows contribute a flush of nutrients as well as fresh water into the estuaries, leading to a negative correlation between salinity and nutrient concentration (Rochford 1951, Schulz 1979, Hodgkin and Lenanton 1980). After examination of the historical and contemporary data for salinity-related bias, analysis has shown that mean total phosphorus concentrations have risen between three and four fold in Peel Inlet between

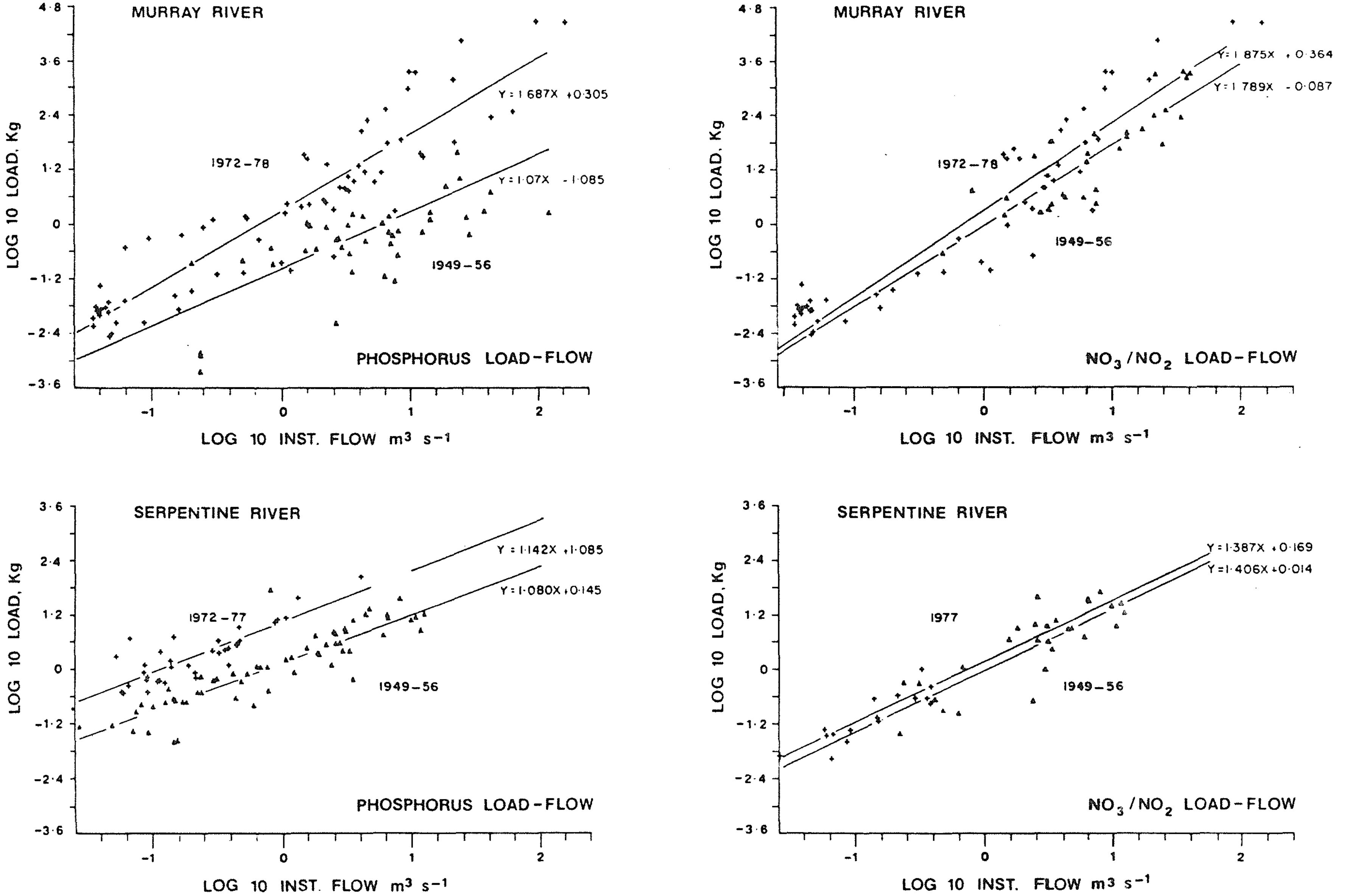


Figure **1.3** Comparison of 1949-56 and 1972-78 load-flow relationships of phosphorus and nitrogen in the Murray and Serpentine rivers.

the 1949-56 period and 1977-79. On the other hand, mean oxidised nitrogen (NO_2/NO_3-N) concentrations did not differ significantly, between the two sample periods. Unfortunately this comparison was affected by the low accuracy of the 1949-56 chemistry and by sample collections biased towards low salinity, and hence high nitrogen concentrations. As a result, the possibility of higher contemporary nitrogen loadings into the estuaries cannot be discounted, and is almost certainly occurring.

In summary, the comparison of historical and contemporary water chemical data has shown that the eutrophication of Peel Inlet, at least, is increasing. These analyses also suggest that the inflowing rivers have been the dominant source of nutrient inflow to the estuaries, rather than the other possible mechanisms listed above. This suggestion is thoroughly examined in both Chapter 8 of this report, where nutrient gains and losses by the estuaries are estimated, and by Black and Rosher (1980), who estimates the nutrient contributions from the groundwater. Also, Gabrielson (1981) and McComb *et al* (1980) provide estimates of nutrient storage in the sediment and algal biomass compartments of the system.

1.3 Distribution of the *Cladophora* Problem

An early requirement in the study of a plant population such as *Cladophora* in Peel Inlet, is the definition of the area in which it occurs. For this reason, Humphries (1978) estimated total algal bottom cover within the 0.5M contour early in this study during the February 1978 field exercise. Subsequent studies by the Botany group (McComb *et al* 1980) have further improved the precision of our knowledge of *Cladophora* distribution and biomass. Humphries' data are shown in Figure 1.4. The Figure reveals that the major algal beds are restricted to two areas: the eastern third of Peel Inlet, from Coodanup to Austin Bay; and Falcon Bay on the western side of Peel Inlet. The subsequent surveys have substantially confirmed this distribution, but have also shown that *Cladophora* is mobile and that, within these broad areas, *Cladophora* abundance varies with time. Large amounts of *Cladophora* do not occur in

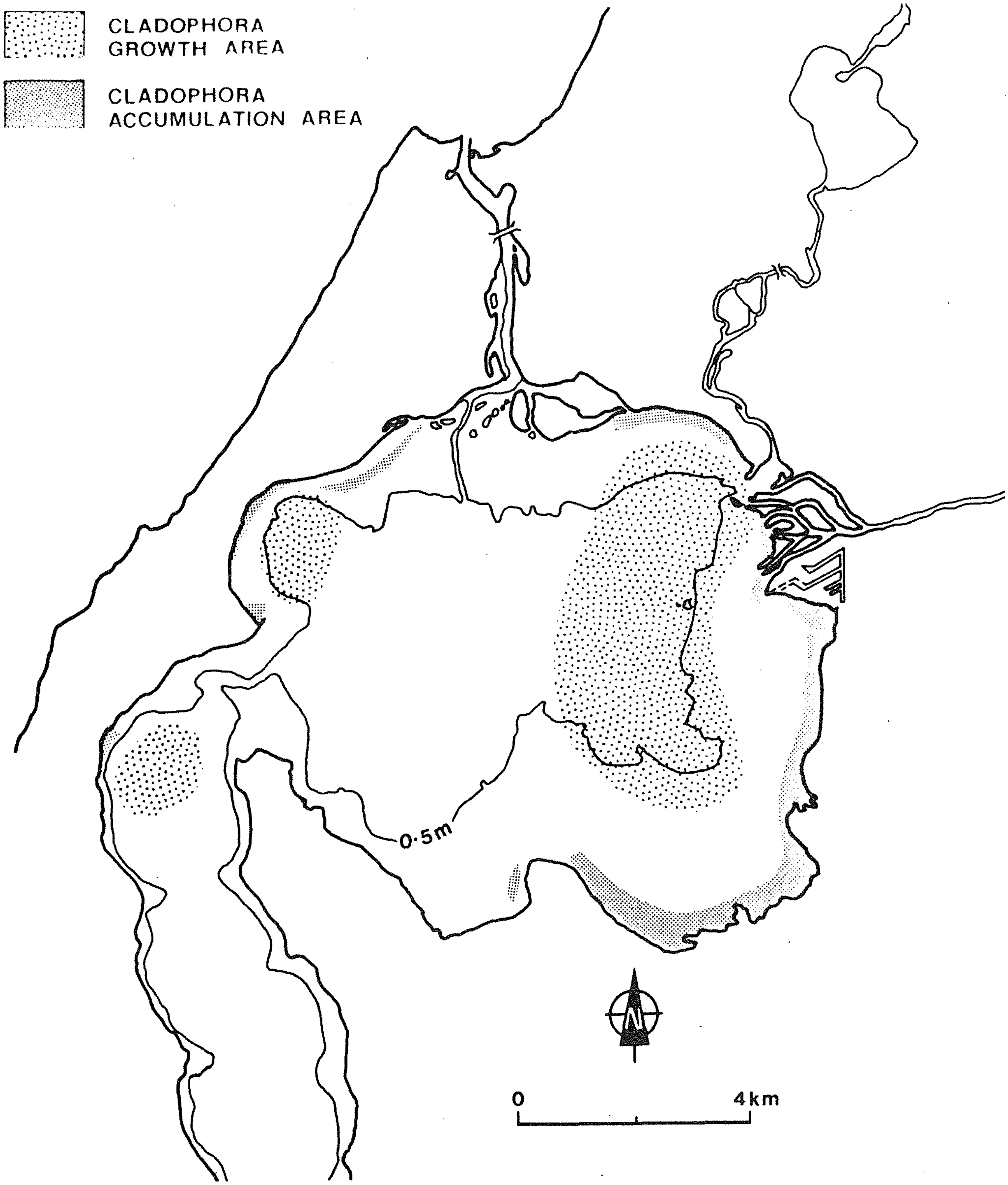


FIGURE 1.4 Principal Areas of *Cladophora* Growth and Accumulation

the deeper regions of Peel Inlet, nor in some shallow areas. Harvey Estuary has only a localised *Cladophora* population at its far north end. The mechanisms leading to this distribution, and the possible manipulation of the mechanisms limiting *Cladophora* distribution for management purposes are discussed in Chapters 9 and 10.

Beached algae are cleared from Coodanup and Navarro (Falcon) beaches by the Peel Inlet Management Authority (PIMA). Considerable amounts of algae accumulate on the shallows and beaches of southern Peel Inlet, but are not cleared, and therefore decompose *in situ*. Figure 1.5 shows a time series and cumulative plots of algae cleared from the two beaches.

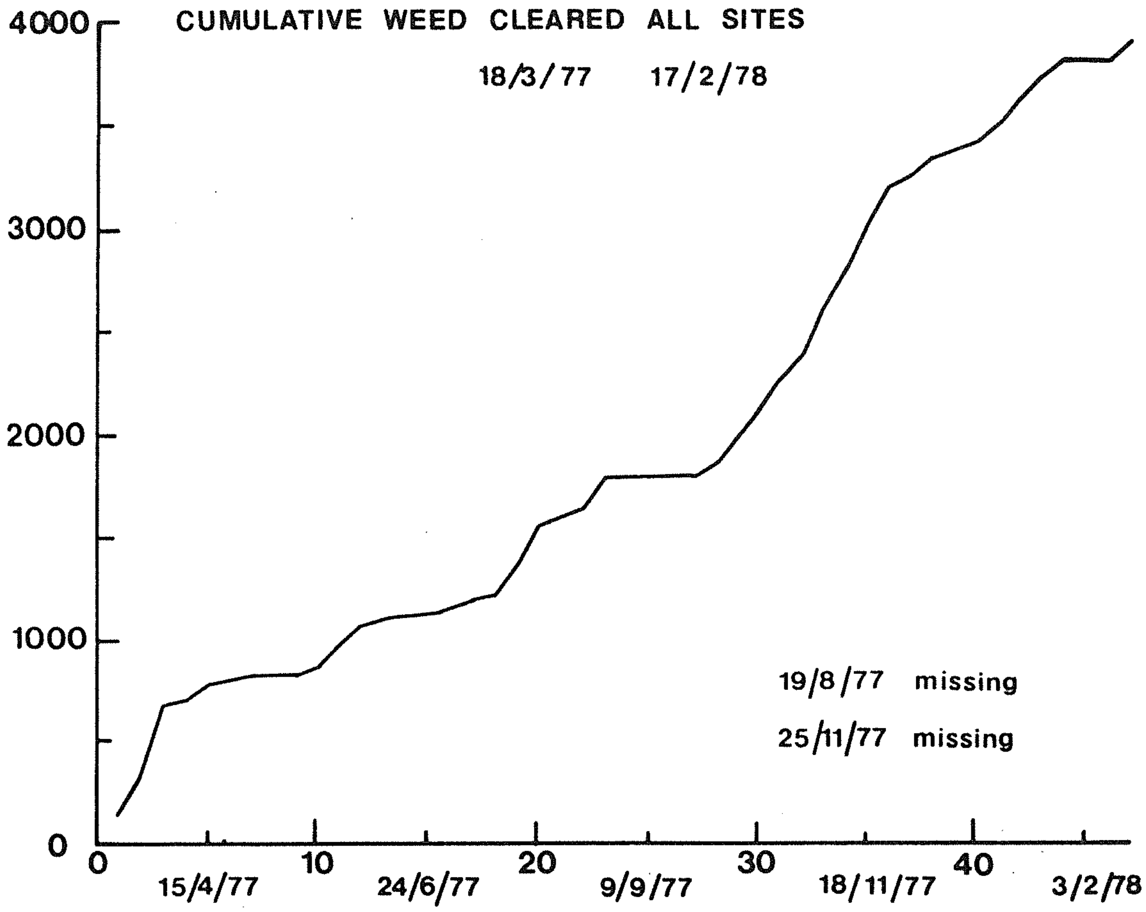
The plotted data consist of estimated weights of weed removed by PIMA workers, and are very approximate measures of weed deposition on the beaches, particularly since weed removal only takes place when necessary. Dell (1976) and Atkins *et al* (1977) suggest that major weed drift and accumulation occurs in Spring and Summer, when *Cladophora* is actively photosynthesising. The curves in Figure 1.5 do not strongly support this suggestion since a strong concentration of weed removal is not apparent in the Spring-Summer months. This question is further examined in Chapter 9.

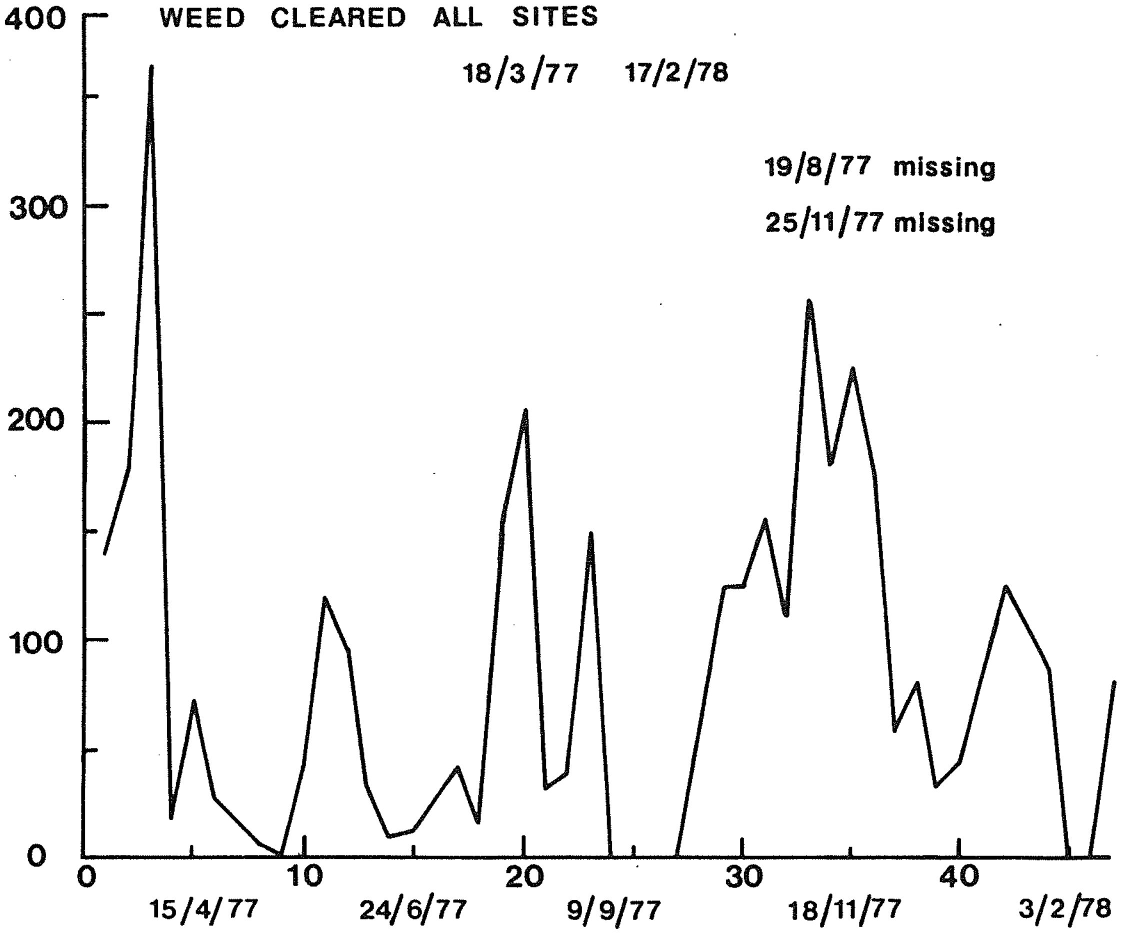
1.4 Design and Execution of the Present Study

Since the specific aim of this phase of the study is:

> "To determine the causes of the excessive growth and accumulation of green algae in Peel Inlet and if possible to propose methods for its control" (Hodgkin 1979),

the CRES group has concentrated heavily upon achieving this objective. From the time of our first contact with the problem, it was clear that, although a considerable amount was known about the estuarine system, relatively little was known of the distribution or biology of the problem alga, *Cladophora* sp. itself, and particularly of its dynamic behaviour (i.e. its fluctuations with time) under natural conditions.





MEAN 83.13 SD 79.48

Figure 1.5

Work on *Cladophora* had been initiated in 1976 by Dr Arthur McComb and students of the Botany Department, University of Western Australia, but their observations had been largely restricted to a single site, Pier 46, at the mouth of the channel into the Yunderup Canals estate. (Figure 1.1). From the beginning of the study it was obvious that a regularly-collected set of field observations was necessary to define the behaviour of *Cladophora* so that information on factors limiting its distribution could be obtained.

The CRES group discussed a sampling strategy internally, and in mid-1976 submitted a proposal to EMAC for a regular sampling programme (Young 1976a). The CRES proposal was refined after further discussion among all contributing work groups, and the sites shown in Figure 1.1 were chosen for the intensive monitoring programme to be managed by Dr P.B. Birch. In addition, the lower reaches of the Murray Serpentine and Harvey Rivers, and those of various agricultural drains entering the system were to be sampled by R.E. Black and co-workers of the Department of Physics, WAIT.

A weekly sampling frequency was chosen for the regular monitoring programme since it was considered adequate to characterise the dynamic behaviour of a macroalga, such as *Cladophora*. It was realized that other processes would be "undersampled" in both space and time - particularly many aspects of the behaviour of dissolved nutrients, phytoplankton tidal motions and river flow behaviour, but a finite budget restricted most of our attention to the weekly time scale.

Dr A.J. McComb and co-workers assumed responsibility for the water chemistry analysis, and for both field and laboratory studies of the physiology and ecology of *Cladophora* (D.M. Gordon), and also initiated studies on the phytoplankton ecology of the estuaries (Lukatelich, 1978). In 1978, members of the Department of Plant Nutrition and Soil Science, UWA, led by Dr D. Kidby, began work on phosphatase activity in the estuarine waters, nutrient exchange between water and sediment (Mr J. Gabrielson), and on the blue-green algae (cyanobacteria), some of which are nitrogen-fixers (Ms. A. Huber).

Physical monitoring and analysis of the system was carried out by R.E. Black and co-workers, particularly river and drain flow gauging, as well as meterological observations at a specially-established station at Robert Bay (Figure 1.1). The Public Works Department of W.A. provided and maintained tide gauges at several points within the system, and also provided river flow records from their permanent gauging stations.

On several occasions during the major field study, which ran from 1 September 1977 until 30 September 1979, "short term intensive field studies" were carried out to gather data on particular processes within the estuarine system. These are discussed in later Chapters and in the reports of other research groups.

In broad terms, the CRES contribution has been to introduce a "systems component" to this study; i.e. to process and disseminate data, to advise on the coordination and integration of the component projects in the study; and to provide data and systems analysis support to all aspects of the study including, where necessary, the use of time-series analysis and mathematical modeling. This contribution is outlined in greater detail in Chapter 2.

2. THE CRES CONTRIBUTION

An estuarine system such as the Peel-Harvey is exceedingly complex and the investigation of any particular ecological problem associated with such an estuary is, therefore, a difficult "systems problem". Here the objective is not to attempt a complete description or explanation of the system behaviour, for that would be impossible in two or three years, but rather to evaluate the behaviour *in regard to the particular ecological problem being encountered, with the objective of solving, or at least helping to solve that specific problem.* In the present case the major problem is, of course, the excessive growth of the nuisance alga *Cladophora* sp. in the Peel Inlet.

The mono-disciplinary nature of science and the strict application of the scientific method (e.g. Popper 1959) has been most successful in solving many scientific problems in the past few centuries. And even in the last fifty years, we have witnessed remarkable progress in science and technology, much of the credit for which can be attributed to this organisational structure of scientific research. But the investigation of environmental and socio-economic systems presents a rather special problem to the scientific community; a problem which is not necessarily best solved by a "multi-disciplinary" approach based on a loose assemblage of separate mono-disciplinary studies (Young and Rennie, 1976; Philip, 1975).

Environmental and socio-economic systems are rather poorly defined, in the sense that the investigator rarely has good *a priori* information on the nature of the various mechanisms which characterise the system and result in the observed behaviour. Furthermore, unlike the laboratory researcher who can carefully plan his experiments in order to discover more about the system and so remove any ambiguities present in the observations, the environmental analyst can rarely resort to the luxury of planned experimentation if he wishes to investigate the system *in situ*. Rather he must make do at, least in part, with passive monitoring exercises aimed at observing the system behaviour during its "normal operation".

There are many problems associated with the analysis of such a "badly defined" system (Young, 1978), not the least being that the monitored data may not contain within them sufficient information to unambiguously identify the major mechanisms *relevant to the problem at hand*. As we shall see in Chapter 5, for example, a thorough investigation of a mathematical simulation model for *Cladophora* growth in the Peel Inlet reveals that the *model* system is light limited for much of the time and that analysis of the weekly data obtained from that model will provide little information on the behaviour of the modeled alga under nutrient limitation.

If we are prepared to believe that this model provides a reasonable speculation on the dynamics of the alga - and it is based on a state-of-the-art understanding of the problem acceptable to most researchers working in the area - then the message is clear. If, in the real world, *Cladophora* growth is light limited for much of the time, then the weekly monitored biomass, nutrient and light data may well prove insufficient to clearly define the behaviour of the alga under conditions of nutrient limitation. In such a situation, it is obviously important to plan other more detailed *in situ* monitoring exercises, coupled with planned laboratory experiments, all aimed at reducing the ambiguity in the weekly data and providing a reasonable hypothesis about the system which will help to define management alternatives.

In this kind of situation, mono-disciplinary research on a particular aspect of the system has to be continually informed about what is happening in the Study as a whole. Otherwise the research may proceed along some perfectly respectable tangent which may be most interesting from the scientific standpoint of the mono-discipline concerned but could be of only marginal use to the Study objectives. Or again, two research programmes whose work must "interface" properly if the mutual results are to be of maximum potential usage to the Study may, if they function completely independently, produce results which do not allow for such later collaborative analysis; see e.g. the modeling activities associated with land-use, hydrology and water quality in the Westernport Bay Study (Young and Rennie, 1976).

2.1 Adaptive Environmental Assessment and Management

The Applied Systems Group (ASG) in CRES has been concerned with the analysis of badly defined systems and the associated problems of environmental study organisation since its formation in 1975. And it was for this reason that the Estuarine and Marine Advisory Committee (EMAC) invited the Group to become a member of this Study Team in 1977. While it was clear that local scientists could well handle most scientific aspects of the proposed study, EMAC felt that the special problems associated with the co-ordination of the various mono-disciplinary projects were such that a "systems component" might be useful, particularly if it could help the Research Co-ordinator Dr Ernest Hodgkin in the overall integration of the Study.

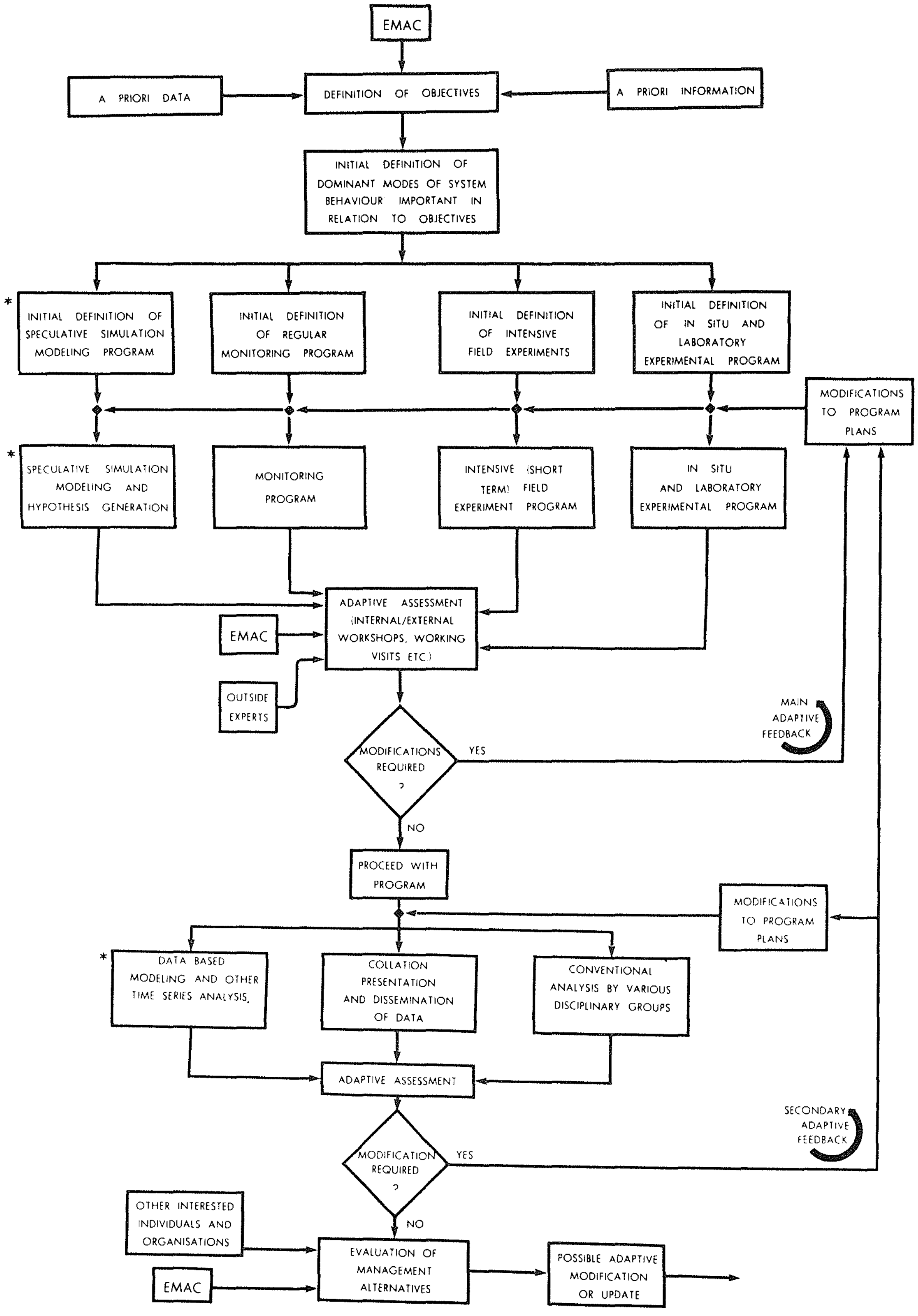
Primarily, applied systems analysis is concerned with the mathematical characterisation of a complex dynamic system for some specific purpose, usually associated in some manner with the operational control, management or planning. In the environmental case, the system is usually so complex, however, that no single scientific discipline can encompass all facets of its behaviour. If exercises in mathematical characterisation are to be successful, therefore, they must often transgress conventional disciplinary boundaries and, throughout the exercise, the analyst should be at pains to consider the system as a single entity composed of a number of interacting sub-systems. For this reason, the applied systems analyst has to be associated with *all* aspects of an environmental study; from the initial planning stages, through data aquisition and processing, to relevant mathematical modeling and the evaluation of management strategies. And it is his job throughout the Study to ensure that the research co-ordinator is made well aware of any possible deficiencies in the programme from an overall systems standpoint.

Ideally, this approach requires great flexibility and would demand day-to-day contact between the CRES team members and the members of other groups working on the Study. In this way, it would be possible to initially define the problem and the information required to address it; to follow this up by the planning and execution of an integrated programme of regular monitoring, intensive field exercises and planned experimentation; to process and analyse the data obtained in this manner using whatever procedures (time-series analysis, mathematical modeling etc. - see Chapter 4) seem most appropriate; and, finally, to use the results of this analysis to suggest possible solutions to the problem at hand; in the present case, the management of the nuisance alga in the Peel Inlet.

This kind of procedure must, if at all possible, be fully adaptive from the very beginning; indeed the term "adaptive environmental assessment and management" has recently been coined to describe such an approach to systems analysis (Holling, 1978). Here at every stage in the programme an effort is made to assess progress and, if necessary, to modify the programme in the light of this progress: in other words, the adaptive approach is not based on a "once-for-all" plan but evolves on the basis of a continual feedback of information on the progress of research in all areas of the Study.

Figure 2.1 is a schematic diagram of the adaptive environmental assessment procedure, particularly as it relates to the Peel-Harvey Study. Note that the first and most important step in this procedure is the *definition of objectives*; unless we are confident of why we want to carry out the Study, then it is likely that the various disciplinary teams will interpret the Study in different ways and this may well lead to fractionation and inefficient operation.

Following the definition of objectives, it is important to consider the nature of the problem, as defined by these objectives. In



NOTE ASTERISKS INDICATE THE MAJOR MODELING ACTIVITIES.
THE PHILOSOPHY BEHIND THESE ACTIVITIES IS DISCUSSED IN THE TEXT.

FIGURE 2.1 Schematic Diagram of the Adaptive Environmental Assessment Procedure, Particularly as it Relates to the Peel-Harvey Study relation to modeling and program planning, this requires that we objectively evaluate all *a priori* information on the system, in order to define the likely "dominant modes" and frequencies of behaviour (see Chapter 4). In the Peel-Harvey case, for example, *Cladophora* growth characteristics are extremely important and it is necessary to assess the most likely growth rates and resulting dynamic behaviour, based on both local data and information in the literature. On this basis, and from the consideration of other factors such as the hydrodynamic characteristics, it is possible to make initial experimental planning decisions such as the definition of those sampling frequencies which are likely to provide us with sufficient information on the *relevant* dynamic behaviour of the system. And in this way, we can proceed to the initial planning of regular monitoring programs, intensive field exercises and both *in situ* and Laboratory research. Also it is possible to initiate speculative model building exercises (see Chapter 5) aimed at generating hypotheses about possible system behaviour.

As shown, all of these aspects of the Study proceed in parallel and should be integrated to the greatest extent possible, with regular inter-group meetings and workshops (including participation from outside experts) in which the results are assessed on a continuing basis, improvements and modifications to the various programs are discussed and the programs modified accordingly, as shown in the "main adaptive feedback loop".

When well into the program, sufficient data will normally become available to allow time-series data-based studies to proceed: the initial processing of such data will, of course, be carried out on a continuing basis throughout the Study, but more sophisticated time-series modeling cannot proceed seriously until the data base is reasonably established. The results of both modeling and other data reduction studies will also need to be assessed at regular intervals and such assessment may well lead to modifications to the Study program. Such modifications may relate to the data analysis studies themselves; on the other hand, they may also indicate inadequacies and required modifications in the experimental and monitoring programs, as indicated by the presence of the "secondary adaptive feedback loop" in Fig. 2.1.

Finally, the results of the various analytical exercises will provide the input for the last element in the assessment procedure; namely the definition and evaluation of alternative management strategies. In line with general adaptive philosophy, we allow for possible feedback modifications based on this evaluation. However, the further into the evolving program we are, the less likelihood there is that such modifications will be necessary (or, indeed, feasible given the time limitations on any study). This last stage will, of course, involve both EMAC and other interested individuals and organisations.

Clearly if an adaptive procedure or 'rolling plan' such as that shown in Fig. 2.1 is to work properly and allow for continual adjustment of the constituent research programmes, it requires close interaction of people associated with the Study; in particular, the Systems Team should make every attempt to meet with members of other Research Teams on a continuing basis and, if possible, to establish a working relationship with them based on mutual help and understanding.

From the beginning, it was clear that such an ideal approach was not possible in the Peel-Harvey case: the remoteness of Canberra from Perth and the Peel-Harvey system prevented day to day personal contact and the resulting time-lags in the adaptive assessment procedure have led to certain problems, delays and misunderstandings from time to time. Bearing in mind the obvious difficulties in this regard, however, the programme has gone well. Telephone and written contact has been maintained throughout and, at times, conferences have even taken place over a telephone link. Fairly regular meetings and workshops have been arranged by the Research Co-ordinator, Dr Hodgkin,and CRES personnel have attended whenever this proved feasible; also members of other research teams have paid working visits to CRES, often to use our computer programs and to carry out joint analysis.

At the very beginning of the Study in October 1977, members of the CRES team travelled by land to Western Australia to take part in the first intensive field exercise on the estuary. Again, later in February and August 1978 another group from CRES helped with the other intensive field exercises. All of these visits have helped

CRES personnel to become well acquainted with the Peel-Harvey system, something which is essential to good systems analysis. They have also helped to make CRES feel a true part of the Study Team and have led to the establishment of excellent working relationships with other research teams. Indeed, throughout this report there is considerable integration and overlap of the CRES contribution with other teams' research. We hope that this will serve to demonstrate the efforts that have been made by all Study Teams to achieve integration.

2.2 Objectives

The objectives of the CRES contribution to the Peel-Harvey Study were specified as follows (Young, 1976a).

- To discuss with the Research Co-ordinator and other Project Team members the objectives of the study and help define these objectives as clearly as possible.

- In consultation with the Research Co-ordinator and other Study Team members, to define a basic data collection programme and the details of additional special intensive field experiments.

- By visiting Western Australia and taking part in joint discussion, workshops and intensive field exercises, to become acquainted with and, hopefully, to gain the confidence of other Study Team members. Also to arrange working visits to Canberra by Western Australian Team members.

- To be responsible for those aspects of the intensive field exercises concerned with the assessment of water circulation and dispersion patterns using dye tracers (so exploiting previous CRES experience in this area).

- To be responsible for the establishment of a computer-based data acquisition, processing and retrieval system; and to provide at specified intervals, or on demand, graphical plots and printouts of this data, together with relevant commentary.

- In discussion with the Research Co-ordinator and other Project Teams, to initiate data and systems analysis exercises, including where necessary computer-based mathematical modeling studies, in the area of hydrology, water chemistry (nutrient behaviour) and aquatic plant growth.

- To report to the Research Co-ordinator at specified intervals on the progress of CRES activities and advise him, on a continuing basis, of possible future directions for integrative research, desirable modifications to the data collection programs etc.

- To assist the Research Co-ordinator, whenever possible, in the planning of the Study Programme. Also to advise him on the preparation of those aspects of the final report concerned specifically with modeling and mathematical systems analysis.

2.3 Details of CRES Involvement

In an attempt to achieve the various objectives discussed in the previous section, the CRES Team contributed to the Study in various different areas. These were chosen both to make maximum use of the expertise of the Team members and also to allow the Team to maintain a good overview of progress in the Study as a whole. In this manner, it was possible to provide the Research Co-ordinator with continuing advice as regards adaptive assessment and program management.

The details of the proposed CRES involvement were first delineated in late 1976 (Young, 1976a). In addition to the advisory role, contributions were made in the areas of data processing and dissemination; data analysis; systems analysis/modeling associated with hydrology; nutrient and biological behaviour; and the planning/

execution of the intensive field exercises. These contributions are outlined below and in subsequent Chapters we will discuss them in greater detail.

(A) Advice to the Research Co-ordinator

Our advisory role has been in relation to two primary aspects of the Study: first, in connection with the planning, management and execution of both the routine (long term) monitoring programme and the special intensive (short term) field experiments (Young and WATERCRES Team, 1977); and second, in relation to the planning and intergration of the Study as a whole. The CRES Team also made a special effort to maintain good scientific contact with the Research Co-ordinator and other W.A. Team members by producing a series of working papers addressing work-in-progress through the Study (see Bibliography).

It should be emphasised that our advice to the Co-ordinator has been intended only to help him in his programme planning and it has been utilised by him, together with advice from other Teams, in order to decide on the final programme details. Hopefully this advice has introduced a degree of systems thinking into the planning and management process: sometimes our advice has been accepted and acted upon; at other times it has been noted but specific action has not been taken. All the time, however, we hope it has helped CRES to maintain good contact with the Research Co-ordinator.

(B) Data Processing and Dissemination

CRES undertook to receive and prepare in computer compatible form, data from the field monitoring programme; and further, to provide a computer-based data analysis and retrieval system able to plot raw or processed data, produce tabulated data summaries and carry out statistical analysis,on request from the Co-ordinator or other Study Teams. Plots, data tabulations and summary statistics, together with brief commentaries were supplied at agreed intervals or on request. Furthermore some 'historical' data processing, particularly of meteorological and water quality data has been carried out as required or requested.

(C) Data Analysis

Certain statistical and other data analysis computer packages are available to the various Study Teams in Western Australia on their own computer systems. Sophisticated time-series analysis programmes such as those developed in CRES are not, however, available and CRES has supplied these to any Study Team which has need of them. In addition, CRES has provided advice on data analysis and introduced other Study Teams to computer based procedures (such as the SYMAP line printer mapping programme) which might be useful to them.

(D) Systems Analysis and Modeling

Perhaps the primary contribution of the CRES applied Systems Group is in the area of data and systems analysis. "Systems Analysis" is a much abused term applied to many different methodological procedures, some of which border on the realms of pseudo-science (see discussion in Young, 1978 and Chapter 4). It is important, therefore, to define what is meant by systems analysis in the present context. Put simply, the mathematical aspects of systems analysis can be considered as nothing more than a systematic, common-sense approach to the mathematical characterisation of a system, based on a clear appreciation of the special properties of *dynamic* systems and dedicated to understanding the system for some defined objective.

The emphasis on dynamic behaviour is most important here since method theories appropriate to static (equilibrium; steady-state) systems are not necessarily applicable to dynamic systems and can produce misleading results. Regression analysis, for example, is much beloved by biological statisticians but it can yield biased parameter estimates and incorrect conclusions (Young, 1968). In general, conventional scientific education does not provide a good understanding and appreciation of dynamic systems.

In the Peel-Harvey Study the CRES Team have utilised computer-based systems analysis procedures in a number of ways and these are discussed in detail in subsequent chapters. The principal exercises, however, have been concerned with

(i) the evaluation of the circulation and flushing characteristics of the estuary on the basis of weekly salinity data (Chapter 7);

(ii) the use of this flushing information in long term nutrient budget calculations (Chapter 8);

(iii) the construction of a speculative stochastic-dynamic model of *Cladophora* growth and its use in the generation of hypotheses on system behaviour (Chapter 5);

(iv) the construction of a data-based *Cladophora* growth model utilising both the weekly monitored data and the flushing information from (i) (Chapter 9);

(v) initial analysis of physical management options (Chapter 10).

As we have pointed out, dynamic systems analysis is not only concerned with mathematical analysis, it also represents a philosophical approach to the understanding of badly defined systems which has certain implications on the management of environmental studies. Throughout the Peel-Harvey Study, therefore, our general approach has been guided by this philosophy and some of the lessons learnt in this regard will also be discussed in later chapters.

(E) Assistance with Intensive Field Experiments

This aspect has been alluded to previously: CRES personnel were involved in the planning and execution of the intensive field exercises in October 1977 and February/August 1978. In particular they organised and took part in dye tracer experiments using Rhodamine fluorescent dyes both for visual and fluorometer based evaluation of circulation and flushing patterns in the estuary. Also CRES personnel were involved in dye tracer experimentation (dye dilution gauging) of the Murray River both during the intensive exercises and, at other times, in association with Mr R. Black of WAIT.

3. DATA MANAGEMENT AND PROCESSING

A rather pedestrian but nontheless important and time-consuming aspect of the CRES contribution to the Peel-Harvey Study has been in the area of data management; i.e. the acquisition, storage, retrieval and dissemination, in appropriate form, of all relevant numerical data obtained in the Study. In addition, we have been concerned with computer aided data processing, ranging from simple statistical computations to sophisticated exercises in time-series analysis. In this Chapter, we outline these contributions and in subsequent Chapters we will describe some of the more important data processing exercises in greater detail.

3.1 Data Management

Even with the sophisitication of modern, high speed digital computers, the management of the large quantities of data generated by an exercise such as the Peel-Harvey Study can be a time-consuming task. Much of the time of a research assistant is required for the development and maintenance of such a data management system which involves the following activities:

(i) preparation in computer compatible form of all raw data, such as those obtained from the weekly monitoring exercises, special intensive field experiments and data from other organisations received in written or printed form;

(ii) acquisition, reading and storage of data from magnetic tapes, e.g. tide records, CSIRO historical data etc;

(iii) verification and correction of all data (this is a major task often consuming a large amount of R.A. time);

(iv) development of a data archival system (based on, and compatible with, ANU UNIVAC computing requirements) involving computer disc and tape storage, and allowing for easy retrieval in various output forms and formats.

(v) retrieval of information from the archival system, preparation (e.g. binding) and dissemination to the research coordinator and other Team members in W.A., either routinely or on request.

We have not included examples of the kind of computer generated information here, but the reader may note that many of the figures in this report are examples of the routinely prepared and disseminated material. Note also that the stored data can be supplied in computer listing, graphical (or other pictorial, e.g. SYMAP), punched card or magnetic tape form.

The construction of the data archival and processing system has required considerable software development including

(i) custom written programs using library plotting routines (ANUPLOT, WPLOT) for the display of time-series data on immediate access hard copy (from VDU on to hard copier or X-Y plotter) or remote access batch plotting (ANU Computer Centre);

(ii) custom written plotting programs for other types of data, e.g. X-Y plots and scatterplots;

(iii) contour plotting, using the SYMAP package and CRES line printer facilities, for display of spatial data (e.g. dye and salinity data obtained during intensive exercises);

(iv) elementary statistical analysis and data reduction including comparison of data input streams using custom written (e.g. CORCROSS, cross correlation) and library programs (e.g. SPSS, GENSTAT);

(v) sophisticated statistical analysis program packages including: CAPTAIN time-series package; local trend estimation using recursive smoothing; spectral analysis based on autoregressive moving average (ARMA) model estimation; refined instrumental variable programs for single and multivariable systems; and model order identification programs;

(vi) Monte Carlo stochastic simulation programs and associated statistical software.

3.2 Data Processing and Modeling

The various programs and computer software developed within the data management system have been used in numerous exercises in data processing ranging from simple statistical calculations, such as sample auto and cross correlation function computation, to complex data manipulations, such as those required in multivariable time-series analysis. Such exercises have been carried out on a day-to-day basis throughout the Study and we can only describe in the present report a few of the more successful and relevant ones. These can be classified under three headings: namely Time-Series Analysis, Speculative Simulation Modeling and Consultancy/Technology Transfer.

3.2.1 Time-Series Analysis

The CAPTAIN time-series analysis package (see Appendix 2) and various associated time-series programs have been used in a number of applications of which the major ones have been:

(i) analysis of dye dilution gauging and dispersion measurements in the Murray River (see Chapter 6);

(ii) analysis of *Cladophora* biomass, Chlorophyll$_a$ and nutrient time-series in relation to nutrient, Chlorophyll$_a$ and *Cladophora* behaviour (this is termed "data-based modeling" - see Chapters 8 and 9);

(iii) analysis of tide height-water flux relationships in the Mandurah Channel (in association with the WAIT Team (Black and Rosher, 1980) - see Chapter 6);

(iv) analysis of site-to-site height gauge data, and the evaluation of short and long term tidal characteristics (see Chapter 7);

(v) analysis of weekly monitored salinity data in order to evaluate site-by-site flushing and evaporation characteristics (Chapter 7);

(vi) analysis of weekly monitored salinity data on single variable site-to-site and multivariable bases, in order to evaluate circulation characteristics (Chapter 7).

3.2.2 Speculative Simulation Modeling

Monte-Carlo stochastic simulation analysis is a powerful tool in assessing the stochastic properties of simulation models. Most simulation models are unrealistically deterministic in form; in other words, the analyst assumes implicitly that the system is completely explainable by the model and his model outputs rarely include any reference to uncertainty. In practice we know that systems, and particularly poorly defined environmental systems, can never be characterised in such deterministic terms - there is always some lack of precision arising from various causes such as measurement errors, system disturbances not accounted for in the model, imprecisely known coefficients or model structure etc.

The CRES approach to this problem is to admit to the uncertainty and to try to quantify it in an appropriate manner using stochastic simulation wherever necessary. This is not an easy task, as we shall see in subsequent Chapters, but it is well worth the effort if only because it emphasises to the reader that the results and predictions of a Study such as this are not exact; rather they are *probablistic* statements based on thorough data analysis and, hopefully, well reasoned scientific judgement by all members of the Study Team.

The stochastic simulation exercises have been carried out in connection with

(i) The evaluation of a "flow routing" model for the Murray River System, in order to estimate flow in the lower, ungauged portions of the river (in association with WAIT (Black and Rosher, 1980) - see Chapter 6);

(ii) a speculative "hypothesis generating" model of *Cladophora* growth dynamics under a phosphorus budget scenario (see Chapter 5);

(iii) a similar model to (ii) but under a nitrogen budget (see Chapter 9);

(iv) nutrient budget analysis in the system as a whole (strictly not simulation analysis, rather an exercise in accounting nutrient flux with probablistic interpretations - see Chapter 8);

(v) an algebraic, data based model of *Cladophora* growth behaviour (see Chapter 9).

3.2.3 Consultancy and Technology Transfer

As mentioned in Chapter 2, CRES has offered general assistance to all W.A. Team members in the areas of data processing and analysis, including the transfer of computer programs when this has been requested. The principal examples of this kind of activity have been

(i) advice on the SYMAP program and its use to the Department of Botany, University of W.A.;

(ii) advice on the nature and use of the CAPTAIN program package and its transfer to the Department of Physics, Western Australian Institute of Technology (WAIT) for use by R.E. Black and his colleagues at WAIT; and also D.F. Wallace of Harbours and Rivers Branch, Public Works Department, W.A.;

(iii) organisation of working sessions in CRES with visitors from W.A., including use of the various CRES computer program packages. This has included visits by R.E. Black, D.F. Wallace, J. Rosher, R.J. Lukatelich, P.B. Birch and A. Huber.

Finally, it should be noted that many more exercises in data processing and analysis were carried out than are discussed in this and subsequent chapters. Here we present only the final, relevant results obtained from a long series of analytical exercises; in most cases the final analyses were preceded by numerous preliminary exercises, some of which have been outlined in previous progress reports (e.g. Hodgkin, 1978). Also we should stress that some of these exercises are not yet entirely complete; merely the present results are our current best thoughts on the system and data, hopefully sufficient for the Study requirements. In the spirit of adaptive environmental assessment, however, CRES will be continuing to analyse these data if internal funding allows this, and the results will be forwarded to the W.A. department of Conservation and the Environment as they are obtained. Exercises which will be continued in this manner are the flushing/circulation analysis (Chapter 7), the stochastic nutrient budget analysis (Chapter 8) and the stochastic appraisal of the data-based *Cladophora* model (Chapter 9).

4. MODELING BADLY DEFINED SYSTEMS

We have explained in Chapter 2 how the Peel-Harvey Estuarine System can be regarded as being "badly defined" in the sense that the behavioural mechanisms relevant to the problem of nuisance algal growth are not well known *a priori* and the ability to conduct *in situ* planned experiments, which may help to define these mechanisms, is severely restricted by logistic and other difficulties. For this reason, it is necessary to approach the mathematical characterisation of the estuarine system with some care. In this Chapter we will outline the basic model building procedures appropriate to badly defined systems and then, in Chapter 5, proceed to discuss in detail the initial stages of this procedure (namely initial model formulation and the generation of working hypotheses) in relation to *Cladophora* growth dynamics in the Peel Inlet.

4.1 The Stages of Model Building

The complete model building procedure utilised by CRES for the mathematical characterisation of badly defined systems is shown in Fig. 4.1 (see Young, 1978, 1981). It is clear from this that the four major stages in model building are: first the formulation and identification of plausible *a priori* model structures possibly, as in the present case, by resort to speculative simulation modeling; second, on the basis of the results obtained in the first stage and in relation to the objectives of the study, the choice or "identification" of appropriate and suitably parameterised model structures; third, the estimation of those parameters which characterise the eventually chosen (identified) model structures; and finally, the *conditional* validation of the estimated models, as implied by the failure to falsify the models as theories of the system behaviour.

A detailed description of all these stages is available in Appendix 3 and so it will suffice here merely to outline the principal features of each stage and show how the various analytical exercises are blended together in the overall, systematic model building procedure.

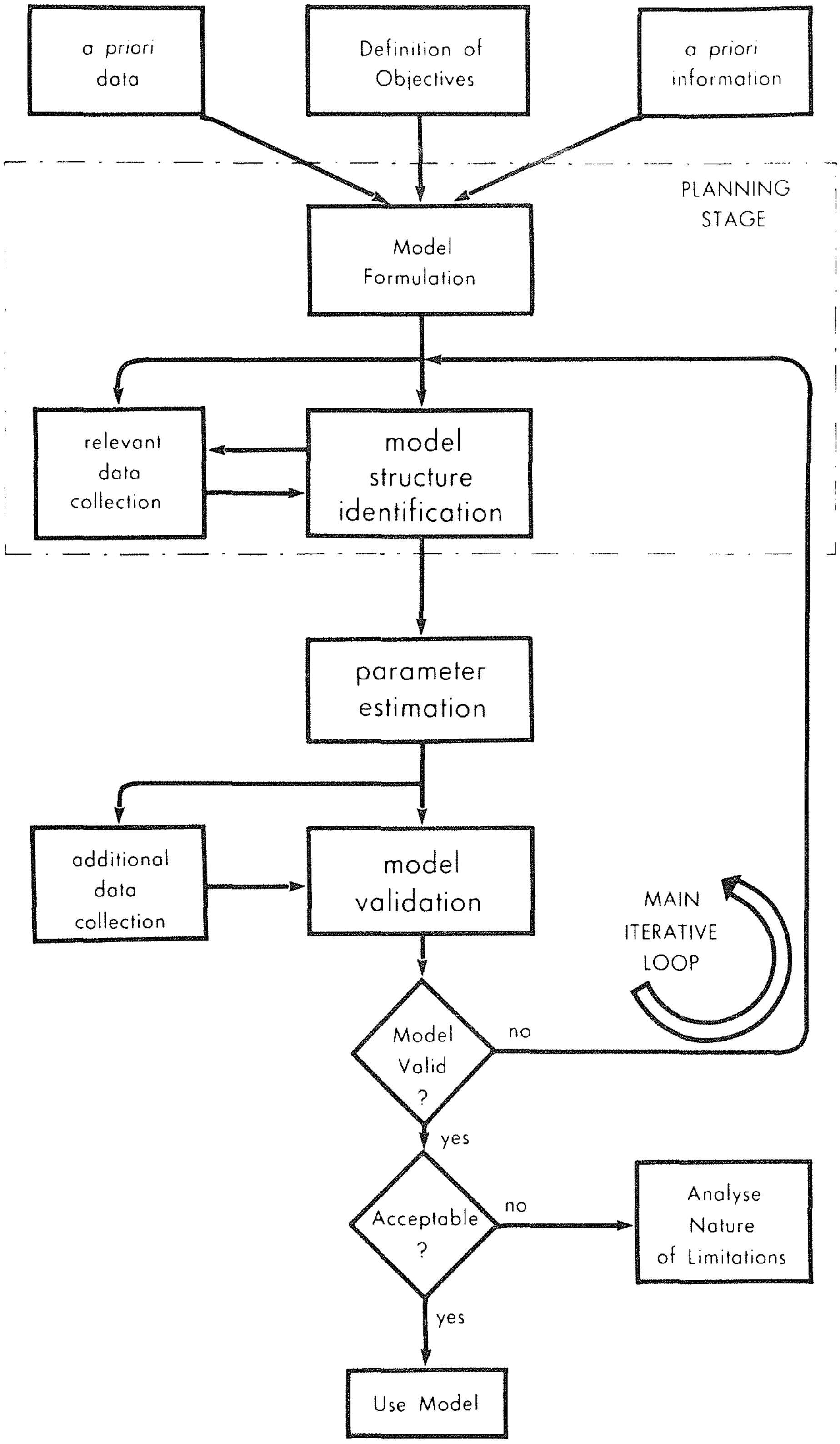


FIGURE 4.1 The Stages in Model Building

4.2 Initial Model Formulation

At the early stages in the investigation of a badly defined system, time-series data relating to the *dynamic* behaviour of the system are likely to be scarce. This was certainly the case in the Peel-Harvey Study, where the lack of such *a priori* data was quickly identified and the need for the initiation of a regular monitoring program aimed at correcting this deficiency was established. In such a situation, there seems no real alternative to utilising some form of *simulation model* as an initial mathematical device for testing theories about plausible causal relationships in the system. By simulation model we mean one whose structure and parameters are explicitly related to the physical, chemical or biological processes that are assumed to characterise the system.

In the case of badly defined systems, such as those encountered in the environmental and socio-economic areas, simulation models are often constrained to be written in the language of the various disciplines who have studied the component processes of the system. This constraint tends to make simulation models rather complex, with many parameters, state variables and non-linear relationships. Under the best of circumstances, therefore, such models may have many degrees of freedom and, with judicious "fiddling", they can be made to reproduce almost any behaviour, even when restricted to a structure and parameter values which are regarded as plausible from a physical standpoint (see Young, 1975, 1976a).

For these reasons, we contend that simulation models can only be useful in the initial analysis of badly defined systems if they are considered within a *probabilistic* context. That is, given the model and the inherent uncertainties in structure and parameter values, the only meaningful and safe analyses must focus on the probabilities of various behaviours. Most importantly, it must focus on the probable structures and parametric relationships which appear consistent with the *dominant modes of behaviour* associated with the *problem* under consideration. By "dominant modes of behaviour", we mean here those behavioural patterns which seem to dominate the observed (monitored) data: in a complex model, there will be many such behavioural patterns defined by the "eigenvalues" associated with the mathematical model equations, but it is well known that only a small number of these patterns will be clearly evident in and "identifiable" from, the observed data; these are the dominant modes of behaviour (see Young, 1978 and Appendix 3).

If this notion is formalised, it implies that we should not evaluate the simulation model as a single entity; in other words as a fixed structure characterised by a set of constant parameters defined in terms of point estimates. Rather we should consider the parameters as inherently uncertain and, therefore, definable only in terms of statistical probability distributions. This Bayesian interpretation leads naturally to the study of a whole *ensemble* of models defined by the various selected structures and their associated parametric probability distributions.

In relation to the equations of the system, this means evaluating the model behaviour for different sets of parameter values represented in terms of probability distributions which are chosen to encompass the complete *range* of *possible* values for the parameters. In addition, because we allow for random disturbances to the system, it is clearly necessary to allow for this input uncertainty in the evaluation of the model. We might also, depending upon the circumstances, wish to consider the model behaviour for different deterministic inputs which are representative of the kind of inputs met in practice; for example, if there is a vector of rainfall inputs to a water quality model, then "wet", "dry", and "average" conditions could be accommodated by different representative deterministic input data sequences (see e.g., Whitehead and Young, 1979).

We are of the opinion that this conceptual base of an uncertain or stochastically defined simulation model should be exploited in methodological terms by recourse to Monte-Carlo simulation analysis. Put simply, such analysis consists of repeated solution of the model equations with the uncertain parameters (and inputs) specified by sampling at random from their assumed parent probability distributions.

This analysis results in a large number of random simulations (or realisations), each providing a unique state trajectory $\underline{x}(t)$ which defines the behaviour in terms of the variations in important state variables;[†] e.g. in the case of *Cladophora* growth, variables such as *Cladophora* biomass, nutrients, water volume etc. (see Chapter 5). This set of trajectories is then examined statistically to investigate the properties of the whole ensemble of simulation models - i.e. statistical procedures are utilised to infer certain properties of the ensemble from the *finite* sample of trajectories obtained from the random simulation experiments. It is, in other words, a method of bypassing the difficulties associated with the analytic solution of non-linear, stochastic differential equations, albeit at some cost in computational terms.

The general aspects of the use of Monte Carlo methods to investigate the properties of an ensemble of simulation models are discussed by Spear (1970). Monte Carlo methods have been used previously in environmental and socio-economic systems analysis (see e.g. Barrett et. al., 1973; Young et. al., 1973 and Whitehead and Young, 1979) but, in these earlier approaches, the ensemble properties were considered mainly in terms of the propagation through time of the probability distribution associated with the state trajectory $\underline{x}(t)$ itself. Here, an alternative procedure is utilised in which the state trajectory $\underline{x}(t)$ obtained from each randomly selected solution of the model equations is examined to see if it is characterised by a behavioural pattern relevant to the problem under consideration. For example, in a socio-economic simulation, the occurrence of high inflation simultaneously with a stagnant economy and high unemployment would define the existence, for that run, of the "stagflation" problem. If the state trajectory does appear to exhibit a problem behavioural pattern, then it is considered that the model parameter vector, say $\underline{\alpha}$, does give rise to *the behaviour* B (in the present example a *Cladophora* bloom of the Peel variety): alternatively, if $\underline{x}(t)$ does not exhibit such characteristics then $\underline{\alpha}$ is associated with *not the behaviour* $\bar{B}$. The end result is N simulation runs in which M parameter vectors led to the behaviour and N-M did not.

[†] $\underline{x}$ denotes the state vector $\underline{x} = [x_1, x_2 \dots x_n]^T$ where $x_1, x_2 \dots x_n$ are the state variables and the T suffix denotes vector transpose (see e.g. Ogata, 1970).

This kind of Monte Carlo analysis is described in more detail in Chapter 5. For the present purposes, it will suffice to say that the aim is to ascertain which parameters are important in giving rise to the problem behaviour. This is achieved by evaluating the sample cumulative probability distributions associated with the model parameters in both the *behaviour* set B and the *not behaviour* set $\bar{B}$. A parameter is then deemed *important* if there is a statistically significant difference between the two distributions and *not important* if this difference is statistically insignificant. The two procedures for assessing the significance of differences in this sense are: first, the application of conventional non-parametric tests such as the Kolmogorov-Smirnov two sample test and the Mann-Whitney test (see e.g., Spear 1970); and second, the use of principal component methods based on eigenvalue-eigenvector analysis of the covariance matrices associated with the parameter vectors (see e.g. Kittler and Young 1973).

Evaluation of the results of the Monte Carlo analysis in the above manner should yield a better understanding of the system in terms of those mechanisms and parameters that appear important to the problem at hand. Such additional insight can be useful in a number of ways. For example, it can lead to the specification of hypotheses about the system behaviour that can be tested by further planned experiments or monitoring exercises; in other words, it can help in the planning of further data collection in the study of the system. As we shall see, it can also indicate to the analyst the possible dominant modes of behaviour of the system; information which will be of crucial importance in the subsequent stages of model building.

Of course, since the analysis is not limited to a single *a priori* model structure, it may result in a number of different hypotheses, each of which will need to be tested; and a number of possible "dominant mode" descriptions, each of which will need to be evaluated during both subsequent time-series analysis and experimental analysis of the real system. It is seen, therefore, that the Monte Carlo methodology is used as a very effective *hypothesis generating* device which is based on a relatively objective analysis of all *a priori* information available about the system.

This latter point helps to emphasise that the simulation models developed in this initial stage of model building should not be considered in the same light as more conventional deterministic simulation models. And, as Spear and Hornberger (1980) point out, they should certainly not be used as the sole basis for either further refinement and enlargement or "fitting" to actual time-series data. In the case of badly defined systems, we strongly advocate that mechanistic simulation models should be viewed principally (although not entirely) within the ensemble context. As such, their use in time-series terms is mainly as a vehicle for indicating dominant model mode mechanisms and descriptions; descriptions which will, in general, be much simpler than the original simulation model description and can, therefore, provide a starting point in the identification of appropriate time-series model structures.

4.3 Time-Series Model Identification and Estimation

Time-series analysis is a systematic, statistically based approach to the problem of dynamic model development which provides an objective method of constructing both black-box (input-output) and mechanistic (internally descriptive) models from time-series data. Despite assertions to the contrary, time-series analysis is much more than model "fitting", as currently practised in many areas of systems analysis and simulation modeling. This is emphasised by the fact that, in time-series analysis, the degree to which the model fits the data is not, in itself, used as an indication of model adequacy: other factors, such as the estimated uncertainty on the model parameters, are equally important and are, as we shall see, an indispensable part of the analysis.

The use of time-series methods as the basis for modeling badly defined dynamic systems has been described at length by Young (1978). As in the previous section, therefore, we will not attempt here to discuss the procedures in any depth. Rather we will concentrate on explaining their role in the overall modeling process and showing how they follow on quite naturally from the initial Monte Carlo based model formulation and identification exercises.

We have seen how the stochastic simulation model experiments can reveal those parameters in the assumed model which appear important in relation to the "problem" behaviour under consideration. In this way, they can also help the analyst to appreciate better the relative importance of the various dynamic mechanisms in the model, to a point where he is able to identify those dynamic modes of behaviour that seem dominant in characterising the problem. Young (1978) has suggested that it is these dominant modes of behaviour which are so important in the subsequent time-series analysis for, if the model is indeed representative of the system, then it is these modes which will be most "identifiable" from the observed data.

There is no proof at present that such a dominant mode theory of dynamic behaviour is generally applicable but experience with practical dynamic systems suggests that it is a reasonable conjecture; indeed it could be argued that the definition of a "problem" behaviour is, in itself, an acceptance of some form of modal dominance. But whether or not the analyst subscribes to such a theory he will, in any specific case, be able to examine the model for evidence of such behaviour. As we shall see in the next Chapter, evidence of this type can be obtained by quite straightforward exercises in systems analysis applied to one of the *model* realisations that exhibit the problem behaviour. This may ential both evaluation of the model structure (e.g., by linearisation) and analysis of the model response $\underline{x}(t)$ (e.g., using time-series methods).

In effect, this analysis of the model in systems terms is aimed at testing the hypothesis of modal dominance. If the hypothesis is supported (as we feel it will be most of the time) then the analyst will have obtained some ideas about possible simple forms of the model which can be used as the basis for further time-series analysis on data from the system itself. If there appears to be no evidence to support the hypothesis (which we feel is unlikely in general) then the analyst will be no worse off and he should at least have a better appreciation for the simulation model dynamics.* The coordinated

---

*we would go further and suggest that this kind of systems analysis applied to the simulation model is *sine qua non* for success in *any* simulation modeling exercise applied to a badly defined system: it would certainly help to avoid some of the more näive exercises in simulation modeling that currently abound in the literature. An excellent example of its value is the analysis of the Forrester world model by the "Global Dynamica" Group at the University of Eindhoven (see e.g. Thissen, 1978).

systems analysis - modeling - data collection strategy whose virtues we extol in this Report should mean that, concurrent with the simulation modeling and systems analysis, exercises in relevant data collection will have been planned and initiated. When these data on the system become available they will allow the analyst to progress one step further in his model building: namely to the identification of a suitable identifiable, time-series representation of the system.

A simple dominant mode characterisation of the simulation model provides an ideal starting point for time-series analysis, the first stage of which is aimed at identifying a dynamic model of the dominant modes associated *with the system itself.* In other words, having tested the hypothesis that the *simulation model* can be represented simply in dominant mode terms, we suggest that the analyst should now proceed to test the hypothesis that such representations are appropriate to the *real system.* The result of this analysis is the identification of a (usually) simple time-series model structure which may be linear or non-linear in dynamic terms, depending upon the nature of the system. It will, however, normally be characterised by a set of parameters which need to be estimated during the subsequent parameter estimation phase of the analysis.

The methodology of time-series model structure identification suggested by Young (1978) is based on the use of recursive estimation procedures in which the model parameters are estimated sequentially while working serially through the data. The model structure is then considered "well identified" if it simultaneously satisfies the following criteria

(1) the recursive estimates of assumed time-invariant parameters are themselves indicative of time invariance *and* the estimates of assumed variable parameters have direct physical interpretation.

(2) The covariance matrix of estimation errors associated with the estimated parameters indicates no problems of over-parameterisation.

(3) The estimated stochastic disturbances to the system are purely stochastic in form and have no systematic components attributable to some physical aspects of the system behaviour or input peturbations.

(4) The residual error sequence associated with the model should possess "white noise" properties and be statistically independent of the deterministic inputs.

Put simply, this identification analysis is aimed at producing a model structure which (a) has a satisfactory physical interpretation; and (b) is identifiable from the available time-series data in the sense that it can be characterised by a *unique* set of well defined parameter estimates. Implicit in these specifications is the requirement for a *parametrically efficient* model representation and the avoidance, therefore, of over-parameterization. This can be considered as a statistically sophisticated application of the "Principle of Occam's Razor", in which the simplest model (hypothesis) consistent with the observations is chosen to explain the data.

Estimation of the parameters that characterise the identified model structure is a fairly straightforward exercise and there are numerous estimation procedures that can be utilised. We would suggest, however, that recursive instrumental variable (IV) techniques provide the currently most flexible approach (see e.g., Young, 1974, 1976b); Young and Jakeman, 1979; Jakeman and Young, 1979) since they are statistically sophisticated yet robust in application terms. And, as we have seen, their recursive formulation makes them useful in the previous identification phase of the analysis (Young, 1978). Moreover, recursive smoothing versions of the IV algorithms are now available (Kaldor, 1978; Young and Kaldor, 1978) which can enhance still further time-varying estimation potential of the IV method. These recursive techniques are available in the CAPTAIN recursive time-series analysis computer package developed first in Cambridge and then in CRES (Appendix 2).

Whatever estimation procedure is used, however, the result will be a set of estimates of the parameters characterising the identified dominant mode model structure, together with some indication of the uncertainty associated with these estimates (usually in terms of an estimation error covariance matrix).

As we pointed out earlier, it is the *complete* statistical results of the estimation exercise that need to be evaluated in order to check on the model adequacy. Thus a good model fit is not, in itself, an indication of a good model. It could well be, for example, that this fit is obtained at the cost of over-parameterization, so that the parameter values will not be defined clearly by the estimates, as indicated by high estimation error variances.

It is important, therefore, that the estimated model should only be accepted as a reasonable representation of the time-series data when the statistical properties of the residual model errors *and* the statistical properties of the estimates are both deemed acceptable by the analyst (Young et al, 1980).

4.4 Time-Series Model Validation

The final and continuing stage in model building is validation; here the model's forecasting ability is evaluated on data *other than that used in the identification and estimation studies.* If the model continues to forecast well over this test data interval, it is assumed that it is *conditionally* acceptable in the sense that, *as far as it is possible to test,* the model seems satisfactory.

Validation is a continuing procedure since the model will need to be re-assessed in the light of future developments and additional data. If major changes in the system take place, for instance, it is likely that the model will need to be modified in some manner because it will not necessarily mirror the changed dynamic behaviour in the new situation. Nevertheless, the continuing process of model assessment based upon a supply of new data should indicate if the model has become questionable in any sense and will, in these circumstances, indicate the need for further model identification, estimation and validation. In such a situation, the recursive nature of the estimation algorithms will greatly facilitate the process of model re-assessment; a process which could entail simply updating the model parameters, but which might require changes in the basic model structure.

The inherently stochastic nature of the model discussed in the previous section also helps considerably in the continuing process of model assessment because it allows for the application of statistical tests regarding the model's suitability. Such tests can help to remove some of the more subjective judgements which are often characteristic of conventional model building procedures.

Of course, the only real validation of a model is that it satisfies the purposes for which it was intended; in other words, that is "works" in practice. We would hope that by going through the systematic procedures suggested here the analyst will be maximising the probability that the model will be acceptable in this sense. But this can never be guaranteed in the case of badly defined systems; the analyst must, unfortunately, "wait and see".

4.5 Model Building and the Scientific Method

Before discussing the application of the above procedure to the Peel-Harvey system, it is worthwhile stressing the relationship between the model building procedure discussed in previous sections and the scientific method (see e.g., Popper, 1959). Model formulation is simply the formulation of hypotheses about the nature of the system; model structure identification and parameter estimation represent initial steps in the deductive procedure that is used to test these hypotheses against data; and model validation is the final step in that deductive procedure in which the analyst attempts to "falsify" the model (or theory) of behaviour and accepts the *conditional* validity of the model if such attempts fail.

It may seem trite and obvious to draw this analogy but it seems necessary. Often simulation modeling of badly defined systems, as at present practised, does not conform to the scientific method; indeed we regard this limitation of many simulation modeling exercises as the main reason for their failure to be fully successful in practical terms.

Too often the reductionist philosophy, which has proved so useful in *well defined* systems analysis (e.g. the conventional physical and laboratory based biological sciences, engineering etc.), is mis-used to bypass the need for holistic and complete model validation. In this manner, the model builder can too easily persuade himself that his model is fully validated when, in fact, it may have surplus, unvalidated content that could prove misleading in subsequent analysis. More than this, such analysis tends to create over-confidence in the (usually deterministic) model, almost to the extent that the analyst appears often to believe that his cherished model *is* the system.

Of course, this does not mean that the reductionist model is necessarily incorrect in *form*; merely it indicates that the richness of structure may be inappropriate to explain the rather simpler observed behaviour and so the model can have surplus content *not validated against observations*. With such possibilities in mind, we should not be reticent to attempt the falsification of simpler hypotheses particularly if we have a reasonable quantity of observational data. While conditionally acceptable hypotheses of this simpler variety may not tell us all about the behaviour of the system, they will tend to indicate those aspects of the system behaviour that are explained by the observational data. And simple models of complex phenomena are not necessarily bad models; Popper extols the virtues of simple theories (models) and explicitly equates simplicity with paucity of parameterisation.

5. *CLADOPHORA* GROWTH DYNAMICS : SPECULATIVE SYSTEMS ANALYSIS AND THE GENERATION OF WORKING HYPOTHESES

In this Chapter we will see how the initial "model formulation" stage of the model building procedure discussed in the previous Chapter has been applied successfully in the Peel-Harvey context. In the case of the *Cladophora* problem in the Peel Inlet, the objective of systems analysis is clearly to construct models which may not only help to explain the reasons for the excessive growth of the nuisance alga, but will also assist in the definition of possible management strategies, which can then be the subject of later economic appraisal within a cost-benefit framework. Such models must, therefore, be *as simple as possible consistent with solving the problem* and they must be capable of evaluation within appropriate funding and time-scale constraints.

To some extent, such considerations limit the scope of the analyst for model choice and he must seek out any methods of simplifying the exercise, while still ensuring that he avoids any possibility of drawing unvalidated conclusions because of lack of sufficient depth in his analysis. The initial exercises in simulation modeling for the Peel-Harvey Study were aimed, therefore, at evaluating plausible model mechanisms under a *phosphorus nutrient scenario;* in other words, the simulation model was formulated on the basis of a phosphorus budget, under the hypothesis that phosphorus, in its various forms, is the major nutrient of importance to the *Cladophora* growth dynamics.

Other possible scenarios, such as those based on nitrogen or nitrogen/phosphorus budgets, were evaluated - although not to the same extent as phosphorus - but they did not seem able to provide behavioural characteristics similar to those associated with the *Cladophora* blooms in the Peel Inlet (see Chapter 9). It is important to note, however, that the analysis was not complete enough to reject the possibility of such alternative scenarios; rather the results obtained with a phosphorus scenario were sufficient to give it preferential acceptance in relation to the alternatives. Needless to say, in a longer term study the alternatives would have been considered more fully.

5.1 The Stochastic Model

The phosphorus budget model consists of four compartments: Cladophora, x_1; phytoplankton, x_2; soluble phosphorus in the water column, x_3 and sedimentary phosphorus, x_4. Two other equations describe the water and sediment balances. A schematic diagram of the whole system is shown in Fig. 5.1. The equations for each compartment are described in detail in Appendix 4[†] and we will consider here only the *Cladophora* equation, which will exemplify the model. The equation is nominally non-linear and takes the form

$$\frac{dx_1}{dt} = \gamma_1 T\ I_b \frac{x_c}{K_1 + x_c}\ g(x_1) - a_{11}x_{11} \qquad (5.1)$$

where, x_1 = *Cladophora* biomass in terms of phosphorus content (μg).

γ_1 = temperature-light-growth coefficient (day^{-1} ^{o}C^{-1} cal^{-1} cm^{2}).

T = water temperature (^{o}C).

I_b = total light at the bottom for the day = $Ie^{-K_T Z}$, where I is actual surface light intensity, K_T is the extinction coefficient and Z is depth (cal cm^{-2}).

x_c = available phosphorus concentration = $\alpha x_3 + (1-\alpha)x_4$ where α is a number between zero and one and x_3 and x_4 are phosphorus concentrations in water and sediment respectively (μg l^{-1}).

K_1 = half saturation (Michaelis) constant for phosphorus uptake (μg l^{-1}).

$g(x_1)$ = biomass (phosphorus) available for active photosynthesis (μg). This term is equal to x_1 for low values of biomass but asymptotically approaches a constant value x_m, which is the masimum photosynthesising biomass.

a_{11} = rate constant for biomass decrease due to all causes, i.e. death, respiration, grazing, export to beaches and loss to sea.

[†] based on Spear and Hornberger (1978).

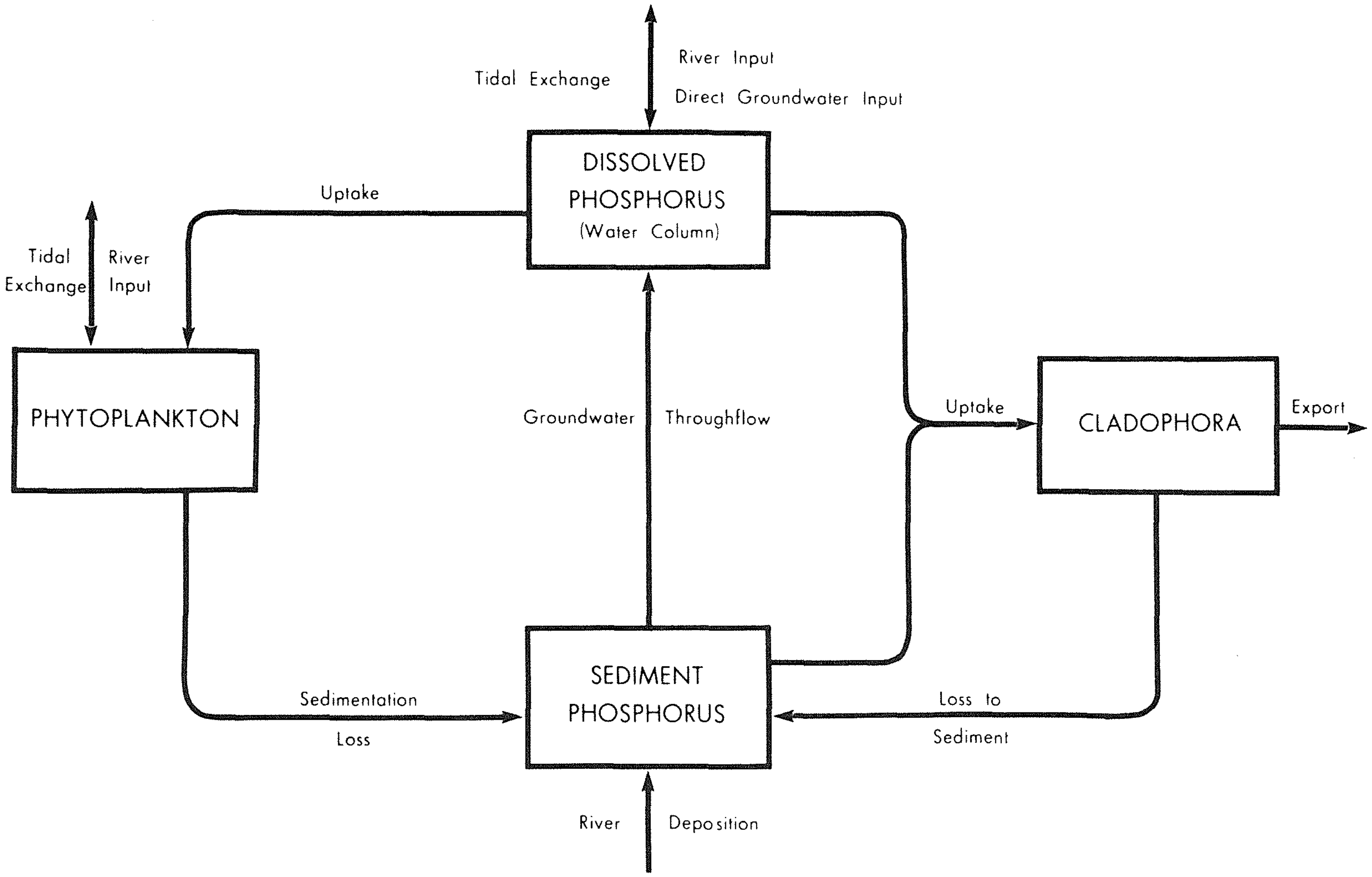


FIGURE 5.1 Schematic of Phosphorus Budget Model

The various coefficients in equation 5.1 and the other model equations were either derived from the literature, inferred from measurements on the Peel Inlet system or estimated by experts familiar with the system. The probability distributions associated with the parameters were chosen in accordance with the uncertainty in their specification: in general, they were chosen as rectangular distributions with limits selected to reflect reasonable upper and lower bounds on the parameter values. Environmental functions required to solve the equations from the specified initial conditions (e.g. temperature, irradiance, river discharge, tidal exchange etc.,) were mostly specified from existing data on the system collected during 1976. In some cases, however, it was necessary to develop time-series sub-models to define environmental forcing functions to the system. For example, a tidal exchange model was estimated in order to provide predictions of tidal exchange based on tidal elevations at Mandurah.† This stochastic model was developed with the help of the CAPTAIN program (see Appendix 2).

5.2 Monte Carlo Analysis

The Monte Carlo analysis entailed 626 random simulations of the model and out of these, 281 exhibited the problem behaviour. Figs. 5.2 to 5.6 show the simulated model variables for three typical runs from the ensemble. Also shown in Fig. 5.7 are the variations in daily solar irradiance (DSI) which, as we shall see in Section 5.4, acts as an important environmental forcing function. The plots for each run are distinguished by the number on the right hand end of the curve (1, 2 and 3): curve 2 corresponds to a "Peel-Harvey Bloom", in other words a "behaviour" (B), because we see that the *Cladophora* blooms in the typical Peel-Harvey manner and phytoplankton remains low; curves 1 and 3 are examples of "not-the-behaviour" ($\bar{B}$), because phytoplankton levels become too high in 1 and *Cladophora* does not achieve a high enough biomass in 3.

The graphs are self explanatory and,for comparison,Fig. 5.2a shows the actual *Cladophora* biomass figures for Pier 46 based on the

---

† this was, of course, prior to the later salinity analysis which yielded superior models of tidal exchange as discussed in Chapter 7.

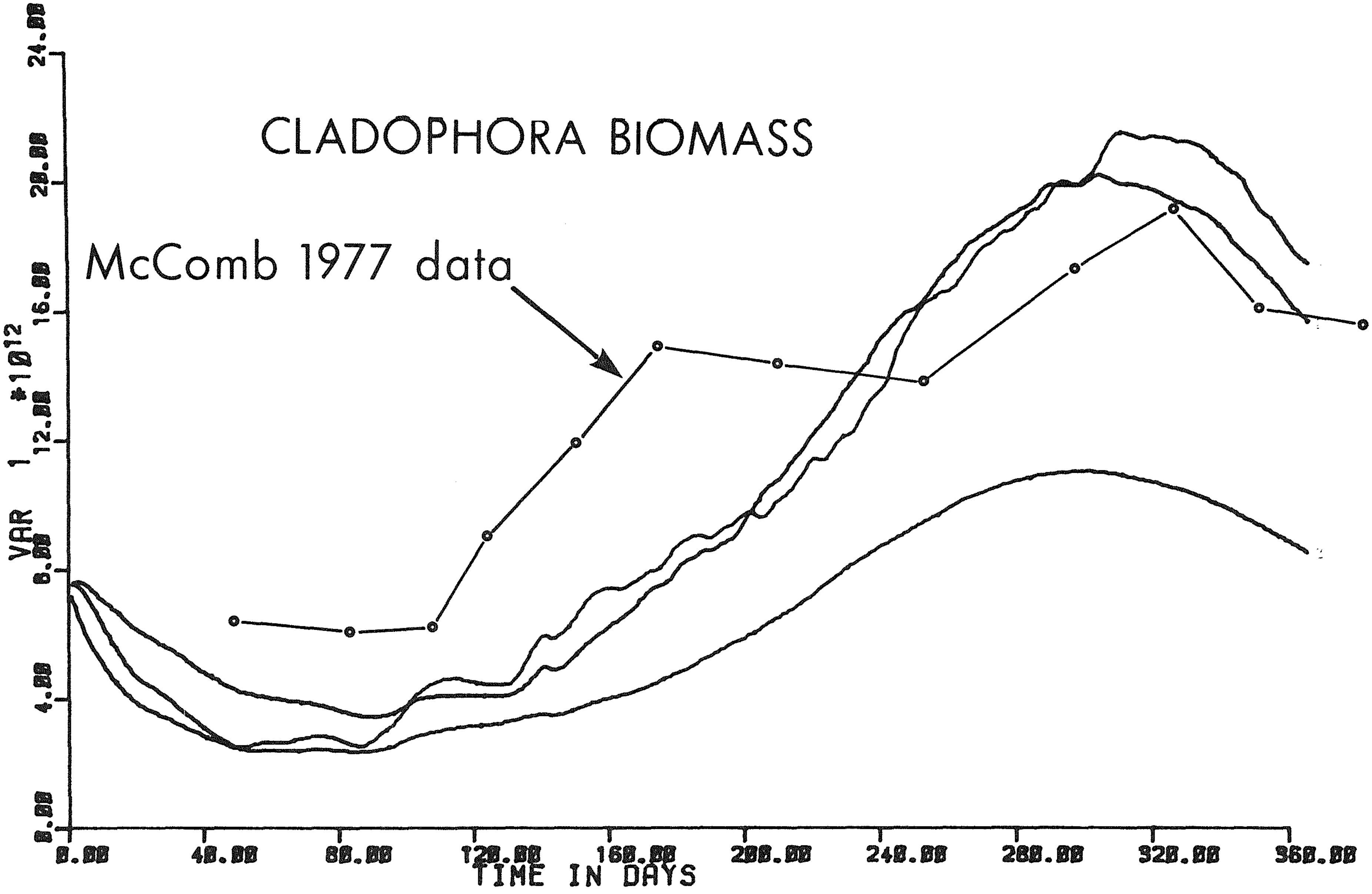


FIGURE 5.2 Speculative Simulation Model for *Cladophora*
- three random realisations for "

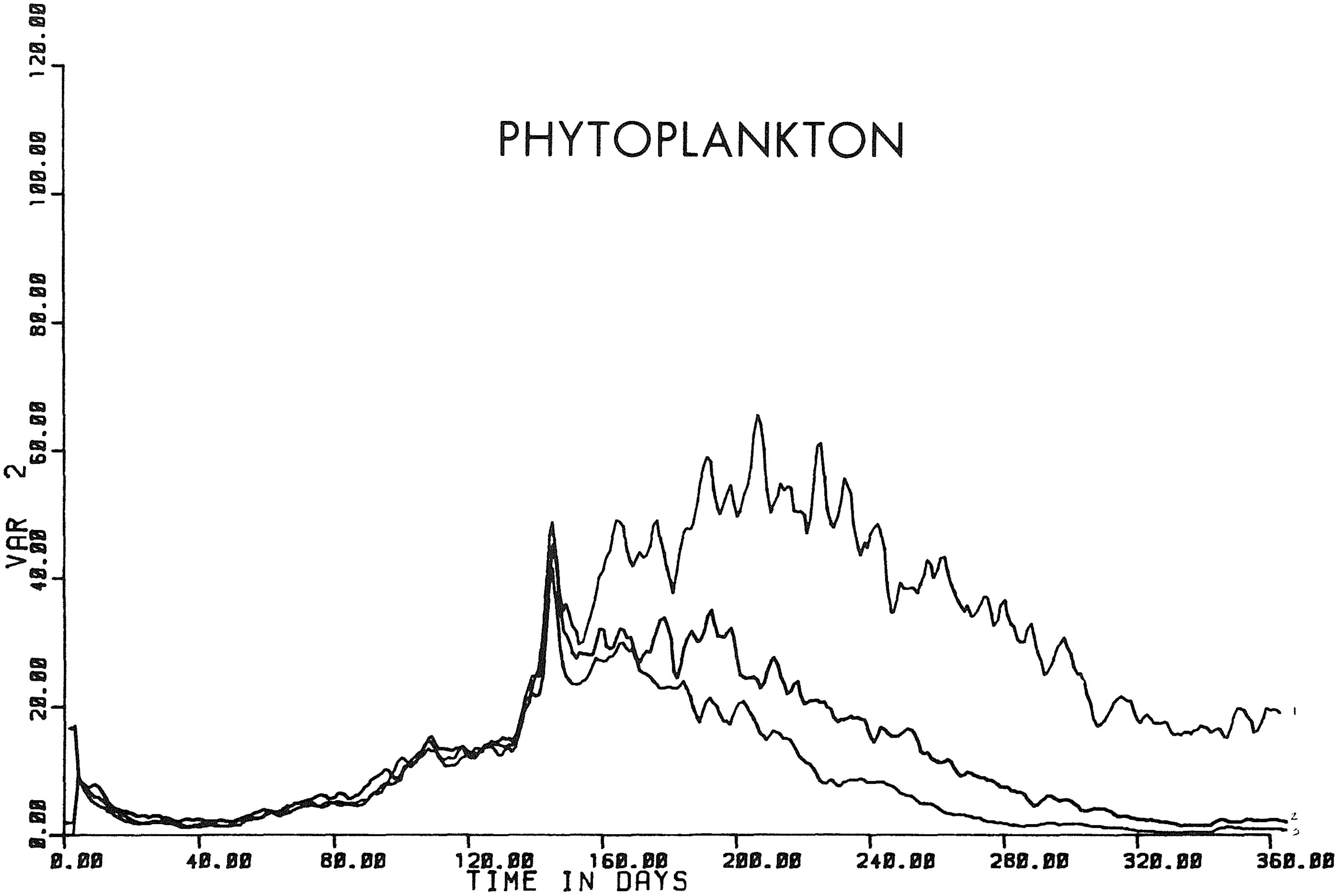


FIGURE 5.3 Speculative Simulation Model for *Cladophora* - three random realisations for phytoplankton

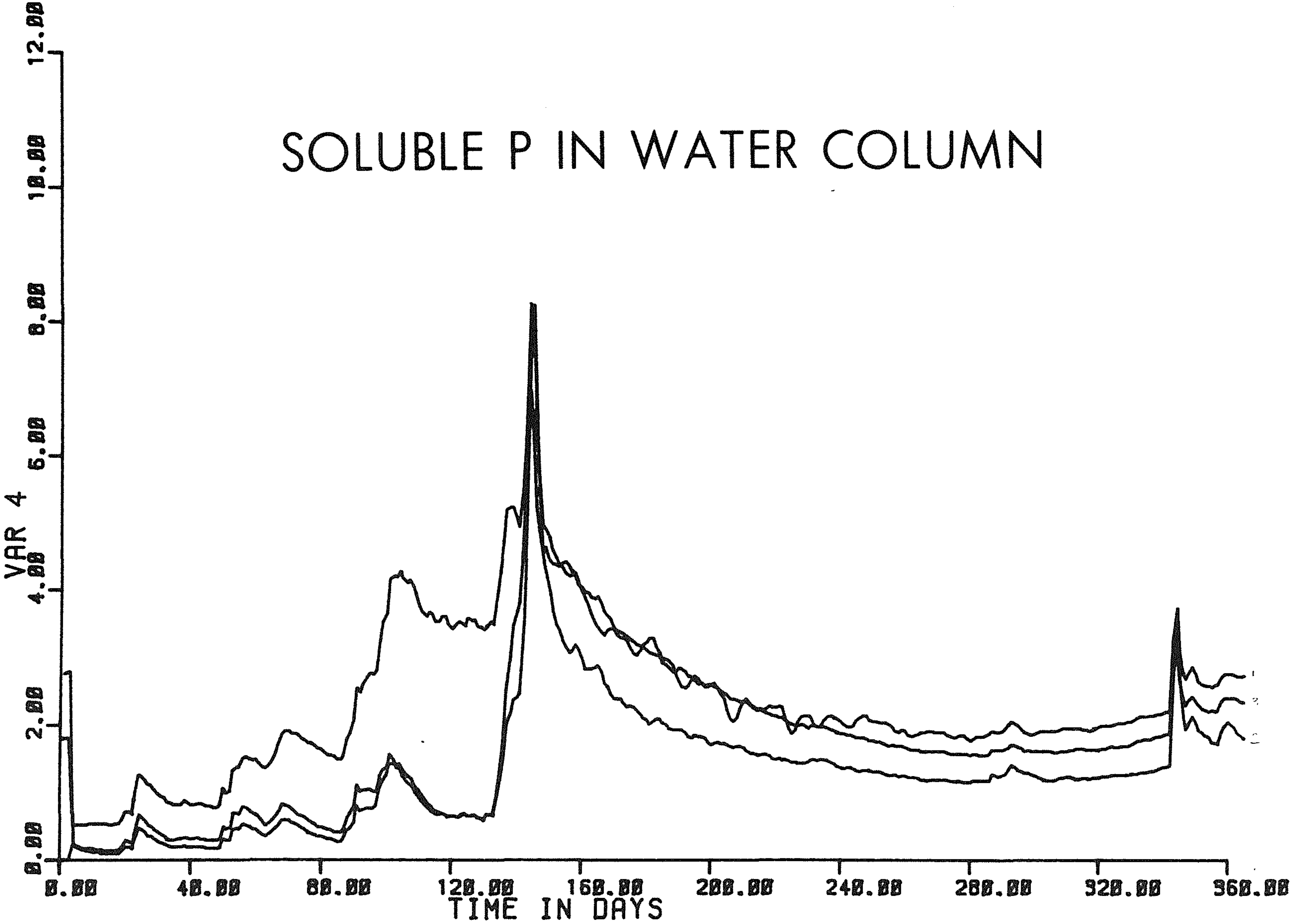


FIGURE 5.4 Speculative Simulation Model for *Cladophora*
- three random realisations for soluble phosphorus

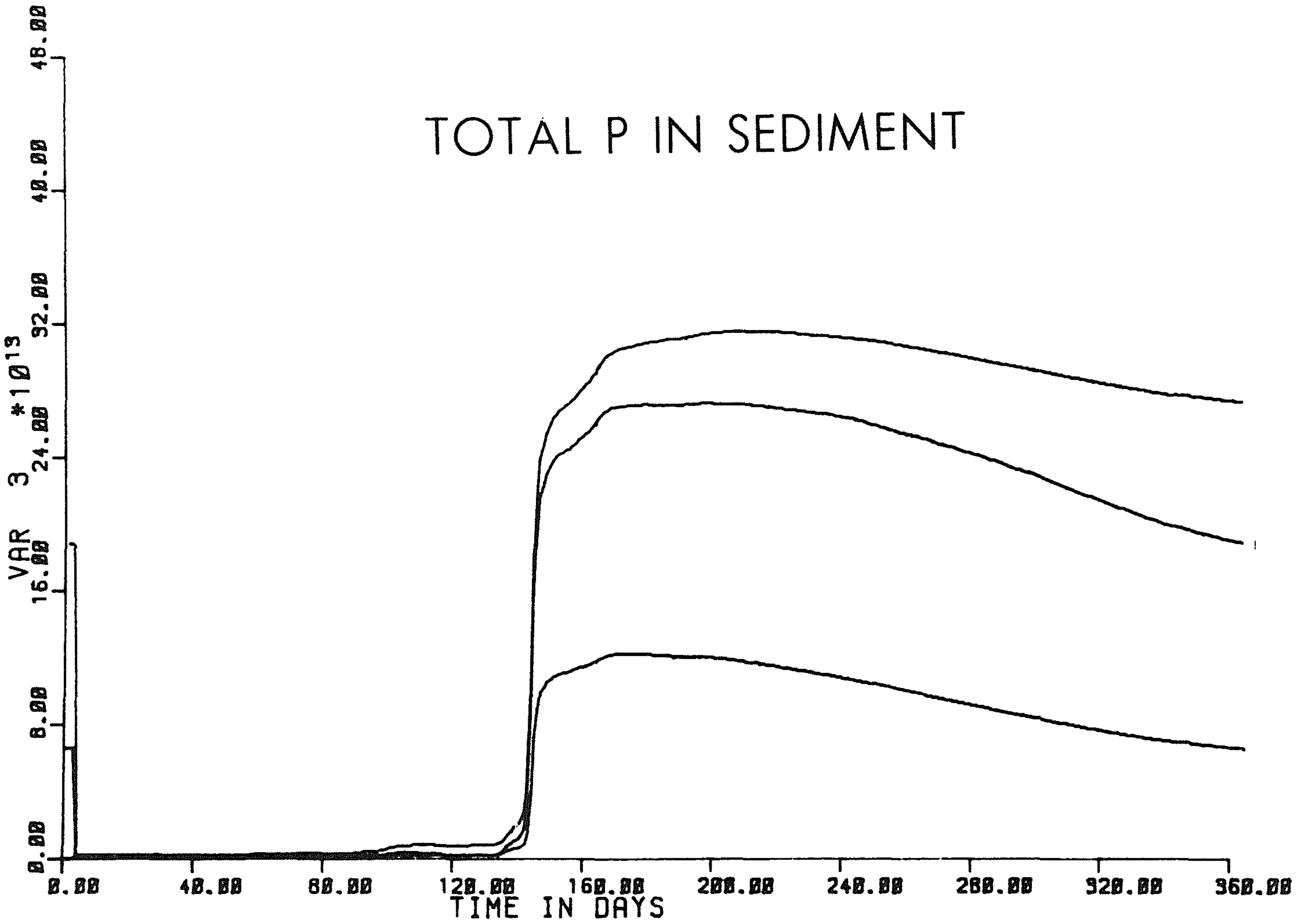


FIGURE 5.5 Speculative Simulation Model for *Cladophora*
- three random realisations for total phosphorus in sediment

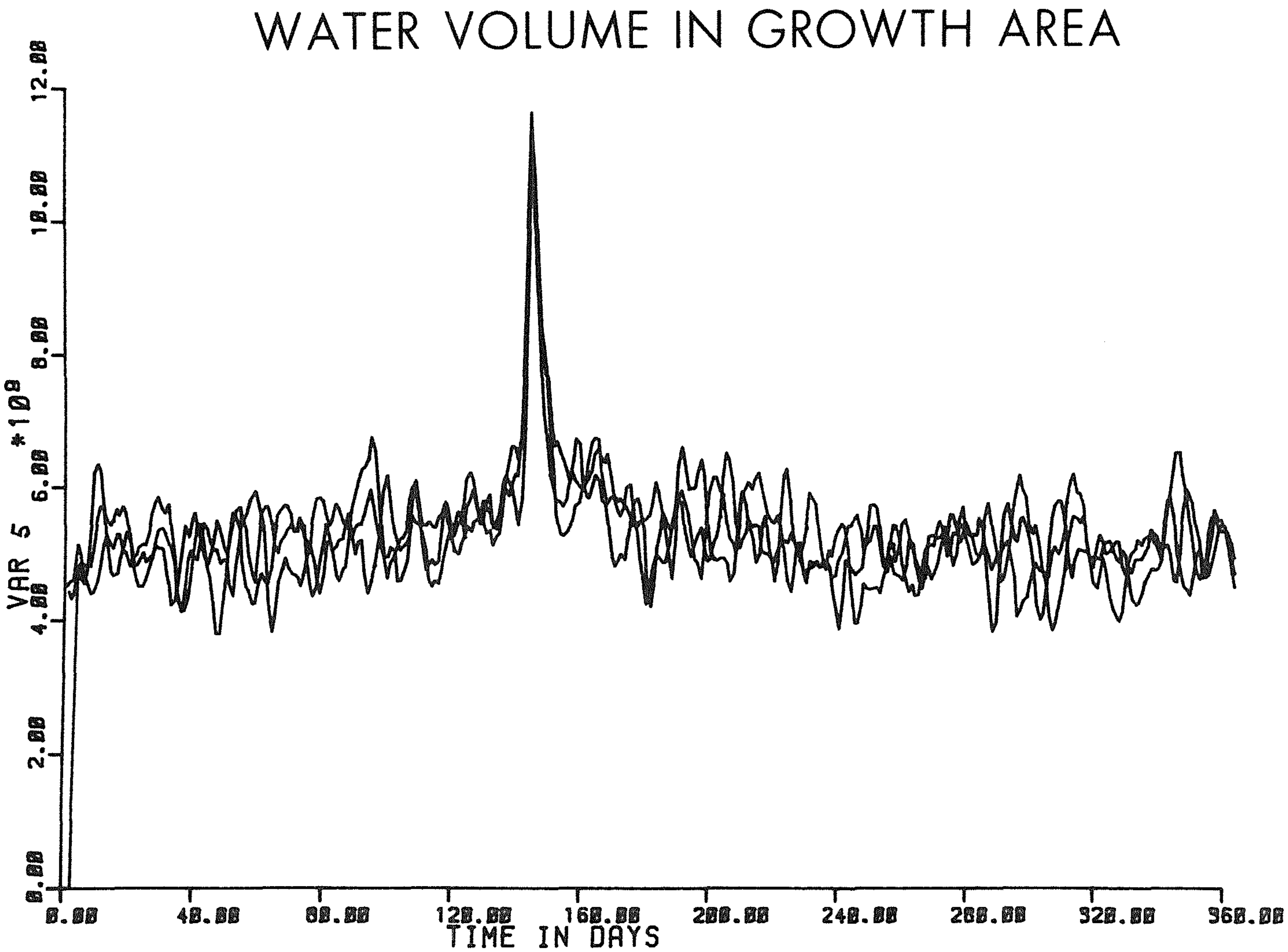


FIGURE 5.6 Speculative Simulation Model for *Cladophora*
- three random realisations for water volume variations

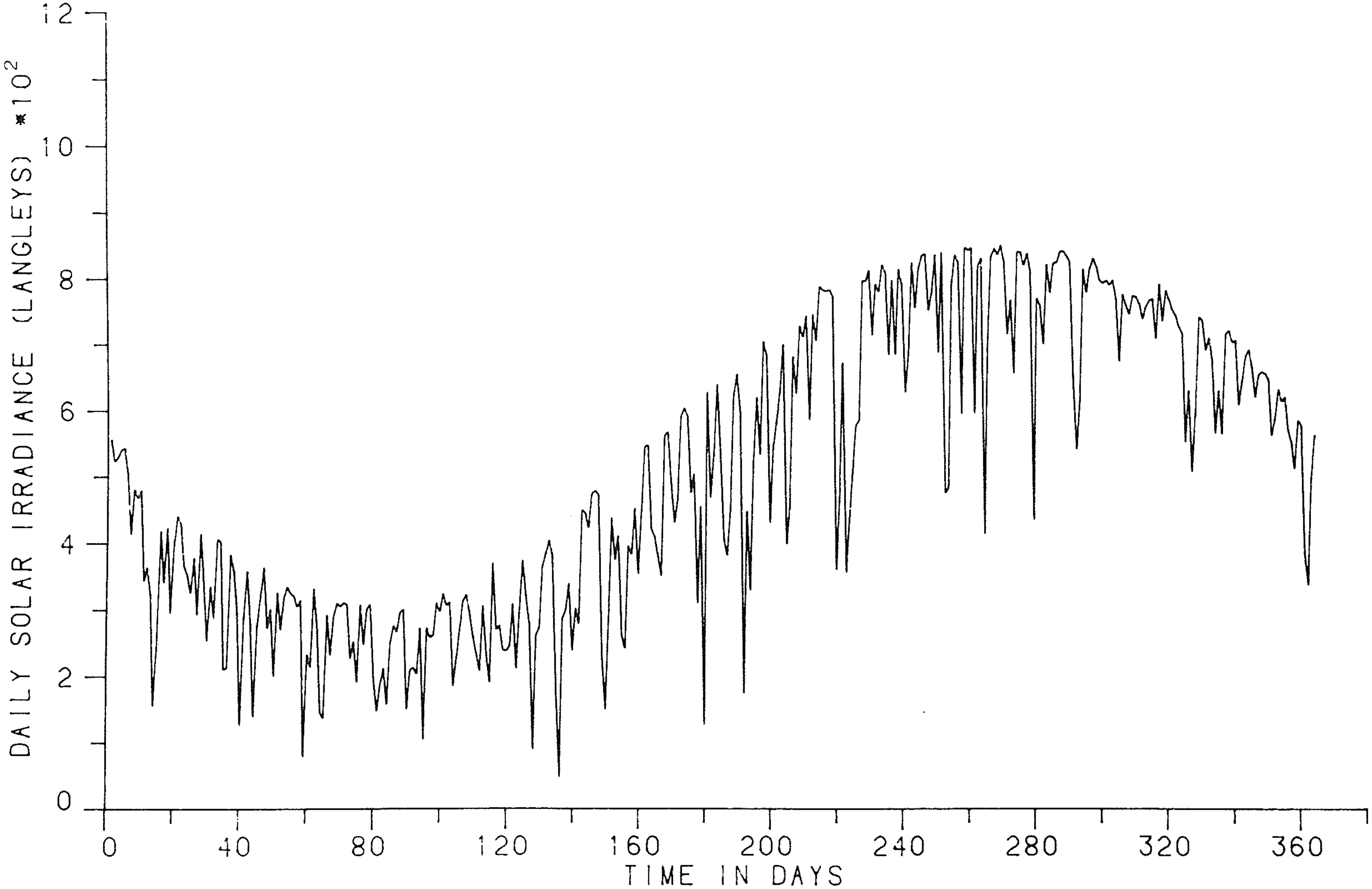


FIGURE 5.7 Speculative Simulation Model for *Cladophora*
- daily solar irradiance variations used in model

observations of McComb et al. (1980).[†] Note, however, the importance of the river discharge in these simulations: the 'spike' in water volume at about 150 days corresponds to this inflow and its effect is apparent on all 3 curves in Fig. 5.6. We see how these volume changes give rise to significant and sustained increases in total P in the sediment (Fig. 5.5) and significant but more transient increases in the soluble P in the water column (Fig. 5.4). The instantaneous effect of this soluble P increase is seen in the increase of phytoplankton biomass (the 'spike' at 150 days) and, superficially, it would seem that the changes in both sediment and soluble P lead to the subsequent rise in *Cladophora* biomass. As we shall see in Section 5.4, however, this correlation is somewhat misleading and the growth of *Cladophora* biomass is much more strongly controlled by the direct solar irradiance (DSI) changes shown in Fig. 5.7.

5.3 The Sensitive Parameters

The statistical sensitivity analysis shown diagrammatically in Fig. 5.8 pointed to three types of model parameters for which uncertainties are critical. The first of these can be described loosely as *Cladophora* growth parameters. It may seem tautalogical to say that the parameters which describe *Cladophora* growth are important in determining "behaviour" when that behaviour was defined primarily on the basis of changes in *Cladophora* biomass. Nevertheless, further comment on two of these parameters is warranted. The parameter x_m, the *Cladophora* maximum photosynthesising biomass, ranked first in importance in the model study. The fact that such a parameter is not generally used in modeling algal growth only reinforces its importance provided that the general concept underlying its use can be justified. The recent work of Bach and Josselyn (1978) in Bermuda, which came to our attention after the completion of the simulation work, gives a basis for cautious optimism on the question of the utility of the x_m concept. They found that 90% of production of a ball-forming *Cladophora* species occurred within the top 3cm of the surface of the mat. This depth corresponded to a density of about 300 gm^{-2} on a dry weight basis for the actively photosynthesising

---

[†] Collected 1977.

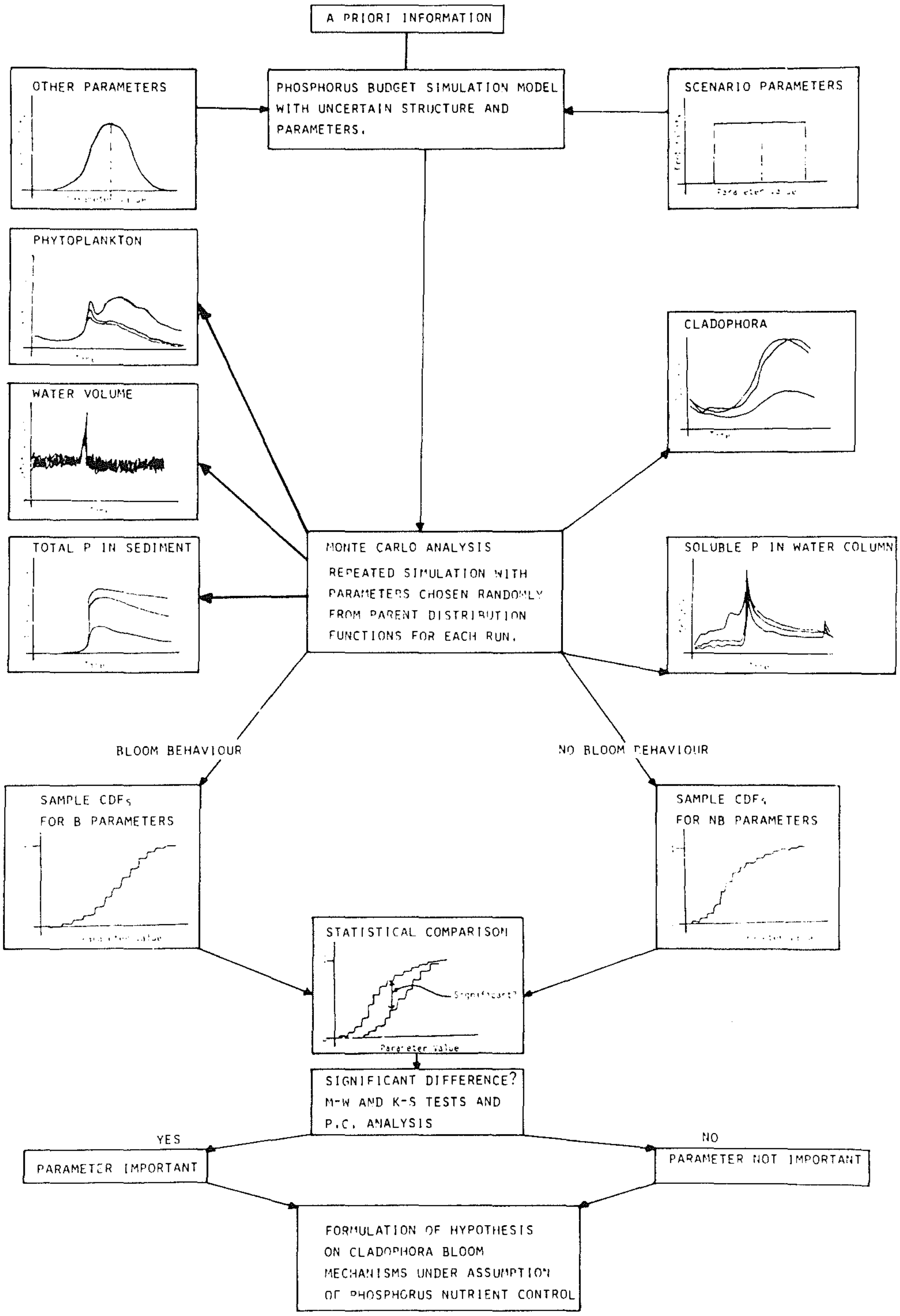


FIGURE 5.8 Speculative Simulation Modeling Organisation Diagram

layer. These results have been confirmed in the present study (McComb et al, 1980) and so there is support both for the notion that an effective layer of photosynthesising biomass can be defined and the finding from the model results that values of x_m in the upper part of the range that we used are most likely to be consistent with the problem-defining behaviour.

The other *Cladophora* growth parameter that deserves comment is a_{11}, the combined *Cladophora* loss rate. This parameter ranked third in importance with regard to model sensitivity, with low values preferred for obtaining the behaviour. Jannson (1974, 1975) used a combined loss rate in her *Cladophora* model that was about a factor of four lower than values routinely used in phytoplankton models. The present analyses and subsequent work by Gabrielson, Birch and Hamel (1980) suggest that such low values are also indicated for *Cladophora* in Peel Inlet and may be appropriate for benthic algae in general. This is consistent with high recycling efficiency and the observed persistence of large quantities of *Cladophora* for extended periods, even after the elimination of the apparent source of enrichment (Hodgkin and Vicker, 1977).

The second type of parameter that was singled out in the sensitivity analyses can be categorized as descriptive of phytoplankton growth. In terms of the phosphorus model, even moderate concentrations of phytoplankton are sufficient to supress the growth of *Cladophora* by limiting the light available at the bottom of the Inlet, and it is primarily for this reason that the phytoplankton parameters are important with regard to sensitivity. Even when a behaviour was obtained in a simulation run, the predicted phytoplankton concentrations were generally higher than those observed in the growth area of Peel Inlet and the predicted water column phosphorus concentrations were lower than observed values. Thus, the model predicts that phytoplankton should be able to grow in Peel Inlet and that in doing so they should lower phosphorus concentrations below those observed.

It is interesting to speculate on why the model behaves in this manner. The most obvious explanation is that the phytoplankton are limited by a factor other than phosphorus. If so, this factor is likely to be some trace element since measurements indicate that available nitrogen is in much greater abundance than phosphorus and since the relatively constant pH implies that carbon limitation is unlikely. An alternate explanation lies in the possibility that *Cladophora* produce an extrametabolite that inhibits the growth of phytoplankton species, a mechanism not impossible in green algae (e.g. Fogg, 1966, Harris 1971). However, investigations into these possibilities are continuing.

The third category of important parameters is related to the sediment compartment. The parameter a_{43}, the sediment-water diffusion parameter (Appendix 4), is high in the sensitivity ranking due to the model prediction that relatively high rates of release of phosphorus from the sediment encourage phytoplankton growth and, as described above, this diminishes the probability of simulating the specified behaviour. Secondarily, low values of a_{43} tend to keep phosphorus in the sediment where the *Cladophora* have access to it.

It is interesting to note that the model is insensitive to the parameter associated with river sediment transport S_p (Appendix 4) in the range of values used in the Monte-Carlo simulations. This insensitivity arises in spite of the obvious but possibly misleading conclusion drawn from the simulations that the input of sediment-bound phosphorus from the river "triggers" the *Cladophora* bloom in the model (see Figure 4). We can infer from this that a highly precise estimate of S_p is not required to explain the problem behaviour but that some idea on the order of magnitude of the river sediment input is essential (note that a reduction of S_p to an order of magnitude less than the lower limit used in the simulations reduces the probability of simulating the behaviour to zero! - see Appendix 4).

Similarly, the parameter a_{41} (Appendix 4) which accounts for nutrient regeneration from scenesing and decaying *Cladophora* was found to be unimportant with regard to model sensitivity. However, the weekly measurements of *Cladophora* biomass made subsequent to the 1976-77 study indicate that the decline of this biomass is very slow. Had such a condition been imposed as part of the definition of model behaviour, it is likely that a_{41} would have been counted amongst the important parameters. It is also clear from the results that low values of S_p lead to rapidly declining *Cladophora* biomass toward the end of a simulation run and consequently this parameter would also be highly ranked if the behaviour criteria were modified. Thus, the entire cycle of nutrient addition, regeneration and release in the sediment, and not merely the magnitude of the diffusion loss, is probably important for understanding the detailed behaviour of the *Cladophora* mat.

In summary, the phosphorus scenario provides one feasible explanation of the nuisance algal problem in Peel Inlet. Examination of the simulation results show that this explanation of the behaviour depends primarily on one feature of the model structure: the presumption that *Cladophora* have access to phosphorus in the sediment and that the sediment contains enough nutrient to support the observed levels of biomass. In the model, the second condition requires that there be a significant input of nutrient to the sediment by the river.

The suggestion that a benthic alga such as *Cladophora* can better utilise sediments as a nutrient source than can phytoplankton suspended in the water column is intuitively appealing but is not a commonly accepted idea. In fact Fitzgerald (1970) argues that even though phosphorus-limited *Cladophora* species in Lake Wingra are in intimate contact with sediments containing large amounts of PO_4, they apparently cannot readily use it, at least under aerobic conditions. On the other hand, Moshiri and Crumpton (1978) point out that the slow but steady release of phosphorus from sediments, even under aerobic conditions, can be significant in the overall phosphorus budget of an estuary. Furthermore, it is conceivable that although the water column appears to be well oxygenated, the night time respiration of the *Cladophora* community itself might deplete the oxygen within the algal mat, if not within the water column, thereby enabling phosphorus to be released into the "inter-algal" water. These and other aspects of the detailed behaviour of *Cladophora* have, however, been the subject of research by our colleagues at the University of Western Australia (McComb et al, 1980; Gabrielson, 1981).

5.4 The Application of Systems Analysis to the Simulation Model Results

Detailed though the above stochastic simulation analysis may be, it does not reveal directly one very important aspect of the system behaviour, although this behaviour is quite obvious from the three typical simulation run results shown in Figs. 5.2 to 5.6. Here it is quite clear that the pattern of *Cladophora* biomass variation is quite similar in form to the variation in daily solar irradiance (DSI) shown in Fig. 5.7; in other words, there is a strong indication that the growth is *light-limited* for much of the time.

This indication is confirmed by two methods of analysis (Young et al. 1978). In the first approach, time-series modeling using the CAPTAIN computer package (Appendix 2) is applied to the *Cladophora* - DSI data, with DSI defined as input and *Cladophora* as output. This yields a first order (two parameter) model which is able to explain much of the variation in *Cladophora*, as shown in Fig. 5.9. Furthermore when the time-variable parameter (TVAR) estimation algorithm in CAPTAIN is applied to the same data, it yields a first order model with the slowly time variable parameter estimates shown in Fig. 5.10, which fits the data *exactly*, without any residual error at all!

The second approach follows from the first: having shown that a simple time-series model with slowly variable parameters can explain the data exactly, it is clear from systems theory that linearisation of the model and subsequent simplification should also produce a simpler model which explains the simulated behaviour. This is confirmed by straightforward if lengthy analysis (linearisation of a 19 parameter non-linear model can be tedious) which reveals that the linearised parameters vary exactly as indicated in Fig. 5.10.

These analytical results show that the *Cladophora* growth *in the model* (and we remind the reader that we are dealing here with a speculative model, not the real system) is controlled by light limitation. Thus while the sediment phosphorus is indicated as a potentially important pathway through which *Cladophora* may receive nutrient input, phosphorus itself may be of lesser importance to the modeled behaviour because it may almost always be in plentiful supply.

When these results were first obtained, it was realised that they could have important practical implications if the real estuarine system behaved in any way like the modeled system. "Normal operation"

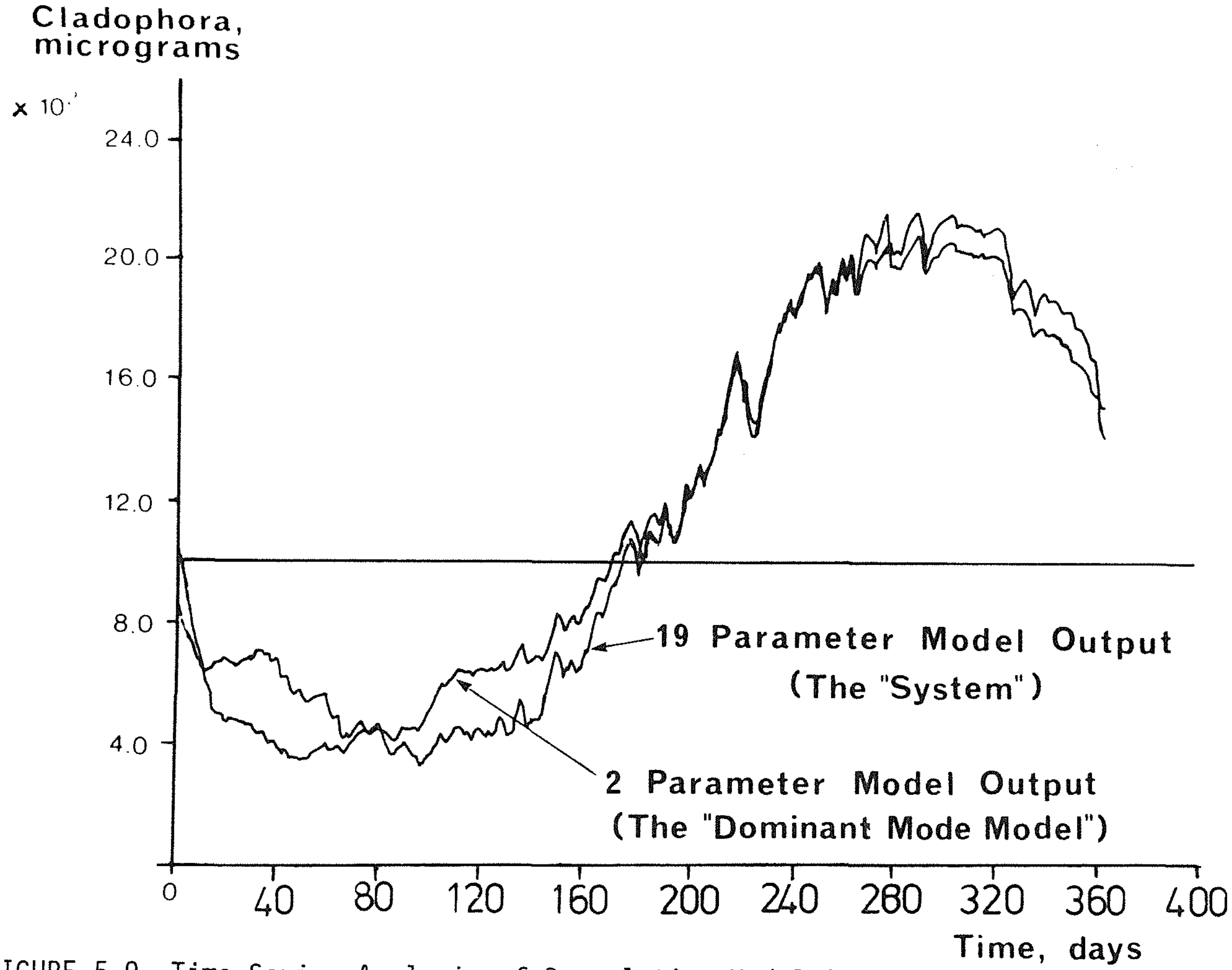


FIGURE 5.9 Time-Series Analysis of Speculative Model Output: Comparison of 2 parameter time-series model with 19 parameter speculative model

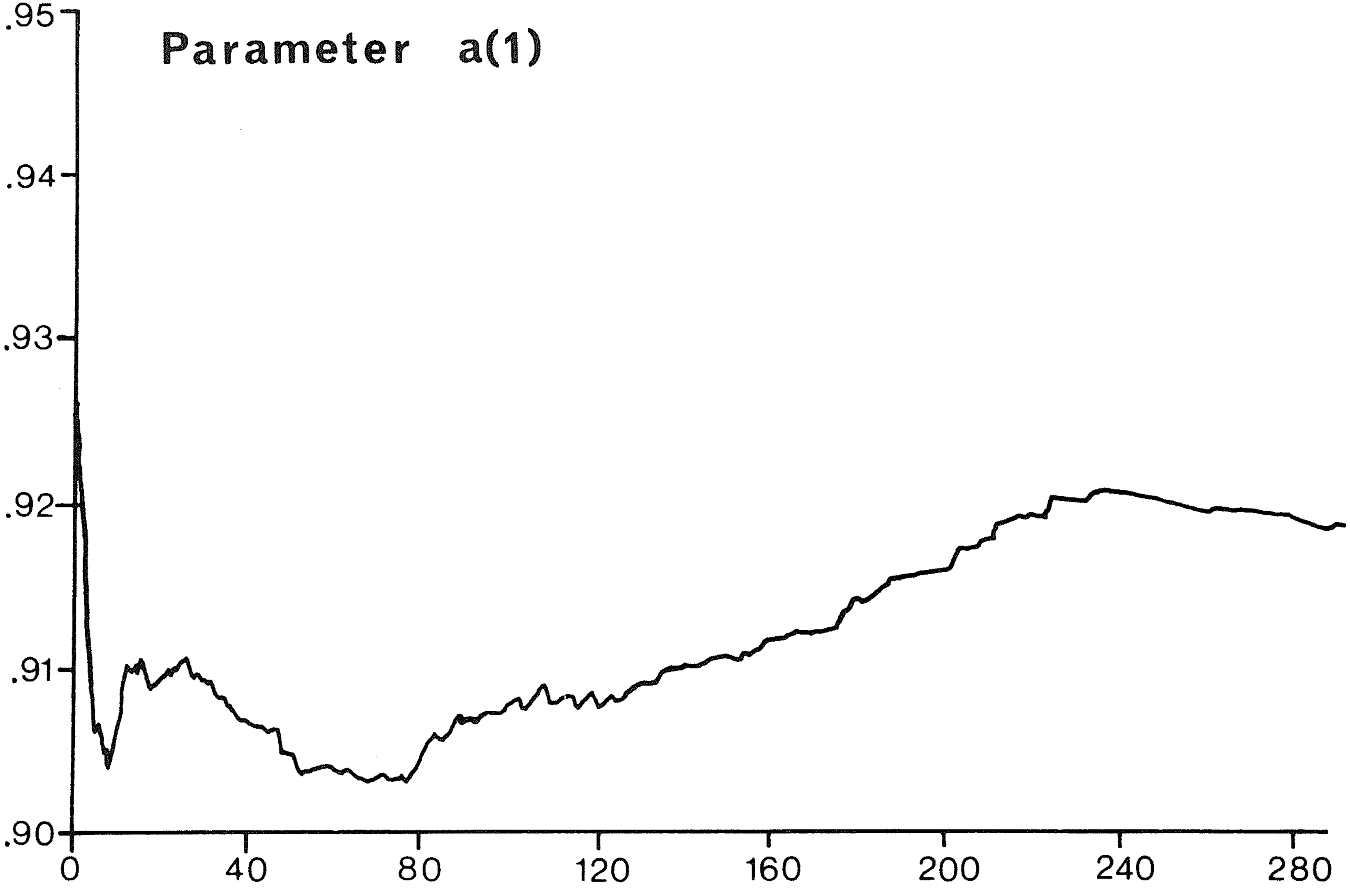


FIGURE 5.10 Time-Series Analysis of Speculative Model Output - estimated variations in parameter a_1 of 2 parameter time-series model

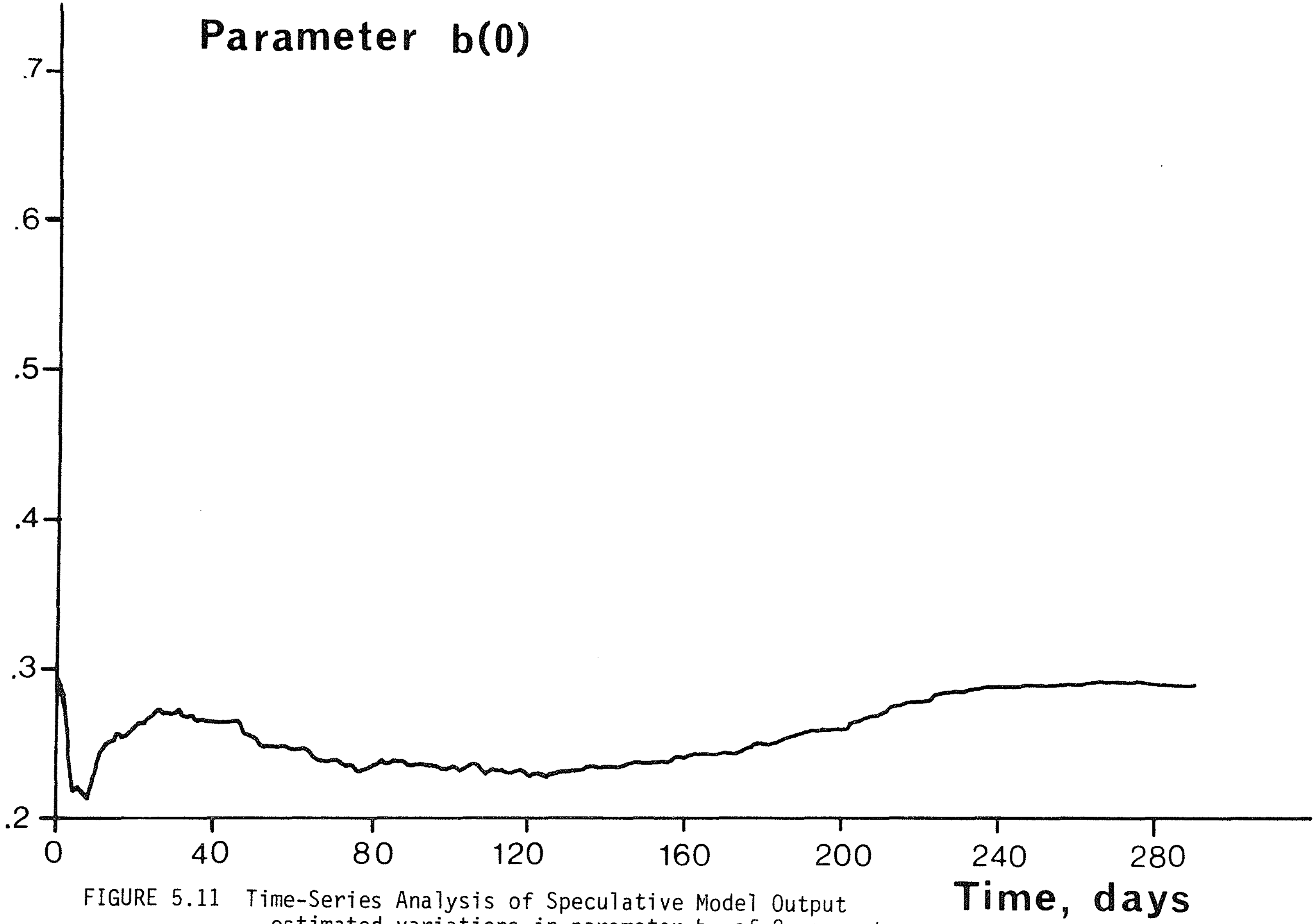


FIGURE 5.11 Time-Series Analysis of Speculative Model Output - estimated variations in parameter b_o of 2 parameter time-series model

of the system under dominantly light limitation conditions means that any time-series obtained from passive monitoring of the system may contain little information on the potentially important dynamic relationships between nutrient and *Cladophora*. In other words the *Cladophora*-nutrient dynamics may not be completely "identifiable" from the weekly monitored data.

5.5 Discussion and Conclusions

On the basis of the results obtained from the analysis described in Sections 5.2, 5.3 and 5.4, we were able to reach the following conclusions which had relevance to the management of the Peel-Harvey Study:

- First, the results in Section 5.3 support strongly the hypothesis that sediment bound phosphorus, probably carried by the Murray-Serpentine river water, enters Peel Inlet, becomes established in the bottom sediments of the Inlet and so is available to promote *Cladophora* growth.

- Second, on the basis of the analysis in Section 5.4, it also seems possible that the weekly monitored biomass data may be insufficient, in themselves, to establish unambiguously the mechansism associated with *Cladophora* growth behaviour.[†]

As a result, we were able to advise the Research Co-ordinator Dr Hodgkin at the time that some experimental tests of the hypotheses derived from these speculative systems analyses were desirable. In particular, we suggested that additional emphasis should be placed on:

(i) measurement of the amounts and forms of particulate and soluble nutrients entering the system, and the fate (e.g. sedimentation, biological uptake, marine loss) of these nutrients within the estuaries. These measurements were attempted during an intensive field exercise in August 1978.

[†] this indeed is a problem with the monitored data and it has been exacerbated by the rather poor results obtained from the regular *Cladophora* biomass sampling (see Chapter 9).

(ii) establishment of a programme to monitor sediment nutrient status at several sampling sites. This program was designed and carried out by John Cabrielson, Department of Soil Science and Plant Nutrition, University of Western Australia in collaboration with members of the Botany Department team;

(iii) laboratory and field experimental studies of *Cladophora* decomposition, and the effects of light, temperature, salinity and nutrients on growth. These studies were already in progress by D. Gordon, P. Birch and A. McComb and provided a fruitful avenue for future collaboration;

(iv) detailed *in-situ* and laboratory experiments to determine factors such as the rates of transfer of available phosphorus from the sediment to the water column, the "inter-algal" water, and into the *Cladophora* itself.

These recommendations and the resulting investigations have led both to improvements in the understanding of the *Cladophora* growth dynamics and modification of the sediment phosphorus hypothesis, both of which are discussed elsewhere in this report (Chapters 8 and 9). This is a good example of adaptive environmental assessment (Chapter 2) in action: initial systems analysis, while not attempting to establish clearly the causal mechanisms controlling system behaviour, is able at an early stage in the Study to utilise all the available data and information to systematically generate plausible hypotheses on system behavour. In this manner, it can function both as useful adaptive feedback mechanism in the Project management, and an early integrator of work contributed by the various participant groups in the Study.

6. HYDROLOGICAL CHARACTERISTICS I : PRELIMINARY STUDIES

In the previous Chapter we have seen how, prior to the collection of regularly monitored data, it is possible to use stochastic simulation modeling as a vehicle for generating hypotheses about the system behaviour; and how, in turn, these hypotheses can lead to the design of experiments and monitoring exercises aimed at trying to falsify the hypotheses, in accordance with the scientific method.

But such speculative modeling cannot, by definition, be an end it itself (although it is not unusual in the systems and ecological literature to find even purely deterministic simulation modeling used in this manner). As more information is gained about the nature of the system, so the speculative nature of the analysis can be reduced and, hopefully, replaced by exercises aimed at interpreting the data obtained from regular monitoring and planned *in situ* or laboratory experiments. Of course, recognising the poorly defined nature of the system (Chapter 4), it is unlikely that we will ever be able to predict its behaviour completely without ambiguity. But at least we should be attempting to make the speculative element as small as possible.

One aspect of the system where we might hope to reduce speculation to a minimum is hydrology,and it is this topic with which we are concerned in the present Chapter. The major hydrological and meteorological details of the Peel-Harvey System are described by Black and Rosher (1980). Here, therefore, we will report only on those aspects of the system hydrology considered by the CRES Team and assume that the reader will refer to Black for background information on the hydrological nature of the whole Peel-Harvey area; including details of factors such as climatology,river and drain hydrology, groundwater and water balance in the Estuary. It should also be noted that some of the CRES hydrological analysis, including the Murray River flow modeling and the analysis of the tide height-volume flow relationships at Mandurah, have been carried out in close cooperation with the WAIT Team: in these cases, we have concentrated here on the CRES contribution and, again, other details can be obtained by reference to Black and Rosher (1980). For this reason, however, there may be some overlap between the CRES and WAIT Reports.

Even a cursory evaluation of the *Cladophora* problem in the Peel-Harvey System points to the potential importance of hydrological factors, and the speculative modeling discussed in the previous chapter has emphasised this fact. We have seen that the major potential source of nutrient enrichment in the estuary, for example, is via the associated river systems. As we see in Figs. 6.1 and 6.2, the Peel Inlet is fed by the Murray River system, including the North and South Dandalup tributaries and the Serpentine River; the Harvey Estuary is fed by the Harvey River and the numerous drains associated with farming operations around the Estuary. In all cases, it is known that quite high levels of nutrients, such as nitrogen and phosphorus, are contained in the river and drain waters, and that a heavy nutrient load enters the estuarine system during the high river flow months of Winter.

The fate of such nutrient rich water - which may contain nutrients in dissolved or particulate form - is, of course, dependent upon many factors, of which the most important are probably the circulation and tidally induced flushing patterns of the system. These factors also affect the distribution of other potential nutrient inputs: Sewell (1978), for example, has speculated that groundwater inputs arising from septic tank sewage enters the Inlet and provide a possible mechanism for excessive algal productivity in the Coondanup area. And it is clear from Fig. 6.2 that groundwater inputs may make a more general contribution to the system, introducing nutrients into both the Peel Inlet and the Harvey Estuary.

If we are to assess these and other plausible hypotheses it is necessary to evaluate the hydrological characteristics carefully in some manner, so providing the kind of information required for

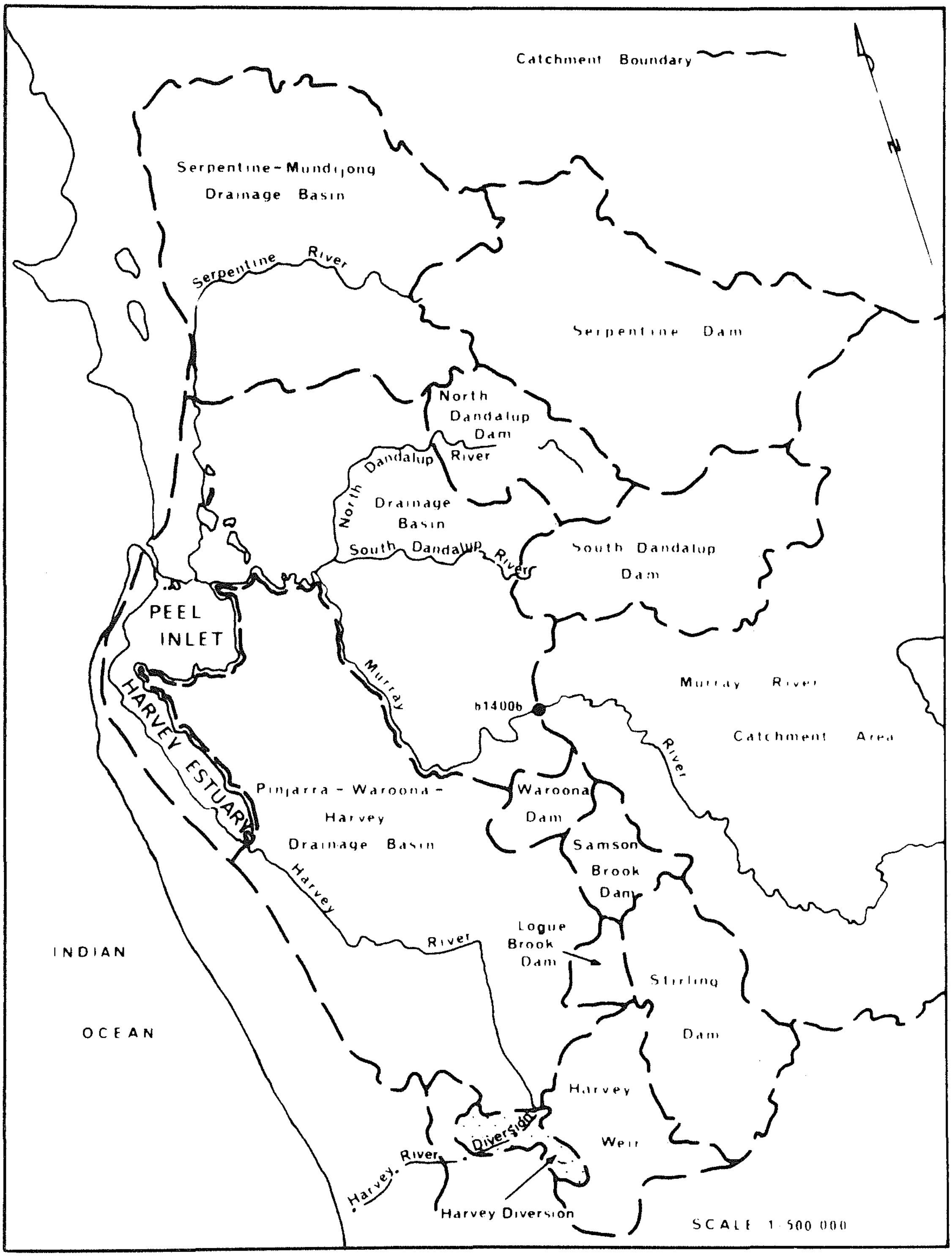


Fig. **6·1** PEEL INLET & HARVEY ESTUARY CATCHMENTS
(after PWD 47461-1-1A)

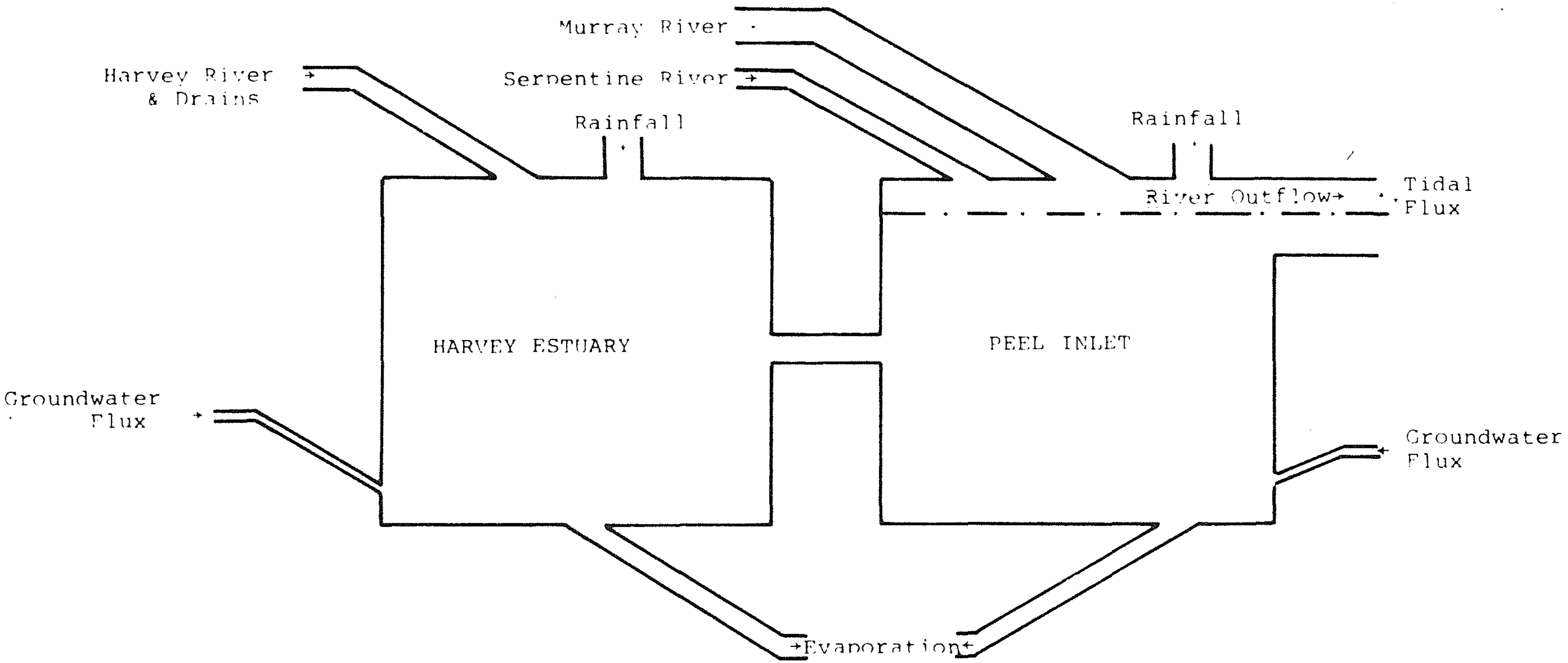


FIGURE 6.2 Peel Inlet/Harvey Estuary: Water Balance Model

later nutrient budget analysis and *Cladophora* growth studies, as discussed in Chapters 8 and 9. But the form of such hydrological analysis must be specified carefully: conventional procedures range from simple regression analysis to highly complex computer based simulation modeling (see e.g. Fleming, 1975). And, as we have stressed previously, it is necessary to choose an approach which is well suited to the objectives of the exercise and conforms with the level of time and funding available to the study.

In the present case, it is tempting to consider some complex modeling procedure based on the computer solution of a partial differential equation (i.e. distributed parameter or spatio-temporal) description of the complete Peel-Harvey system described in Fig. 6.1 and shown diagrammatically in Fig. 6.2. An approach similar to that used by Steedman and Craig (1979) in the Cockburn Sound Study, for example, has great superficial attraction since it provides for a relatively detailed characterisation of the system and its circulation patterns. But it is not without its disadvantages: first, modeling of this type can be quite costly in computational terms, often requiring considerable computer model development time and high CPU overheads; second, the richness of detail is normally in marked contrast to the poverty of the data base, so that much of the descriptive fineness is obtained by engineering interpolation based on the solution of complex finite difference models, with many assumed parameter values and boundary conditions. Also, as descriptors of the observed data, such models can sometimes be disappointing (see e.g. Young, 1978; Young and Rennie, 1976).

An initial assessment of the proposed Peel-Harvey Study programme indicated that, both in relation to the amount of funding available for systems analysis and in regard to the objectives of the study, it was better to consider a somewhat simpler approach to the characterisation of the hydrology in the Peel-Harvey System. Acceptance of the proposed data monitoring programme (CRES 1977), which was clearly desirable from the standpoint of biological research, meant that weekly data would also become available on salinity and tidal data. Coupled with other information on rainfall, evaporation and river drain flows, this meant that a quite comprehensive data base for both hydrological and other relevant variables would become established as the Study progressed. As a result, it was decided that, wherever possible, systems analysis should be *data based* with simulation modeling, as such, restricted to exercises in speculative analysis, such as those discussed in the previous Chapter, or for filling 'gaps' in the available data.

In the field of hydrology, such data based analyses usually lead to a very good explanation of observed time-series, sometimes rather better than that obtained by a complex simulation model. Also model development and use is computationally much less expensive and demanding than for equivalent simulation models. But this data-based model structure is only as rich as the data allow and interpolation of the kind possible in large finite difference models is clearly impossible (although interpolation of a more limited kind is feasible and can be extremely useful). It was felt, however, that if such detail was eventually seen to be required it should, in any case, be based on a full and efficient appraisal of the monitored data as provided by data based model analysis of the kind proposed. In other words, if complex simulation modeling exercises were eventually deemed necessary in order to assess possible management alternatives, then it should be based on a full appreciation of the data from a time-series standpoint, so minimising the very real possibility of including inadequately validated "surplus content" which can, and has in the past, lead to misleading model predictions (see e.g. Young, 1978).

In this Chapter, we describe data based analysis in relation to the modeling of flow entering the Peel Inlet from the Murray River. We also refer briefly to other hydrological studies in which CRES has played some part; namely the analysis of time-series associated with experiments on the tidal exchange characteristics in the Mandurah Channel and dye tracer studies in the Murray River. Before we describe this work, however, it should be emphasised that, while all the analysis is data based and utilises advanced techniques of recursive time-series analysis, it is not, unless otherwise stated, "black box" modeling in the sense of attempting to explain input-output data in a totally abstract manner. Rather the object is to obtain a parametrically efficient representation which has *as much descriptive content as seems warranted by the information contained in the monitored data.* As we have pointed out, such analysis does not exclude later simulation modeling which is aimed at providing richer mechanistic detail, should this be required; on the contrary, by indicating the level of detail and the associated minimal parameterisation that is justified by the data, it provides a sound basis for such later developments. It is clear, therefore, that the investigations described here are in the best tradition of the adaptive environmental assessment philosophy discussed in Chapter 2.

6.1 Flow Routing for the Murray River System

The complete Peel-Harvey hydrological system is shown diagrammatically in Fig. 6.2. Data on most fluvial and groundwater inputs are available from the WAIT Study (Black and Rosher 1980). However, information on the Murray River input and the tidal flushing/circulation characteristics is not available directly and has to be estimated on the basis of other measurements.

As shown in Fig. 6.1, the Murray River is gauged only in its upper reaches, with gauges in its two upstream tributaries, the Hotham and Williams Rivers, and a major gauge at Hughes Bridge. In order to evaluate the Peel Harvey system fully, it is clearly necessary to estimate the flow actually entering the Peel Inlet: for example, to compute nutrient loadings on a weekly basis, the weekly monitored nutrient concentrations must be multiplied by appropriate flow measures, and those from Hughes Bridge are obviously not appropriate since they do not take into account the dynamic changes that occur in flow over the intervening 36km of river between Hughes Bridge and the Inlet. What is required then is a "flow routing" model which takes the physical characteristics of the river system into account and yields an estimate of flow into the Inlet based on the flow measured at Hughes Bridge.

Conventionally, the problem of flow routing in rivers is addressed by hydrologists in two steps: the first being the choice of a suitable method (i.e. mathematical model structure); and the second the selection of numerical values for coefficients in the model.

Methods are usually classified as either "hydraulic" or "hydrologic" depending on whether or not the St. Venant equations are somehow employed in the derivation of the model structure. Regardless of the method chosen, however, the estimation of model parameters is almost always accomplished in practice by "fitting" the predicted flows to noisy observations. Consequently, on application to actual rivers, the "hydraulic" method favoured by the purist may be no better than the simpler "hydrologic" methods (Young, 1978). Besides, the latter can always be interpreted as an approximation[†] to the former should recourse to fundamental hydraulic principles be an over-riding concern (Price, 1975; Weinmann and Laurenson, 1977). The weight of empirical evidence also tends to substantiate the claim that simple routing methods are adequate for most purposes (Price, 1975; Keefer, 1976; Weinmann and Laurenson, 1977).

Thus, at least when enough data are available, it appears that the determination of parameter values is more important to the development of a good routing procedure than is the choice of model structure. Most hydrology texts present formulae for determining the parameters of the standard routing methods from observed upstream and downstream hydrographs for a stream reach; e.g. Chow, (1964) and Price, (1975) give a host of up-to-date recipes for calculating parameters associated with several of the better known model structures. These widely-used estimation formulae are deterministic, however, and assessment of effects of uncertainty in the calculated parameters is rarely undertaken.

When an observed flow hydrograph for the downstream end of the reach over which routing is to be performed is not available, the problem of choosing both the model structure and the parameter values is exacerbated. In this case, one of the requirements of a usable structure is that the associated parameters can be estimated from hydraulic characteristics of the river, from information on similar rivers or from any other source that does not depend upon measured downstream flows. Under these circumstances, the uncertainty in the parameter estimates is of obvious importance and predictions based on a routing procedure can only be meaningful in a probabilistic context. In the present case, we are interested in routing flows

---

[†] although, of course, both are approximations to the 'real world' and there is no reason why one should be any better an approximation than the other.

from the gauge at Hughes Bridge on the Murray River, to Peel Inlet, and the assessment of uncertainty is clearly important in relation to any later utilisation of the routing model for water and nutrient budgets in the Inlet.

A full description of the flow routing model and the results of the modeling exercise are given in Appendix 5 which is based on Whitehead et al (1978). The river system is subdivided into N reaches, each described by the following ordinary differential equation

$$\frac{dQ}{dt} = \frac{I}{K}(I-Q) \qquad (6.1)$$

where

Q = river flow (m^3/unit time)
I = inflow from upstream reach (m^3)
K = time constant, 'time of travel', or 'residence time' of reach.

As K is a "residence time" parameter, it is a function of flow and is defined in the normal manner, i.e.

$$K = \frac{V}{Q}$$

where V is the changing volume of the reach. Taking note of the fact that

$$V = A\Delta x; \quad Q = Av$$

where A is the changing cross sectional reach area, Δx the reach length and v the mean flow velocity, it is clear that K can be defined alternatively as

$$K = \frac{\Delta x}{v} \qquad (6.2)$$

Since v is not directly available for measurement, it must be estimated from Q and a well known empirical relationship is used here of the form

$$v = aQ^b \qquad (6.3)$$

where the coefficients a and b are evaluated both by theoretical analysis based on the hydraulic characteristics of the system and by empirical methods based on the results of dye tracer experiments carried out under different flow conditions (see Appendix 5, and Black and Rosher, 1980). Such analysis yields estimates of a and b of 0.3 and 0.4, respectively,and the relative uncertainty in these estimates is discussed later and in Appendix 5.

It should be noted here that there is an implicit assumption of mass conservation in the model (6.1) to (6.3); in other words, additional mass flow is neither added nor lost between upstream and downstream sites. This becomes apparent if we consider 'steady state' or 'equilibrium' conditions: then $dQ/dt = 0$ and we see from (6.1) that $I = Q$. In systems terms, we say that the steady state gain (SSG) between I and Q is unity: if mass is added by rainfall-runoff processes between upstream and downstream location, then we would expect the SSG to be greater than unity; if water is lost by evaporation or to the groundwater, however, SSG would be less than unity.

When the model calibration in the above manner is applied to the river between the confluence of the Hotham and Williams Rivers and Hughes Bridge, therefore, its implicit steady state gain of unity considerably under-estimates the flow at Hughes Bridge, although agreement on the timing of peaks in the hydrograph is good, as shown in Fig. 6.3, which gives the results based on 1978 data. This is only to be expected, of course, since the model does not account for rainfall-runoff behaviour between the upstream and downstream stations. Extension of the model to include the detailed simulation of such factors is possible but, in this case, it was decided that the objective of the modeling did not demand such an increase in complexity. Instead a simple time-series analysis exercise was carried out on the upstream-downstream flow data in order to evaluate the gain in flow terms occuring down the river system.

Time-series analysis in this case is very straightforward and requires only a single run on the CAPTAIN time-series program package (Appendix 2). This analysis both identifies the structure of a simple "black-box" model between the upstream and downstream sampled flow data and obtains estimates of the parameters which

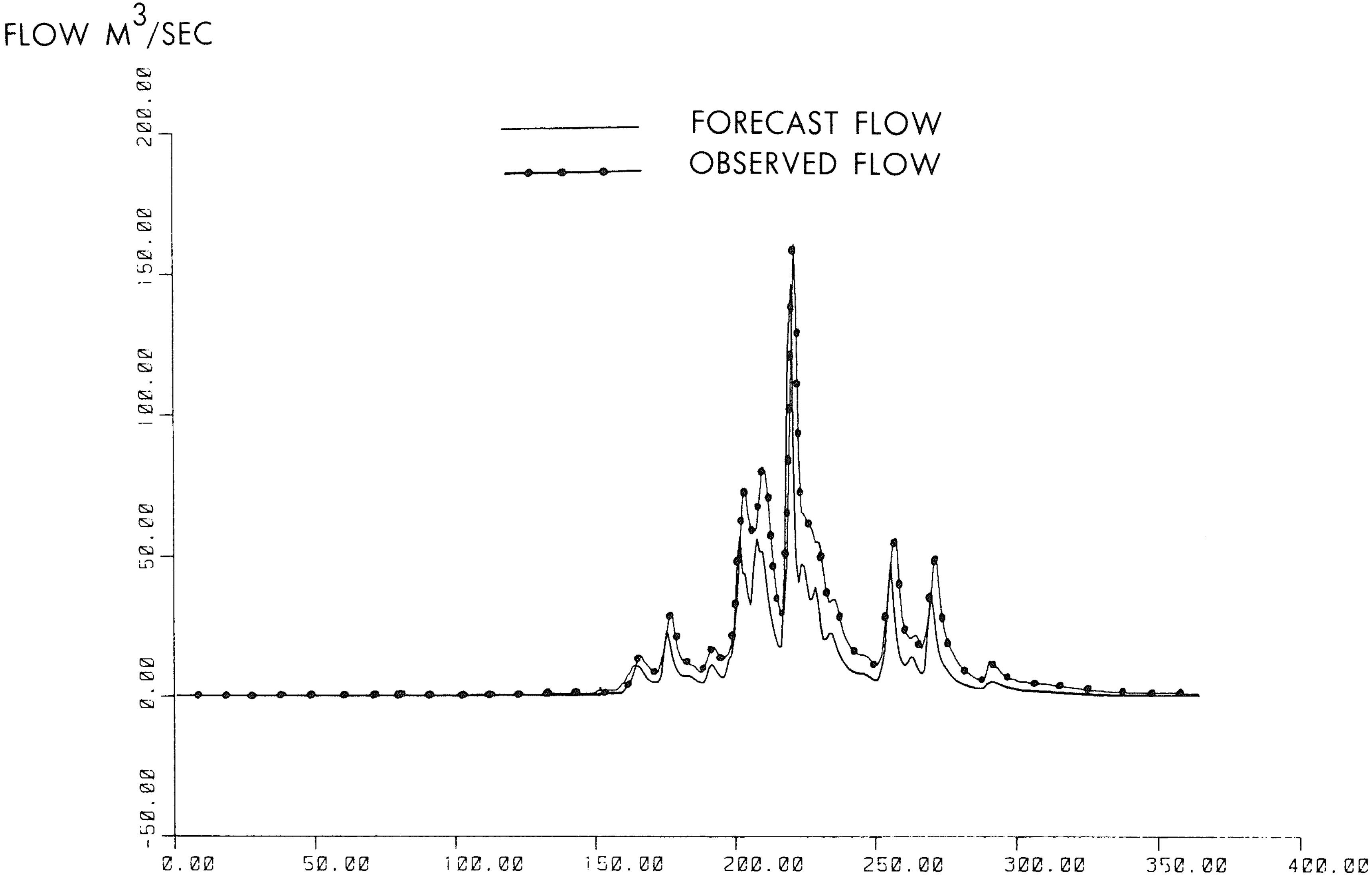


FIGURE 6.3 Predicted and Observed Flow at Hughes Bridge Assuming Lateral Inflow

characterise this model.

The model in the present example is found to be of the form

$$\hat{x}_k = -\hat{a}_1\hat{x}_{k-1} - \hat{a}_2\hat{x}_{k-2} + \hat{b}_o u_k + \hat{b}_1 u_{k-1} \tag{6.4}$$

Where $\hat{x}_k$ is the model output (deterministic estimate of flow at Hughes Bridge) at the kth sampling instant; u_k is the model input (measured upstream flow) at the kth instant; and $\hat{a}_i$, $\hat{b}_i$ are coefficients estimated by CAPTAIN as

$$\hat{a}_1 = -0.62\ (0.04); \quad \hat{a}_2 = 0.11\ (0.03)$$

$$\hat{b}_o = 0.06\ (0.02); \quad \hat{b}_1 = 0.65\ (0.04)$$

Here the figures in brackets are the estimated standard errors in the coefficients.

The agreement between the deterministic model output $\hat{x}_k$ and measured flow at Hughes Bridge, denoted by y_k, is excellent, as shown in Fig. 6.4 and the model (6.4) provides a good estimate of the flow gain down the system via its 'steady state gain' (SSG) characteristic. This SSG is obtained by considering the relationship between $\hat{x}_k$ and u_k in the steady state or equilibrium condition, i.e. when $x_k = x_{k-1} = x_{k-2}$; and $u_k - u_{k-1}$ (equivalent to dQ/dt in the continuous-time case considered earlier): we see from (6.1) that in this situation,

$$(1.0 + a_1 + a_2)\hat{x}_k = (b_o + b_1)u_k$$

or

$$\hat{x}_k = \frac{b_o + b_1}{1+a_1+a_2}\ u_k = \frac{0.06 + 0.65}{1-0.62+0.11}\ u_k = 1.45\ u_k$$

This simply means that, on the average, the flow at Hughes Bridge is 1.45 times greater than that at the upstream input; i.e. lateral inflow between the two stations contribute 45% more flow at Hughes

Bridge than that forecast by the 'unity gain' deterministic model on the basis of upstream flow alone.

With this result in mind, it is straightforward to modify the SSG of the deterministic flow routing model from its 'built in' value of unity to 1.45 and, as might be expected, the model then explains the measured data quite well (Fig. 6.5), although not as well as the time-series model (Fig. 6.4).

The reader might ask why, since the time-series model provides a better description of the observed flow data, we do not utilise it in preference to the flow routing model. The reason is simply that we wish to extend the model downstream from Hughes Bridge in order to estimate flow into the Peel Inlet. And, of course, we do not have time-series data available for this downstream section of the river system and cannot, therefore, use the data based CAPTAIN procedures to obtain a time-series model for this portion of the river. The flow routing model, on the other hand, allows us to utilise the river morphometry data in place of the unavailable time-series flow data in order to infer the *probable* flow characteristics.

But if we are to use flow routing modeling downstream Hughes Bridge, it is necessary to estimate the SSG of the system in order to allow for lateral inflow over this downstream portion of the river system. This gain is estimated by two methods:

(i) the first is to use a simple ratio of the basin areas weighted by mean annual precipitation: the SSG for Hotham, Williams to Hughes Bridge is then 1.39 according to this ratio, a number slightly lower than the CAPTAIN estimated value of 1.45;

(ii) the second is to assume that the basin yield (Appendix 5) for the lower part of the Murray Catchment is somewhat higher than for the upstream portions, i.e. approximately 0.15 (Collins, 1974).

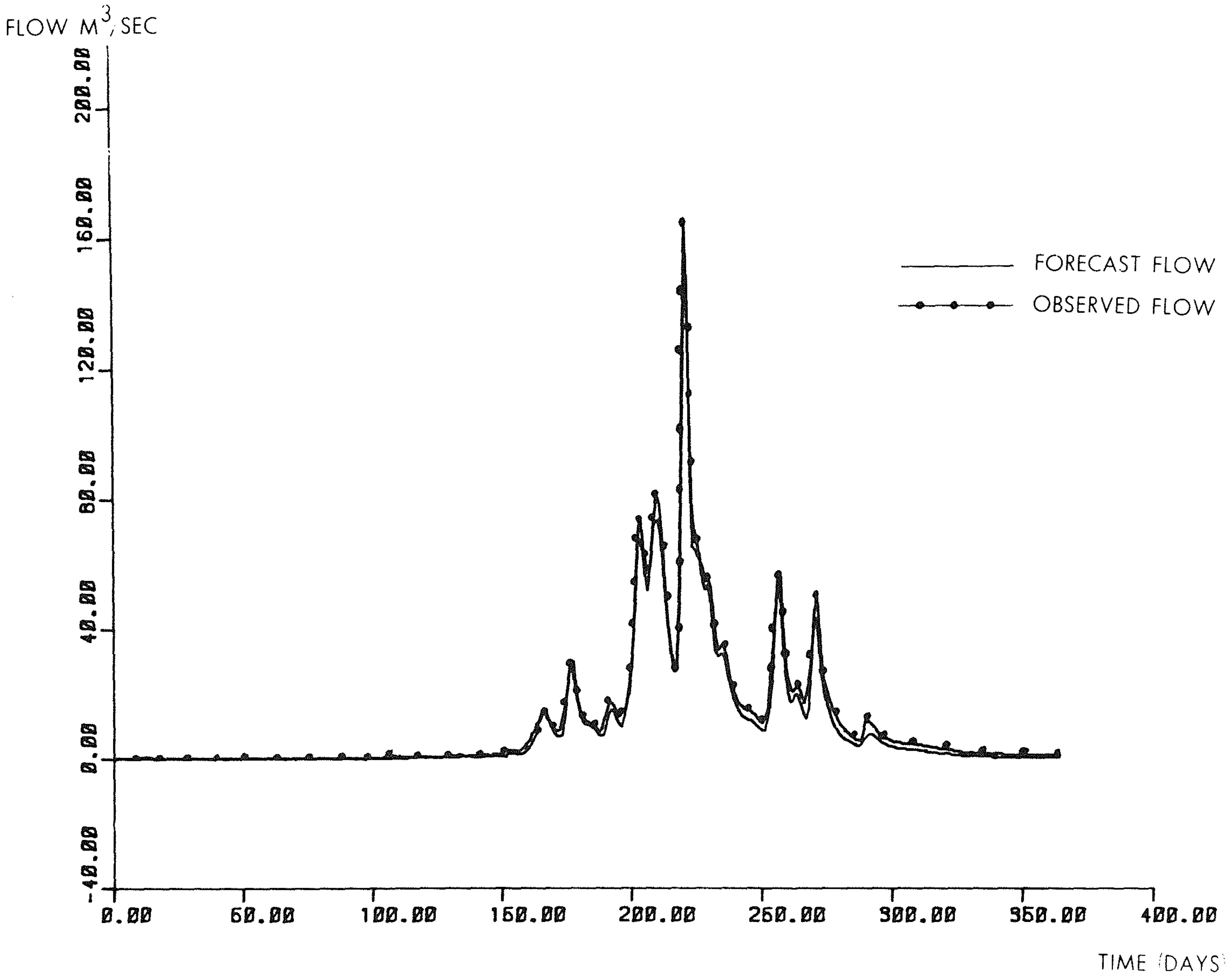


FIGURE 6.4 Predicted and Observed Flow at Hughes Bridge from Time-Series Model

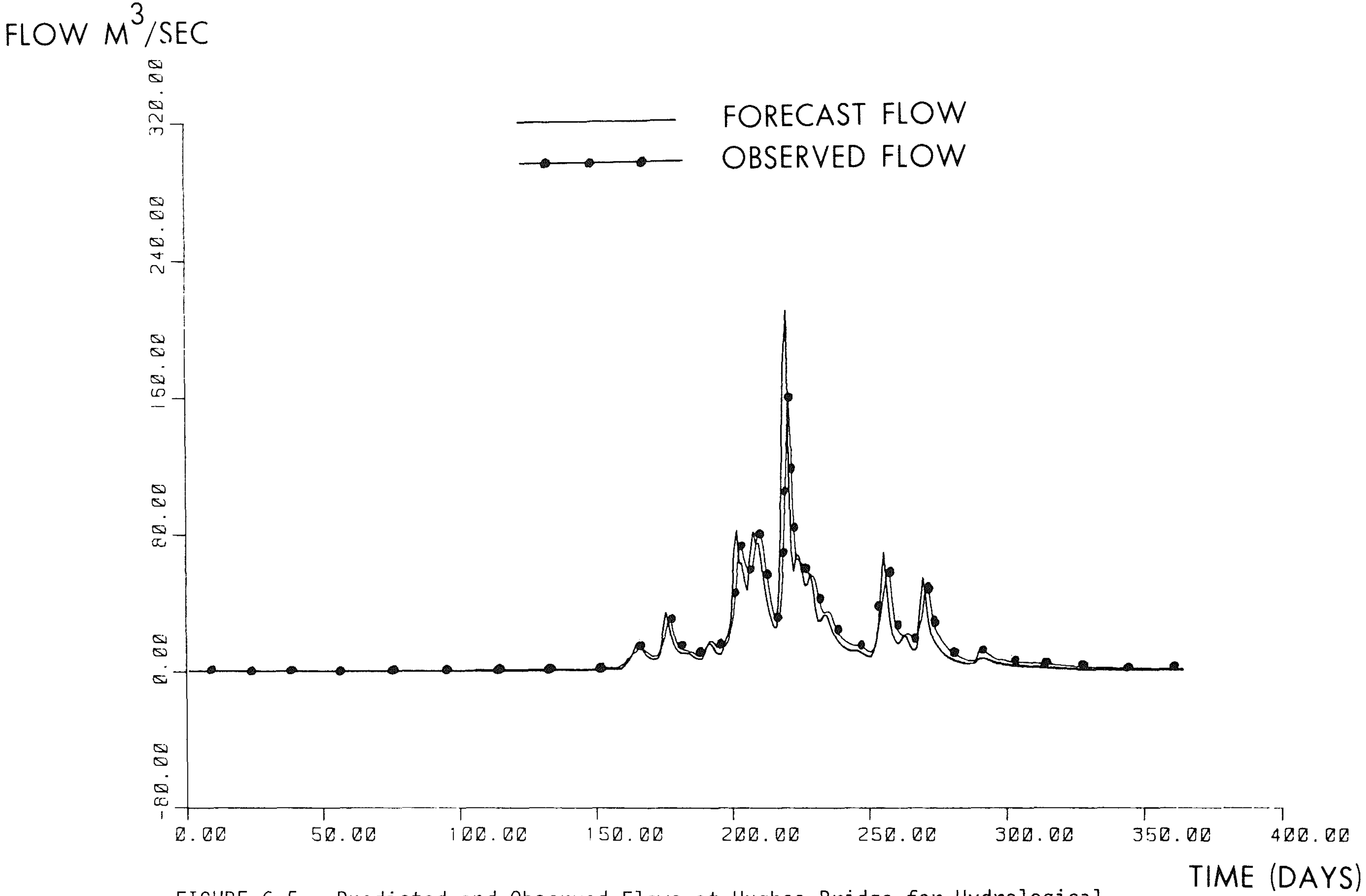


FIGURE 6.5 Predicted and Observed Flows at Hughes Bridge for Hydrological Model with Estimated Lateral Inflow

Based on these methods, the SSG for Hughes Bridge to Pinjarra, for example, is between 1.08 (from (i)) to 1.15 (from (ii)). On this basis, the average values for the SSG was assumed and, for the section to Pinjarra, this was found to be 1.1. Again the relative uncertainty in this estimate is discussed later and in Appendix 5.

The flow routing model obtained in the above manner can yield estimates of downstream flow in the form of the deterministic model outputs. But the various coefficients (a, b and the SSG modifications) as well as the number of reaches, N, are not known exactly; rather they are inferred on the basis of the available information and data. As a result, it is better to consider the model in stochastic terms with the various parameter estimates considered as random variables.† In this manner, the downstream flow estimate itself becomes a random variable and must be viewed in probabilistic rather than the more conventional deterministic terms.

In the present case, the uncertainty was introduced into the evaluation of the model results by resort to Monte Carlo simulation analysis, employing an approach similar to that used in connection with speculative *Cladophora* growth model described in Chapter 5. Here, the unknown parameters a and b were defined as having Gaussian distributions with means 0.3 and 0.4, and standard deviations 0.03 and 0.04, respectively; while the SSG was similarly defined with mean 1.11 and standard deviation 0.05. For simplicity N was treated as deterministic and maintained constant for the Monte Carlo experiments; the effect of its uncertainty on the model predictions was than assessed by separate stochastic experiments. The reasons for this and the choice of the above parameter values are, however, discussed further in Appendix 5.

Finally, in order to ensure that the true distributions are within ±15% of the estimated distributions with 95% confidence, 82 realisations

---

† of course all hydrological models are characterised by uncertain parameters and, although it is not the normal approach at present, they should be considered in this manner.

(i.e. 82 separate random simulations) were utilised in accordance with the requirements of the non-parametric statistical methods utilised in the evaluation of the Monte Carlo simulation results (Spear, 1970).

The ensemble average characteristics of the model, as evaluated by the Monte Carlo analysis, are illustrated in Fig. 6.6 which shows the plot of mean flows at Pinjarra together with standard error bounds obtained by averaging the results of the 82 realisations for the year 1978. From these results, and by reference to the results obtained in a similar manner for the upstream reaches (see previously and Appendix 5), we can conclude that the model is satisfactory for our present purposes. The timing of flow peaks is probably not greatly in error and the average weekly or monthly flows are unlikely to differ from the 'true' values by more than about 10%. The forecast peak flows cannot, however, be considered very accurate and this must be taken into account in any utilisation of the model.

The flow routing model obtained in the above manner provides a straightforward and simple method for estimating the flows entering the Peel-Harvey Estuary from the Murray River System. Together with the gauged flows for other rivers and estimates of ground water influx (Black and Rosher, 1980) it allows us to obtain an estimate of all fluvial inputs to the Estuary over the Study period. We will see later in Chapter 8 how these estimates are essential to the quantification of various aspects of the system behaviour of importance to the Study. In the next Chapter, however, we must consider another aspect of the system hydrology; namely the flushing and circulation characteristics.

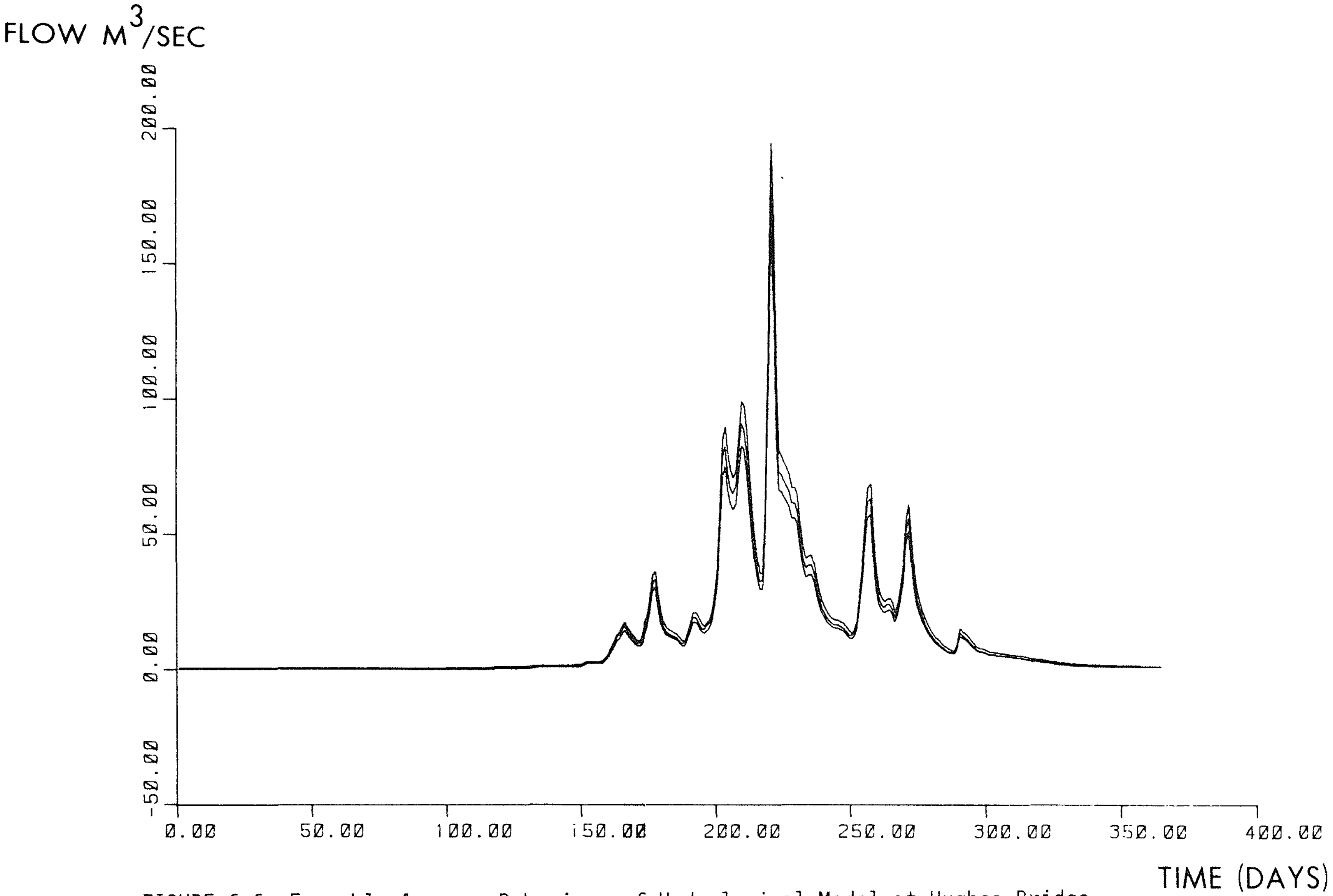


FIGURE 6.6 Ensemble Average Behaviour of Hydrological Model at Hughes Bridge

7. HYDROLOGICAL CHARACTERISTICS II : INTENSIVE FIELD EXPERIMENTS AND THE FLUSHING/CIRCULATION CHARACTERISTICS OF THE PEEL-HARVEY SYSTEM

Considering again the diagrammatic representation of the hydrologic system shown in Fig. 6.2, we see that, having obtained estimates of all fluvial and groundwater inputs, it is now necessary to examine the manner in which water is both circulated around Peel Inlet as the result of various hydrodynamic factors; and lost to the system, via both tidal flushing to the Indian Ocean and evaporation effects. The CRES contribution in this area has been two-fold: first we have been involved in the planning and execution of the three intensive, short term studies of the Estuary in which dye tracer experiments were used to gain some insight into the flushing and circulation patterns; second we have employed statistically based procedures to obtain a stochastic model of the flushing and circulation characteristics which is based on the analysis of the weekly salinity data obtained during the regular monitoring programme.

7.1 Intensive Field Experiments

Full details of the two intensive field experiments of October 1977 and August 1978 are given in Appendix 4 and it will suffice here to mention the major results obtained from the experiments. The field experiment of Feburary 1978 yielded largely qualitative results which are not discussed here.

The objective of the first experiment in October 1977 was to obtain a qualitative or, if possible, a semi-quantitative evaluation of flow characteristics in the Sticks Channel between Peel Inlet and Mandurah. In the event, various difficulties including a rapid deterioration of weather led to curtailment of the exercise before a full set of interpretable data were available and, as a result, the exercise became largely qualitative. In this more limited sense, however, it proved most valuable. (Humphries and Michell, 1978, Appendix 6).

The experiment consisted of the injection of a large quantity (20 litres) of 20% (W/V) Rhodamine WT dye (4kg dry weight of dye) into the water of estuarine origin midway between sampling sites 2 and 3, as shown in Fig. 7.1. Injection took place at 2300 hrs on October 6th and all of the sites shown in Fig. 7.1 were sampled as regularly as possible (see Appendix 6) for dye concentration and salinity until 1600 hrs on October 7th, when N - NW winds of 6m. sec^{-1} caused cancellation of the measurement program. Irregular measurements were taken thereafter both in the Inlet and off Mandurah Bridge. Also during the experiment current metering was carried out at site 3 and various tide gauge measurements were available from PWD Harbours and Rivers Branch.

On the basis of the results, the following picture of the system over a tidal cycle emerges.

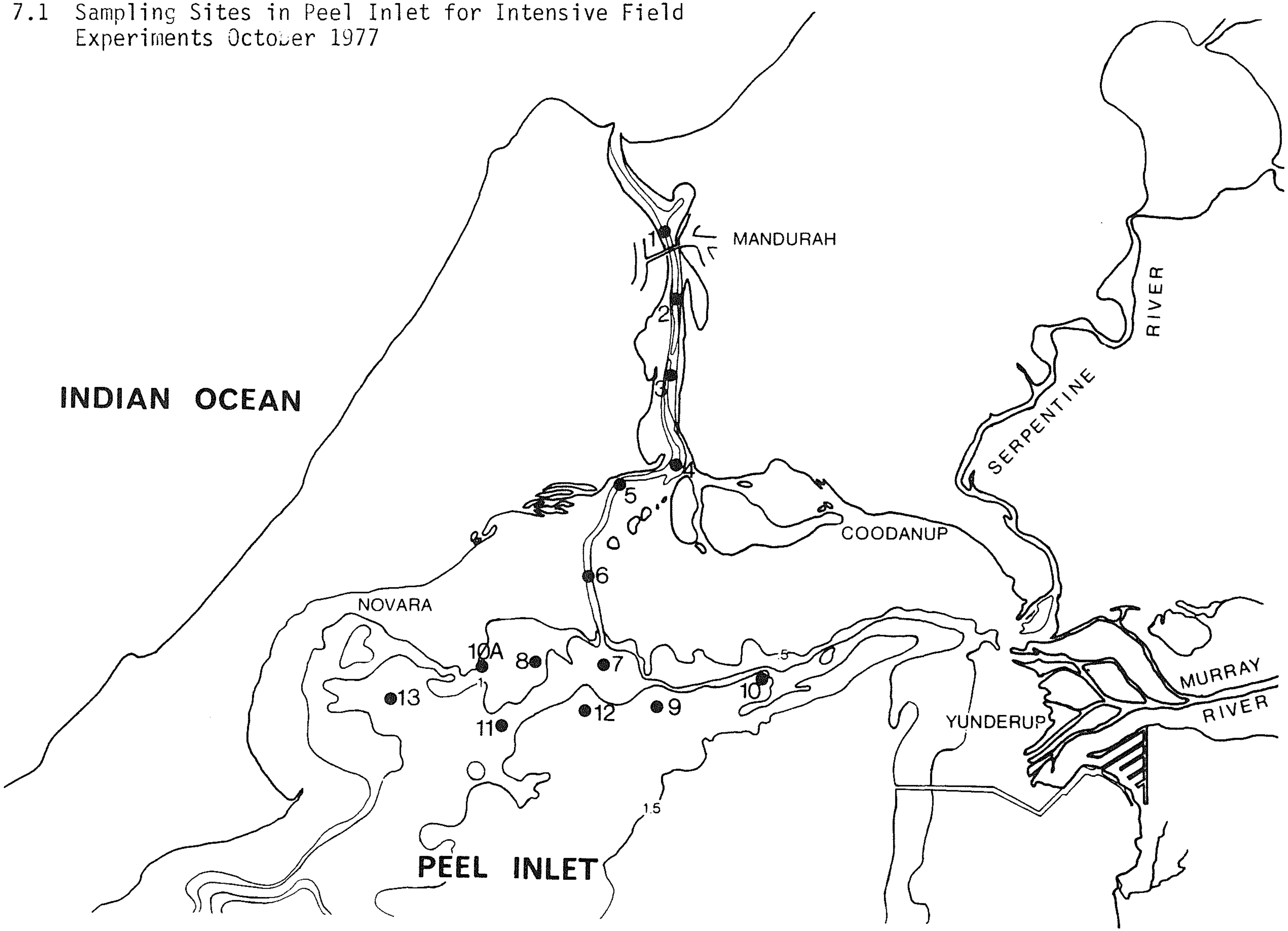
(i) The behaviour of the dye mass and salinity provide a consistent set of information on circulation and mixing patterns within the system;

(ii) in the Mandurah Channel, from sites 2 to 4, a marine water mass (34.5 $^{o}/oo$) drove estuarine water into Sticks Channel, with very little detectable mixing. Dye was held in estuarine water(24-26 $^{o}/oo$) in front of the halocline, and was carried in the surface water, again with little mixing;

(iii) between sites 4 to 6, mixing began to occur, predominantly between sites 5 and 6. Water velocity apparently increased as the water mass shoaled between sites 4 and 5, the face of the salt wedge steepened and dye seems to have slid to the bottom of the halocline. Mixing and dilution of both salt and dye continuously occurred over this reach;

(iv) from site 6, dye on the bottom at higher concentration than at the surface, penetrated the main body of Peel Inlet. This dye was contained in slightly salt-enriched

FIGURE 7.1 Sampling Sites in Peel Inlet for Intensive Field Experiments October 1977



water. Following the dye mass was a continuously dispersing, partly diluted water mass from Sticks Channel. This mass caused transitory salinity stratification at sites 7, 8, 9 and 12 by pushing under the estuarine water mass. The presence of this salt-enriched water was also detected at sites 11 and 13, although vertical salinity stratification was not observed;

(v) 12 to 15 hours after dye injection, the N - NW squall caused turbulent mixing of the Peel Inlet water mass. All vertical stratification of salinity and dye concentration disappeared, although horizontal stratification persisted. During this time, tidal flow reversed and water containing dye retreated from the Inlet along Sticks Channel, at least to site 6. The behaviour of water on the Peel Inlet shallows is not known;

(vi) about 16 hours after dye injection, tidal inflow to Peel Inlet occurred again. This event, although not fully monitored, appeared to push dyed water further into Peel Inlet, towards Falcon, and possibly even into Harvey Inlet;

(vii) dye was detected moving out to sea at the Mandurah traffic bridge, between 48 and 52 hours after initial injection. There was no dye in the Mandurah Channel between 15 and 38 hours after injection, or again after 56 hours.

It is clear that the experimental data provide a useful qualitative picture of mixing and circulation events over a tidal cycle. Under the conditions monitored, tidal exchange appears to occur in a limited manner between the Sticks Channel and the Western side of the Inlet. This is in general agreement with the results obtained by Beer and Black (1979) using drogue float experiments and theoretical analysis.

Further information on tidal exchange was obtained from the results of the second intensive field experiment in August 1978. Here 50 litres of 20% Rhodamine WT solution (10kg dry weight) was injected across the width of the Murray River main channel, near to the mouth, between posts 44 and 45, at 0645 on 14th August. The Inlet was then sampled intensively for dye concentration and salinity at various grid locations over the next six days until dye concentrations again approached background levels.

The results are presented in detail in Appendix 6, where contour plots of the distribution of dye and salinity at various times during the exercise, as obtained from the ANU computer plotting package SYMAP, are presented in sequence to aid the reader in appreciating the dynamic changes that occurred over the experimental period. These SYMAP plots, an example of which is given in Fig. 7.2, provide a good picture of the short term tidal movements and the effects of wind mixing and river inflow on the distribution of dye and salinity within Peel Inlet. The plots can be considered as a series of moving picture "stills", with the spatial distribution of dye and salt, as inferred from the sampling results, frozen instantaneously. We see that the dye movement was dominated by the interaction of tidal forcing and river outflow until the afternoon of Thursday August 17, when strong wind mixing of the water column destroyed the strong vertical stratification apparent in the SYMAP salinity plots.[†]

In addition to the above qualitative picture, it is possible to obtain a simple quantitative evaluation of the flushing characteristics from the monitored data. For the period of the experiment there was a pronounced halocline, and sampling with depth showed that the dyed water did not mix with the denser, more saline bottom water. For each sample period, therefore, the total quantity of dye in the inlet can be estimated by multiplying the concentration by the depth of the halocline and then integrating this expression over the whole of the Inlet. The resulting dye mass figures are

---

[†] We note that these data could provide the basis for an interesting, detailed hydrodynamic modeling study aimed at explaining short term tidal and circulating behaviour (in contrast to the longer term studies considered in the present Study).

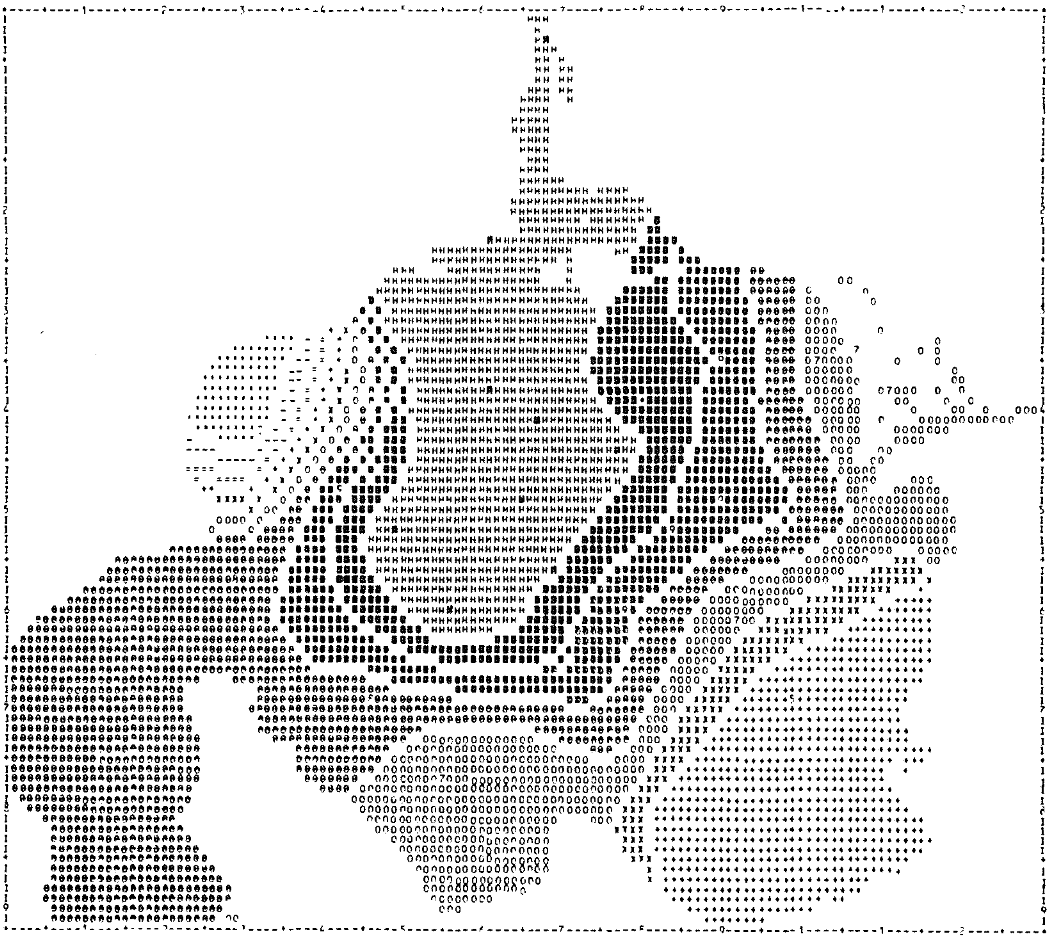


FIGURE 7.2 Typical Contour Map of Bottom Salinity for Peel Inlet (SYMAP)

normalised and plotted against time in Fig. 7.3.

Although the results in Fig. 7.3 can only be approximate given the uncertainties associated with the calculation, the general form of the curve is what might be expected: the dye mass estimate quickly reaches a peak as dye water entered the Inlet from the Murray River and then decays to background levels exhibiting some tendence to oscillate sinusoidally in the recession part of the curve in sympathy with tidal movements.

Also shown in the plot is the output of a time-series model fitted to the data: this indicates that the system is described by

$$x_k = 0.78x_{k-1} + 0.08u_k + 0.1u_{k-1} + 0.04u_{k-2} \qquad (7.1)$$

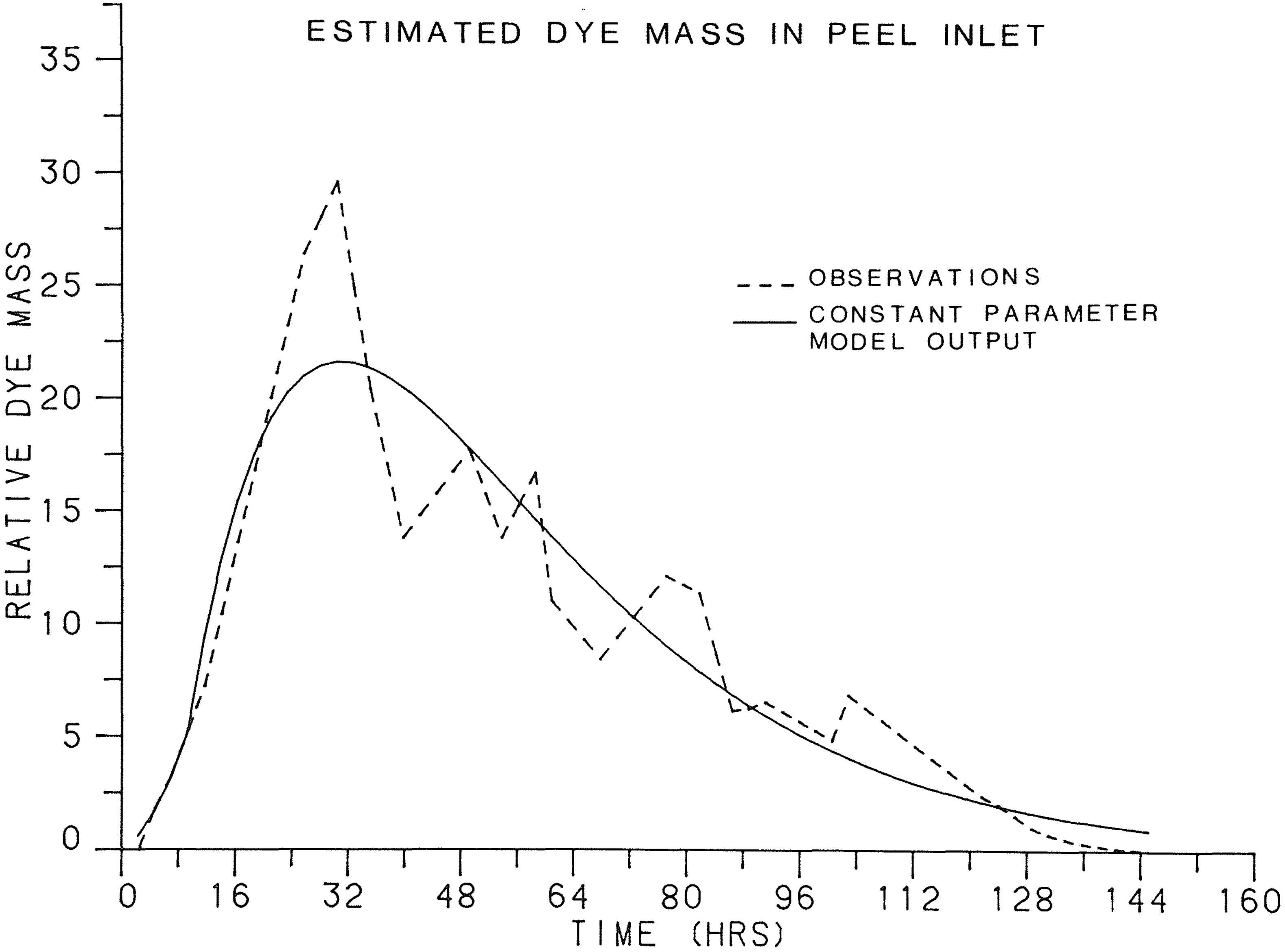
where the sampling interval is one day. This indicates a flushing time constant (residence time) of 0.57 weeks and a flushing rate of 1.75 per week.

Bearing in mind the limitations of the analysis, with the concentrations at sampling sites assumed to apply uniformly for the whole area around the site, and with the possibility of the dye appearing itself rather non-conservative in this kind of application where 'losses' can occur due to heterogeneity, we might assume that flushing rate will, if anything, be rather lower than indicated by Fig. 7.3. And since, as we shall see in the next section, this experiment was carried out during the period of maximum flushing, we might conclude *from this experiment alone* that maximum flushing time is of the order of one week. This tentative conclusion is confirmed by later salinity analysis discussed in the next section.

During the intensive field exercises several secondary experiments were carried out in parallel with the main dye experiments. Of these, two should be mentioned here: first, dye tracer studies in the River Murray between a dye injection point upstream of Pinjarra Wier and Yunderup; and second, the analysis of data obtained from a tide height - volume flow exercise carried out in the Mandurah Channel, by the WAIT Team. Both exercises are, however, described by Black and Rosher (1980) and the reader is referred to their report for full details.

FIGURE 7.3

ESTIMATED DYE MASS IN PEEL INLET



The CRES role in these secondary studies was two-fold. In the case of the dye tracer experiments, the idea was to exploit our previous experience with the use of Rhodamine WT dye for river dye dilution gauging and dispersion analysis in order to initiate exercises that would lead to a better understanding of the ungauged portion of the Murray River (see Chapter 6). In the case of both the dye tracer and volume flow experiments, the CRES role was also to carry out initial data analysis using time-series methods and to then pass on information about these data processing techniques to the WAIT Team. In this manner, it was possible for all subsequent planning and execution of similar experiments, as well as data analysis, to be carried out by the WAIT Team themselves, as discussed in their Report (Black and Rosher, 1980). We believe this is a good example of how useful "technology transfer" can occur if multidisciplinary exercises such as the Peel-Harvey Study are carried out on an *active* interdisciplinary basis.

Here it will suffice to illustrate the kind of data analysis that was initiated by CRES and carried out in these joint studies. One exercise, for example, is concerned with the time-series modeling of the dye tracer data obtained in the August 1978 experiments on the Murray River. Fig. 7.4 shows the comparison of model output with dye concentration measurements at Site 3 (Ravenswood). Full details of the data for all reaches between injection and Ravenswood are given in Appendix 6. It is interesting to note here that these kinds of time-series models are not only useful in their own right as a description of the dispersion characteristics of the stream but they can, in a very simple manner, provide estimates of the dispersion coefficients appropriate to the system (see Beer and Young, 1980; Young, 1980), without needing to resort to the conventional "moment analysis". Table 7.1, for example, shows the dispersion coefficients calculated in this manner for all of the reaches.

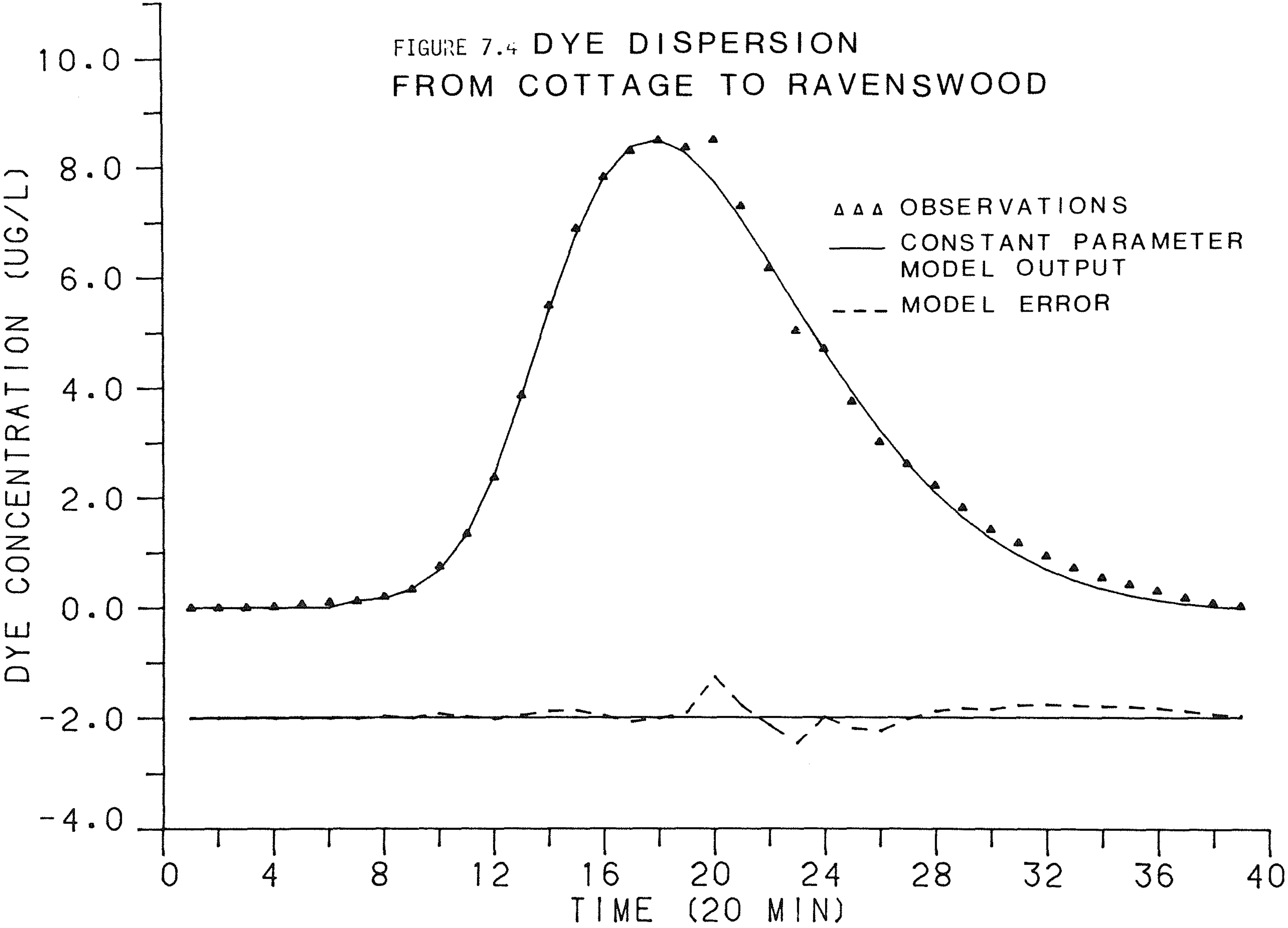


FIGURE 7.4 DYE DISPERSION FROM COTTAGE TO RAVENSWOOD

TABLE 7.1

REACH	LENGTH (km)	DISPERSION COEFF. (m^2/s)	VELOCITY COEFF. (m/s)
0 - 1	0.95	65.8	0.46
1 - 2	4.5	13.5	0.19
2 - 3	9.6	8.7	0.14
3 - 4	5.1	6.9	0.08

SITE 0 - INJECTION POINT
SITE 1 - PINJARRA WIER
SITE 2 - THE COTTAGE
SITE 3 - YUNDERUP

7.2 Evaluation of Salinity Changes : Theoretical Preliminaries

The hydrologic regime of the Peel Harvey Estuarine system is forced by a markedly seasonal climatic pattern (Black and Rosher, 1980). Most rainfall and resultant river flow occur in the Winter months between May and October; while during the hot, dry Summer, river flow often ceases completely and high evaporation, coupled with low tidal flushing, leads to hypersaline conditions with salinities in the Harvey Estuary often reaching levels greater than 50 $^{o}/oo$.

We can examine this behaviour in more detail by looking at Fig. 7.5 which shows the variations in salinity at Site 4 (Coodanup) together with the associated total evaporation and total flow variations. The salinity-time series curve for each year, can be thought of as comprising three distinct parts. Consider 1977-8: until about October 31, 1977 (week 10) the salinity and evaporation remain more or less constant (at 23 $^{o}/oo$ and 3mm respectively) and there is some rainfall marking the end of the winter rains. This situation appears to change around November 8, 1977 when the salinity and the evaporation, start a steady rise. This represents the summer phase of the data when evaporation far exceeds the river flows. The salinity rises steadily as the evaporation increases, reaching a hypersaline state with a maximum salinity of 47 $^{o}/oo$ on March 28, 1978 (week 31) - some seven weeks after the peak value of evaporation. As the evaporation declines the salinity declines as well until the river flows begin to dominate the dynamics. As the river flows slacken

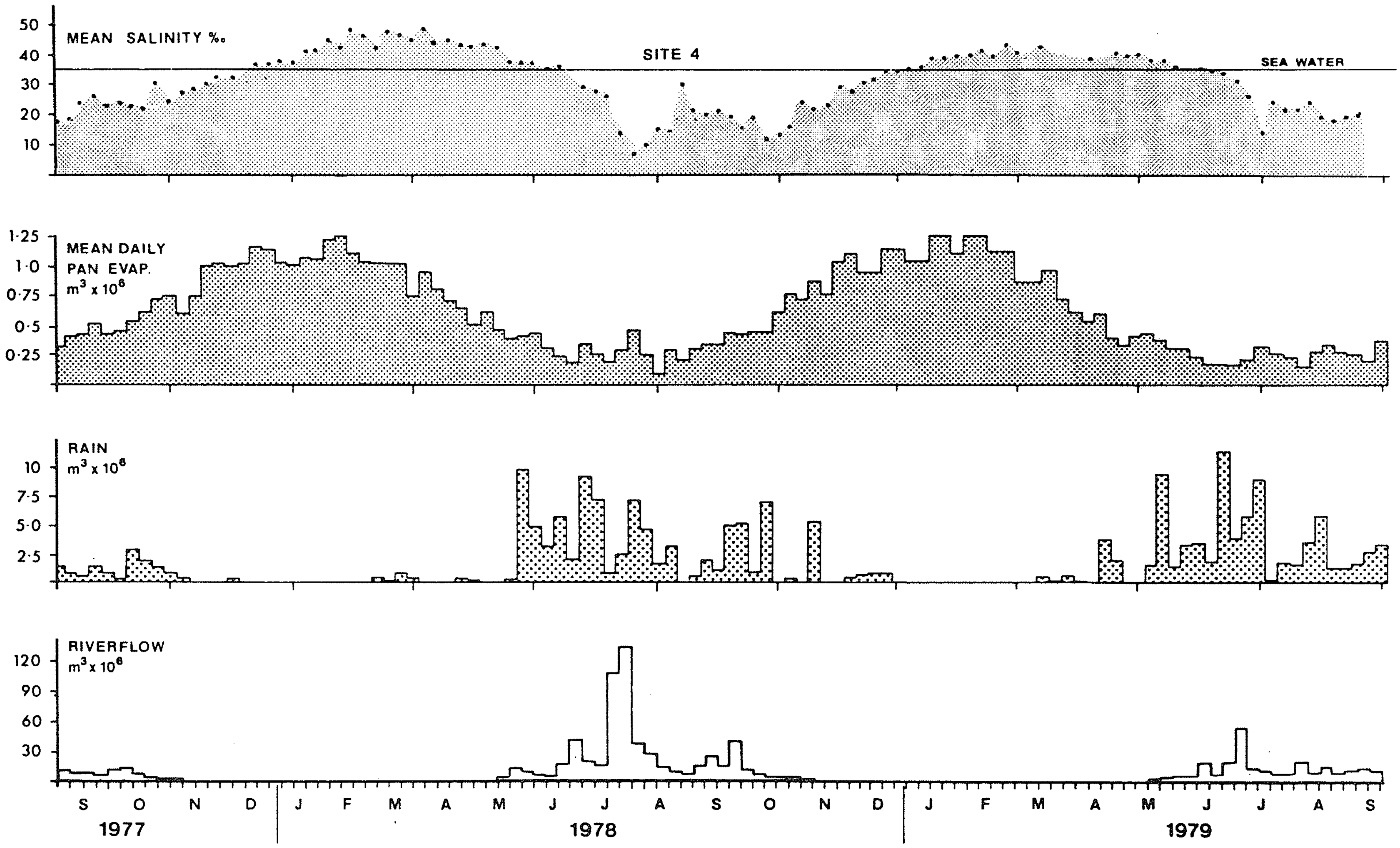


Figure 7.5 Weekly salinity, evaporation, rainfall and total river flow.

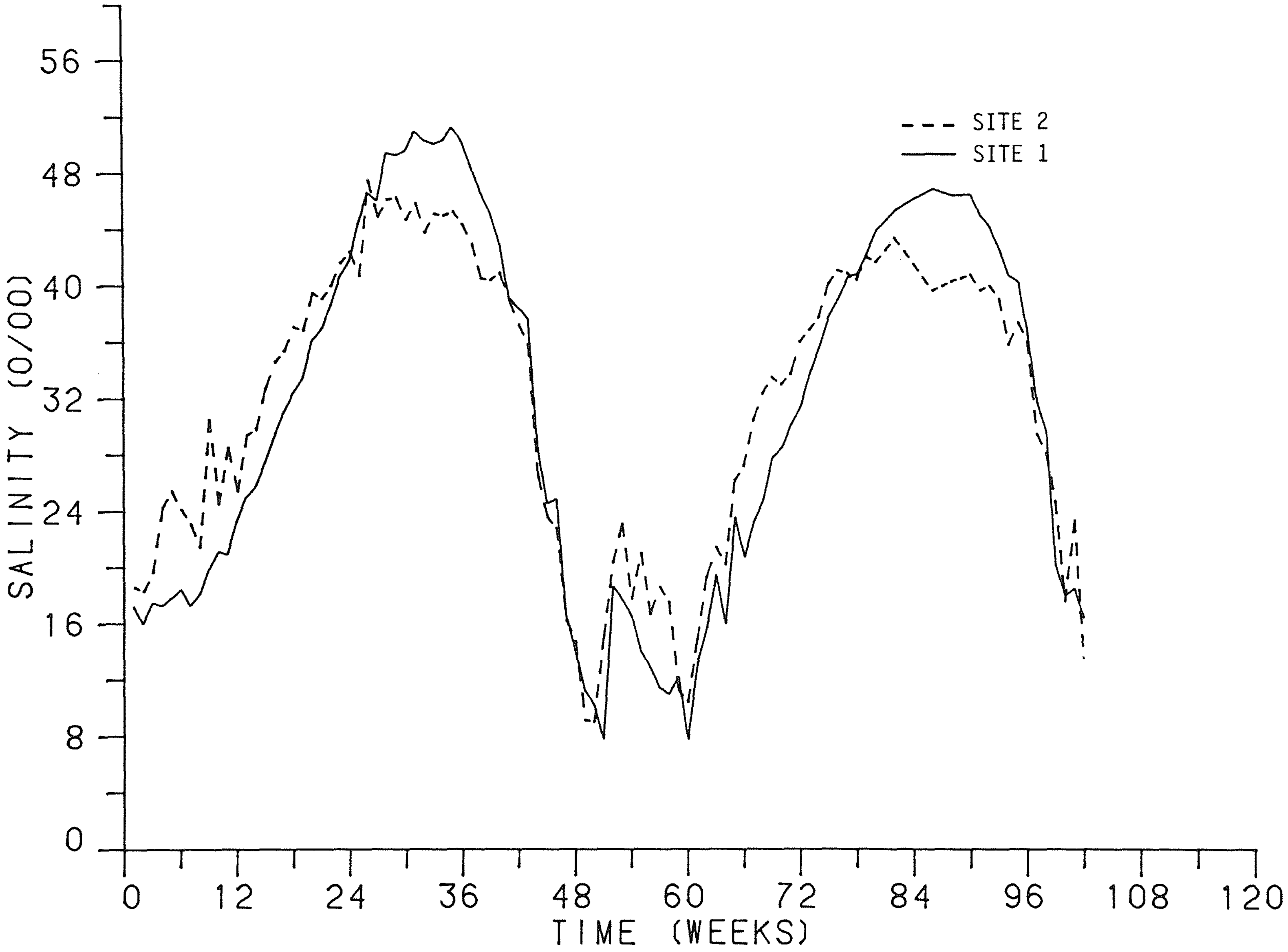
the above cycle starts to repeat.

Despite the fact that the 1978 rains started to fall from May 23 (week 39) there is no obvious response to this in the salinity data until five weeks later when the salinity starts to drop markedly. We thus infer that the transition between a saline and freshwater input on the left hand side of (2.2.3) occurred on June 26, 1978 (week 44). During 1978 there appear to have been two distinct flow periods, one in the July-August period and one in late September. The rise in salinity on August 22, 1978 (week 52) occurred during this interflow period. River flow dominated the input again for a short while in September but beginning from October 25, 1978 (week 61) the intrusion of marine water had re-asserted itself and the salinity started its gradual rise.

During the Winter months of 1978 the salinity transects from sites 1, 2, 3, 4 and 7 showed evidence of stratification with less saline water (presumably from the rivers) on top of more saline water (presumably from the ocean). In order to simplify the subsequent analysis, the complications due to such stratification have been ignored by using the average value of the surface and depth salinity measurements. In addition to its simplicity there are compelling reasons for doing this in the absence of more detailed knowledge of nutrient and salt transport in the system. In a later section of the report we shall use our residence time values to obtain an estimate of the nutrient loss from the system. As, in general, one does not know whether some proportion of nutrient lost to the sea re-enters on the next incoming tide any salinity estimates that are going to be used in computation of nutrient flushing should allow for both surface and bottom salinities. Of course, the utilisation of simple average values is not necessarily the best way of incorporating such information but additional analysis indicated that the results were not particularly sensitive to this factor.

The changes in salinity from site to site obviously provide us with useful information on the dynamics of the estuary. Fig. 7.6, for example, shows the salinities measured over 102 weeks of the

FIGURE 7.6 Variations in Salinity at Sites 1 and 2, Peel Inlet



Study at Sites 2 (at Harvey Entrance) and 1 (in the Harvey Estuary). In both cases, the seasonal variation discussed above is apparent: during Summer (weeks 0-40), the salinities rise to peak values as the result the high evaporation and low flushing rate conditions; they then began to reduce as temperatures fall at the end of Summer; finally and quite suddenly with the onset of river flow, the salinities drop below ocean levels (weeks 40-65) and the system is clearly dominated by riverine water entering from the Murray, Serpentine and Harvey Systems.

We can see a definite changing dynamic relationship between the variations in salinity at Sites 1 and 2 from Fig. 7.6, with the peak Summer salinity some 5 $^{o}/oo$ higher at Site 1 and with a clear "lagged" relationship occurring subsequent to the heavy river flows of the Winter period: during the Spring to early Summer weeks 65 - 90, for example, salinity in the Harvey Estuary rises much more slowly than at Harvey Entrance but eventually achieves significantly higher levels over the mid-Summer period between weeks 80 and 90. This is in contrast to the high river flow period where changes in salinity are quite similar at both sites.

By looking at the salinity changes occurring at all monitored sites in the Estuary (Part 3 of the Report) and interpreting them in the above manner, it is possible to obtain a good qualitative feel for the flushing characteristics of the systems. But if we are to obtain a quantative picture in terms of flushing times and rates, it is clearly necessary to analyse the salinity data in some manner.

A simple method of analysis was suggested and utilised in the first Progress Report (Hodgkin, 1978). This entails visualising the estuarine system as a series of continuous stirred tank reactor (CSTR) mechanisms[†] and evaluating the response characteristics of these CSTR systems by reference to the first 32 weeks of monitored salinity data. Here we will pursue this approach further, enhancing the CSTR analysis to allow for a more complete description of the system and considering the nature of this description in relation to the 102 weeks of salinity data available at the time of the writing of this Report.

[†] or compartments.

The approach is based on the conservation of mass of salt and can be considered as a more sophisticated equivalent of the approach outlined by Godfrey (1977). In order to provide a background to the subsequent data analysis, it is instructive to consider the system from the simplest theoretical standpoint. If we let the total salt mass in a compartment of Volume V be represented by M, then the salinity S is defined as

$$S = M/V \tag{7.2}$$

while the mass conservation equation can be written as

$$\frac{dM}{dt} = \text{Mass Flow in - Mass Flow out}$$

i.e.

$$\frac{dM}{dt} = Q_i S_i - QS \tag{7.3}$$

where Q_i is the flow rate of water with salinity S_i into the compartment while Q is the flow rate of water with salinity S leaving the compartment. Note here that, over very short time scales of the order of the normal tidal cycle, the flow rates Q and Q_i are likely to be highly variable quantities. However, over the weekly time-scales that are of interest to the present study, we would expect them to be represented by "average" values which are approximately equal and either constant or only slowly variable in comparison to the dominant time constants of the system. An assumption of complete mixing now enables us to write equation (7.3) in the form

$$\frac{d(VS)}{dt} = Q_i S_i - QS \tag{7.4}$$

where V is the volume of the compartment; in other words we assume, for simplicity, that the "output" salinity S is representative of the salinity over the whole compartment. Note here that, because of the simplicity of the representation and the great degree of aggregation inherent in this particular mathematical description, we cannot assume that Q, Q_i and V are directly related to equivalent *real* measurable variables in the system. Rather they represent the *effective* values of these variables appropriate to the simplicity of the formulation and the degree of aggregation.

This concept of *effective* rather than *real* variables is extremely important in systems analysis. The intent to represent the system mathematically in the simplest manner consistent with the objectives of the analysis means that model variables are often defined at the aggregate or macro-level. At this level, it is important not to necessarily consider the internal model variables in relation to equivalent variables defined at the micro-level; they must be considered within the context of the model formulation and at the level of aggregation appropriate to that formulation. But we will have more to say on this topic as the analysis proceeds.

Since both the salinity S and the volume V are time variable quantities, it is necessary to expand the left hand side of (7.4) to yield

$$V\frac{dS}{dt} + S\frac{dV}{dt} = Q_iS_i - QS$$

or,

$$V\frac{dS}{dt} = -(Q + \frac{dV}{dt})S + Q_iS_i$$

so that the rate of change of salinity, under the assumption of complete mixing, is given by

$$\frac{dS}{dt} = -\{\frac{Q}{V} + \frac{1}{V}\frac{dV}{dt}\}S + \frac{Q_i}{V}\;S_i \qquad (7.5)$$

This is a first order ordinary differential equation with *time variable coefficients* of the general form

$$\frac{dS}{dt} = -a(t)S + b(t)S_i \qquad (7.6)$$

Using the same systems terminology employed previously in Chapter 6, this first order system has, at any time, a steady state gain (SSG) given (when $\frac{dS}{dt} = 0$) by

$$SSG = \left[\frac{S}{S_i}\right]_{ss} = \frac{b(t)}{a(t)} = \frac{Q_i}{Q + \frac{dV}{dt}} \qquad (7.7)$$

and a time constant (or residence-time) T_F of the form

$$T_F = 1/\{\frac{Q}{V} + \frac{1}{V}\frac{dV}{dt}\} \qquad (7.8)$$

Alternatively, given the present application, we can say that T_F is the "flushing time constant" and that the "flushing rate", F is defined by†

$$F = \frac{Q}{V} + \frac{1}{V}\frac{dV}{dt} \qquad (7.9)$$

Typically, if we consider a sampling interval of one week, then T_F will be measured in weeks and F in weeks^{-1}; i.e. F will be a measure of the proportion of the compartment exchanged or flushed to the ocean per week. The SSG, is of course, dimensionless.

Nominally SSG, T_F and F are properties associated with *time invariant parameter linear systems*. In these circumstances, if the initial salinity S_0 is zero (i.e. freshwater) and there are steady input conditions, then the flushing time constant represents the time taken for the salinity intrusion from the Ocean to result in a rise in estuarine salinity of $(1 - e^{-1})$ or 63.4% of its final steady state value $(b/a)S_i$. Conversely, during the river dominated outflow phase, again under steady input conditions, the flushing time constant represents the time for salinity to fall to e^{-1} or 36.6% of its original value. Also we can see from (7.7) that, in the complete steady state with $\frac{dV}{dt}$ and $\frac{dS}{dt}$ both zero, then

$$SSG = Q_i/Q \qquad (7.10)$$

---

† note that the present analysis is more complex than conventional analysis so that these terms should be interpreted *within the context of this analysis*.

so that if $Q_i = Q$, then $S = S_i$ as we would expect. And from (7.8) and (7.9), if the volume remains constant, then

$$T_F = V/Q \quad \text{and} \quad F = Q/V \tag{7.11}$$

which are again the conventional hydrological definitions of residence time and flushing rate (see previous footnote).

But the model (7.6) does *not* have time-invariant parameters; the parameters are nominally, at least, functions of variable flow rates and volumes. Consequently the model can exhibit behaviour which is interpretable as either that of a *time-variable parameter linear* system or a *nonlinear* system, depending upon the outlook of the analyst. As a result, properties of time-invariant parameter linear systems, such as steady state gain and flushing rate, are not strictly applicable and must be treated with some care. With this caveat in mind, however, it is possible to continue with the analysis and consider the further implications of equation (7.6).

During transient conditions of the kind met in practice, it is clear from (7.9) that the flushing rate is given by the sum of the conventional flushing rate Q/V and a transient flushing rate $\frac{1}{V}\frac{dV}{dt}$, which is a function of the ratio of changes in effective compartmental volume to the effective compartmental volume itself. Thus, if there is a strong positive rate of change of volume, as during heavy river inflow to the Estuary, then we would expect the flushing rate to increase markedly; or conversely, if the rate of change is negative, as when evaporation losses are high during Summer, then the effective flushing rate is likely to be significantly less than the normal value Q/V.

To continue further with this kind of analysis, we must attempt to expand equation (7.5) be evaluating $\frac{dV}{dt}$. But what are the contributions to $\frac{dV}{dt}$ and what is their relative importance in regard to the observed changes in salinity?

Employing a similar approach to that used in the derivation of equation 7.5, we can construct a simple aggregative hydraulic model of the system in the form of connected tanks, as shown in

Fig. 7.7. Here one tank is representative of the ocean effects whilst the other represents a compartment within the estuarine system. The rate of change of effective volume V for this compartment can be described approximately by the small perturbation equation[†]

$$\frac{dV}{dt} = \frac{d(Ah)}{dt} = \frac{h_i - h}{R} + Q_R - Ae \qquad (7.12)$$

where h and A are, respectively, the depth of water in, and the surface area of the compartment appropriate to the definition of the effective volume V; h_i is the depth of water associated with the input location and measured with respect to the same reference datum as h;

Q_R is the river inflow;

and e = E-R is the effective evaporation, namely evaporation E minus rainfall R.

Note that V, A, h, Q_R and e in equation (7.12) are, once again, the *effective* rather than the real values of these variables; in particular, dV/dt should be interpreted as the rate of change of volume *effective* in the sense of inducing changes in salinity. Thus, during the hypersaline Summer period, the major mechanism for salinity change is clearly evaporation, since this is the only mechanism which can lead to salinities greater than the oceanic level of 35 ^{0}/oo; conversely, during the Winter period salinities are depressed well below the oceanic level mainly as the result of high river flushing effects. And we are concerned here with the changes in volume resulting from these effects *which induce the observed changes in salinity.*

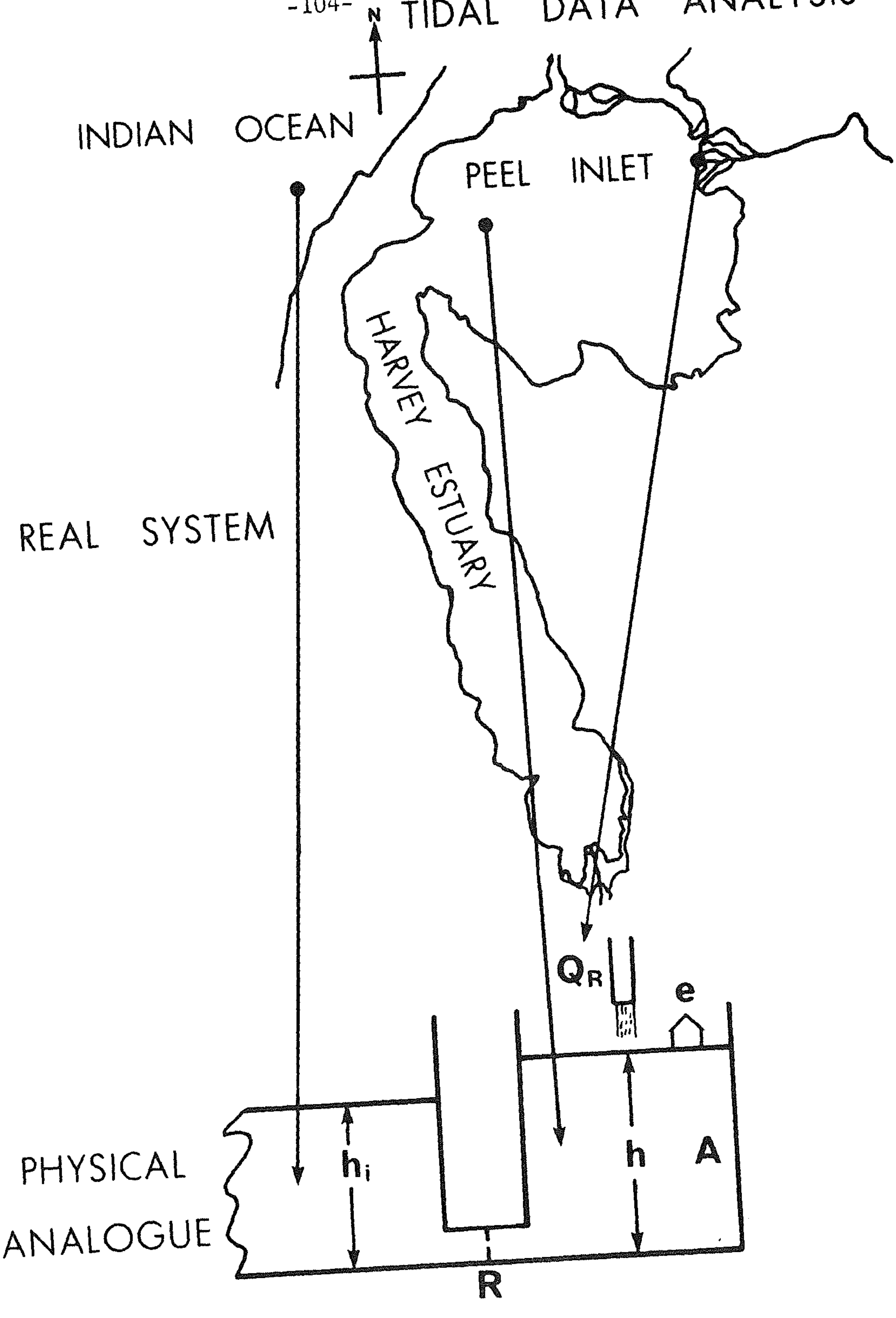
Continuing with the analysis we can expand equation (7.12) to obtain

$$A\frac{dh}{dt} + h\frac{dA}{dt} = -\frac{1}{R}h + \frac{1}{R}h_i + Q_R - Ae$$

or,

$$\frac{dh}{dt} = -\left(\frac{1}{AR} + \frac{1}{A}\frac{dA}{dt}\right)h + \frac{1}{AR}h_i + \frac{1}{A}Q_R - e \qquad (7.13)$$

[†] this assumes that the flux of water from the inlet is proportional to the level difference with proportionality constant 1/R.



MATHEMATICAL MODEL

$$A \cdot \frac{dh}{dt} = \frac{h_i - h}{R} + Q_R - A \cdot e$$

FIGURE 7.7 Simple Model of Level Changes in Peel Harvey System

In a similar manner to equation (7.5), this equation can be written as a time variable parameter, first order, ordinary differential equation of the form

$$\frac{dh}{dt} = -\alpha(t)h + \beta_0(t)h_i + \beta_1(t)Q - e \qquad (7.14)$$

where α, β_0 and β_1 are possibly time variable coefficients in parameters defined by

$$\begin{aligned} \alpha(t) &= \frac{1}{AR} - \frac{1}{A}\frac{dA}{dt} \\ \beta_0(t) &= \frac{1}{AR} \qquad (7.15) \\ \beta_1(t) &= \frac{1}{A} \end{aligned}$$

On a weekly time base, Q_R and e are dominantly seasonal with e strongly sinusoidal in form and Q_R being effective mainly during Winter, both as shown in Fig. 7.5. On the other hand, we would expect h_i to affect h on a much shorter time scale, say in a matter of hours. This is confirmed by time-series analysis of tidal height gauge data from Mandurah and Chimneys which reveals that, over the short term, h is related to h_i by

$$\frac{dh}{dt} = -\alpha h + \beta_0 h_i$$

with $\alpha = \beta_0 = 37.3$ (i.e. a "time constant" $1/\alpha$ of 0.027 weeks or 4.5 hours). Fig. 7.8(a) compares the output of this model with the observed tide heights measured at Chimneys over a 14.5 day period and we see that it is very effective in explaining the data. The model parameters were estimated using the CAPTAIN package. A similar analysis between daily mean tide heights at Mandurah and Coodanup also provides a good explanation of the data as shown in Fig. 7.8(b); although the lag is longer in this case (a pure time delay of 1 day), as might be expected, it is clearly almost instantaneous on a weekly time base.

The above results suggest that the dynamic lag effects in equation (7.14) arising from the presence of the term $-\alpha(t)h^\dagger$ are extremely

---

†note that since $\alpha = \beta_0$ we see from (7.15) that $\frac{1}{A}\frac{dA}{dt}$ must be very small, as we might expect.

FIGURE 7.8(a)

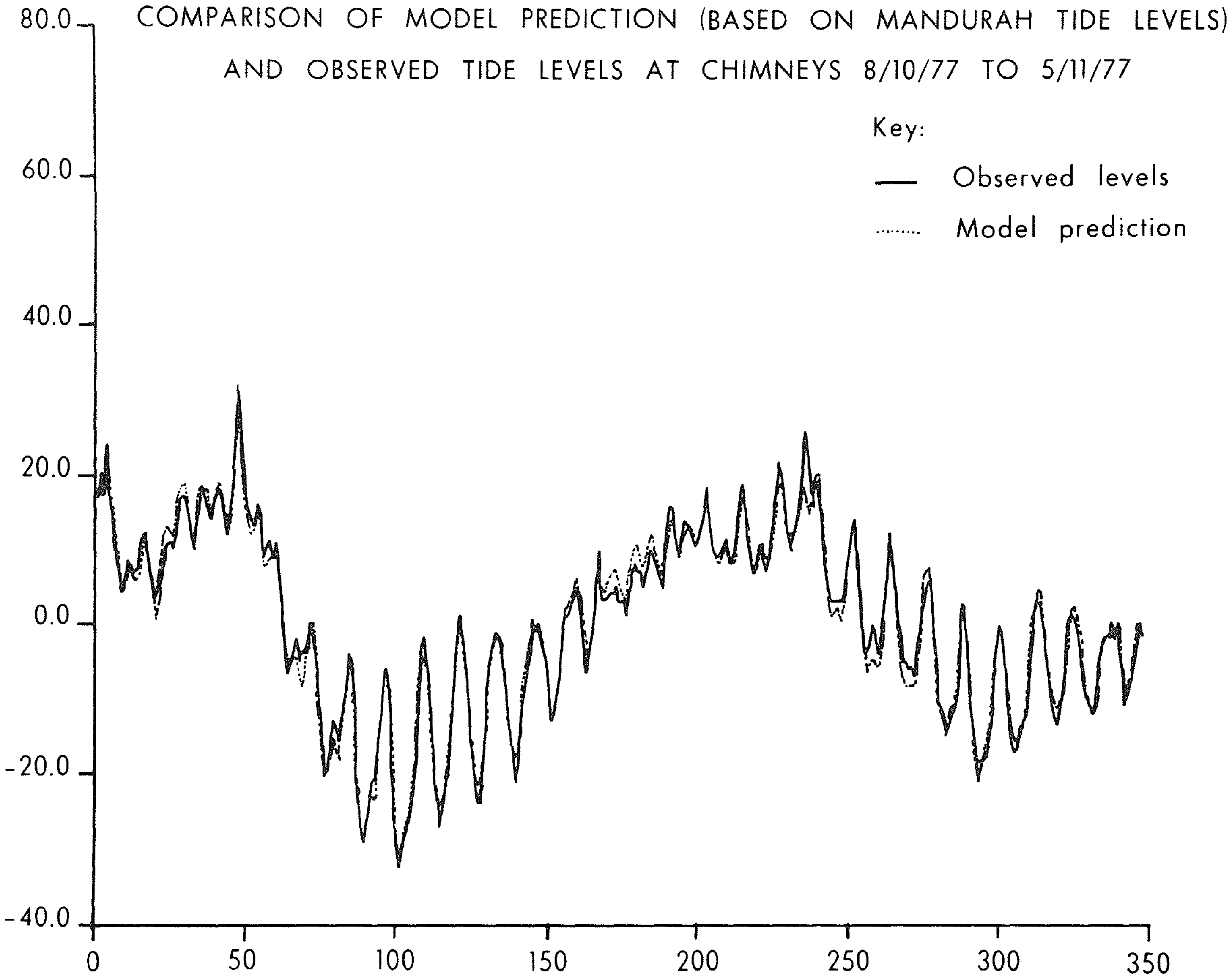
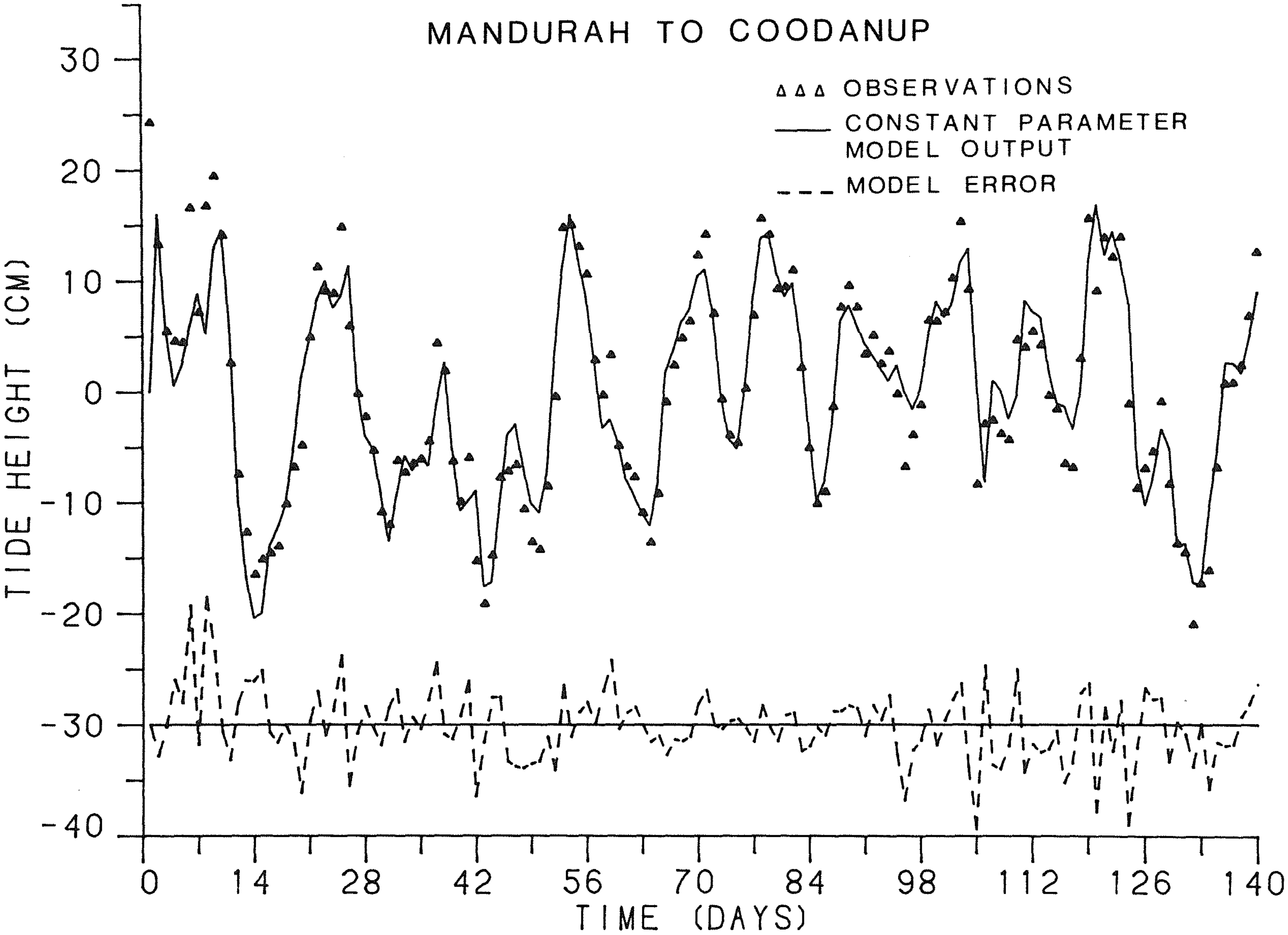

COMPARISON OF MODEL PREDICTION (BASED ON MANDURAH TIDE LEVELS)
AND OBSERVED TIDE LEVELS AT CHIMNEYS 8/10/77 TO 5/11/77
Key:
Observed levels
Model prediction
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
0
50
100
150
200
250
300
350

FIGURE 7.8(b) Comparison of Model Prediction (based on Mandurah Tide Levels) and Observed Tide Levels at Coodanup



small on a weekly time scale; for example, the slow seasonal variations in e will have very little effect in the short term while, in the long term, h will follow fluctuations in e with negligible lag. From a systems standpoint, we would say that the system is high bandwidth in frequency response terms so that low frequency inputs, such as e, pass through the system and affect the output h instantaneously (in a weekly sense) without any dynamic lag and with attenuation defined solely by the low frequency gain of the system.

The implications of these behavioural patterns on the salinity variations described by equation (7.5) are clear: depending upon the time of year, the term $\frac{1}{V}\frac{dV}{dt}$ will be dominated by the rates of change of whichever input (h_i, Q_R or e) in (7.13) happens to be providing the major stimulus to changes in salinity. Thus, during the Summer period, we would expect $\frac{1}{A}\frac{dA}{dt}$ to be dominated by the evaporative effects so that F in equation (7.9) will be given approximately by an expression such as,

$$F \simeq \frac{Q}{V} + \frac{1}{e}\frac{de}{dt} \qquad (7.16)$$

The analysis in this section which has led to equations (7.5), (7.13) and (7.16) has been purposefully simplistic in order to provide the general reader with some feeling for the *possible* dynamic behaviour of the system and, in particular, to supply a simple, mathematically based understanding of the possible mechanisms which induce the observed salinity changes in the Peel-Harvey system. However, we would stress two aspects of this analysis:

(i) the formulation in terms of *effective* variables defined at the aggregative level appropriate to the problem, in this case the compartmental level on a weekly time base;

(ii) the omission of any secondary lag effects, for example between measured evaporation changes and the resultant fluctuations in *effective* volume.

The first point is most important in systems terms and rather unusual from the standpoint of more conventional hydrodynamic analysis. It is a *holistic* device which allows for the formulation, identification and validation of simple aggregative descriptions of dynamic behaviour, as we shall see in the next section. But it is a device which must be used and interpreted carefully. Since the internal model variables are *"effective"* and not *"real"* variables[†], the coefficients or parameters in the model also have to be interpreted in similar terms. As a result, the common reductionist device of inserting parameters measured at a micro-level directly into the model equations can be extremely dangerous: holistic models defined in terms of effective variables must be identified, estimated and validated holistically, on the basis of the measured data.

The second point merely means that, while the models as formulated here can provide a useful stimulus for time-series model identification and estimation, we should not expect them to provide a complete background to such analysis. In particular, we should not be surprised if secondary lag effects are identified in the analysis which lead to a modification of the simple, theoretically formulated models discussed here.

Finally, since our analysis is both simple and unconventional we should, perhaps, counter possible arguments that it is too simplistic in relation to such a complex system as the Peel-Harvey Estuary; after all most analyses of estuarine dynamics are much more complicated than this and suggest that much greater detail is required (e.g. Smith, 1980).

Surprisingly, the idea of including great detail and complexity in the formulation of the theoretical mathematical model does not necessarily conform with the usual interpretation of the scientific method (Popper, 1959). As we have pointed out in Chapter 4, this requires that the scientist formulates a hypothesis (model in our

---

[†] both terms are placed in quotation marks to indicate that they should not be interpreted literally

case) and then performs planned experiments or monitoring aimed at *falsifying* this hypothesis: failure to falsify then indicates *conditional* acceptance of the hypothesis, until fresh evidence is obtained which either leads to falsification or, more likely, to modification of the original hypothesis into a new conditionally acceptable form.

Such an approach proves rather difficult when the system is badly defined and there is little opportunity to conduct *in-situ* planned experiments. In this situation, the analyst must attempt to falsify his hypotheses by referring only to the monitored data obtained during the normal operation of the system and, as we have pointed out in Chapter 2, the information content of this monitored data may not be sufficient to unambiguously define the system behaviour.

The complex, detailed model with many unknown parameters is the most vulnerable in these circumstances. It is well known that great difficulties can be encountered in attempting to "optimise" a complex multi-parameter model so that it adequately explains or "fits" the data. And even if it can be achieved, the ability of the model to fit the observations does not necessarily prove that the model is a satisfactory representation: over parameterised models can be made to fit data very well but the parameters of the model so obtained can be ill-defined (i.e. possessing high estimation error variance) that the model will perform extremely poorly in forecasting *future* behaviour. Of course, this does not mean that complex model is *necessarily* incorrect in *form;* merely it indicates that the richness of structure *may* be inappropriate to explain the rather simpler observed behaviour and so the model can have "surplus content" *not validated against observations* (Young, 1978).

With such possibilities in mind, we should not be reticent to attempt the falsification of a simpler hypotheses particularly if, as in this case, we have a reasonable quantity of observational data. While conditionally acceptable hypotheses of this simpler variety may not tell us *all* about the hydrodynamic behaviour of the system, they will tend to indicate those aspects of the system behaviour that are explained by the observational data. And simple models of complex phenomena are not necessarily bad models: Popper, for example, extols the virtues of simple theories (models) and explicitly equates simplicity with paucity of parameterisation.

In this spirit, we do not attempt further theoretical expansion of the equation (7.5) in the classical hydrodynamic tradition[†]; rather we assess the general structure of the equivalent model (7.6) against the weekly salinity data using recursive time-series methods. This step can, in statistical terms, be considered as an exercise in *identifying* that model structure which seems most appropriate to the explanation of the observed behaviour (Chapter 4).

7.3 Evaluation of Salinity Changes: Time-Series Analysis

If we consider first the relationship between the salinities at sites 2 and 1, then a model such as (7.6) will relate the changes in salinity S at the 'output' site 1 to changes in salinity at the 'input' site 2. Since we have discrete-time (weekly) data, however, it is more convenient to consider a discrete-time version of this equation: if we denote the measured salinity at site 1 for week k by y_k and the measured salinity at site 2 for the same week by u_k, then this model takes the form

$$y_k = -a_{1k}\, y_{k-1} + b_{ok}\, u_k + \gamma_k \tag{7.17}$$

where a_{1k} and b_{ok} are possibly time-variable coefficients and γ_k represents stochastic effects. In the *time-invariant parameter case* it can be shown that a_1 is related to a in (7.6) by

$$a_1 = e^{-aT_s}$$

where T_s is the sampling interval, in this case unity (one week), i.e.

$$a = -\log_e a_1$$

[†] although the classical hydrodynamicist would probably prefer to work with distributed parameter, partial differential equation representations rather than the simpler lumped parameter models discussed here.

Although these relationships are not strictly correct in the time variable parameter case, they are acceptable approximations in the present circumstances and we can assume, therefore, that

$$a(t) = -\log_e a_{1k} \qquad (7.18)$$

at each (kth) sampling instant.

Nominally we might expect both a and b in equation (7.6) to be time variable but on the average, over long periods of time, it seems likely that $b(t) = Q_i/V$ will tend to vary only slowly and may be approximated as a constant. This is borne out in statistical analysis and so, for the present purposes, we assume that b (and, therefore, b_o), is constant and evaluate only significant changes in the estimate $\hat{a}(t)$ of $a(t)$ via changes in the estimate $\hat{a}_{1k}$ of a_{1k}. Such evaluation is based on the estimation of the parameters in the model (7.17) using the CAPTAIN programme package.

Using this approach, we see straight away that the assumption of time-invariance for *both* a_{1k} and b_{ok} is invalid: Fig. 7.9 shows the output of a model of the form:

$$\hat{x}_k = -\hat{a}_{1k}\hat{x}_{k-1} + \hat{b}_{ok}u_k \qquad (7.19)$$

with $\hat{a}_{1k}$ and $\hat{b}_{ok}$ set to the best *constant* estimates from the instrumental variable (IV) estimation algorithm used in CAPTAIN. This model can be considered as the deterministic part of the model (7.17) and we see that the model fitting error $\hat{\xi}_k = y_k - \hat{x}_k$ is highly structured with a strong sinusoidal component. Bearing in mind the theoretical background, this suggests (Young, 1978) that the relationship has some time variable parameter (or nonlinear) properties. These are investigated by use of the time-variable parameter (TVAR) estimation algorithm in CAPTAIN, which yields the results shown in Figs. 7.10 and 7.13.

Fig. 7.10 shows the output of the model (7.19) using the TVAR estimated value of $\hat{a}_{1k}$: we see that the data are explained reasonably well with the error $\hat{\xi}_k$ now quite small and random in form. The estimate $\hat{a}_{1k}$ is given in Fig. 7.11 and it is clear that is has quite significant changes with a strong seasonal

FIGURE 7.9 Variations in Salinity at Site 1 - Constant Parameter Model

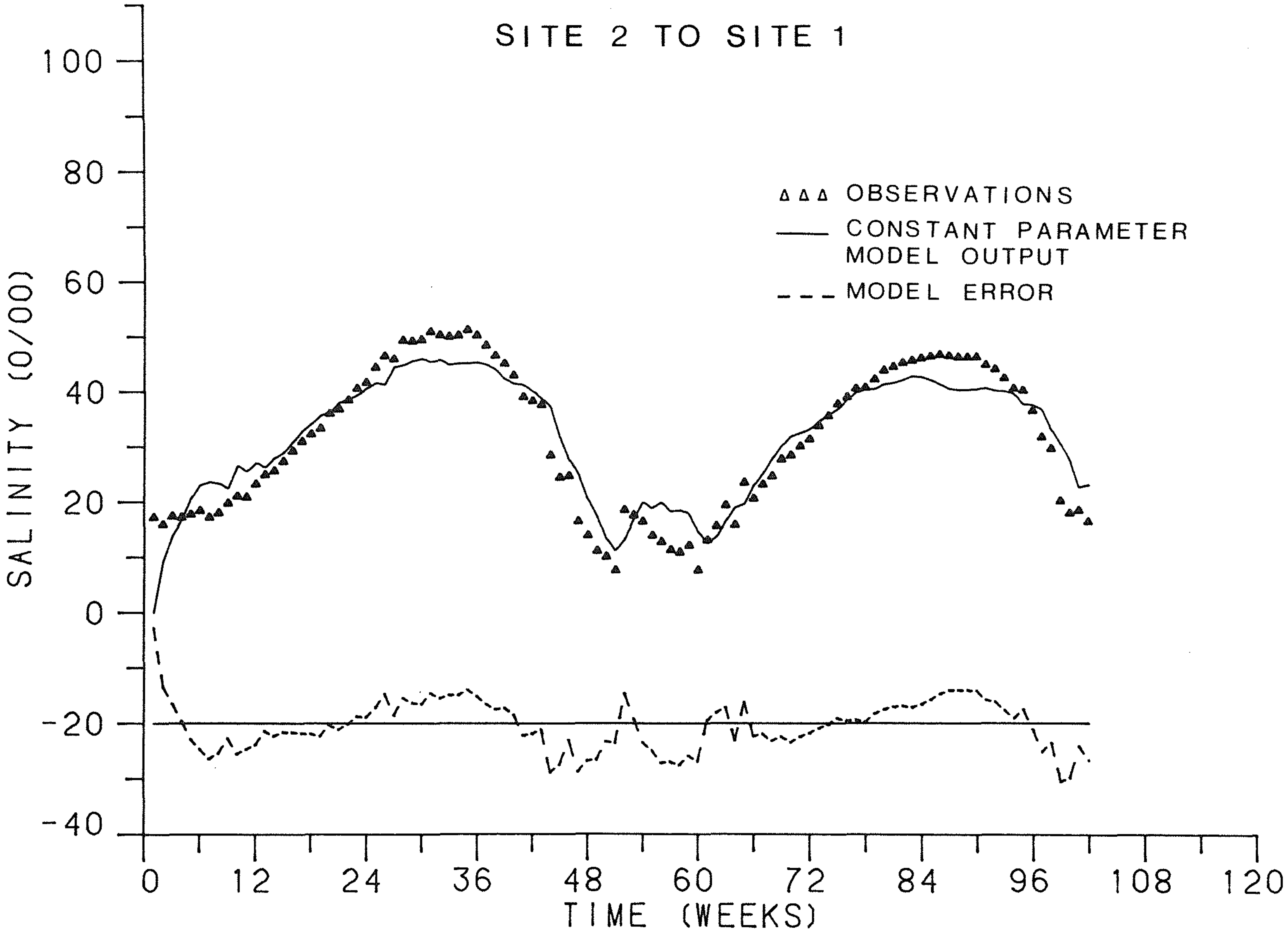


FIGURE 7.10 Variations in Salinity at Site 1 - Time-Variable Parameter Model

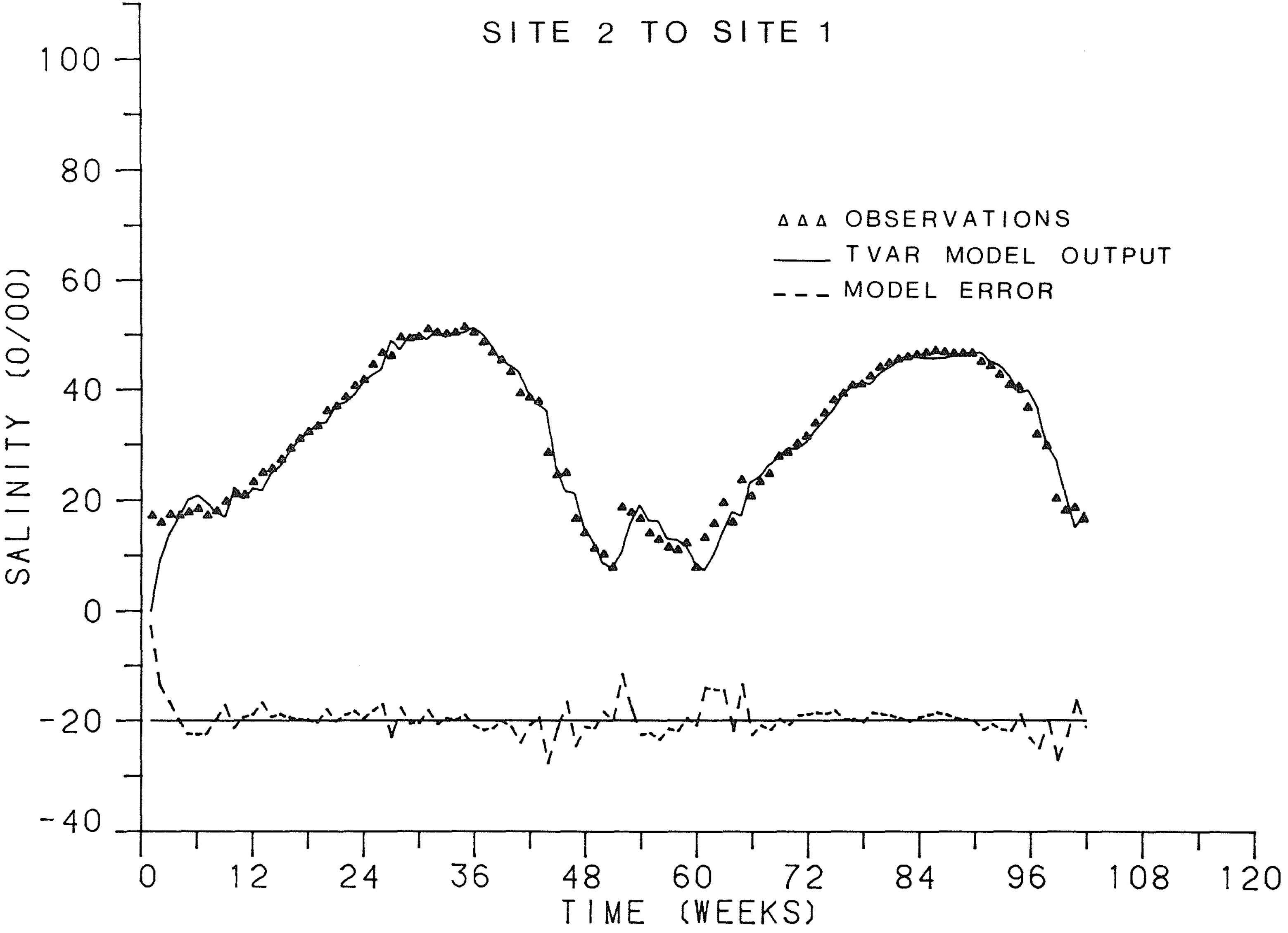


FIGURE 7.11 Variations in Salinity at Site 1 - Estimate of Time-Variable Parameter a_k

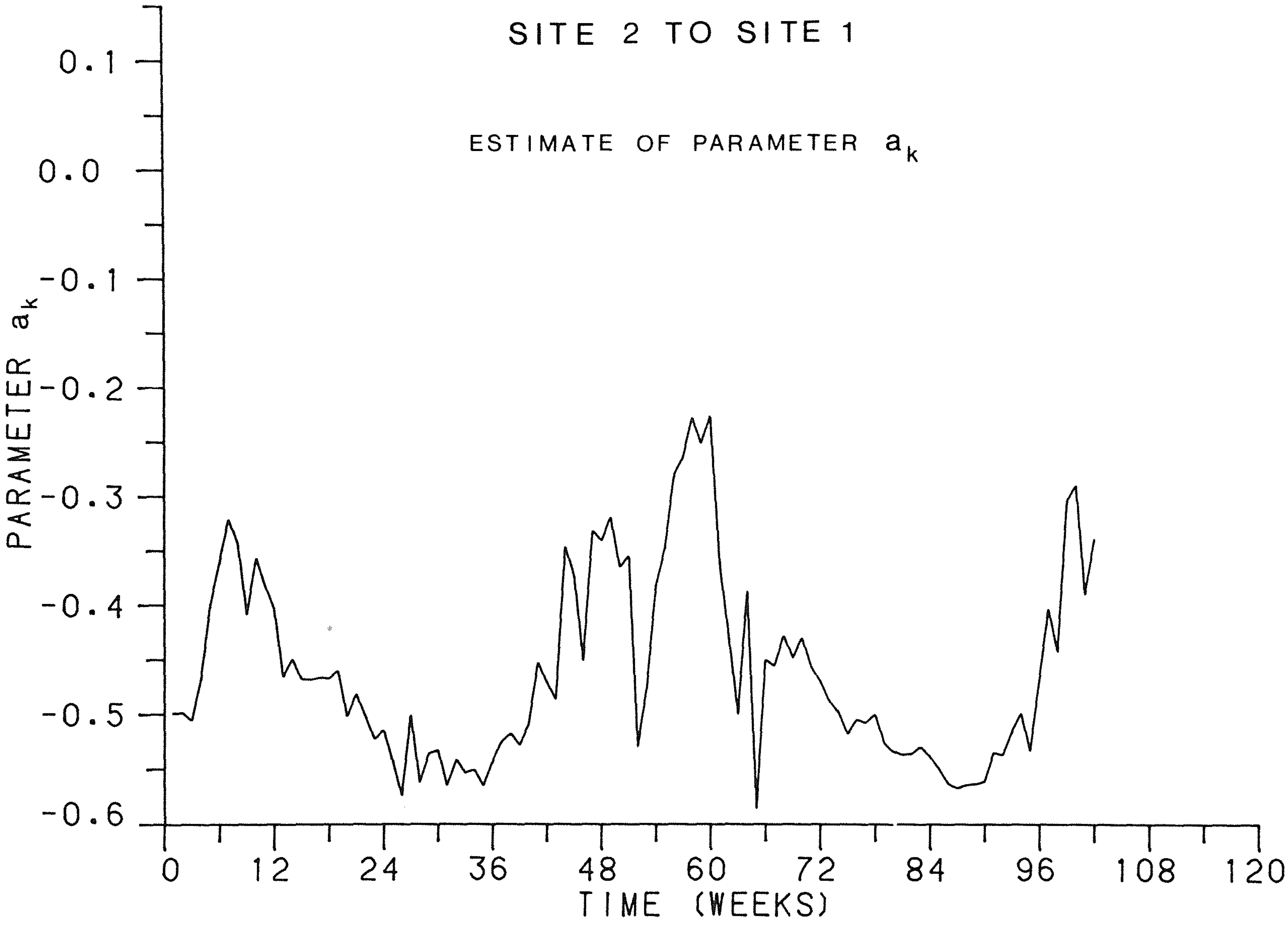


FIGURE 7.12 Variations in Salinity at Site 1 - Estimate of Time Variable Parameter a(t)

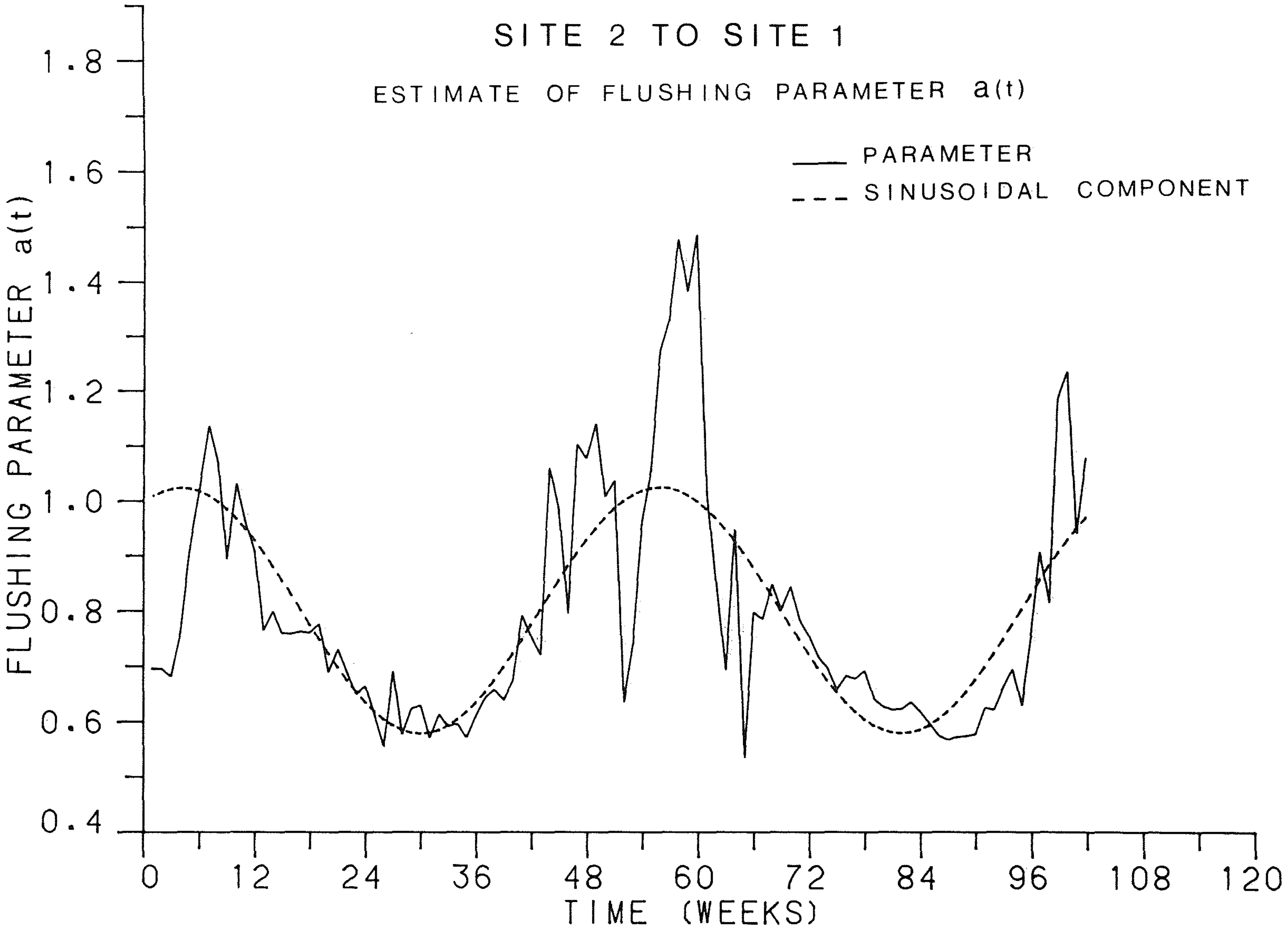
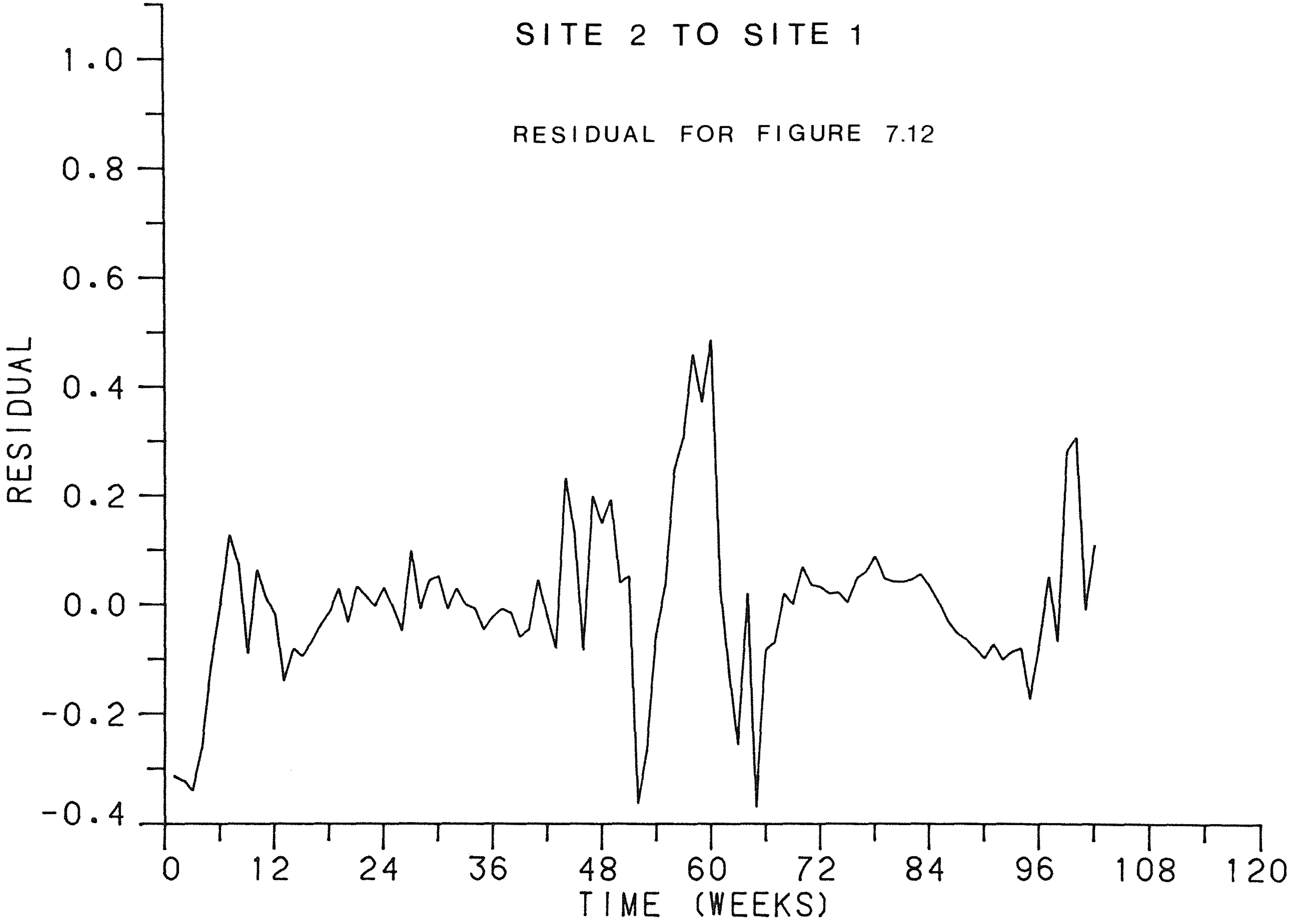


FIGURE 7.13 Residual for Figure 7.12 with Sinusoidal Variation Removed



(sinusoidal) component. This is emphasised in Fig. 7.12, which shows the estimate $\hat{a}(t)$ of a(t) obtained by reference to equation (7.18), i.e.

$$\hat{a}(t) = -\log_e \hat{a}_{1k}$$

Here, a sinusoid $\hat{a}_s(t)$ has been fitted to the estimation results and is shown dotted. This sinusoid has the form

$$\hat{a}_s(t) = 0.80 + 0.22 \sin \{\frac{2\Pi}{52} (t + 9.0)\} \qquad (7.20)$$

The residuals between the sinusoid (7.20) and a(t), i.e. $\tilde{a}_s = \hat{a}(t) - a_s(t)$ are plotted in Fig. 7.13 and it can be seen that $\tilde{a}_s$ has zero mean with large deviations which occur during the Winter period and, as expected, seem to be correlated in some manner with the fluctuations in river flow. By reference to Fig. 7.5, we recall that evaporation is also dominantly sinusoidal in form and that the sinusoidal component in a(t) leads the effective evaporation sinusoidal by several weeks; indeed cross correlation analysis indicates a maximum correlation of 0.71 at a lead of 13 weeks. Since this lead time period is a quarter of the yearly period it is indicative that a(t) is a function of the *rate of change of evaporation* since e(t) is strongly sinusoidal and so there should be a phase lead of one quarter of a cycle between $\frac{de}{dt}$ and e.

The above results are consistent with the hypothesis of equation (7.5) in which dV/dt is given by equation (7.12). Under this hypothesis a(t) is defined as

$$a(t) = \bar{a} + f\,(\frac{dQ}{dt}R\,,\ \frac{de}{dt}\,,\ \delta) \qquad (7.21)$$

where $\bar{a} = \frac{Q}{V}$ can be considered as the constant or slowly variable "long term flushing rate", while f(·) is some function of the rate of change of river discharge Q_R, the rate of change of effective evaporation e = R-E and δ, a term representing all other factors, such as the long term changes in tidal height known to occur in

Western Australia (Provis and Radok, 1979), which may have some importance and should be borne in mind in subsequent analysis. From equation (7.20) we see that $\bar{a}$ is, in this case, 0.8 and the variations around this mean, as shown in Fig. 7.13 are indeed functions of $\frac{dQ_R}{dt}$ and de/dt.

At this point, it would be possible to pursue the nature of the functional relationship f(·) in more detail and, having identified the functional form in (7.21), to then re-process the salinity data using some method of nonlinear estimation[†]. But such extensions, although extremely interesting from a research standpoint, do not seem warranted in the present situation since the estimate $\hat{a}(t)$ in Fig. 7.12 *itself* provides us with an indication of the flushing characteristics of the system which should be adequate for our present purposes.

It will be noted that, because of our stochastic analysis, this estimate $\hat{a}(t)$ is a random variable with specified statistical properties; in particular we are able to estimate the standard error bounds, which indicate the degree of uncertainty associated with the estimate. These standard error bounds are not particularly good estimates of the uncertainty in this case (Young et. al, 1971) but they tend to err on the conservative side; in other words, the estimated standard errors are likely, if anything, to be greater than the actual standard errors.

On this basis, Fig. 7.12 and the associated standard error bounds indicate the changing flushing characteristics between the Peel Inlet and Harvey Estuary over the whole study period. A summary of these characteristics is given in Table 7.2, which shows the range of flushing rates estimated over the annual cycle, together with their estimated upper and lower bounds and associated flushing times. Here, the maximum and minimum flushing rates for "evaporation effects" are evaluated by reference to the sinusoidal variations described by equation (7.20): they can be interpreted as the

---

[†] indeed this will be a subject of future research in CRES.

TABLE 7.2

SITE 2 TO SITE 1

ESTIMATED FLUSHING RATES : PEEL INLET-HARVEY ESTUARY
(Flushing Times Shown in Parentheses)

Description	Estimate (weeks^{-1})		Lower Bound (weeks^{-1})		Upper Bound (weeks^{-1})	
Long Term (Q/V)	0.8	(1.25)	0.6	(1.7)	1.0	(1.0)
Minimum (Summer)	0.6	(1.7)	0.4	(2.4)	0.8	(1.3)
Maximum (River Flushing)	1.4	(0.7)	1.1	(0.9)	2.0	(0.5)
Min. (Evap. Effects)	0.6	(1.7)	0.4	(2.4)	0.8	(1.3)
Max. (Evap. Effects)	1.0	(1.0)	0.8	(1.3)	1.4	(0.7)

contribution to the *apparent* rates arising from the evaporation effects alone. We can interpret the figures in Table 7.2 as suggesting that flushing of the Harvey Estuary into Peel Inlet takes, on the average, between 1.0 and 1.7 weeks (in other words, the flushing rate is between 1.0 and 0.6 per week). The maximum flushing time, in mid-Summer, is between 1.3 and 2.4 weeks (i.e. flushing rate between 0.8 and 0.4 per week). And the minimum, during high river flow periods, is between 0.9 and 0.5 weeks (i.e. flushing rate between 1.1 and 2.0 per week).

Whilst the exchange characteristics between Peel and Harvey are interesting, it is clearly more important for the purposes of the Study to evaluate the exchange between the Peel-Harvey System and the Indian Ocean, since this indicates losses from the system. We can use a similar analytical approach to that discussed above but the input salinity changes (S_i) are not so easy to define. The input salinity can be interpreted as the forcing function to the system. In the case of exchange between the Estuary and the Ocean, this forcing function is not directly measureable: during the Summer period the major input water is from the Indian Ocean with normal ocean levels of salinity ($35^{o}/oo$); while during heavy river flow periods in Winter it is from fluvial sources with much lower salinities. And we can easily see the effects of these changes in the forcing function by examining the resulting fluctuations in salinity levels at the various sites in the Estuary.

With these factors in mind, S_i can be defined as a step-like function, as shown in Fig. 7.14 where, for reference, the variation, in salinity at site 4 (Coodanup) are also plotted for the whole Study period.† Here the upper level of the step is 35^o/oo, indicating ocean forcing; and the lower level is 10^o/oo, indicating a mixture of river and ocean forcing. The switching between the two levels can be determined by carrying out CAPTAIN analysis and choosing switching times so that the model is optimal both in terms of its ability to explain the data (high coefficients of determination, R_T^2); and the definition of its parameter estimation error variance norm (EVN); (see Young et. al, 1980).

This approach was applied to the data from all sampling sites in the system and the results are given in Table 7.3. The maximum (Summer) and minimum (Winter) flushing times at each site obtained from this table are also given adjacent to the location of each sampling site on a map of the Peel-Harvey system in Fig. 7.15. This map also shows by means of arrows the main circulation details in the Peel Inlet. These were obtained both by reference to the intensive dye experiments and using time-series analysis of the salinity data, as discussed below.

Figs. 7.16 to 7.18 are typical of the analyses used to generate Table 7.3: they show the detailed estimation results for site 4 with Fig. 7.16 illustrating the fit between the time variable parameter model and the sampled data, Fig. 7.17 providing the estimate $\hat{a}_{1k}$ in this case, and Fig. 7.18 the estimate $\hat{a}(t)$ and the sinusoidal fit to this estimate (dotted).

The time-series analysis used to infer the circulation patterns in Fig. 7.15 is quite simplistic. It is possible to conceptualise the direction and the approximate magnitude of the circulation in the Peel Inlet and Harvey Estuary through application of the flushing model. The basic idea is to apply equation (7.6) between each pair of sampling sites with the salinity time series from one site representing S and the time series from the other site being S_i. The direction of the mean circulation over the time period

---

† the variations in salinity measured at Mandurah (Part 3 of the Report) support this approach.

TABLE 7.3

FLUSHING RATES AT SAMPLING SITES
(Equivalent Flushing (Residence) Times in Weeks Shown in Parentheses)

SITE 1

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.2 (5.0)	0.12 (8.3)	0.29 (3.4)
Minimum (Summer)	0.08 (12.5)	0.01 (>30)	0.16 (6.3)
Maximum (River Flushing)	0.42 (2.4)	0.31 (3.2)	0.53 (1.9)
Min. (Evap. Effects)	0.13 (7.7)	0.05 (20.0)	0.21 (4.8)
Max. (Evap. Effects)	0.29 (3.4)	0.20 (5.0)	0.38 (2.6)

SITE 2

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.24 (4.2)	0.16 (6.3)	0.31 (3.2)
Minimum (Summer)	0.16 (6.3)	0.1 (10.0)	0.24 (4.2)
Maximum (River Flushing)	0.43 (2.3)	0.34 (3.3)	0.53 (1.9)
Min. (Evap. Effects)	0.19 (5.3)	0.12 (8.3)	0.26 (3.8)
Max. (Evap. Effects)	0.29 (3.4)	0.21 (4.8)	0.37 (2.7)

SITE 5

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.18 (5.6)	0.09 (11.1)	0.29 (3.4)
Minimum (Summer)	0.10 (10.0)	0.02 (>30)	0.19 (5.3)
Maximum (River Flushing)	0.59 (1.7)	0.45 (2.2)	0.77 (1.3)
Min. (Evap. Effects)	0.12 (8.3)	0.04 (25.0)	0.22 (4.5)
Max. (Evap. Effects)	0.24 (4.2)	0.15 (6.7)	0.36 (2.8)

SITE 3

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.26 (3.8)	0.18 (5.6)	0.33 (3.0)
Minimum (Summer)	0.18 (5.6)	0.11 (9.1)	0.25 (4.0)
Maximum (River Flushing)	0.71 (1.4)	0.59 (1.7)	0.83 (1.2)
Min. (Evap. Effects)	0.21 (4.8)	0.14 (7.1)	0.29 (3.4)
Max. (Evap. Effects)	0.30 (3.3)	0.23 (4.3)	0.38 (2.6)

SITE 6

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.21 (4.8)	0.11 (9.1)	0.31 (3.2)
Minimum (Summer)	0.14 (7.1)	0.05 (20.0)	0.24 (4.2)
Maximum (River Flushing)	0.50 (2.0)	0.37 (2.7)	0.63 (1.6)
Min. (Evap. Effects)	0.16 (6.3)	0.07 (14.3)	0.26 (3.8)
Max. (Evap. Effects)	0.26 (3.8)	0.16 (6.3)	0.37 (2.7)

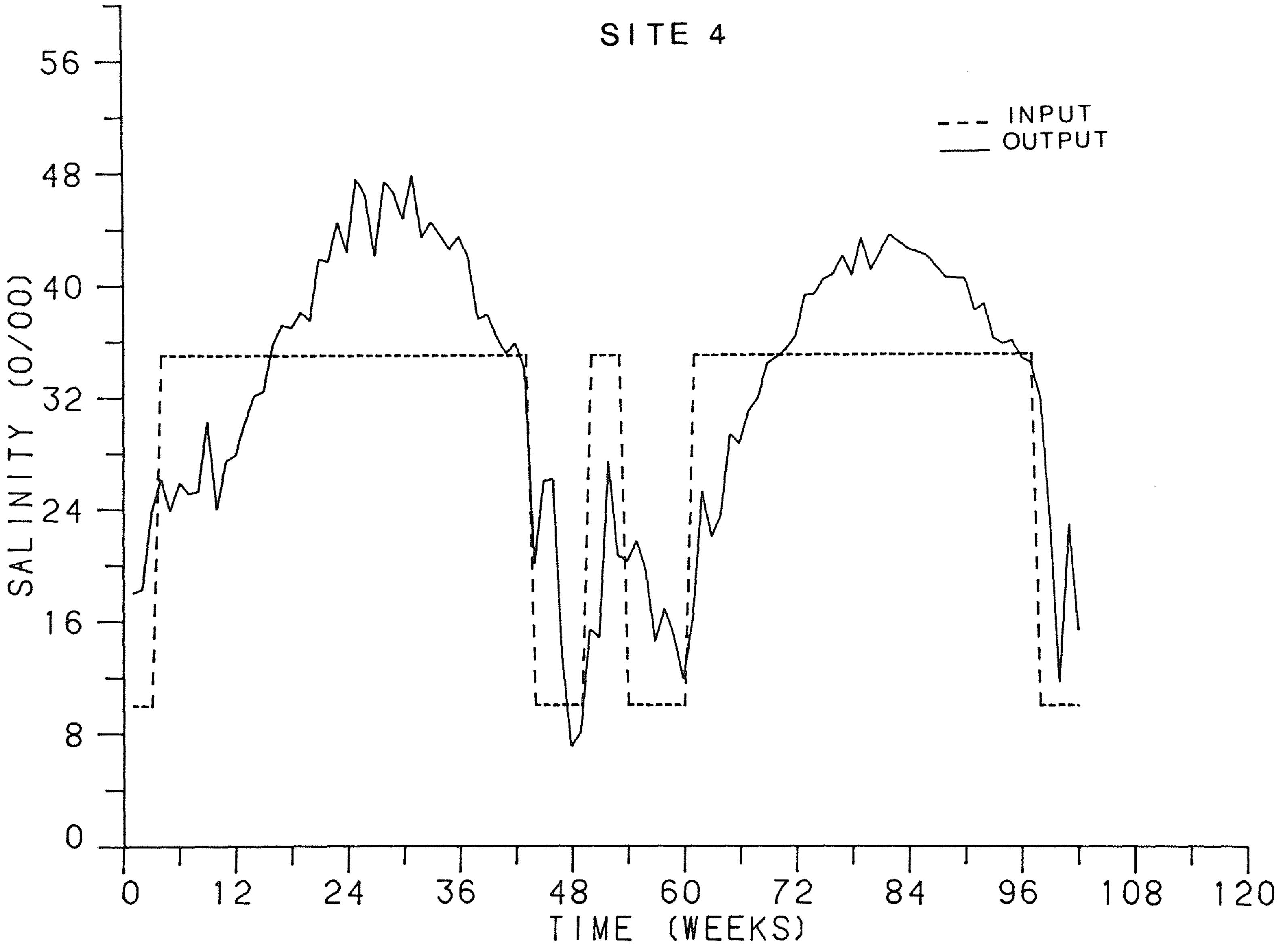
SITE 4

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.25 (4.0)	0.17 (5.9)	0.33 (3.0)
Minimum (Summer)	0.16 (6.3)	0.08 (12.5)	0.24 (4.2)
Maximum (River Flushing)	0.59 (1.7)	0.48 (2.1)	0.71 (1.4)
Min. (Evap. Effects)	0.19 (5.3)	0.11 (9.1)	0.27 (3.7)
Max. (Evap. Effects)	0.30 (3.3)	0.21 (4.8)	0.40 (2.5)

SITE 7

Description	Estimate (weeks^{-1})	Lower Bound	Upper Bound
Long Term	0.24 (4.2)	0.16 (6.3)	0.31 (3.2)
Minimum (Summer)	0.18 (5.6)	0.11 (9.1)	0.25 (4.0)
Maximum (River Flushing)	0.53 (1.9)	0.43 (2.3)	0.63 (1.6)
Min. (Evap. Effects)	0.20 (5.0)	0.13 (7.7)	0.27 (3.7)
Max. (Evap. Effects)	0.28 (3.6)	0.20 (5.0)	0.36 (2.8)

FIGURE 7.14 Salinity Variations for Site 4 - Estimated Input and Observed Output



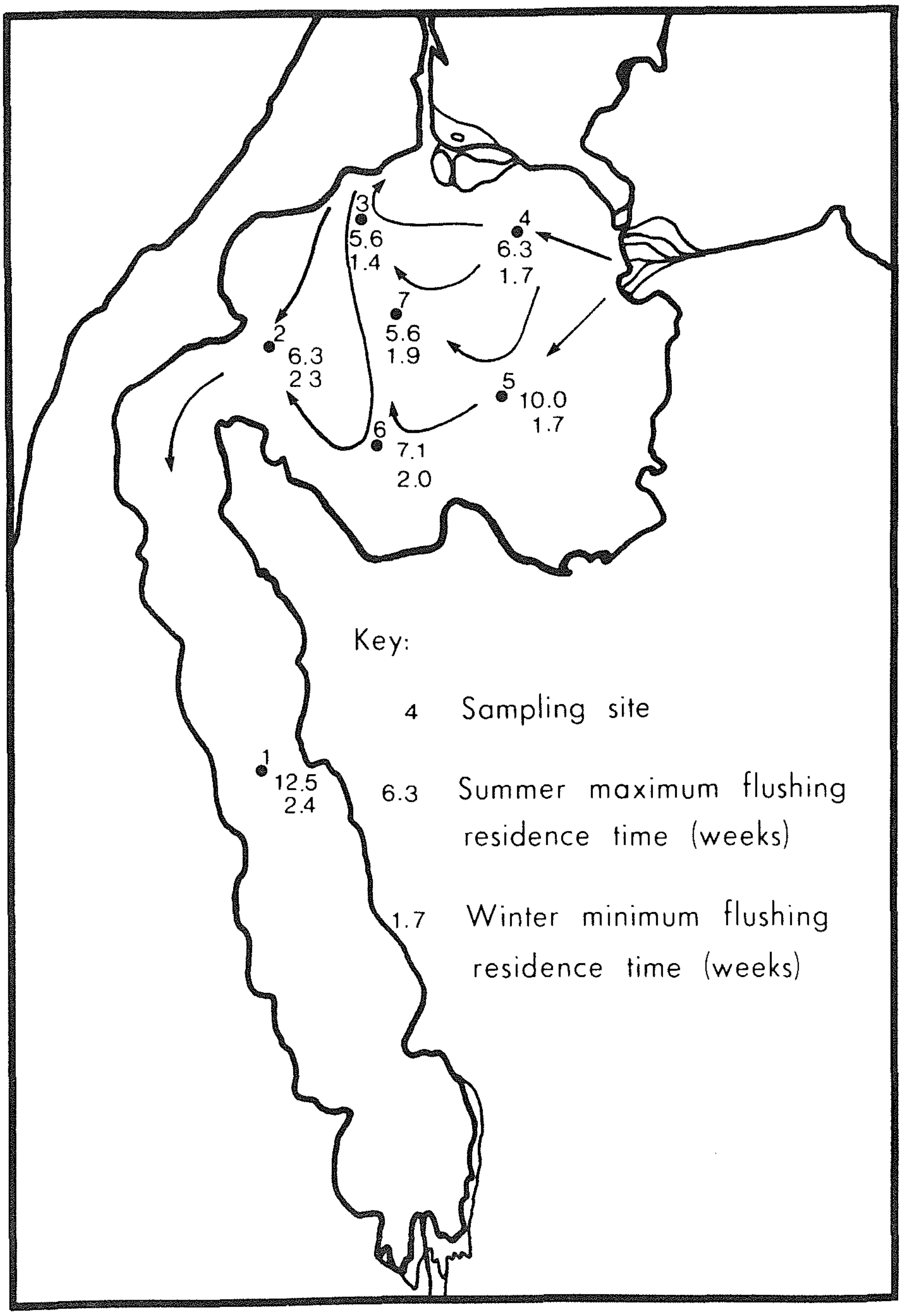


FIGURE 7.15 CIRCULATION DIRECTIONS AND FLUSHING RESIDENCE TIMES IN PEEL INLET AND HARVEY ESTUARY

FIGURE 7.16 Salinity Variations for Site 4 - Time-Variable Parameter Model

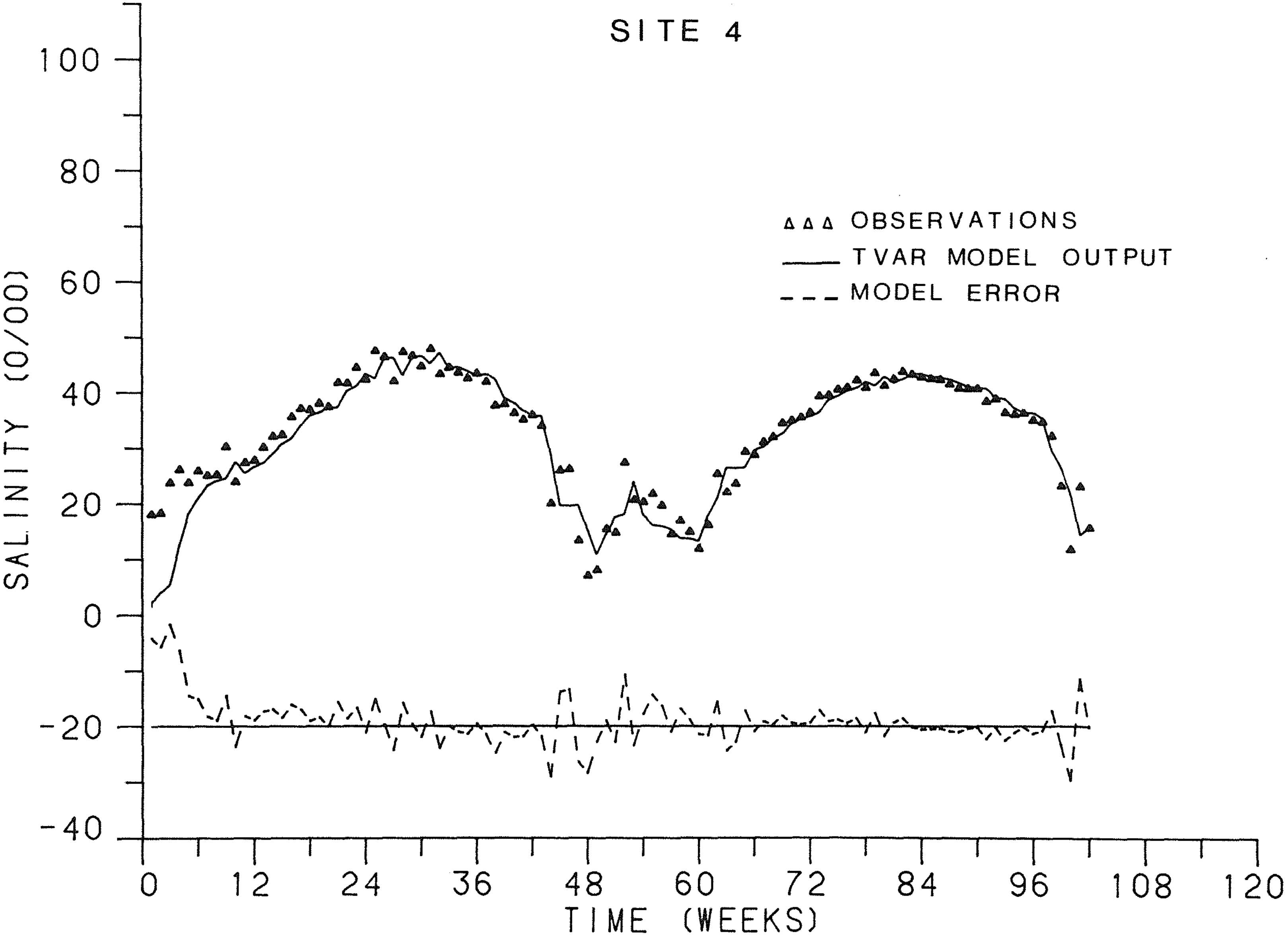


FIGURE 7.17 Salinity Variations for Site 4 - Estimate of Time-Variable Parameter a_k

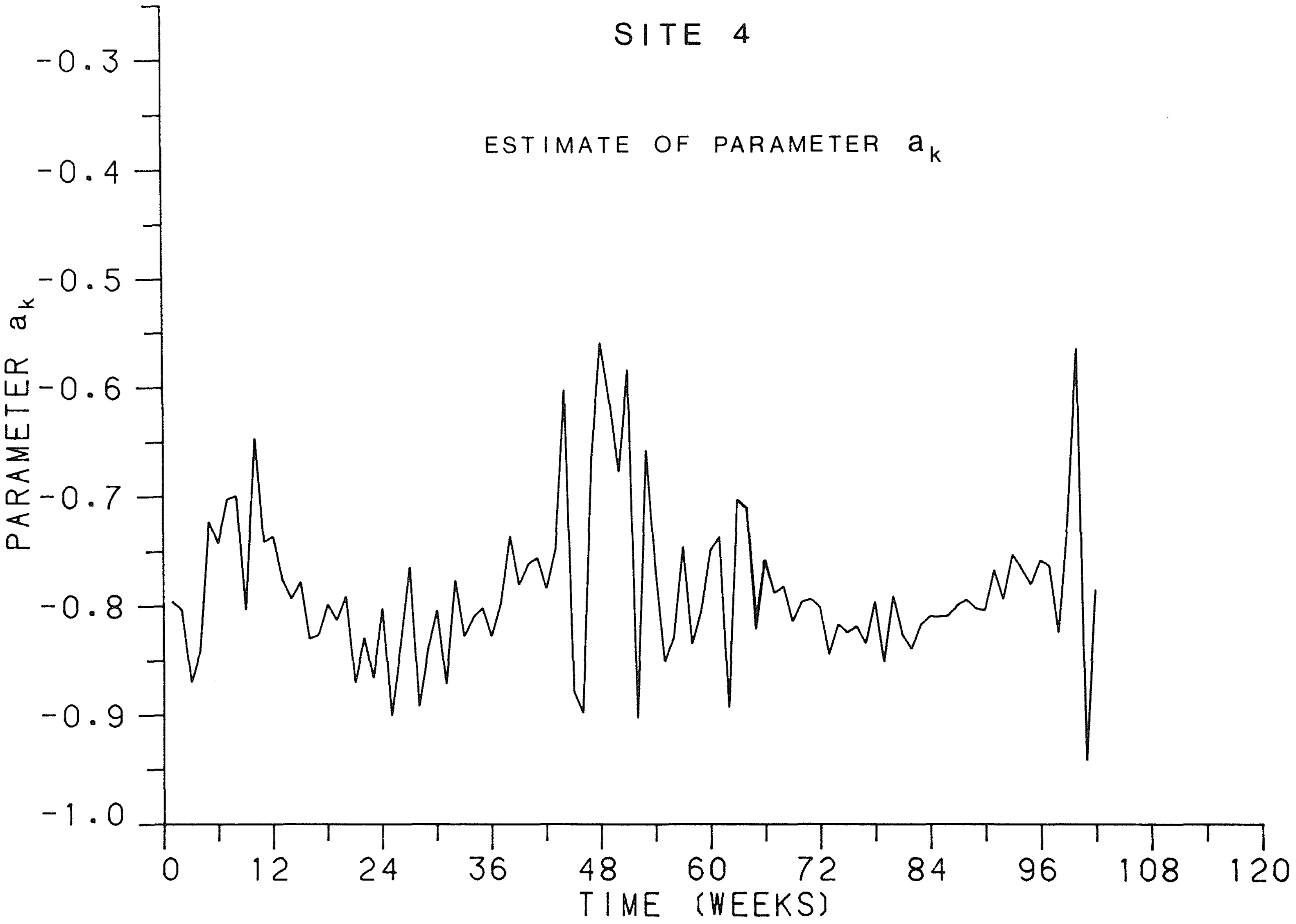
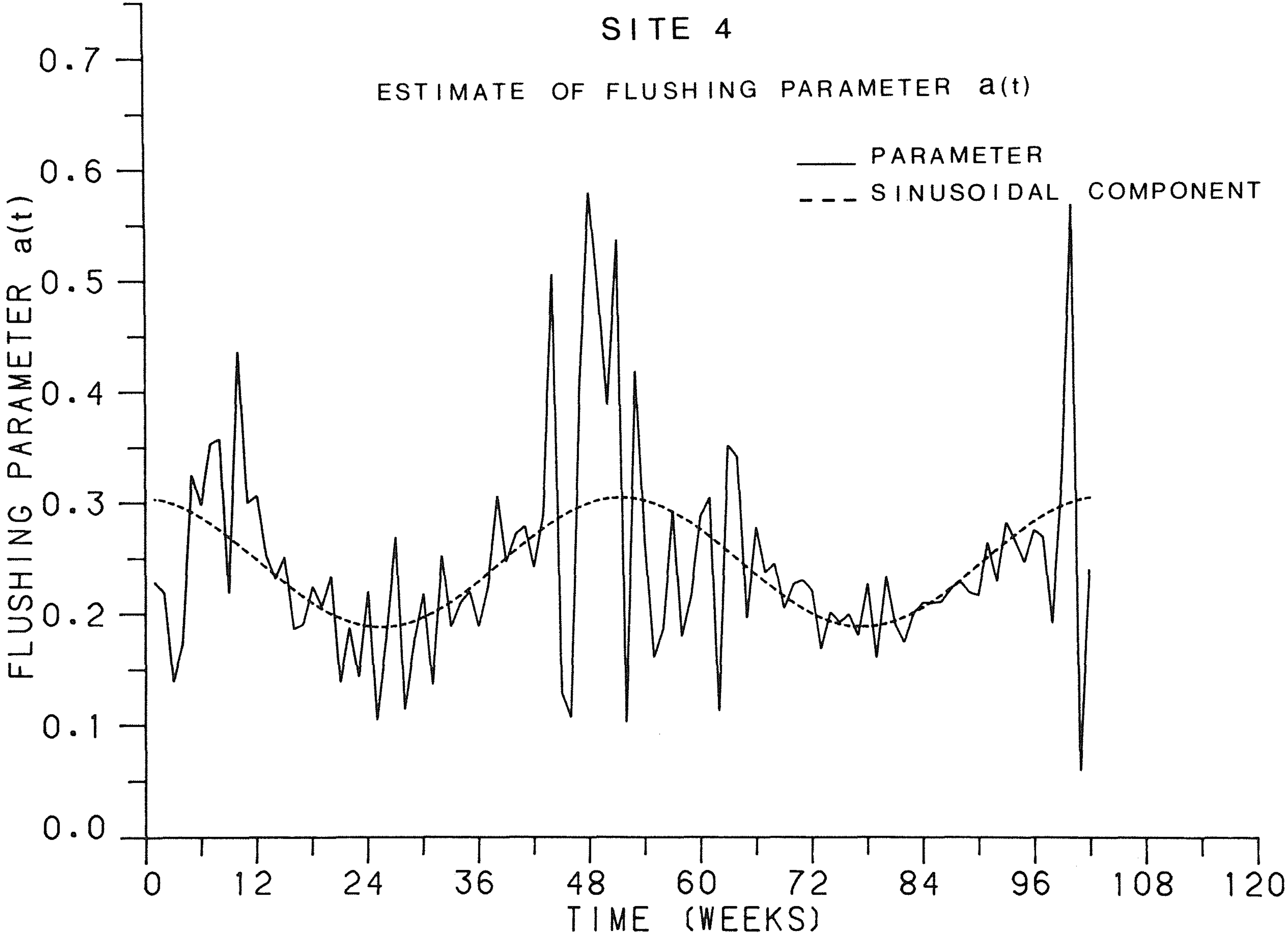


FIGURE 7.18 Salinity Variations for Site 4 - Estimate of Time-Variable Parameter a(t)



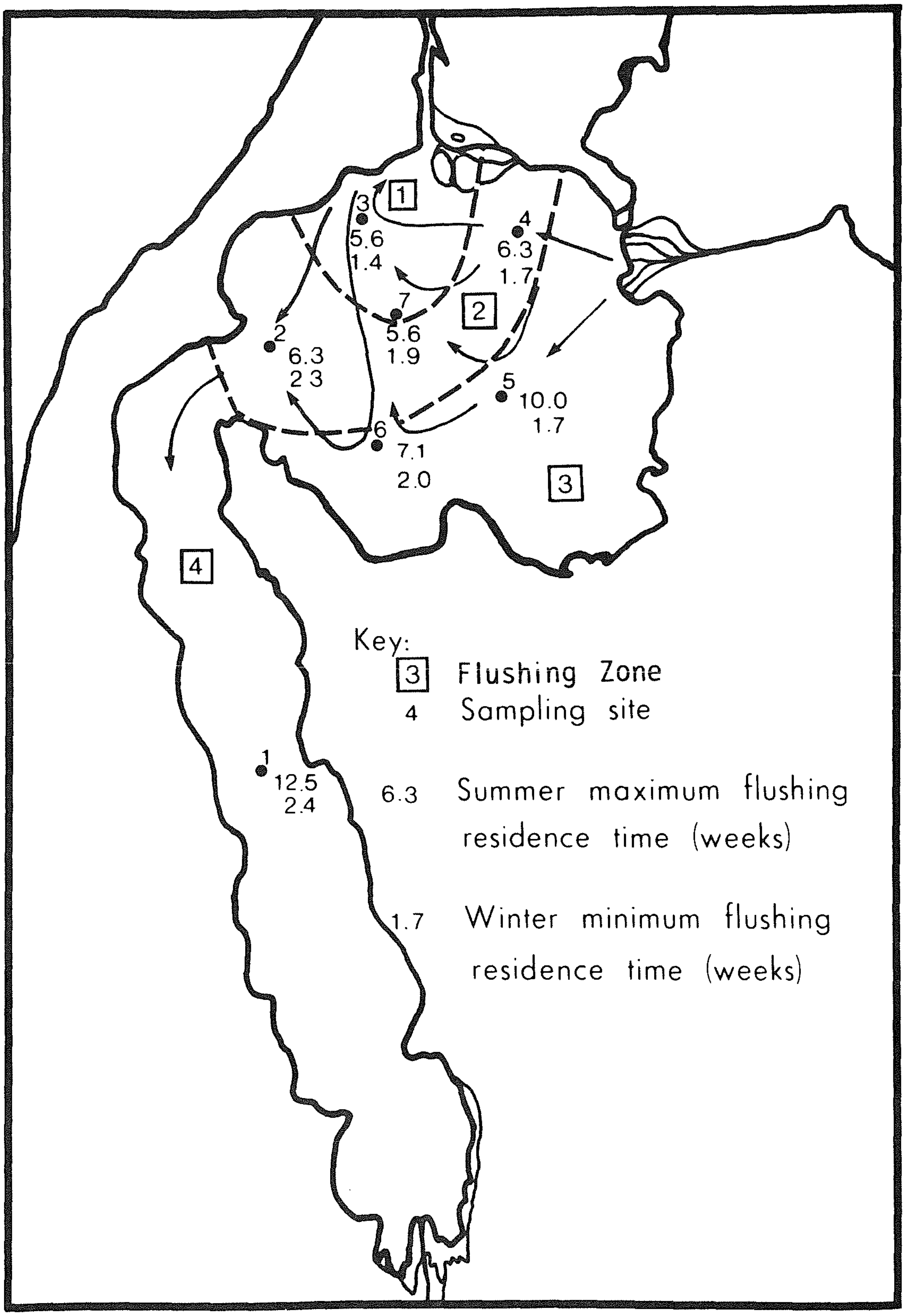


FIGURE 7.19 CIRCULATION DIRECTIONS AND FLUSHING RESIDENCE TIMES IN PEEL INLET AND HARVEY ESTUARY

represented by the data set is determined by examining the R_T^2 and EVN statistics (Young et. al, 1980) of the two models and choosing the one which looks most appropriate according to these criteria and is so assumed to define the *preferential* direction of mean flow. The results of this are given in Table 7.4 and lead to the circulation models of Figs. 7.15 and 7.19.

This method provides a visualisation of the mean flow over the duration of the analysed data set. In practice one would expect the actual flow on any particular day to be a complicated amalgam of tidal effects, wind forcing and river induced circulation that may appear quite different to the long term flow of Figure 7.15. Also we would stress that this statistical analysis did not yield a very clear picture of circulation in the Inlet and we present it here only because it tends to confirm the circulation patterns deduced from the analysis of other data, including those from the intensive dye experiments. More thorough multivariable time-series analysis might give a clearer indication of flow patterns, however, and we may be looking into this possibility in future research.

TABLE 7.4

The log EVN for site to site salinity modelling. The chosen models (high R_T^2; lowest log EVN) are boxed.

		OUTPUT FROM					
		2	3	4	5	6	7
OUTPUT TO	2	-	$\boxed{-4.99}$	-	-	$\boxed{-5.06}$	-5.29
	3	-4.69	-	$\boxed{-5.48}$	-	-	$\boxed{-5.81}$
	4	-	-4.03	-	-4.34	-	-4.53
	5	-	-	$\boxed{-4.63}$	-	-4.34	-3.7
	6	-3.92	-	-	$\boxed{-5.4}$	-	$\boxed{-4.65}$
	7	-4.57	$\boxed{-5.43}$	$\boxed{-5.59}$	$\boxed{-5.06}$	$\boxed{-4.68}$	-

7.4 Discussion

The results obtained from the special intensive experiments and salinity data analysis provide a quite clear picture of the circulation and flushing characteristics of the Peel-Harvey system in relation to the various sampling sites, as summarised in Fig. 7.15. If we consider the Peel Inlet as a whole, as we may need to in relation to *Cladophora* problem, then the average flushing characteristics can be computed, as shown in Table 7.5.

TABLE 7.5

AVERAGE FLUSHING RATES FOR PEEL INLET BASED ON THE SIX SAMPLING SITES (Equivalent Flushing Times Shown in Parentheses)

Description	Estimate (weeks^{-1})	Lower Bound (weeks^{-1})	Upper Bound (weeks^{-1})
Long Term (Q/V)	0.23 (4.3)	0.14 (7.1)	0.32 (3.1)
Minimum (Summer)	0.15 (6.7)	0.05 (20.0)	0.23 (4.3)
Maximum (River Flushing)	0.53 (1.9)	0.43 (2.3)	0.67 (1.5)
Min. (Evap. Effects)	0.17 (5.9)	0.08 (12.5)	0.26 (3.8)
Max. (Evap. Effects)	0.28 (3.6)	0.19 (5.3)	0.37 (2.7)

When considering the results in Tables 7.4, 7.5 and Fig. 7.15, a number of points should be taken into account:-

(i) First, as the estimated flushing rate becomes smaller so the estimates of the flushing times (shown in parentheses) become sensitive to even small standard errors and, in certain cases, the lower bound on the flushing rate indicates very low levels of tidal exchange with flushing times greater than 20 weeks. Clearly some care must be taken with the interpretation of such high values which are, we would stress, only indicators of *transient* behaviour. In this sense we might conclude, on the basis of Table 7.5, that the average tidal exchange period for Peel Inlet during Summer is some 7 weeks with a lower bound of 4 weeks and upper bound of 10 weeks.

(ii) A second point concerns the estimates of the maximum flushing rates and their associated minimum flushing (residence) times. Because of the difficult nature of the estimation problem in the time variable parameter situation considered here[†], there will usually be some attenuation of the estimated parameter values, particularly during periods of rapid variation, such as we encounter here with the onset of high river flow conditions. As a result, there is a tendency in the present situation to *under* estimate the peak parameter value (rate) and so *over* estimate the flushing times. Thus, in relation to Table 7.5, we might expect the maximum flushing rate F to be greater than the estimated 0.53 week^{-1} (T_F = 1.9 weeks) and probably, given the very rapid parameter changes occurring at the time, greater even than the upper bound of 0.67 (T_F = 1.5 weeks). This is consistent with the results obtained in the August 1978 dye tracer experiment which was, by coincidence, carried out during the week of the estimated maximum river flow induced flushing (week 50). Here we see from Fig. 7.3 and equation (7.3) that a $T_F = 0.57$ of a week is indicated (flushing rate, F = 1.75). We can conclude fairly confidently, therefore, that maximum flushing of the Inlet occurs at the time of maximum rate of change of river flow and that normally, the flushing time under these conditions is less than one week.

(iii) Given that the evaporation and river effects appear to be incorporated into the a(t) parameter in equation (7.6), our analysis would seem to indicate that $\bar{a}$, the constant mean value of the parameter a(t), in equation (7.20), should be approximately equal to the parameter "b" in (7.6)

[†] solutions to this problem have only emerged in the past decade

and that they should provide a measure of Q/V ($= Q_i/V$), the long term flushing rate. The estimation results confirm that $\bar{a}$ and b are indeed insignificantly different when considered in relation to their standard errors and, from Table 7.5, we see that $\bar{a} = 0.23 \pm 0.09$; in other words, the average long term flushing time lies between 3.1 and 4.3 weeks. Further, if we do assume that $\bar{a} = Q/V$,[†] then these results suggest that between 0.14 (14%) and 0.32 (32%) of the Inlet is exchanged during each weekly period. This is in general agreement with Beer and Black's (1979) theoretical calculation of 17% exchange on each tidal cycle, although the mean value (23%) is a little higher.

(iv) It is evident from Fig. 7.15 that the two dominant factors controlling the mean circulation patterns are the marine tides and the discharge of water from the Murray-Serpentine River system. The discharge from these rivers seem strong enough to restrict tidal exchange during high flow periods to the centre-west of the Inlet (sites 2, 3, and 7). The Harvey River appears to have a somewhat smaller flushing effect with the minimum residence times at sites 1 and 2 larger than those at sites 4 and 5.

(v) If we consider the relationship between the flushing times at different sites than, as might be expected, site 3 (Sticks Channel) has the shortest minimum residence time of 1.4 weeks while sites 4, 5 and 7 all have similar values of between 1.7 - 1.9 weeks. Sites 2 and 6 at the South-west of the Inlet have the longest residence times with 2.3 and 2.0 weeks, respectively. These results imply that, during the first flush of the Murray and Serpentine Rivers, water is driven down past site 5 before it moves

---

[†] Note our previous caveats on this assumption.

upwards towards the Sticks Channel. This effect is not so marked, however, to the southwest of the Inlet (although residence times are still only about 2 to 2.4 weeks), probably because of the lesser but still appreciable Harvey River flushing effect through the Harvey Estuary (note that minimum residence times at sites 1 and 2 are virtually identical, although the maximum Summer values are quite different at 11.8 and 6.1 weeks, respectively).

During the Summer period the Estuarine system can be decomposed approximately into the 4 major areas numbered 1 to 4 on Fig. 7.19: first, sites 3 and 7 at the mouth of the Sticks-Mandurah Channel with residence times of 5.6 and 5.7 weeks, respectively; second, sites 2 and 4 across the middle of Peel Inlet with residence times 6.1 and 6.3 weeks, respectively; third, sites 5 and 6 to the south-east of Peel Inlet with residence times of 10 and 7 weeks, respectively; and finally, site 1 in the Harvey Estuary with the longest residence time of 11.8 weeks. Note, however, that site 5 (Austin Bay) is quite poorly flushed in Summer with a residence time comparable to that of the Harvey Estuary, and that although Falcon Bay (site 0) data have not been analysed (since data are only available after week 50), it appears to behave in a quite similar manner to site 2. In summary, the Peel Inlet is relatively stagnant during Summer, particularly towards the south-east corner, but there is quite strong river flushing even in this south-east corner during the five Winter months, June to October.

(vi) Finally, it is instructive to consider the implications of the flushing models on a situation when rainfall and river flow inputs are negligible since this exposes a weakness of the presently estimated model. If we consider the main *Cladophora* growth at site 4, for example, then equation (7.6) has the form[†]

$$\frac{dS}{dt} = - [0.25 - 0.06\{\sin \frac{2\Pi}{52} (t - 12.4)\} S + 0.25S_i \quad (7.22)$$

since a(t) is dominated by $a_s(t)$ if $Q_R = 0$. If we now let $S_i = 35^0/oo$, the marine salinity, then the maximum and minimum value of S over the year can be estimated by setting dS/dt = 0. This shows that

$$\frac{0.25 \times 35}{0.25 + 0.06} < S < \frac{0.25 \times 35}{0.25 - 0.06}$$

i.e.

$$28.0 < S < 46.0$$

where it will be noticed that, surprisingly at first, the upper bound of $46^0/oo$ agrees with the *observed* maximum salinity at site 4 (which, of course, *includes* the effects of river flow and rainfall); and that the lower bound of $28^0/oo$ is *less than* the marine value of $35^0/oo$. Of course, in the absence of fresh water inputs, there is no mechanism for depressing the estuarine salinity below $35^0/oo$ in this manner.

This somewhat paradoxical result indicates one limitation of the flushing model (7.6) with the presently estimated parameter values. The estimates of $\hat{a}(t)$ and $\hat{b}$ are obtained using *constraint-free* estimation procedures; in other words, we are not able to impose any practically meaningful constraints on the estimated model - such as the conditions that $S_{min} \geq 35^0/oo$ in the absence of fresh water inputs. This difficulty

---

[†] it is interesting to note that the maximum value of $\frac{1}{e}\frac{de}{dt}$ obtained by reference to the evaporation data is 0.07 which compares well with the sinusoidal amplitude of 0.06 in (7.22), as we might hope from the theoretical analysis

could be overcome, as we have mentioned previously, by extending the present analysis using nonlinear optimisation procedures to re-estimate the parameters within the presently identified model structure, but with physically meaningful constraints introduced. There is, however, an alternative and simpler approach which, while approximate, will serve the purposes of the present Study.

Since, in this case, $\hat{b} = .25$ with a standard error range between 0.33 and 0.17 we can, given the physical interpretation above, justifiably, set $\hat{b}$ to 0.31 (i.e. 0.25 + 0.06) so that then

$$\frac{0.31 \times 35}{0.25 + 0.06} < S < \frac{0.31 \times 35}{0.25 - 0.06}$$

$$\text{i.e.} \qquad 35 < S < 57 \qquad (7.23)$$

In this manner we have constrained $S_{min} = 35^o/oo$ and corrected, albeit approximately, the bias introduced into the estimation by the inability to introduce constraints. As a result, we now have a result which makes reasonable physical sense in the zero rainfall-flow condition. This approximate result must be checked later by constrained estimation, but it gives us a better provisional idea of the system flushing characteristics and can, as we shall see in Chapter 10, be used to assess the possible behaviour of the estuarine system under alternative management strategies.

7.5 Conclusions

In this Chapter, we have assessed the hydrodynamic characteristics of the Peel-Harvey Estuarine System on the basis of time-series data obtained from both the intensive dye-tracer experiments and the weekly monitoring exercises. The analysis reported here attempts to provide a description of the system at the aggregate (macro) level appropriate both to the choice of sampling site locations (six in Peel Inlet, one in the Harvey Estuary) and an adequate explanation of variations in salinity *on a weekly time-scale*. In this sense, it can be considered as more detailed and complete than conventional salinity based flushing analysis (e.g. Ellis et. al, 1977) and considerably less complex than classical hydrodynamic modeling using partial differential equation representations (e.g. Steedman and Craig, 1979).

Our choice of model has been guided totally by the objectives of the Study and has been aimed at producing a description which provides a good explanation of the available (salinity) data and is in a suitable form for reaching *initial* conclusions in relation to the management of the *Cladophora* problem. In particular, these results provide an appropriate level of information on flushing dynamics for studies of *Cladophora* behaviour (Chapters 5 and 9) and evaluation of a nutrient budget for the system (Chapter 8). The analysis could be extended somewhat to obtain more statistically efficient estimation of the model parameters and, in such a form, it could provide a natural prelude to subsequent modeling exercises aimed at further and more detailed evaluation of those management strategies which involve the modification of hydro-dynamic characteristics. The possibility of such strategies is discussed later in Chapter 10.

8. NUTRIENTS AND PHYTOPLANKTON

8.1 Introduction

The purpose of this chapter is to provide an integrated assessment of the nutrient status of the estuarine system. This entails estimates of nutrient loading rates, both internal and external, nutrient loss processes and rates, and the responses of the phytoplankton to differing levels of nutrient availability. The questions of nutrient supply for benthic algal growth are addressed in detail in Chapter 9, and will only be treated briefly here.

The Peel-Harvey system is experiencing excessive, and probably increasing rates of external nutrient loading with time (Humphries 1980, Humphries and Henderson 1980). There are two different, but complementary approaches to the problem of estimating nutrient loading. The first approach entails the collection of both flow and nutrient concentration data from inflowing and outflowing streams and channels, leading to the computation of a simple nutrient budget, as discussed in Section 8.4.

The second approach attempts to evaluate nutrient cycling processes within the system, and the importance of this cycling to nutrient availability for plant growth. Such studies are extremely difficult, and are currently being carried out for this system, and others elsewhere. However, the large size and low sampling intensity of the estuarine system precludes a detailed appreciation of these processes, which are discussed further in Section 8.3.

The Peel-Harvey estuarine system has characteristics not found in many eutrophicated estuaries so far studied. In particular,

(a) both Peel and Harvey are very shallow, with mean depths of about 1 m, and a very high surface:volume ratio.

The rates of sediment nutrient release or uptake depend substantially on this ratio (Welch, 1980);

(b) both water bodies are relatively well-mixed, at least vertically. Pronounced vertical stratification exists for only short periods of time, and its absence reflects the high level of wind mixing of the water column. Superficial sediment is frequently advected into the water column. Whether this enhances or impedes sediment nutrient release is the subject of ongoing research by J.O. Gabrielson, Department of Soil Science, University of Western Australia;

(c) there are banks of macroalgae accumulate over sediment resulting in reducing conditions at the sediment surface.

The ultimate aim of nutrient cycling and budget studies is to predict the concentration and mass of nutrients contained within various parts of the system. More importantly, the prediction of the magnitude and direction of changes due to altered rates of external nutrient loading is necessary in order to assess the effectiveness of proposed management options. Such detailed prediction is not possible at present, but enough data exist to assess the consequences of various degrees of alteration to the rates of external nutrient loading.

We feel that the methods outlined in this chapter provide a certain methodological advance on the computation of long term estuarine nutrient fluxes for systems like the Peel-Harvey estuary. Previous methods have relied either on exhaustive and intensive sampling (Stevenson *et al.*, 1980) or on the use of diffusive fluxes to estimate nutrient fluxes (Imberger *et al.*, m.s.). However, Beer and Young (1980) have shown that in riverine situations the major dispersion process is non-Fickian and so a diffusion coefficient is inapplicable. A physically meaningful parameter that describes dispersion in rivers is the residence time of water particles.

If these observations are also true in estuaries - and the flushing and circulation analysis of Chapter 7 implies that they are true at least for Peel Inlet - then the use of flushing times for nutrient flux evaluation should produce more accurate estimates than the use of diffusive fluxes. But more research will be required, particularly in relation to different spatial and temporal scales than those used in the present study (medium sized, narrow inlet estuary, long term sampling) before any firm conclusions can be reached in this respect.

With the above observations in mind, it is clear that the estimation of nutrient fluxes is difficult but it is essential, in this study, to be able to develop a methodologically sound estimate of these fluxes. We feel that the approach described in this chapter, while not perfect, does provide the most reasonable, cost effective method available at this time.

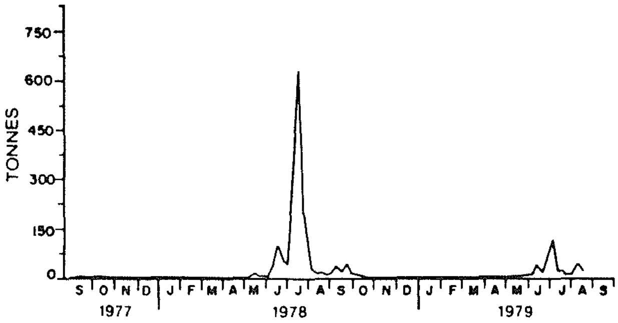
8.2 External Nutrient Inputs

Most attention was given to the estimation of external nutrient loadings into the estuarine system because studies of historical changes in nutrient load-flow relationships (Humphries 1980, Humphries and Henderson 1980) suggested that the *Cladophora* problem was due to import of nutrients from the agricultural catchments (Chapter 1).

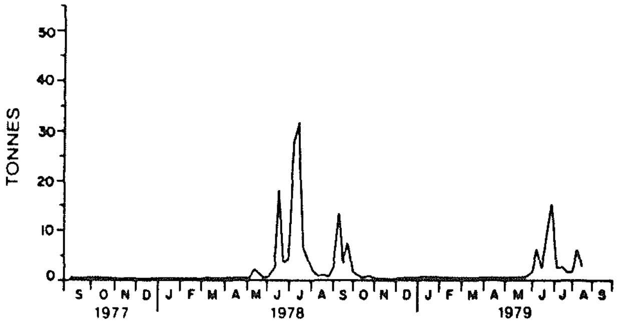
8.2.1 Rivers and Drains

Weekly sampling of the Murray, Serpentine and Harvey Rivers and, to a more limited degree, associated agricultural drains was carried out for 110 weeks, from September 1977 until September 1979. Figure 1.1 shows sampling locations. Flow data were collected for the Harvey River by this study (Black and Rosher, 1980), and by the Public Works Department for the Murray and Serpentine Rivers. Routing of river flows to the estuary are discussed in Chapter 6 and by Black and Rosher (1980). The details of weekly nutrient loading estimates, and of the estimation of drain loads when sampling was not carried out are given in Black and Rosher (1980).

Total annual nitrogen and phosphorus loadings are given in Table 8.1. Most nutrient input to the estuarine system occurred in winter, during periods of high river flow, as shown in Figure 8.1.



Total nitrogen input into the estuary.



Total phosphorus input into the estuary.

Figure 8.1

TABLE 8.1

Peel Inlet and Harvey Estuary - Relative Contribution of Input Waterways 1977/78; 1978/79.

Year	Data		River Systems - % of Total Input			
			Murray	Serpentine	Harvey	Total
1977/78	Discharge	m^3 x 10^6	289	65	206	560
		% total	51	12	37	100%
	Total Nitrogen	tonnes	1153	116	317	1586
		% total	73	7	20	100%
	Total Phosphorus	tonnes	25	23	73	121
		% total	21	19	60	100%
1978/79	Discharge	m^3 x 10^6	86	55	150	291
		% total	29	19	52	100%
	Total Nitrogen	tonnes	110	108	292	510
		% total	22	21	57	100%
	Total Phosphorus	tonnes	4	12	51	67
		% total	6	18	76	100%

The relative contributions of the rivers to estuarine nitrogen and phosphorus loading from year to year are shown in Figure 8.2. It should be noted that nutrient input was much less in the very dry year 1979 than in 1978, when rainfall and river flow, although low, approached the long-term mean. Harvey Estuary and Peel Inlet respond quite differently to periods of high external nutrient loading. The Harvey River is now an agricultural drain, receiving nutrient-enriched water from irrigated agriculture. Consequently, Harvey Estuary receives a more consistent nutrient load than does Peel Inlet. The phosphorus is mostly in available form, as PO_4-P, and high levels of phytoplankton growth occur when compared with Peel Inlet. The Serpentine River also drains the agricultural coastal plain catchment, but usually delivers lower loads of nutrients into Peel Inlet, which are flushed more quickly than those in Harvey Estuary. Mean total-P and PO_4-P concentrations are much higher in the Harvey River, and vary less than in the Murray River. Both estuaries receive a high loading of phosphorus during the period of river flow (Figure 8.3). The elevated phosphorus concentrations fall more rapidly in Peel Inlet than in Harvey Estuary, which is more poorly flushed (Chapter 7).

In wet years, the Murray dominates the winter nitrogen budget of the system (Figures 8.2, 8.3d), and consequently in Peel Inlet there are greatly elevated inorganic nitrogen concentrations during this time (Figure 8.3d), which fall relatively rapidly to background levels. Harvey Estuary is frequently N-deficient, due to lower catchment N-yields, particularly in summer. Also, the favourable phosphorus status of Harvey Estuary led to the formation of a large N-fixing *Nodularia spumigena* bloom in 1978 and 1980, discussed in more detail later.

8.2.2 Rainfall and Groundwater

In 1977-78 mean concentrations of total N and total P in rainfall were 41 $\mu g\ l^{-1}$ and 8 $\mu g\ l^{-1}$ respectively. The estimated volume of rainfall falling directly onto the estuarine system was 99×10^6 m^3 in that water year, which results in total loads of 4 tonnes of N and 0.8 tonnes of P from this source. These loads comprise 0.25% and 0.67% of estimated riverine N and P inputs during the 1977/78 water year.

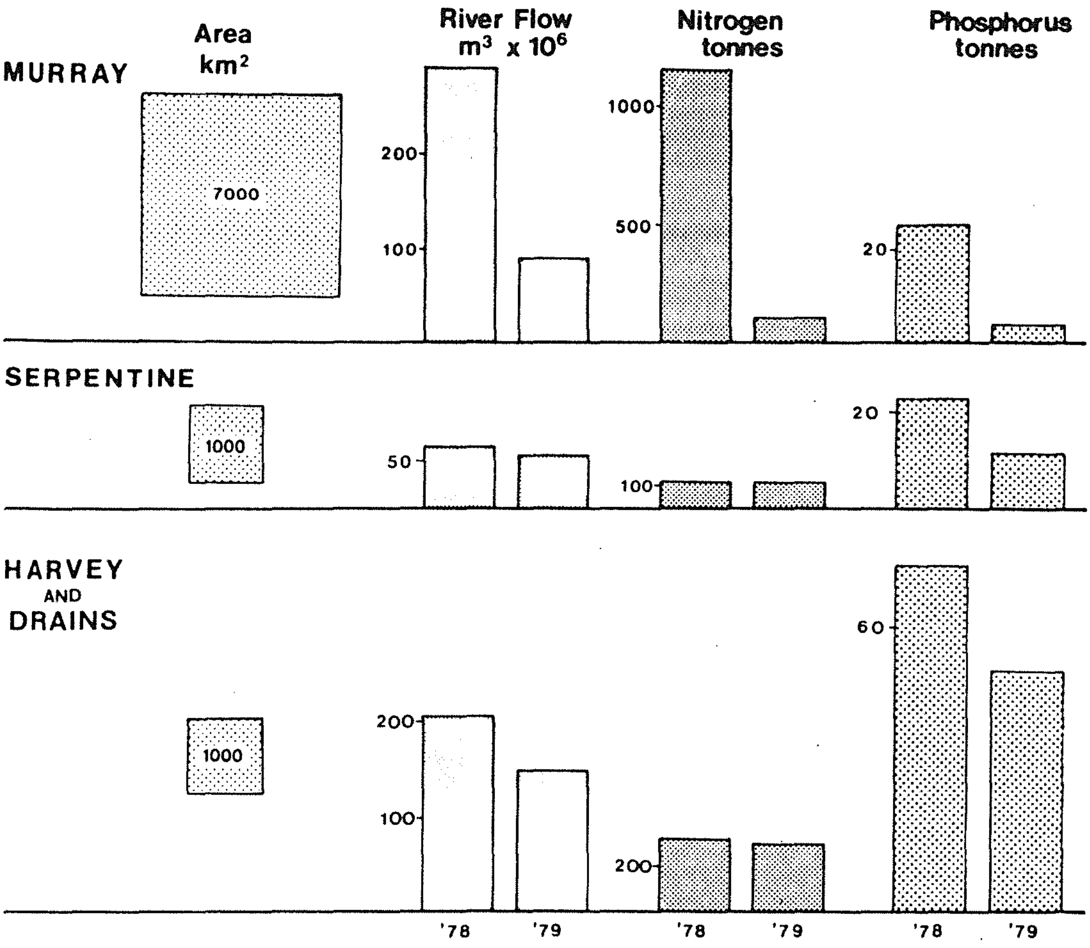


Figure 8.2 Relative nutrient contribution of the three rivers.

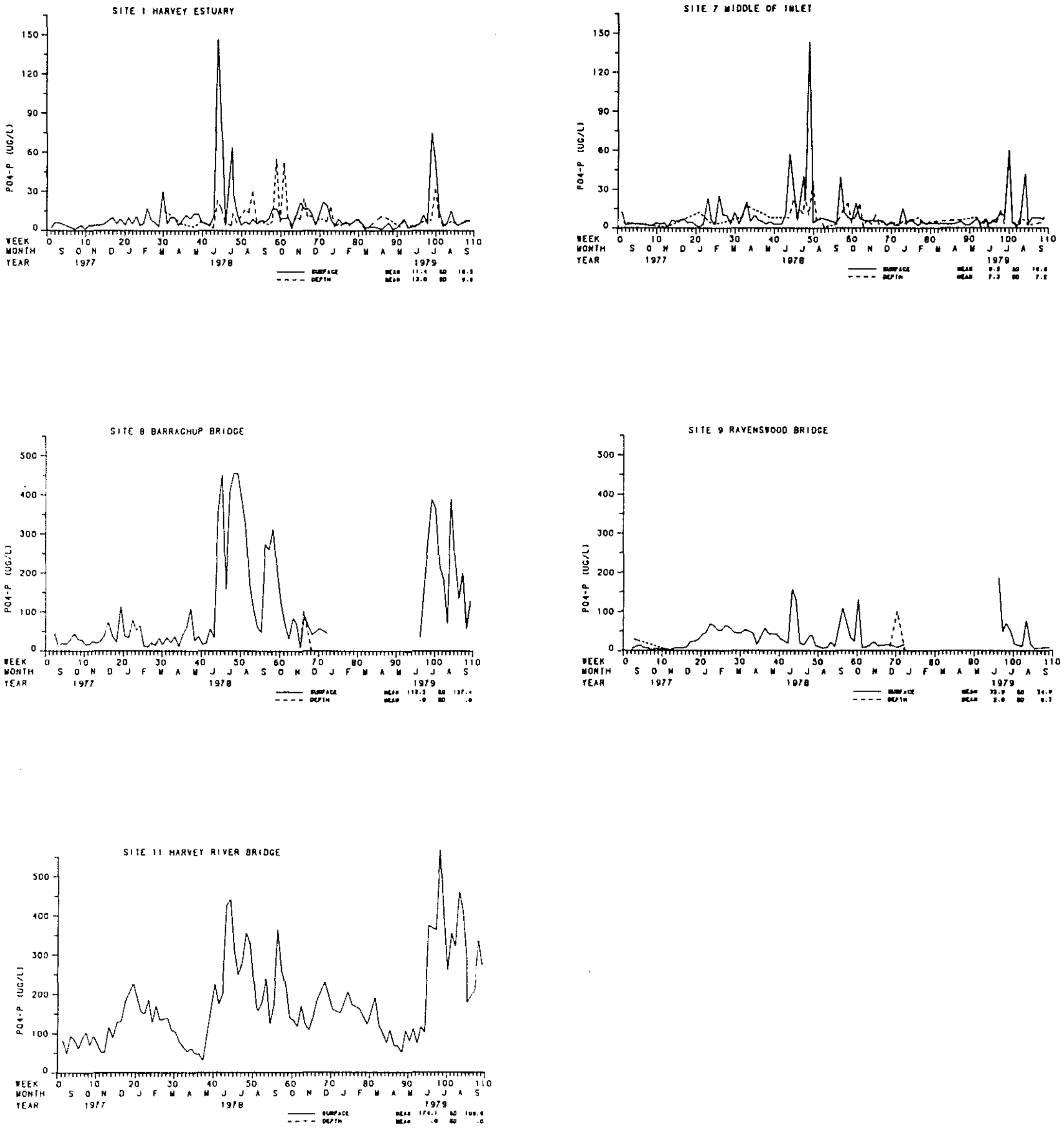


FIGURE 6.3(a) Concentration-time Curves of PO_4-P for Sites 1,7,8,9 and 11

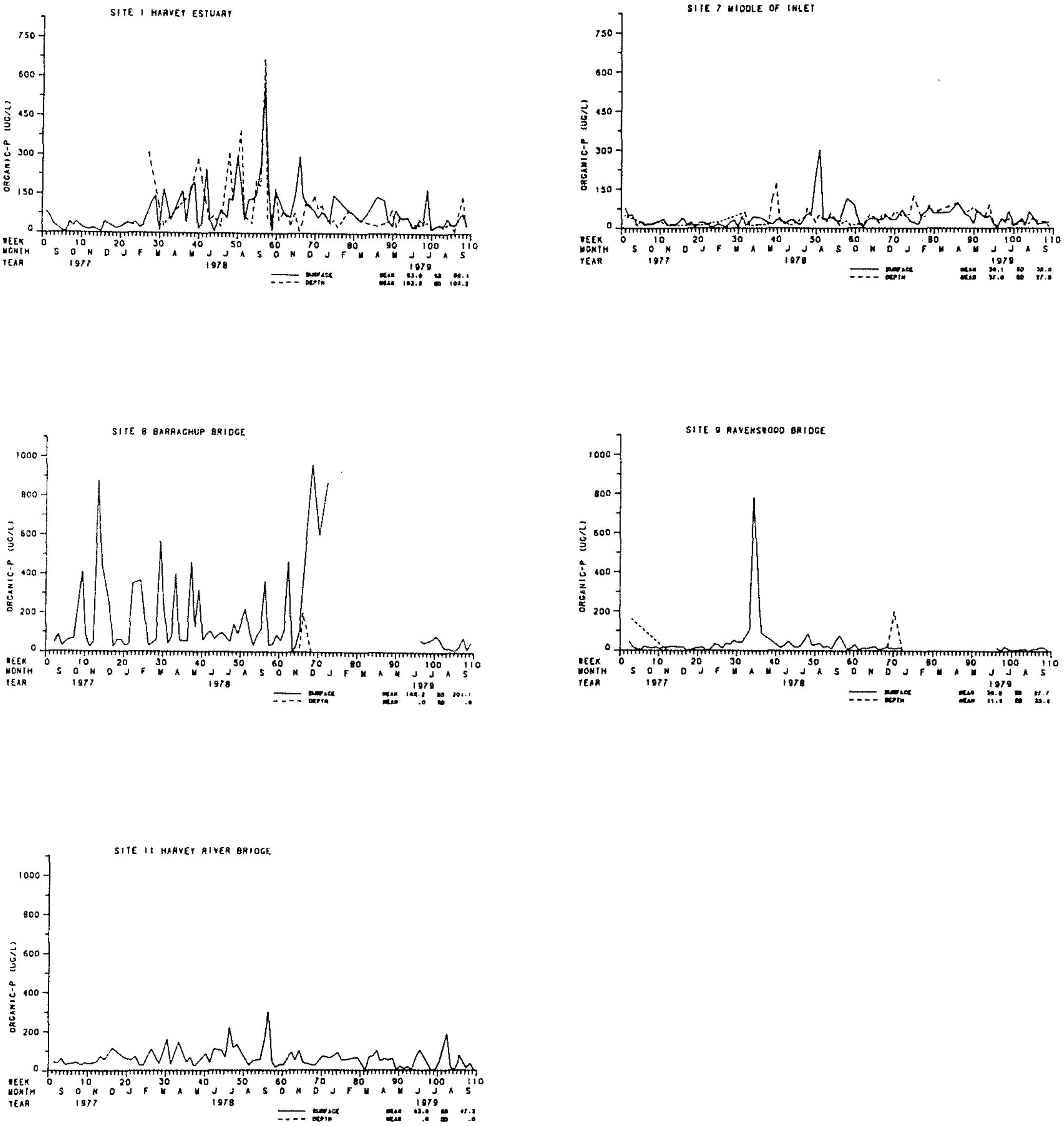


FIGURE 8.3(b) Concentration-time Curves of Organic-P for Sites 1,7,8, 9 and 11

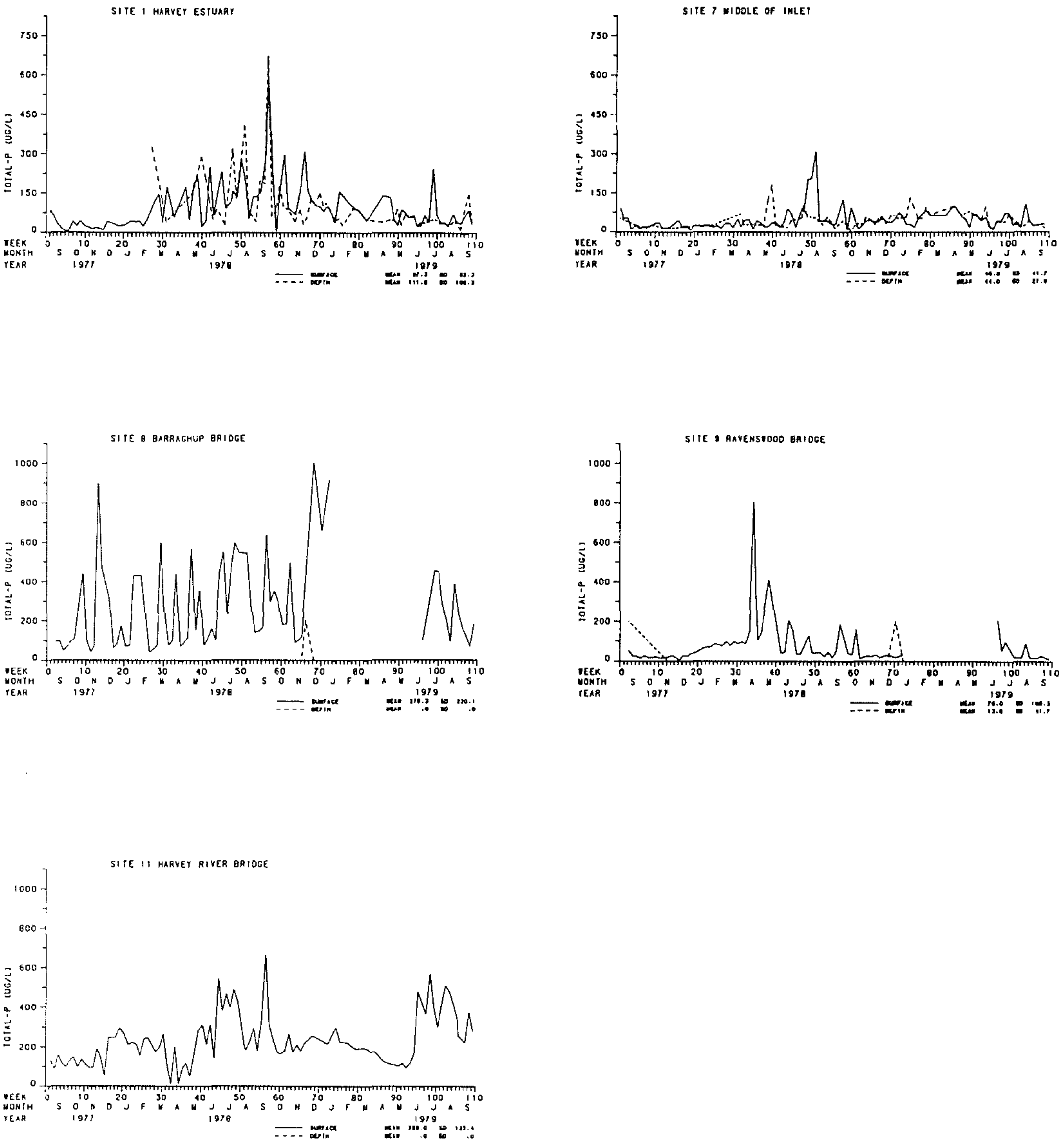


FIGURE 8.3(c) Concentration-time Curves of Total-P for Sites 1,7,8, 9 and 11

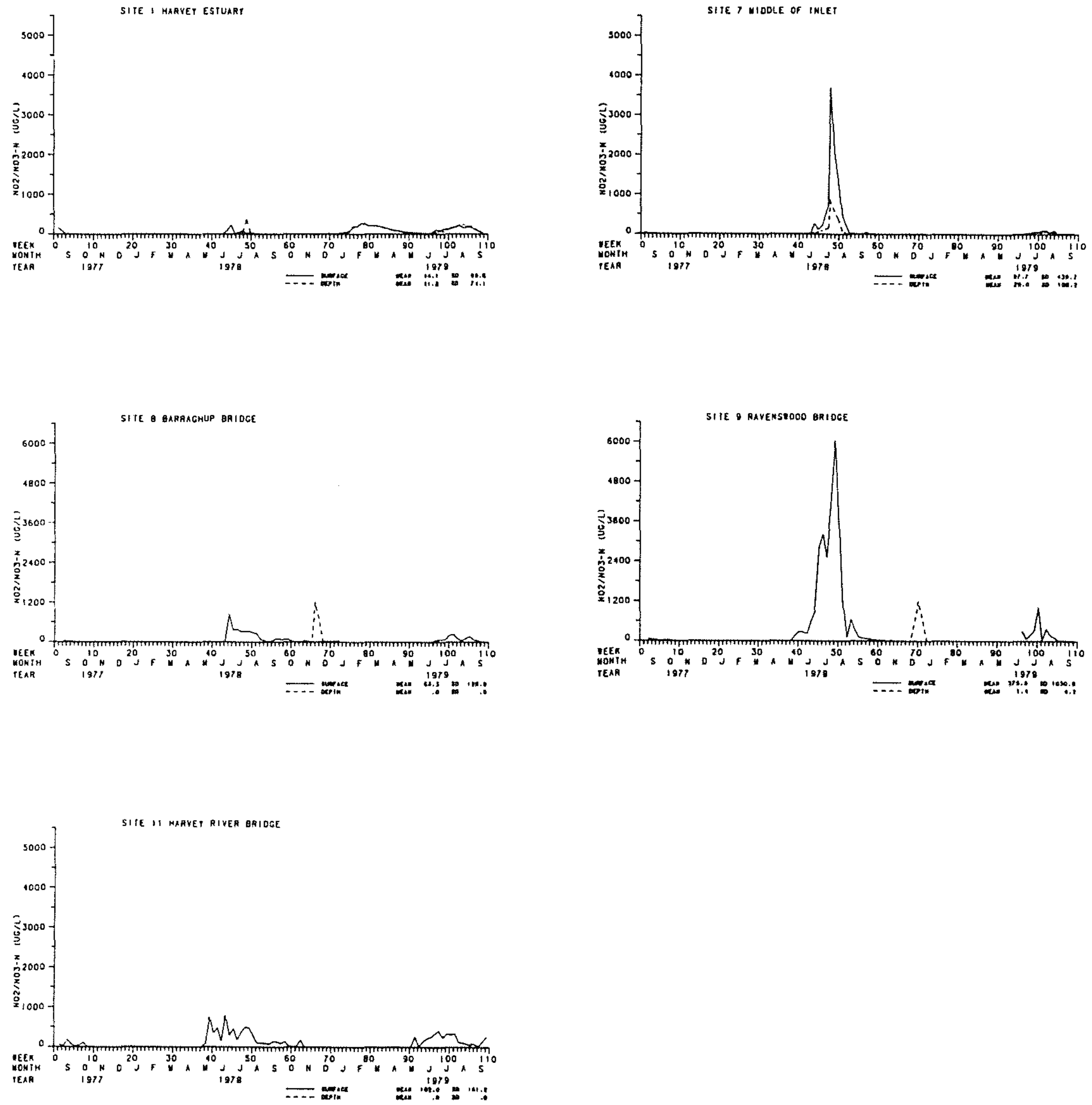


FIGURE 8.3(d) Concentration-time Curves of NO_2/NO_3-N for Sites 1,7,8, 9 and 11

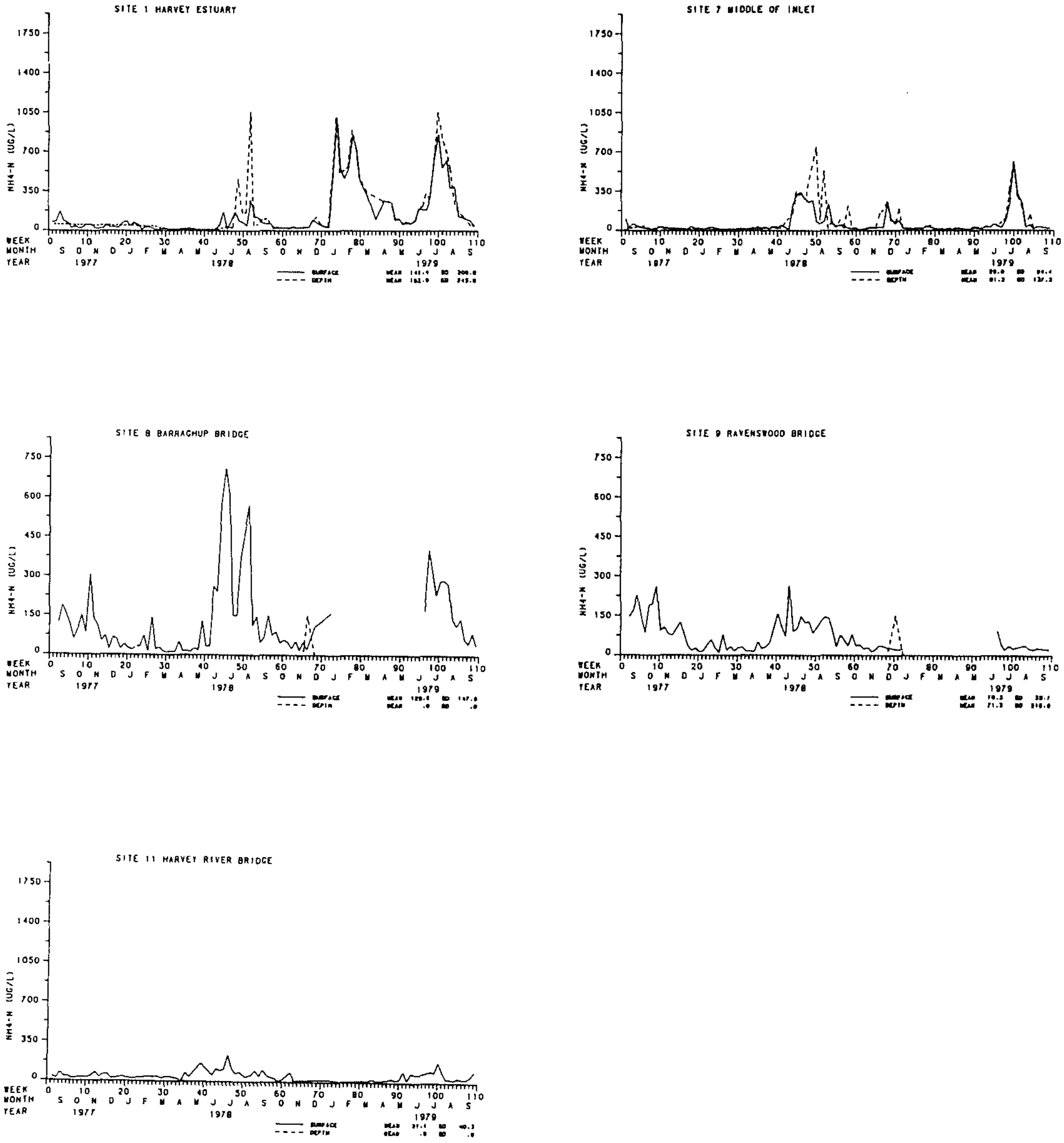


FIGURE 8.3(e) Concentration-Time Curves of NH_4-N for Sites 1,7,8, 9 and 11

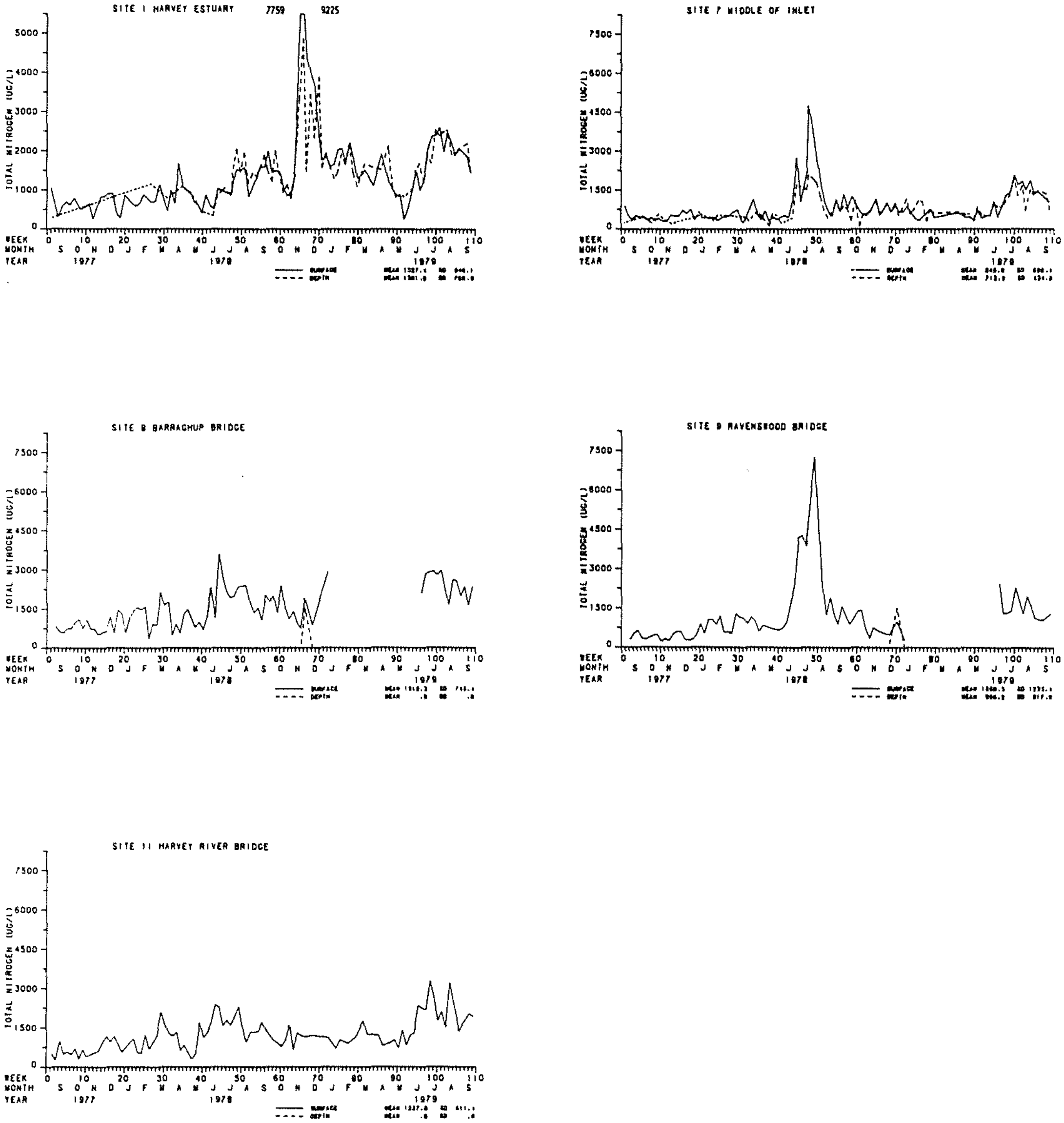


FIGURE 8.3(f) Concentration-time Curves of Total Nitrogen for Sites 1,7,8, 9 and 11

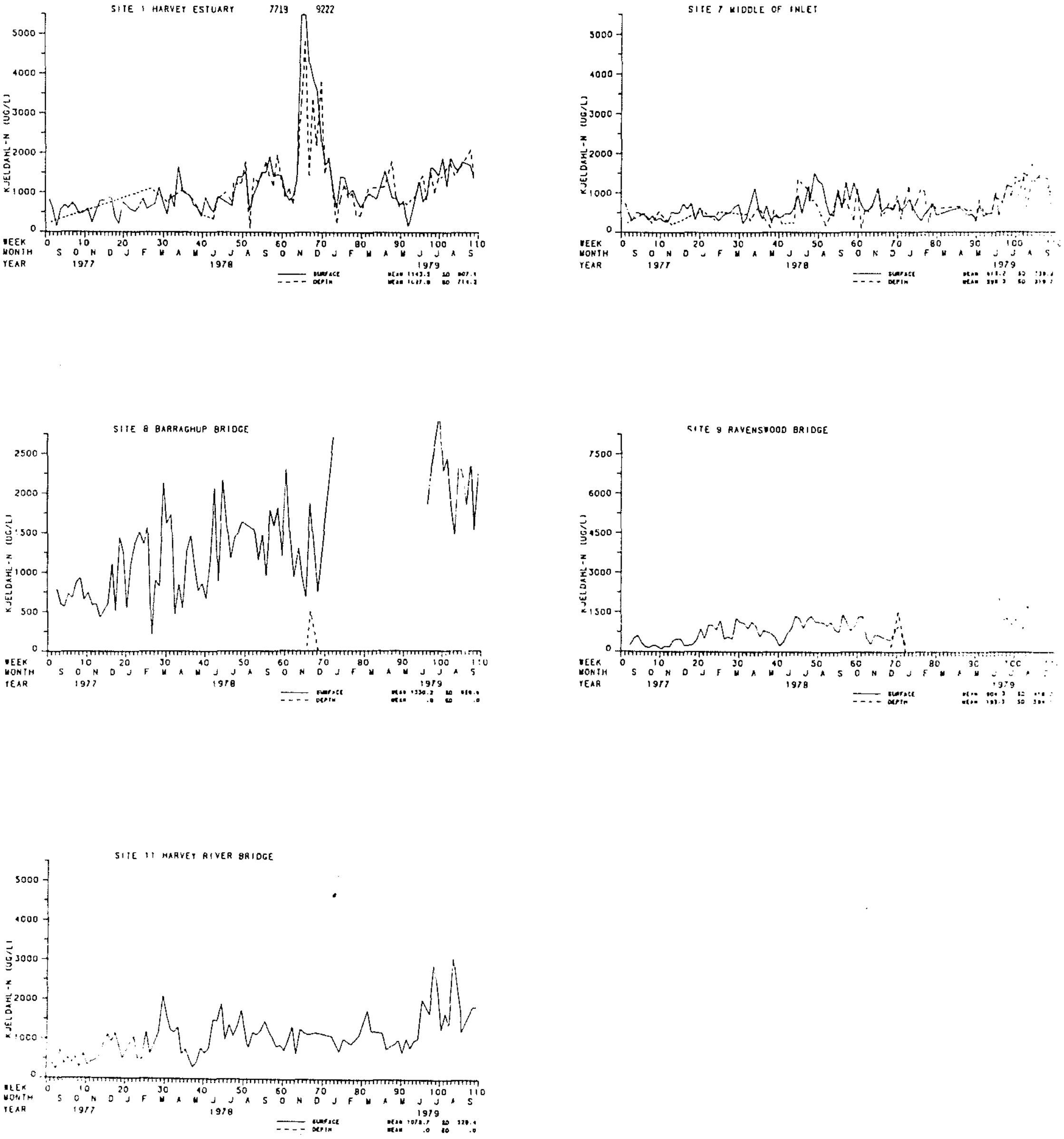


FIGURE 8.3(g) Concentration-time Curves of Kjeldahl-N for Sites 1,7,8, 9 and 11

Groundwater contains high concentrations of both nitrogen and phosphorus when compared with those of surface water. Phosphorus concentrations are about twice those of the Serpentine and Harvey Rivers. Black and Rosher (1980) estimate the annual groundwater input at 2×10^6 M^3, and the *maximum* groundwater nutrient input at less than 1% of that entering via rivers.

8.2.3 Nutrient Input and Loss from the Sea

The sea may be either a source or sink of nutrients to the estuarine system, depending upon the direction of nett hydrodynamic forcing and relative nutrient concentrations. Based on a limited number of samples, the total-N and total-P concentrations in seawater are about 50% of those in Peel Inlet for the dates sampled.

The direct measurement of material flux between estuaries and ocean is extremely difficult, and is the subject of active on-going research (Imberger *et al.*, m.s., Kjerfve and McKellar 1980). Limited attempts were made in this study to measure nutrient and chlorophyll$_a$ fluxes directly (Black and Rosher 1980, Lukatelich and McComb 1980).

A simplifying assumption used for the computation of the estuarine nutrient budget discussed in Section 8.4 is that salt and non-conservative nutrients behave similarly. In other words, the estuary to sea flushing rates, based on the analysis of temporal salinity variation in Chapter 6, have been used to estimate the marine nutrient flux with the estuarine system.

8.3 Internal Nutrient Loading

There are three main pathways through which nutrients may enter or leave the water column from sources within the system. These are sediment-water interchange, internal biological uptake and decay, and nitrogen fixation. The relative importance of these pathways is poorly understood, and the nutrient pool sizes are difficult to measure. Table 8.2 contains the best current estimates of these pools. Turnover times are not known to date, but various pieces of information make it possible at least to rank the relative importance of internal compared with external nutrient loadings at various times.

TABLE 8.2 **ESTIMATED MEAN NUTRIENT POOL SIZE (TONNES) FOR VARIOUS COMPONENTS OF THE PEEL-HARVEY ESTUARINE SYSTEM**

	NITROGEN (tonnes)	**PHOSPHORUS (tonnes)**
Plants		
Cladophora[1]	640	55
Benthic macroalgae[1] (excluding *Cladophora*)	130	11
Seagrasses[2]	106	11
Phytoplankton[3]	12.1	1.7
Benthic microalgae[4]	139	20
Bacteria, fungi	no estimate	
Fringing marshes[5]	327	48
Animals		
Fish (commercial catch)[6]	20.9	1.3
Crabs[6]	0.7	0.04
Prawns[6]	0.7	0.04
Zooplankton	no estimate	
Benthic molluscs[7]	26.3	1.7
Other benthic invertebrates	no estimate	
Birds[8]	1.6	0.1
Water[9]	173	12
Sediment[10]	2 377	259

Notes:

[1] Mean of four grid studies and 1976-77 estimate.

[2] S. Carstairs, *pers. comm.*

[3] Mean of 110 weekly samples, Peel-Harvey Study.

[4] September 1979 estimate, R.J. Lukatelich, *pers. comm.*

[5] February 1980 estimate.

[6] Four year (1975-1979) mean of professional catch only. Data courtesy of R.C.J. Lenanton from Department of Fisheries and Wildlife catch statistics.

[7] Estimated from mean production estimates of the two major species from Wells, *et al.* (1980)

[8] Based on seasonal abundance data (1976-1977) courtesy of J.A.K. Lane and G. Pearson. Body weight data from G.M. Storr (W.A. Museum) and G. Pearson (W.A. Wildlife Research Centre).

[9] Mean of 110 weekly samples, Peel-Harvey Study.

[10] Mean of four grid studies, J.O. Gabrielson *pers. comm.* Top 2 cm of sediment layer only.

The sediments are by far the largest N and P store within the system, and work is currently progressing to determine their importance in buffering water column concentrations of N and P. Table 8.3 suggests that the sediments maintain water column total N and P concentrations to a little more than twice those of marine water. External loading, mostly from rivers, superimposes peaks of nutrient concentration on top of this background level. Gabrielson (1981) estimates that the absorption/desorption characteristics of the estuarine sediments would maintain a concentration of 5-20 $\mu g\ l^{-1}$ PO_4-P in the water column, with release rates between 0-4 μg P m^{-2} day^{-1}.

Figure 8.4 shows a major secondary diatom bloom during September-October 1978 which was presumably initiated by nutrients of sedimentary origin, following the period of riverine nutrient loading. Water column surface nutrient concentrations during this time (Figure 8.3) were insufficient to account for the chlorophyll$_a$ levels attained.

TABLE 8.3

Comparison of Mean Marine and Peel Inlet Nutrient Concentrations based on Seven Samplings.

	Total N (μg/l)	NO_3-N (μg/l)	NH_4-N (μg/l)	Total P (μg/l)	PO_4-P (μg/l)
Peel Inlet (estuary)	971	15.3	49.2	50.4	5.4
Mandurah Bay (marine)	482	3.3	12.4	25.7	5.9
Ratio Peel: Mandurah Bay	2.01	4.64	3.97	1.96	0.92

The nutrient release causing this bloom was probably related to decomposition at the sediment-water interface of the winter (July-September) diatom bloom of 1978 (Figure 8.4). *Nodularia* blooms in Harvey Estuary may also be initiated by inorganic phosphorus of sedimentary origin (Figure 8.5).

Figure 8.5 highlights the importance of internal loading at the sediment-water interface further. Using chlorophyll$_a$: tissue nitrogen: tissue phosphorus ratios (Healy 1974, 1978), assuming that only inorganic forms of N and P were available, and calculating the *expected* chlorophyll$_a$ concentration on the basis of the most limiting nutrient, it was possible to calculate a residual series from the difference between observed minus expected chlorophyll$_a$ concentrations. This was carried out for sites in both Peel Inlet and Harvey Estuary. Positive deviations in these curves indicate probable phytoplankton growth from recycled and/or sedimentary nutrients. Negative deviations indicate a rate of nutrient supply higher than the ability of the phytoplankton population to take it up. Periods of significant negative deviation occur when river flows deliver high loads of inorganic N and P to the estuarine system. Much of this nutrient load is lost directly to sea (see section 8.4).

Nitrogen fixation, notably by the cyanobacterium *Nodularia spumigena* was significant, particularly during summer 1978 in periods of high inorganic phosphorus availability and inorganic N deficiency. This

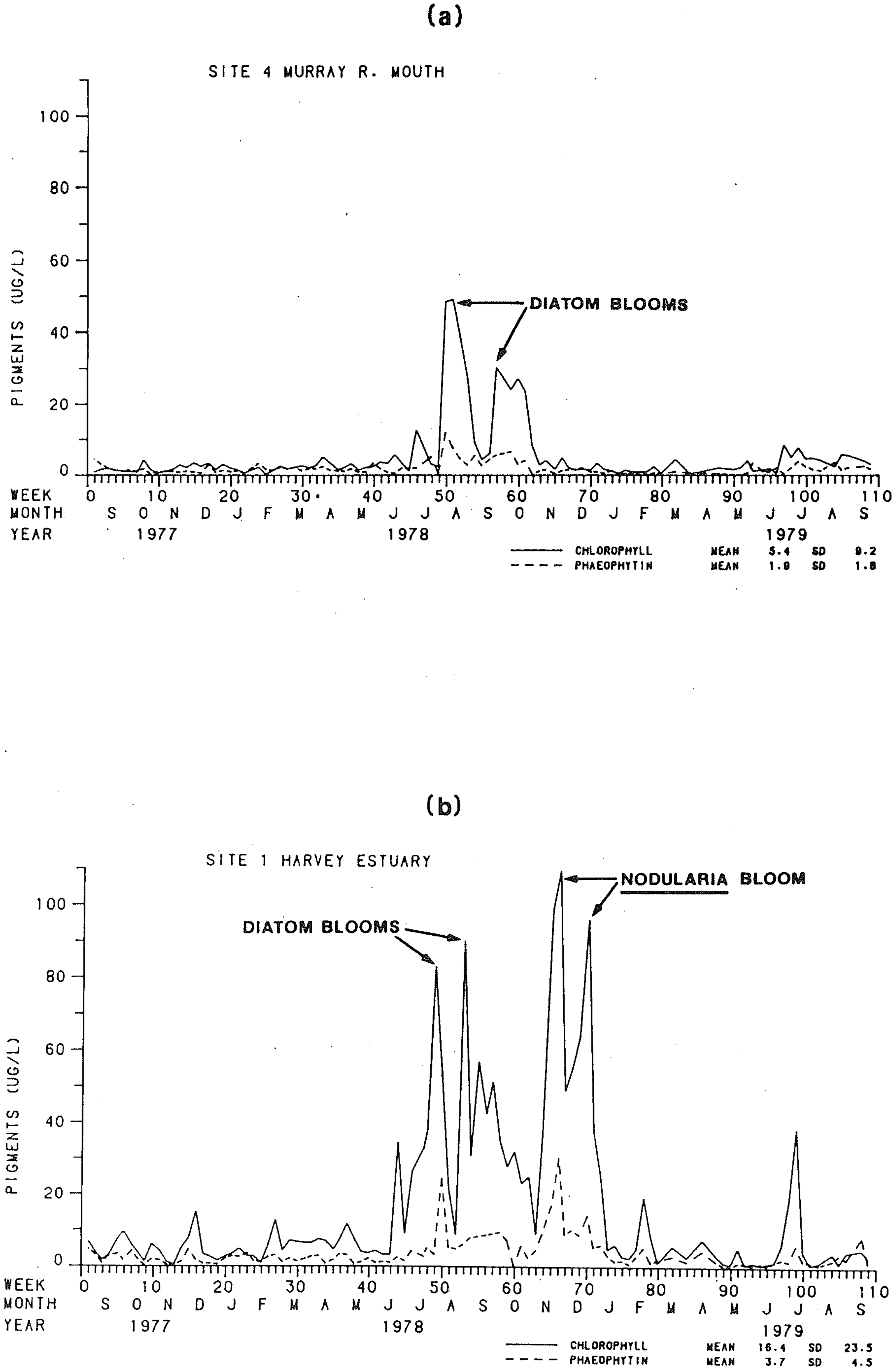


Figure 8.4 : Chlorophyll a levels in (a) Site 4, Peel Inlet and, (b) Site 1, Harvey Estuary.

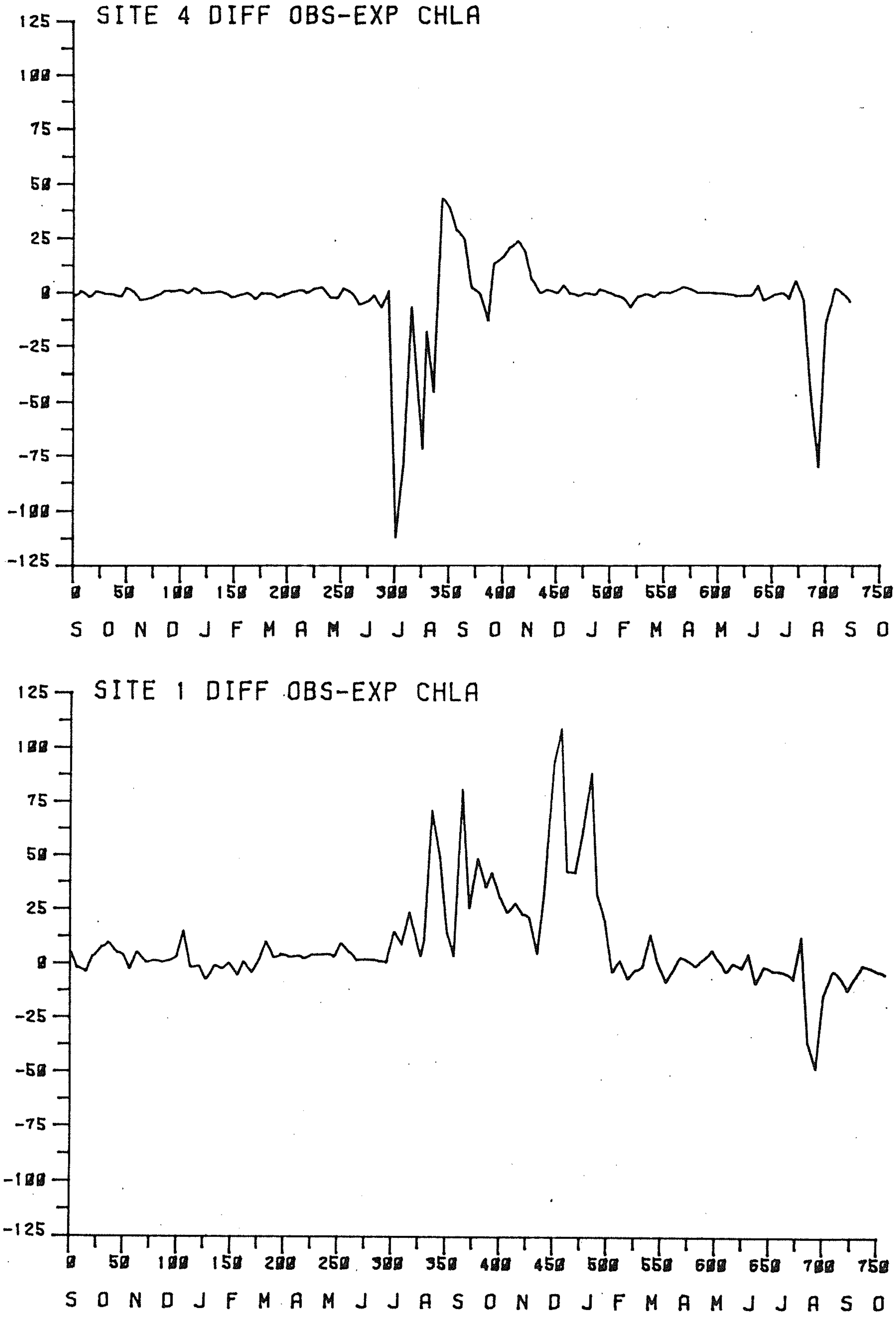


Figure 8.5 : Plots of the difference between observed chlorophyll a concentrations and those expected on the basis of water column nutrient concentrations. Positive deviations indicate a possible contribution of nutrients from recycling; negative deviations indicate that nutrient supply was greater than that which could be utilised by the phytoplankton.

prolonged period of active fixation is shown in Figures 8.4 and 8.5. The chlorophyll$_a$ peaks in Harvey Estuary between November 1978 - January 1979 were almost all due to *Nodularia*. This bloom fixed large amounts of nitrogen in Harvey Estuary (Figure 8.3e, f) during this period, estimated at about 270 tonnes, or 85% of the Harvey River input in the 1977/78 water year. *Nodularia* blooms have occurred subsequently, and in the summer of 1980-81 an extremely large *Nodularia* bloom occurred.

8.4 A Nutrient Budget for the Estuarine System

A simple nutrient budget of the water column of the estuarine system was computed as shown in Figure 8.6. The Thiessen-weighted estuary sectors (volumes) used in this computation are shown in Figure 8.7.

Briefly, the weekly budget was estimated as follows (Figure 8.6):

1. Observed river/drain inflow volumes, and the volume of rainfall directly falling on the surface of the estuary were multiplied by their observed total N and total P concentration giving the total estimated weekly nutrient input. Nutrient inputs from other sources, for example groundwater, were ignored (see Figure 8.1).

2. The nutrient load contained in the estuarine water column (Figure 8.8) was obtained by summing the products of sector volumes and the observed total N and total P concentrations at each sampling site (Figure 8.7).

3. The estuarine sector water column loads calculated in 2. were multiplied by the observed sector flushing rates, calculated from the salinity time series (see Chapter 7 for discussion), leading to the estimated total N and total P marine loss for that week. The implicit assumption in doing this is that the flushing time (the reciprocal of the flushing rates) is significantly longer than the sampling interval of one week. Though this is true for most of the year, the flushing time drops significantly during river inflows, and hence the estimates are likely to be unreliable

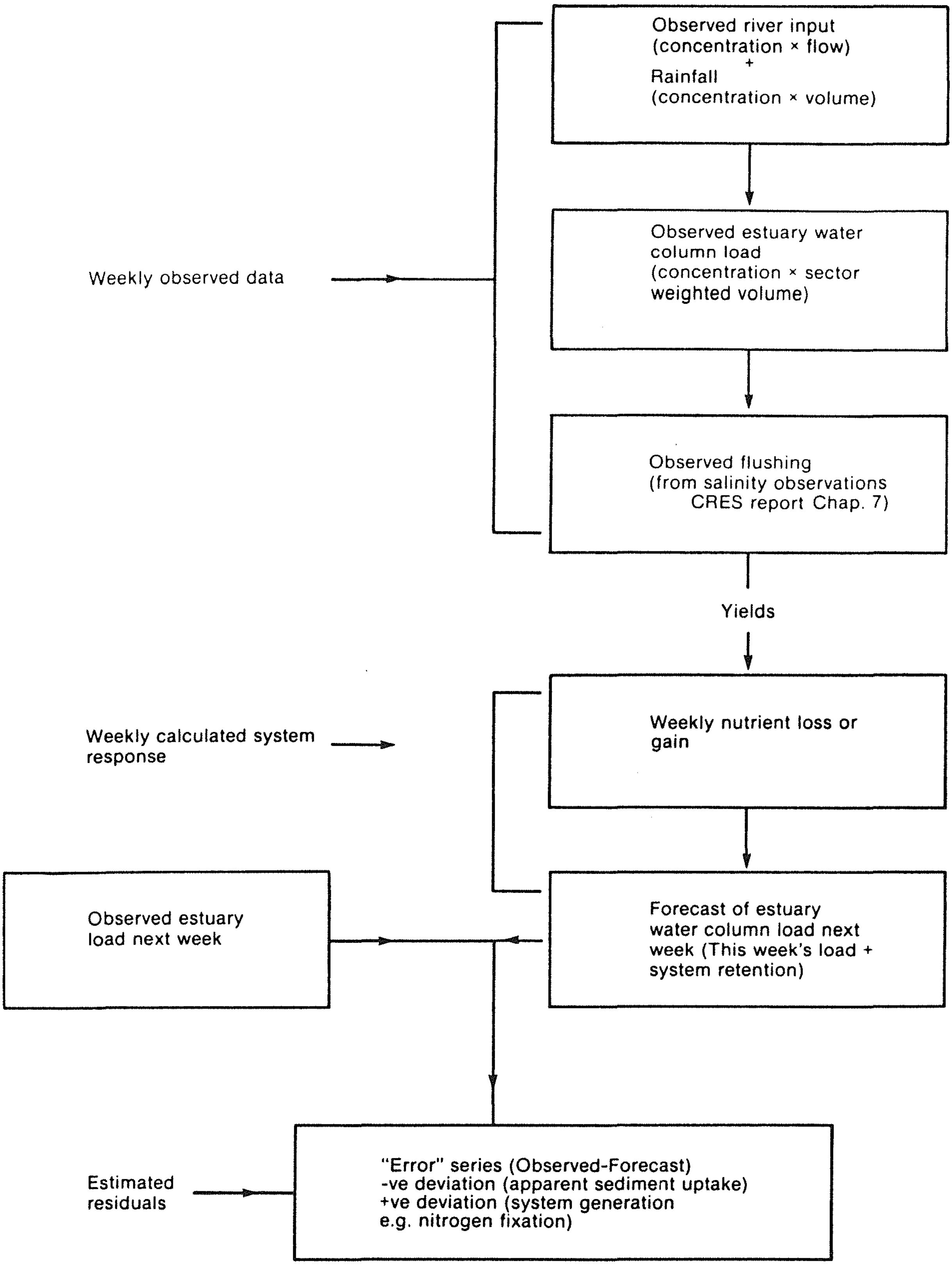


Figure 8.6 The nutrient budget calculation (nitrogen and phosphorus).

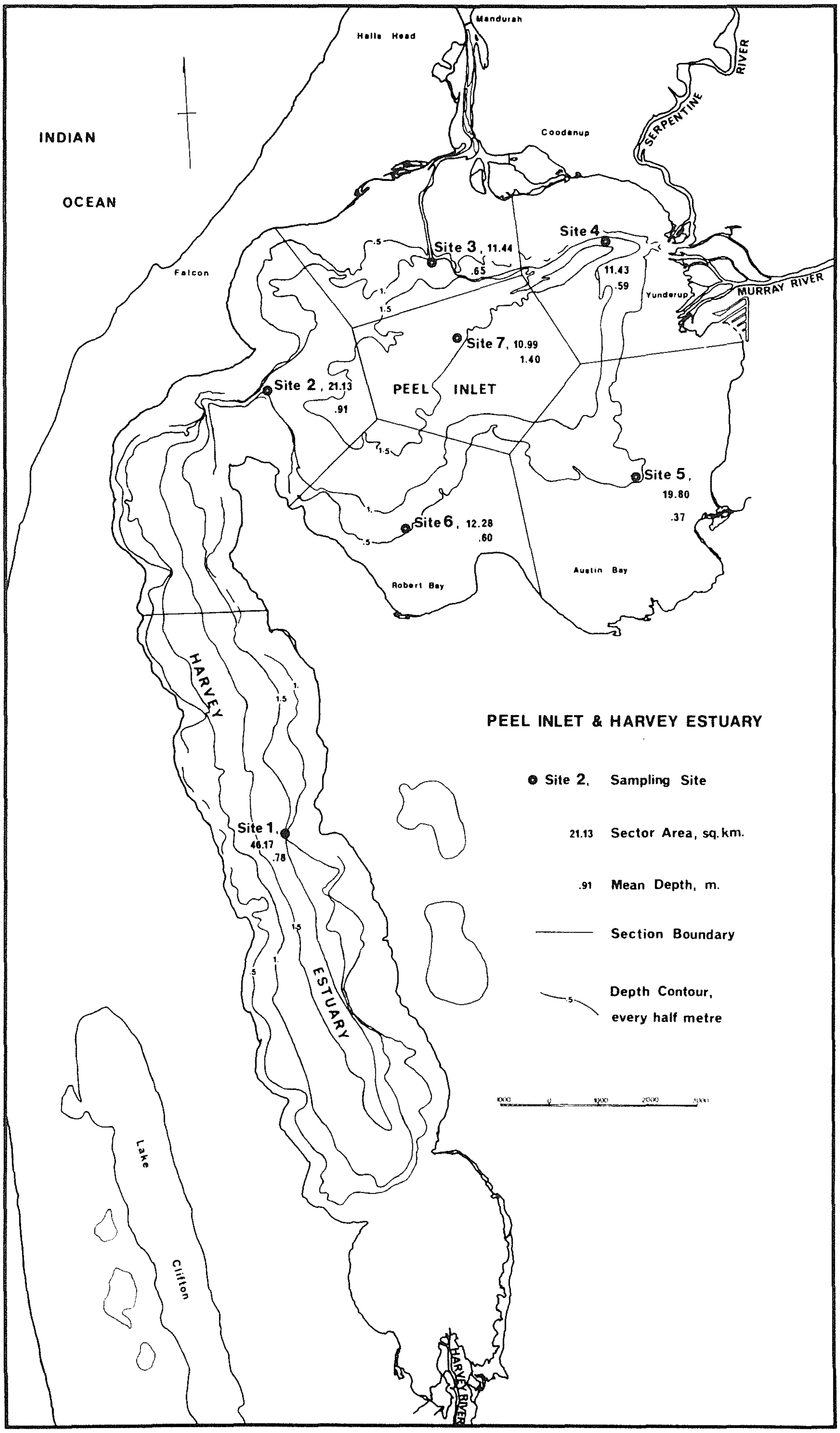
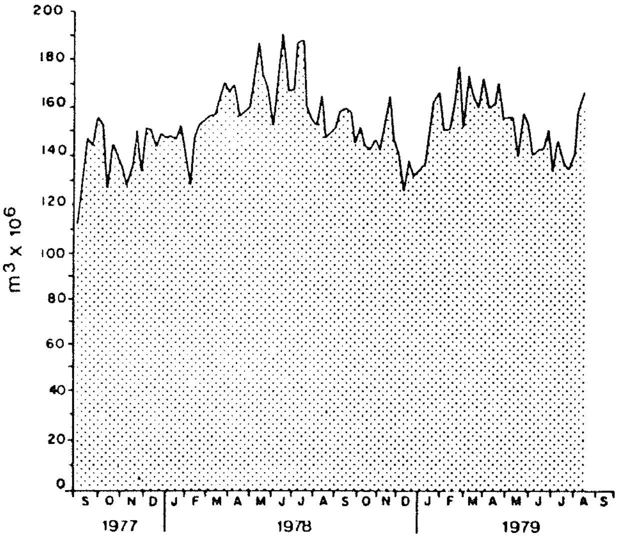
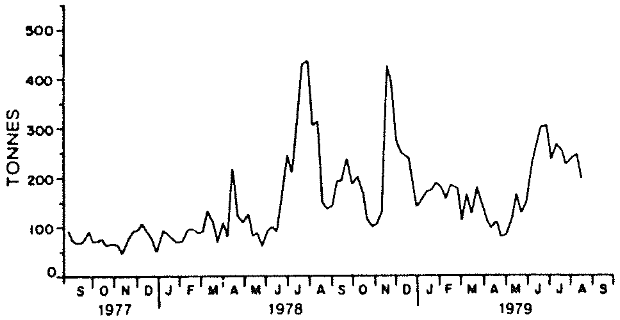


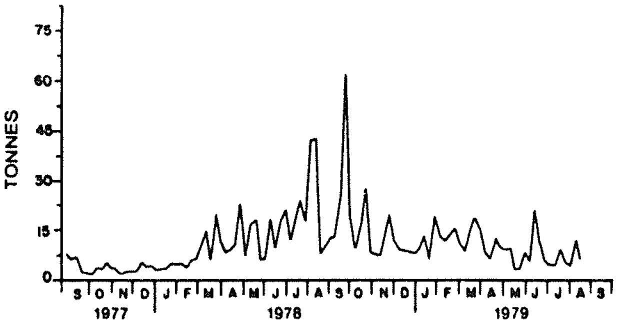
FIGURE 8.7 Thiessen Polygon Sectors (Volumes) Used for the Computation of the Nutrient Budget



Total estuary volume. Mean 152 m³ x 10⁶.

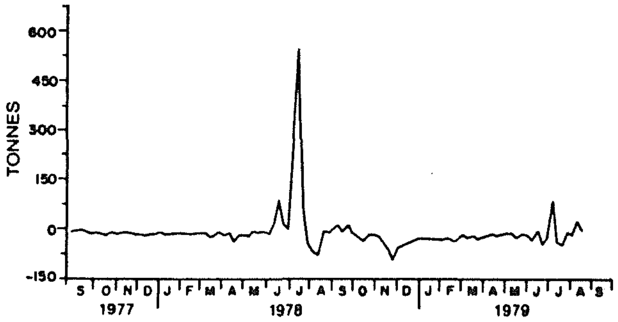


Total nitrogen load in the estuary water column.

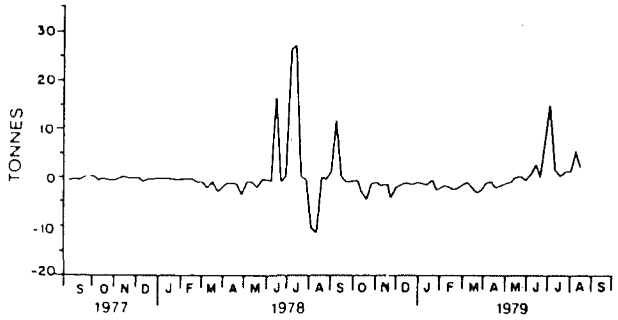


Total phosphorus load in the estuary water column.

Figure 8.8

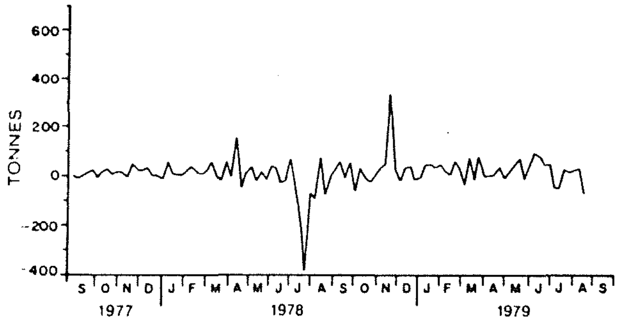


Total nitrogen load budget (gains - losses).

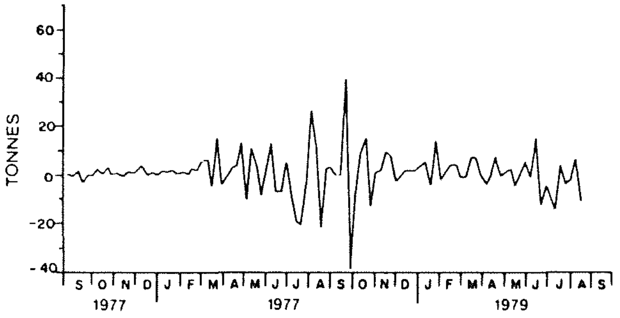


Total phosphorus load budget (gains - losses).

Figure 8.9



Total nitrogen load in estuary water column (observed - estimated).



Total phosphorus load in estuary water column (observed - estimated).

Figure 8.10

during these times. The estimates of flushing time used in the nutrient budget calculation were checked independently with the result of the August 1978 dye experiment (see Figure 7.3, Chapter 7). This showed that the observed maximum system flushing rate was within one confidence limit of the estimated maximum flushing rate.

4. The calculated weekly marine nutrient loss from 3. was compared with the estimated weekly nutrient gain (from 1.), and the system response, either as a nett gain or loss, calculated (Figure 8.9).

5. The estimated N and P input (from 1.) was added to the nett system gain or loss (from 4.); this provided a forecast of the water column nutrient load for the following week, which was in turn compared with the observed water column nutrient load for that week. The difference between the observed and predicted series is plotted in Figure 8.10.

Note that nutrient *input* by the sea has been implicitly treated in the calculation of the flushing rate. The omission of an explicit marine nutrient input was deliberate, because a time-series of marine nutrient concentration was not available and, more importantly, unambiguous estimates of the volume of exchanged marine water and solutes were not possible. An initial assumption of the analysis was that the marine component of both nutrient removal and loading into the estuarine system would approximate a constant, particularly at a weekly time scale and that this leads to the approximately constant base levels observed on the N and P plots.

This assumption may be examined further in Figure 8.10, the plots of the N and P residual ("error") series. These series oscillate, approximately randomly, about a mean of zero. There are some systematic deviations from zero, particularly in the case of N, but these are interpretable. The large negative deviation in N load on week 48, for example, is due to apparent gross sedimentation of inorganic N from the water column by a phytoplankton bloom during winter riverine enrichment of the estuarine water column. Again, the large positive deviation in N load on week 65, which implies internal generation or loading of N into the water column, was during the massive *Nodularia* bloom mentioned earlier, which fixed about 270 tonnes of N.

The phosphorus residual series is much more noisy, and is dominated by the Harvey Estuary sector (Figure 8.7). There are two points to note here. Between weeks 1-25, total phosphorus was incorrectly determined (Atkins *pers comm.*), leading to the apparent reduced variance in *all* phosphorus load and concentration time-series (see Figures 8.3c,8.8, 8.9, 8,10). Secondly, wind stirring seems to advect fine sediment and detritus from the bottom into the water column in Harvey Estuary. These particles rapidly sediment, and in many cases do not represent P available for growth. The particles probably absorb inorganic P, leading to violent positive and negative fluctuations in the total P status of the water column.

The dynamics of phosphorus within water bodies are complex, and poorly understood, and it is not possible to interpret these coarse spatial and temporal patterns further at this time. The pattern of P behaviour in Peel Inlet appears simpler than in Harvey Estuary (Figure 8.3 a-c), however, and is more closely related to riverine loading sedimentation and subsequent recycling of P by micro-organisms.

These observations suggest that the proposition of a fairly stable marine input and removal of nutrients is likely, and that this base level is superimposed upon by riverine, sediment and other loadings. Input from the sea, together with continuous loading from the sediments results in a "base" water column load of about 75 tonnes of N and 7.5 tonnes of P (Figure 8.8).

Table 8.4 contains the estimated N and P budgets for the estuarine system, allowing for the poorly defined marine nutrient loading, and making the assumptions discussed above.

The mean annual nutrient flushing rate ($\bar{F}$) is defined as

$$\bar{F} = \frac{\Sigma \text{ gross marine nutrient loss}}{\Sigma \text{ observed weekly nutrient load}}$$

For 1977/78 $\bar{F} = 0.23$, and for 1978/79 $\bar{F} = 0.19$

TABLE 8.4

Annual Nutrient Budget *

1. Nitrogen

1977/78 (tonnes N)		1978/79 (tonnes N)	
Marine input	873	Marine input	866
River & rain input	1615	River & rain input	595
	Σ 2488		Σ 1461
Flushed	1409	Flushed	1805
System gain	+ 1079	System loss	- 344
% gain + 43		% gain - 24	
(System in net *retention*)		(System in net *depletion*)	

2. Phosphorus

1 77/78 (tonnes P)		1978/79 (tonnes P)	
Marine input	47	Marine input	46
River & rain input	113	River & rain input	92
	Σ 160		Σ 138
Flushed	110	Flushed	114
System gain	+ 50	System gain	+ 24
% gain + 40		% gain + 17	
(System in net *retention*)		(System in net *retention*)	

* Assuming (i) net system volume change over 1 year is zero.
(ii) marine N and P concentrations are constant.

The summed total system water volume multiplied by $\bar{F}$ gives the volume of estuary water flushed, which is assumed to be replaced by an equivalent volume of marine water, having a mean total N concentration of 482 $\mu g\ l^{-1}$ and total P concentration of 26 $\mu g\ l^{-1}$ (from Table 8.3).

The marine nutrient load into the estuarine system is computed in the usual fashion. The nutrient budget for the 1977/78 and 1978/79 water years is given in Table 8.4.

8.5 Conclusions

The system N balance is critically dependent on large river flows from the plateau zone of the Murray catchment. In the dry water year 1978/79, the estuary was in negative N balance, in contrast to the wetter 1977/78.

Phosphorus input is much less sensitive to drought, because the coastal plain rivers, which carry most of the incoming P, are more reliable (Black and Rosher 1980) and some, as in the case of the Harvey River, are agricultural drains fed by irrigation water.

It seems likely that external, riverine N loading will be difficult to reduce, and internal N loading (due to fixation) may only be reduced if available phosphorus is reduced. A reduction in external P loading from the dominant riverine inputs will depend, in turn, on a reduction in phosphorus loading from the coastal plain soils.

9 CLADOPHORA BIOMASS DYNAMICS: SPECULATIVE STOCHASTIC AND DATA-BASED MODELING

9.1 Introduction

This chapter describes two additional approaches to the modeling of *Cladophora* biomass dynamics. The first is an extension of the speculative simulation modeling based on a "phosphorus scenario", as described in Chapters 4 and 5 of this report. This extension of the Monte Carlo approach assumed a nitrogen-limited phytoplankton and *Cladophora* system, and, like the phosphorus scenario described earlier (see also Hornberger and Spear 1980; Spear and Hornberger 1980) was used early in the study to investigate the possibility of N-limitation of *Cladophora* growth.

The second modeling approach used simple, data-based, algebraic equations to simulate *Cladophora* growth processes and variation in *Cladophora* standing crop. This *a postiori* modeling has been carried out for two main reasons:

(a) to integrate the field and laboratory data with a conceptual model of *Cladophora* growth, so that any anomaly in that integration may be understood and corrected.

(b) to extrapolate the model to both observed and simulated field situations, so that the effects of possible alterations to the estuarine system (in terms of *Cladophora* growth) may be assessed.

In contrast to the differential equation formulations of the speculative P- and N- scenario simulation models, these data based modeling studies have used mathematical fits to empirically-measured growth data. Some of these functional fits are shown in Figure 9.1.

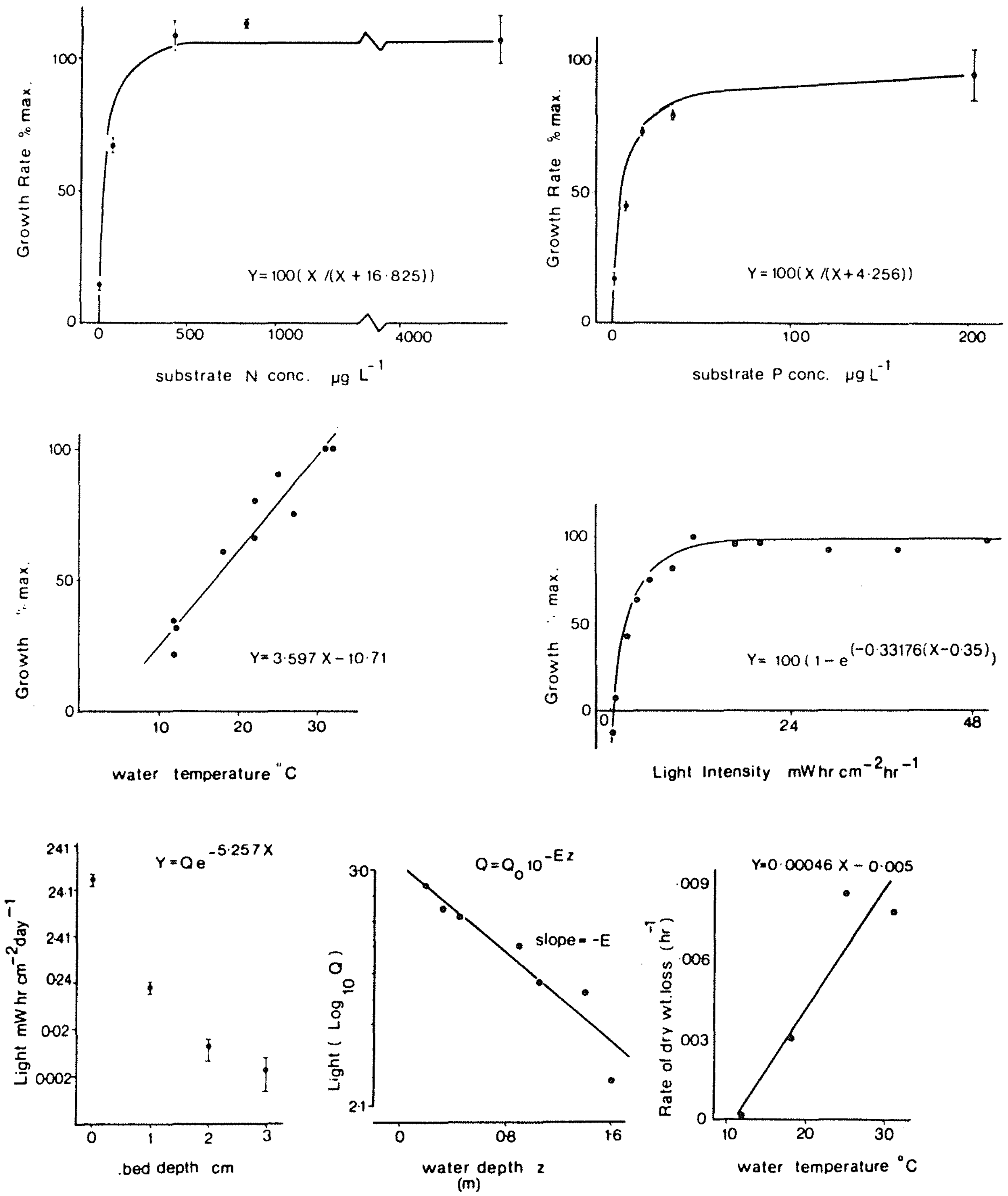


Figure 9.1 Functional fits to experimental data as used in *Cladophora* simulation models.

9.2 Speculative Simulation Modeling of *Cladophora* - the Nitrogen Scenario

The nitrogen scenario model closely follows the structure and philosophy of the phosphorus model discussed in Chapter 5. There are, however, substantial structural differences, and these are discussed below.

The structure of the N- model is shown in schematic form in Figure 9.2. Comparison of this figure with Figure 6.1, the P-scenario schematic, shows that the nitrogen budget model of the *Cladophora* growth area is more complex than that for phosphorus. This is due to the more complex behaviour of nitrogen as an element in ecosystems; for example the existence of biological N fixation, significant levels of atmospheric addition and loss of N from water bodies, and the reduced binding to sediment particles by inorganic forms of N.

The main reason for dividing water and sediment N into organic N and inorganic N compartments is that the organic N fraction is likely to be of restricted availability to algae. If this were not the case, then there would seem to be so much available N in both the sediments and water of the growth area that N- limitation of growth would never occur. The structure of the model permits control of the rate of organic N to inorganic N conversion, by choosing low values the conversion rate parameters k_{34} and k_{56} (see equations 9.3, 9.4, 9.5) hence partly limiting growth. Further, the parameter η (see equations 9.1, 9.2) specifies the fraction of organic N directly available (e.g. urea) for algal uptake.

Another feature of importance is the choice of routing N- fixation via the sediment organic N compartment. It is probable that fixation occurs in the water column, sediments and epiphytically on the *Cladophora* mat, (Huber 1980) and so could potentially introduce N directly into any of these compartments. Despite this, and for simplicity, it was decided to route nitrogen entering the system via fixation through the sediment organic N compartment. This decision although unusual seems quite realistic, since fixed nitrogen is probably unavailable for algal uptake until the fixers themselves have decomposed.

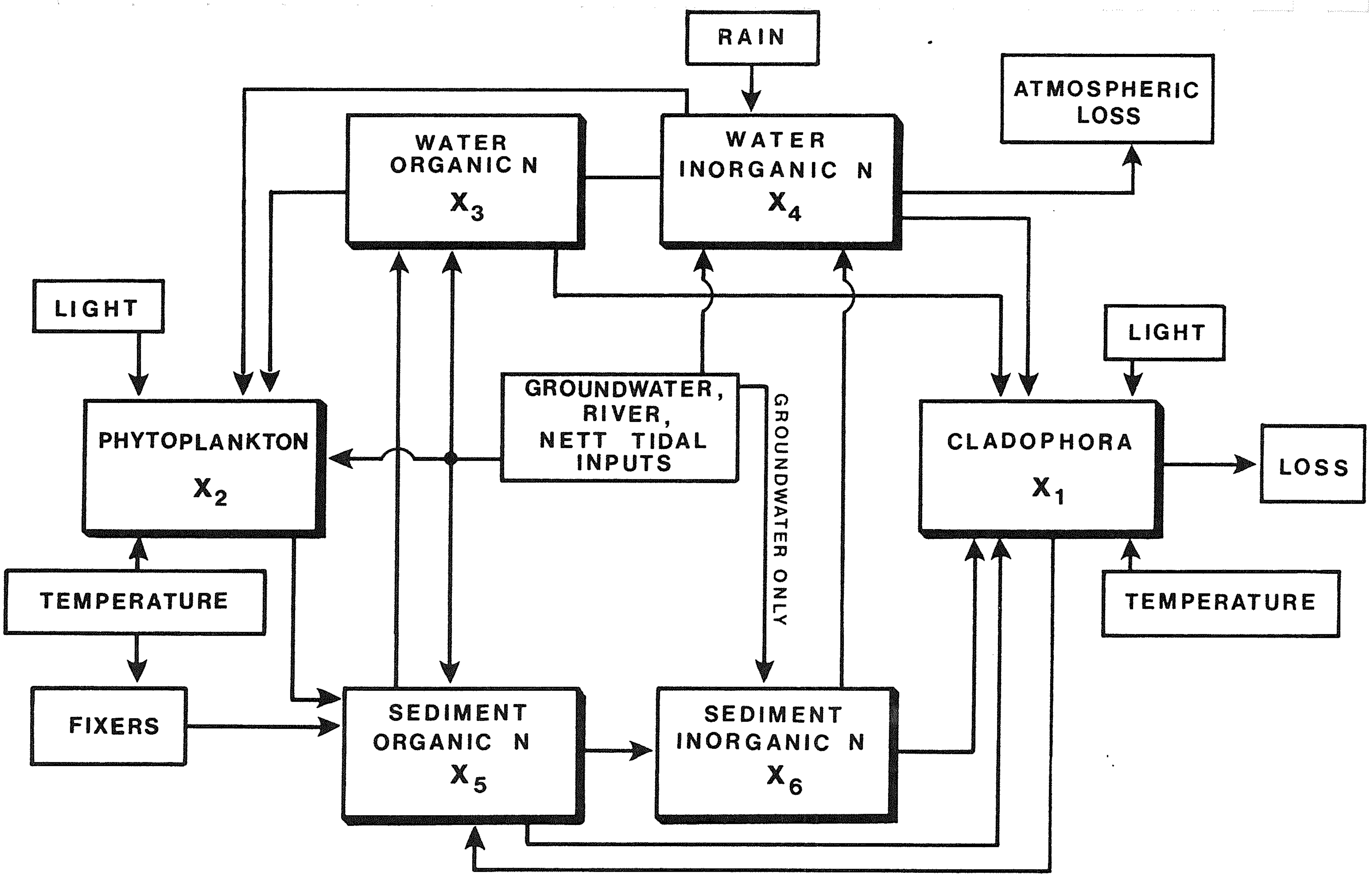


FIGURE 9.2 SCHEMATIC OF NITROGEN BUDGET MODEL

The main effect of routing fixed nitrogen through the sediment organic N compartment is to delay its release through to other parts of the system.

An important parameter in the phosphorus simulations was the amount of particle-bound phosphorus sedimented into the *Cladophora* growth area. The only analogous mechanism available for nitrogen seems to be the input of particulate (= detrital) N into the sediments and sedimentation of fixed N. The parameter W_R^o (see equation 9.5) was inserted for this purpose.

The equations describing each state variable and transfer process shown in Figure 9.2 are discussed in the next section.

9.3 Nitrogen Budget Model Equations

The nitrogen budget model equations are given below in equations (9.1) to (9.6). Table 9.1 contains the value ranges for the parameters of the model equations. The parameter values for each individual annual simulation were selected at random from the ranges specified in the table.

9.3.1 Nitrogen Mass-balance for the *Cladophora* Compartment

$$\underbrace{\frac{dX_1}{dt}}_{\substack{\text{net}\\\text{rate of}\\\text{change of}\\\text{biomass}}} = \underbrace{\gamma_1 \, T \, I_b \cdot \frac{X_c}{K_1+X_c} \, g(X_1)}_{\text{growth}} - \underbrace{a_{11} \, X_1}_{\substack{\textit{in situ}\text{ losses}\\\text{and export}}} \qquad (9.1)$$

where,

X_1 = *Cladophora* biomass in terms of nitrogen (μg);

γ_1 = temperature-light growth coefficient ($\text{day}^{-1}\text{ly}^{-1}{}^\circ\text{C}^{-1}$);

T = water temperature (°C);

I_b = total light at the bottom for the day ($= Ie^{-K_T Z}$, where I is actual surface light intensity, K_T is the extinction coefficient and Z is the depth) (cal. cm^{-2});

TABLE 9.1

NITROGEN MODEL PARAMETERS

Tentative limits for the rectangular probability distributions for the parameters of the nitrogen model.

PARAMETER	SYMBOL	DESCRIPTION	RANGE OF VALUES	UNITS
1.	γ_1	*Cladophora* growth-temp/light coefficient	1×10^{-4} to 3×10^{-4}	day.$^{-1}$ ly.$^{-1}$ °C^{-1}
2.	K_1	" half saturation constant (N)	1 to 141	µg l^{-1}
3.	a_{11}	" loss rate	1.25×10^{-3} to 6.25×10^{-3}	day.$^{-1}$ °C^{-1}
4.	γ_2	Phytoplankton growth coefficient	0.05 to 0.15	day.$^{-1}$ °C^{-1}
5.	I_s	" optimal irradiance	150 to 500	ly
6.	x_p	water column N available to phytoplankton ($x_4 + \eta\, x_3$)	5×10^{1} to 5×10^{3}	µg l $^{-1}$
7.	K_W	light attenuation coefficient (water)	0.45 to 1.3	m^{-1}
8.	k	light shading coefficient (phytoplankton)	.003 to .009	(m^{-1} µg l^{-1})$^{-1}$
9.	K_2	Phytoplankton half saturation constant	1 to 141	µg l^{-1}
10.	a_{22}	" loss rate	2.5×10^{-3} to 7.5×10^{-3}	day.$^{-1}$ C^{-1}
11.	u_G	groundwater N concentration	200 to 2200	µg l^{-1}
12.	a_{53}	organic N sediment-water diffusion parameter	1×10^{6} to 5.05×10^{7}	l day.$^{-1}$
13.	X_S^*	maximum sediment N concentration	2.0×10^{3} to 3.0×10^{3}	µg l^{-1}
14.	λ_2	Phytoplankton loss to sediment	0.3 to 0.9	dimensionless
15.	λ_1	*Cladophora* loss to sediment	0.3 to 0.9	dimensionless
16.	X_m	" maximum photosynthesising biomass	5×10^{11} to 25×10^{11}	µg
17.	β	ground water partitioning coefficient	0 to 1	dimensionless
18.	α	*Cladophora* nutrient source parameter	.95 to 1.0	dimensionless
19.	ρ	tidal exchange efficiency parameter	0.5 to 0.9	dimensionless
20.	η	proportional availability of organic N to algae	0 to 1	dimensionless
21.	k_{34}	conversion rate, water org.N → inorg.N	5×10^{-4} to 8×10^{-4}	day.$^{-1}$
22.	k_{56}	conversion rate, sediment org.N → inorg.N	5×10^{-4} to 8×10^{-4}	day.$^{-1}$
23.	k40	rate of N loss to atmosphere	1×10^{-2} to 2×10^{-2}	°C^{-1} day.$^{-1}$
24.	F	N input by fixation	0.0 to 0.0	µg day.$^{-1}$
25.	c	concentration of inorganic N in rainfall	0.0 to 0.0	µg l^{-1}

X_c = available N concentration to *Cladophora*, = $\alpha(X_4+\eta X_3) + (1-\alpha)(X_6+\eta X_5)$ where α and η may vary between 0 and 1, and X_3, X_4 are organic and inorganic N in the water column, and X_5, X_6 are organic and inorganic sediment N concentrations (μg l^{-1});

K_1 = Michaelis half-saturation constant for N uptake (μg l^{-1});

$g(X_1)$ = biomass (nitrogen) available for active photosynthesis;

a_{11} = loss rate constant-death, grazing, export to beaches, respiration etc. (day^{-1}).

9.3.2 Nitrogen Mass-balance for the Phytoplankton Compartment

$$\underbrace{\frac{dX_2}{dt}}_{\substack{\text{net}\\ \text{change of}\\ \text{biomass}}} = \underbrace{\gamma_2\, T\, \frac{ef}{K_T Z}\, (e^{-\alpha_1} - e^{-\alpha_o})\, \frac{X_p}{K_2+X_p}\, X_2}_{\text{growth}}$$

$$\underbrace{-\, a_{22}\, X_2}_{\text{losses}} + (\underbrace{Q_R N_R}_{\substack{\text{river}\\ \text{inflow}}} + \underbrace{Q_{Ti} N_T - Q_{To}\, X_2}_{\substack{\text{net tidal}\\ \text{input}}})\, \frac{1}{V_w} \tag{9.2}$$

where,

V_w = water volume (l);

X_2 = phytoplankton biomass concentration, as N(μg l^{-1});

γ_2 = temperature-growth coefficient (day^{-1} °C^{-1});

e = Naperian base;

f = photoperiod (fraction of a day);

K_T = light extinction = K_w+K_p where K_w is due to water and dissolved material and K_p is due to phytoplankton self-shading; K_p is assumed to be directly proportional to phytoplankton biomass, i.e., it is calculated as kX_2 (m^{-1});

Z = water depth (m);

$\alpha_1 = (I/I_s)e^{-K_T Z}$;

I = average light intensity for the day (cal cm^{-2});

$a_0 = I/I_s$;

X_p = available N concentration in the water $\equiv (X_4 + \eta X_3)$;

η = fraction of organic N available for *Cladophora* and phytoplankton uptake;

a_{22} = rate constant for death, respiration, grazing etc.(day^{-1});

Q_R = river flow rate (l day^{-1});

N_R = nitrogen concentration of phytoplankton in river inflow (μg l^{-1});

Q_{Ti} = daily tidal inflow (l day^{-1});

Q_{To} = daily tidal outflow from growth area (l day^{-1});

N_T = nitrogen concentration of phytoplankton in estuarine water external to *Cladophora* growth area;

9.3.3 Organic Nitrogen Mass Balance for the Water Column

$$\begin{aligned}
V_w \frac{dX_3}{dt} &= Q_{Ti}\, u_T^o - Q_{To}\, X_3 + Q_R\, U_R^o + (1-\beta)Q_G\, U^o{}_G \\
&\qquad \text{advection terms} \\
&- \alpha\, \gamma_1\, TI_b \frac{\eta X_3}{k_1 + X_c}\, g(X_1) \qquad \textit{Cladophora} \text{ uptake} \\
&- \gamma_2\, T \frac{ef}{K_T Z} (e^{-\alpha 1} - e^{-\alpha\phi}) \frac{\eta X_3}{K_2 + X_p} X_2 V_w \\
&\qquad \text{phytoplankton uptake} \\
&+ \underbrace{a_{53}\,(X_5 - X_3)}_{\text{transfer from sediment}} - \underbrace{K_{34} X_3 V_w}_{\text{transfer to inorganic compartment}}
\end{aligned} \qquad (9.3)$$

New variables and parameters introduced in this equation are:

X_3 = organic N concentration in water ($\mu g\ l^{-1}$);

U_T^o = organic N concentration in water external to growth area ($\mu g\ l^{-1}$);

U_R^o = organic N concentration in river inflow ($\mu g\ l^{-1}$);

β = ground water partitioning coefficient;

Q_G = ground water inflow rate ($l\ day^{-1}$);

U_G^o = organic N concentration in ground water ($\mu g\ l^{-1}$) - possibly zero? ;

a_{53} = organic N sediment to water diffusion parameter ($l\ day^{-1}$);

X_5 = sediment organic N concentration ($\mu g\ l^{-1}$);

k_{34} = conversion rate, organic N to inorganic N in water (day^{-1}).

9.3.4 Inorganic Nitrogen Mass Balance for the Water Column

$$V_w \frac{dX_4}{dt} = Q_{Ti}\, U_T^I - Q_{To}\, X_4 + Q_R\, U_R^I + (1-\beta)\, Q_G\, U_G^I$$

advection terms

$$- \alpha\, \gamma_1\, TI_b \frac{X_4}{K_1+X_c}\, g(X_1) \qquad \textit{Cladophora}\ \text{uptake}$$

$$- \gamma_2\, T \frac{ef}{K_T Z} (e^{-\alpha l} - e^{-\alpha\phi}) \frac{X_4}{K_2+X_p}\, X_2\, V_w$$

phytoplankton uptake

$$+ \underbrace{a_{64}\, (X_6-X_4)}_{\text{transfer from sediment}} + \underbrace{k_{34}\, X_3\, V_w}_{\text{transfer from organic N}} - \underbrace{k_{40}\, TX_4\, V_w}_{\text{atmospheric loss}} + \underbrace{PAc}_{\text{rainfall addition}} \qquad (9.4)$$

Parameters and variables not defined previously are:

X_4 = concentration of inorganic N in water ($\mu g\ l^{-1}$);

U_T^I = concentration of inorganic N in estuary water external to the growth area ($\mu g\ l^{-1}$);

U_R^I = inorganic N concentration in inflowing river water ($\mu g\ l^{-1}$);

U_G^I = inorganic N concentration in groundwater ($\mu g\ l^{-1}$);

a_{64} = inorganic N sediment to water diffusion parameter ($l\ day^{-1}$);

k_{40} = rate of N loss to atmosphere ($°C^{-1}\ day^{-1}$);

P = precipitation on surface of growth area ($mm\ day^{-1}$);

A = surface area of growth area (m^2);

c = concentration of inorganic N in rainfall ($\mu g l^{-1}$).

9.3.5 Organic Nitrogen Mass Balance for the Sediments

$$V_S \frac{dX_5}{dt} = \underset{\text{limiting concentration}}{\left(1 - \frac{X_S}{X_S^*}\right)^3} \quad \underset{\text{river deposition}}{Q_R W_R^o} \quad + \quad \underset{\text{groundwater throughflow}}{\beta Q_G (U_G^o - X_5)}$$

$$+ \underset{\text{phytoplankton sedimentation}}{V_W \lambda_2 a_{22} TX_2} \quad + \quad \underset{\textit{Cladophora}\text{ loss to sediments}}{\lambda_1 a_{11} TX_1} \quad - \underset{\text{transfer to water column}}{a_{53} (X_5 - X_3)}$$

$$- \underset{\textit{Cladophora}\text{ intake from inter-algal water}}{(1-\alpha)\, \gamma_1\, TI_b \frac{\eta X_5}{K_1 + X_c} g(X_1)} \; - \underset{\text{transfer organic N}\rightarrow\text{inorganic N}}{k_{56} X_5} \quad + \quad \underset{\text{nitrogen fixation}}{F} \qquad (9.5)$$

where,

V_S = sediment volume (1);

X_5 = organic N concentration in sediment ($\mu g\ 1^{-1}$);

X_S = total sediment N concentration = $X_5 + X_6$ ($\mu g\ 1^{-1}$);

X_S^* = 'maximum' total sediment N concentration ($\mu g\ 1^{-1}$);

W_R^o = particulate organic N in river inflow ($\mu g\ 1^{-1}$),

k_{56} = rate of conversion, organic N inorganic N (day^{-1});

F = N input from fixers ($\mu g\ day^{-1}$).

9.3.6 Inorganic Nitrogen Mass Balance for the Sediments

$$V_S \frac{dX_6}{dt} = \underset{\substack{\text{concentration}\\ \text{limiting}\\ \text{function}}}{\left(1 - \frac{X_S}{X_S^*}\right)^3} \underset{\substack{\text{groundwater}\\ \text{throughflow}}}{\beta Q_G (U_G^I - X_6)} + \underset{\substack{\text{transfer}\\ \text{organic N} \rightarrow\\ \text{inorganic N}}}{k_{56} X_5}$$

$$- \underset{\substack{\text{transfer to}\\ \text{water column}}}{a_{64} (X_6 - X_4)} - \underset{\substack{\textit{Cladophora}\text{ uptake from}\\ \text{interalgal water}}}{(1 - \alpha) \gamma_1 TI_b \frac{X_6}{K_1 + X_c} g (X_1)} \qquad (9.6)$$

New terms introduced into this equation are:

X_6 = inorganic N concentration in sediment ($\mu g\ 1^{-1}$).

Note that the term $k_{56}X_5$ accounts for all conversions of sediment organic N into sediment inorganic N, for example, decomposition of *Cladophora*, phytoplankton, riverine and groundwater inorganic N.

9.4 Results of the Speculative Nitrogen-budget Modeling

As in the case of the speculative P-budget described in Chapter 5, the outcomes of each annual *Cladophora* simulation were classifed as 'behaviours' (B), where the model output resembled that of the actual data plotted in Figure 5.2; or 'non-behaviours' ($\bar{B}$), where no resemblance was apparent. The simulation technique is described in detail in Chapter 5, and the Monte Carlo analysis logic flow is given in Figure 5.8. In more than 500 annual simulations, *no* runs classified as 'behaviours' occurred. The results, however, can be grouped in two classes:

1. High levels of dissolved inorganic nitrogen in the water column (state variable X_4) led to protracted phytoplankton blooms (X_2). This in turn caused shading of the *Cladophora* population (X_1), and a sharp decline in biomass due to light starvation. This effect was intensified due to nitrogen recycling within the water column, which tended to prolong the duration of the simulated phytoplankton blooms.
2. High rates of nitrogen for *Cladophora* growth, in the absence of significant phytoplankton, led to a *Cladophora* population explosion, and a plateauing of biomass when complete self-shading (specified by $g(X_1)$) was achieved.

These results suggest that *Cladophora* is *never* directly N-limited, while phytoplankton populations suffer frequent N-limitation. This conjecture is strongly supported when, two years or so after this work was completed, sufficient field and laboratory data exist to examine the hypothesis. For example, Figure 9.3 shows *Cladophora* growth rate as a function of tissue phosphorus and tissue nitrogen concentration, (from Birch *et al.*, 1981). This figure defines 'critical concentrations' of tissue N and P, above which growth occurs at the maximal rate, provided that no other factors are limiting. The critical tissue nitrogen concentration is about 20 mg g^{-1} dry weight.

Figure 9.4 contains the time-series of field tissue nutrient data from site 4 in Peel Inlet. It is obvious from this figure that *Cladophora* is virtually never N-limited. In contrast, phosphorus is always a limiting nutrient, and probably controls growth rate at times of the year when light and temperature conditions ameliorate. It has also been shown that the first winter diatom bloom is N-limited (Chapter 8), and the presence of the N-fixing cyanobacterium *Nodularia spumigena* in Harvey estuary provides strong evidence indeed for a simultaneous water column phosphorus surplus and nitrogen deficiency during summer river inflows from the Harvey River.

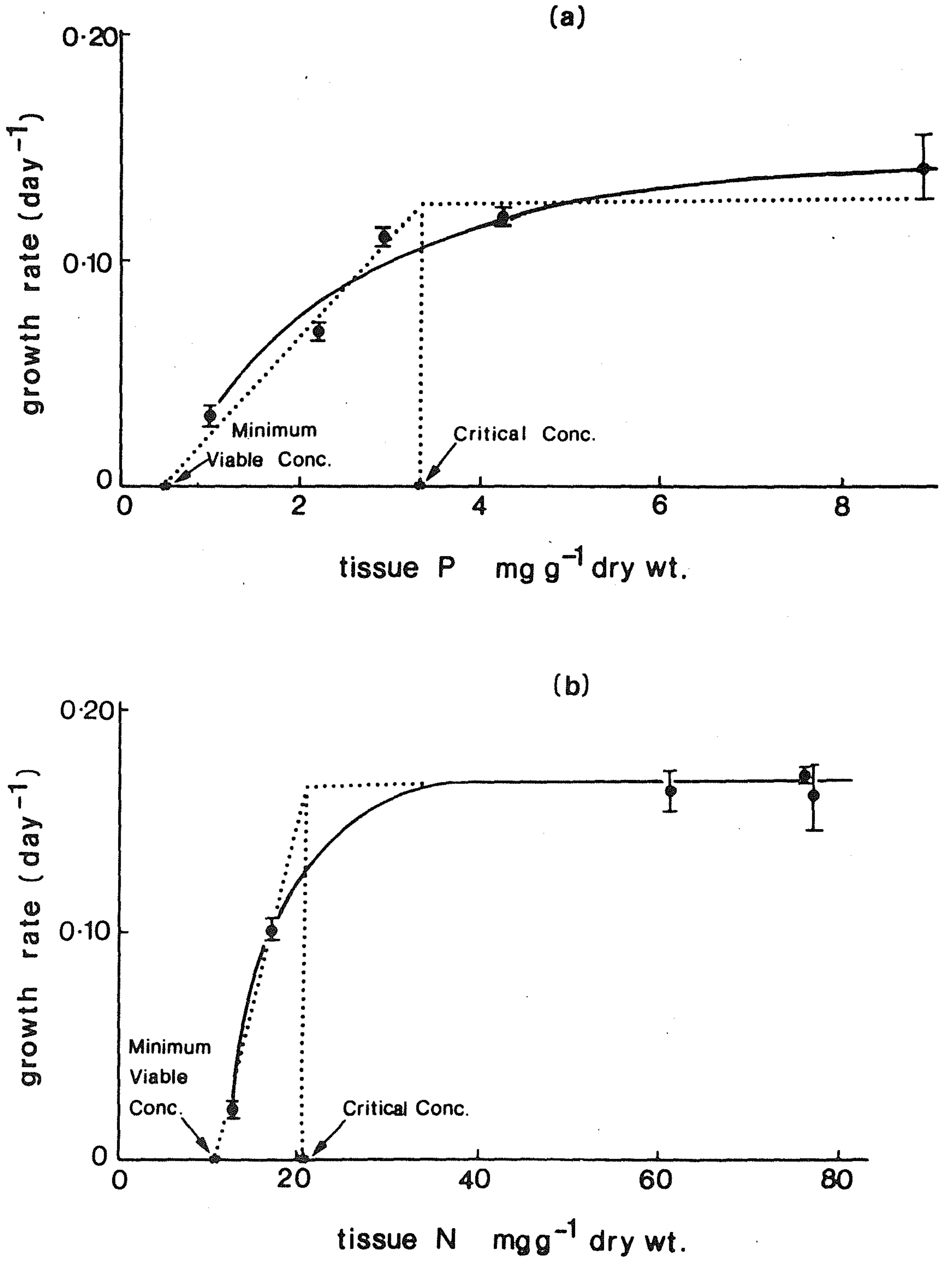
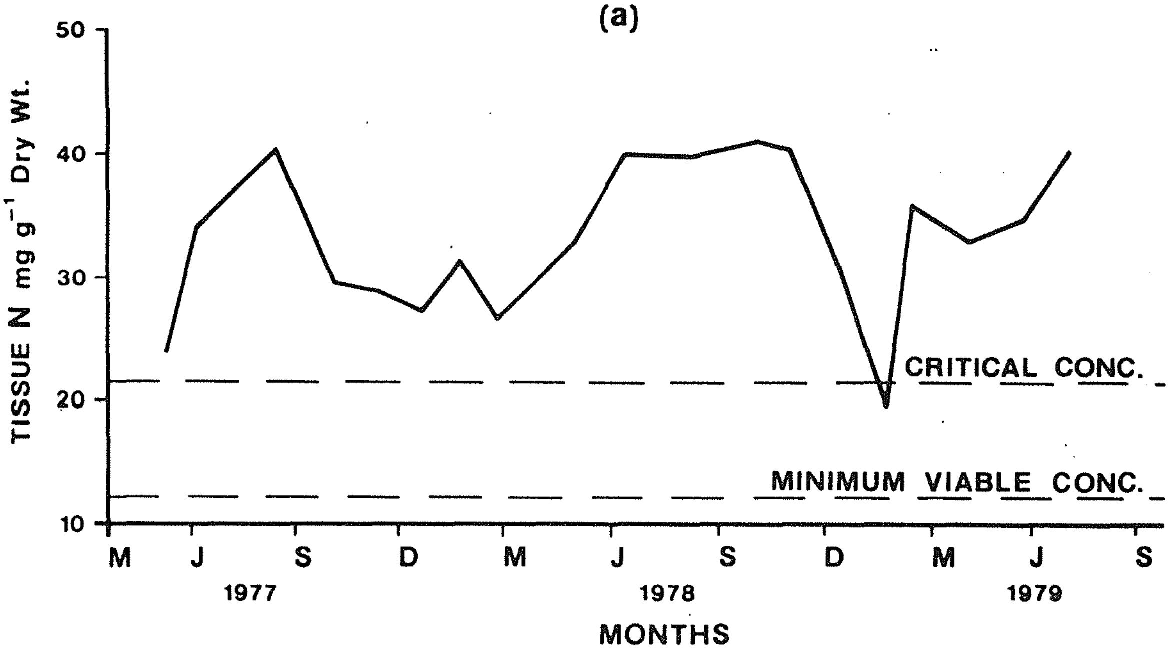


Figure 9.3: Growth rate of Cladophora as a function of (a) tissue phosphorus and (b) tissue nitrogen concentration.



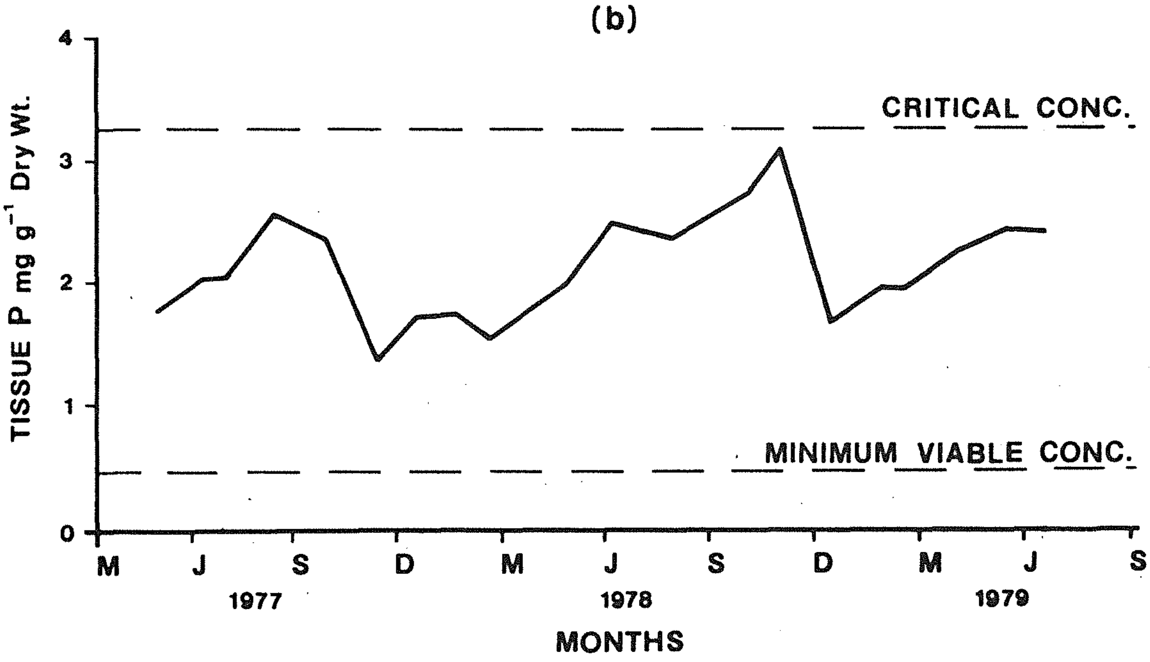


Figure 9.4 : Concentrations of (a) tissue nitrogen and (b) tissue phosphorus in Cladophora at site 4. The critical concentration is defined as the minimum tissue concentration which is associated with maximum growth rate. The minimum viable concentration is the tissue concentration at which there was zero growth (see Fig. 9.3).

The above discussion supports the conclusions of Chapter 5 (and of Spear and Hornberger 1980), and attest to the value of the speculative simulation approach in the preliminary analysis of environmental problems. Thus the results of the speculative N-budget modeling carried out early in the study in 1978, are in remarkable agreement with the laboratory and field measurements gathered later.

9.5 *Cladophora* Biomass Dynamics: Simple Data-Based Modeling

This *a posteriori* modeling of *Cladophora* biomass variation attempts to integrate all of the significant field- and laboratory-gathered knowledge of *Cladophora* physiology and ecology, as well as provide estimates of the mechanisms and rates of poorly understood processes. The model has developed through several versions (Humphries 1979, Humphries and Greenaway 1979, Greenaway, Humphries and Birch 1979). The earlier versions were deterministic, algebraic formulations, solved at a weekly time step. The simple algebraic structure has been retained, but has been rewritten in stochastic (Monte Carlo) form, so that the sensitivity of various parameters can be assessed, and the uncertainty in the model structure and parameters can be taken into account. The rationale and mechanics of Monte Carlo simulation is discussed in greater detail in Chapters 4 and 5.

Two other major changes have been made to the basic model versions of Humphries and Greenaway (1979) and Greenaway *et al.*, (1979). Firstly, a flotation sub-model has been incorporated which estimates *Cladophora* ball flotation from the algal bed during photosynthesis, and secondly, a flushing term obtained from the salinity-based estuary flushing model of Chapter 7, provides a mechanism for the transportation of *Cladophora*. The model's assumptions, structure, and the results of our sensitivity analyses and simulation runs are discussed in detail in the following sections.

9.5.1 Components of a *Cladophora* Growth Model

The complexity of a model should reflect the use for which it is designed. In this case, in order to be consistent with the study objectives, we have aimed to model the *important* properties of *Cladophora* and its environment as *simply as possible*, so that

1. the knowledge of *Cladophora* physiology and behaviour is summarized concisely, and the interactions between *Cladophora* behaviour and its present external environment may be examined;

2. the varying levels of uncertainty in that knowledge may be expressed in a stochastic (Monte Carlo) form;

3. the model adequately reflects the current behaviour of *Cladophora* in the field;

4. possible future scenarios for Peel Inlet may be examined in terms of their effects on *Cladophora* growth, in order that various management options (Chapter 10) may be assessed in terms of their probable effectiveness.

With these points in mind, let us proceed to define the components of an adequate *Cladophora* growth model for our present purpose.

Estuarine systems have marked seasonal fluctuations in variables such as temperature, salinity, light and nutrient concentration. The amplitude of these fluctuations exceeds the tolerance range of many marine organisms, which either do not occur in the estuaries at all, or are constrained to use them for limited periods of time (Hodgkin and Lenanton 1980). *Cladophora* obviously persists within Peel Inlet under all conditions, but its growth, flotation, migration and death processes may be strongly influenced by variation in the variables above.

A series of field and laboratory experiments by the Botany group, supplemented by more casual field observations, has examined the effects of the above variables on *Cladophora* growth. Gordon, Birch and McComb (1980) showed that light and temperature variation profoundly affected *Cladophora* photosynthesis, and probably growth; while Birch *et al.* (1981) provided direct evidence of strong temperature effects on growth rate. These findings are similar to those obtained from the speculative Monte Carlo simulations (Chapters 4 and 5). Gordon *et al.* also showed that salinity variations within the range typical of Peel Inlet have little effect on *Cladophora* photosynthetic rate, so the present model takes no account of salinity variation. The details of the modeled light-temperature-growth interaction are outlined in Section 9.6.1. The work of the Botany group (McComb *et al.*, 1980; Birch *et al.* 1981) has shown the importance of N and P, and has provided no indication of *Cladophora* growth limitation by the lesser nutrients. On this evidence, the present model treats only the effects of N and P on *Cladophora* growth, and the details of the mechanisms assumed are discussed in Section 9.6.2.

So far we have only considered the influences of the external environment on the growth of *Cladophora.* Losses of biomass from the Peel Inlet basin to the beaches are the most visible manifestation of the '*Cladophora* problem'. Losses of biomass from an active growth area may be due to at least three causes: senescence and subsequent decomposition *in situ;* grazing; and flotation then transport elsewhere within the estuarine system or to sea. The details of our assumptions on loss terms are given in Section 9.6.3.

Other potentially important components of *Cladophora* biology are ignored, or treated implicitly, in this model. For example, the speculative Monte Carlo model (Chapters 4 and 5) simulated a direct interaction between *Cladophora* and phytoplankton via two mechanisms. Firstly, suspended phytoplankton chlorophyll acted to reduce transparency of the water column, thus reducing the amount of light available to *Cladophora* on the bottom. This data-based model incorporates this effect within a term based on the estimated Photosynthetically Active Radiation (PAR) at the bottom, calculated empirically from observed extinction coefficient and global radiation data. Secondly, the speculative phosphorus budget model permitted direct nutrient competition between phytoplankton and *Cladophora.* This suite of models uses either directly measured tissue nutrient concentrations as an indicator of nutrient status, or calculates nutrient uptake and storage from measures of inorganic nutrient concentration in the water close to the *Cladophora* bed.

9.6 Structure of the Models

The basic logic of the algebraic (GROWMOD) growth models is shown in Figure 9.5. Three algebraic models of *Cladophora* growth have been developed, all of which simulate *Cladophora* biomass variation in the field, and to which various assumptions and spatial scales apply. Gordon, Birch and McComb (1981) have suggested models of *Cladophora* growth which attempt to describe the growth of individual *Cladophora* balls, or isolated fragments. Such models do not produce realistic simulations of *Cladophora* behaviour in the field, because no attempt to model algal loss processes has been made. The major differences between the Gordon *et al.* models and the GROWMOD models are

(a) GROWMOD is solved with a weekly, rather than hourly/daily time-step, because the available field-collected time series of *Cladophora* and environmental variables was only collected weekly;

(b) loss processes (decomposition and export) as well as importation of biomass to a growth area are considered by the GROWMOD model, but not by Gordon *et al.* (1981);

(c) sections of bed, or whole beds, are simulated by GROWMOD, rather than isolated *Cladophora* fragments. In this way, the important consequences of self-shading and decomposition of buried *Cladophora* balls are accounted for;

(d) a most important property of some GROWMOD models is that of stochastic (Monte Carlo) simulation. This technique enables all of the uncertain model parameters to be randomly varied within predetermined limits, and provides an objective method of model sensitivity analysis. The parameter ranges used in the GROWMOD stochastic simulations are given in Table 9.2.

All of the *Cladophora* models apply only to areas of the estuaries deeper than 0.5 m. In shallow water, wave action appears to prevent successful *Cladophora* colonization and growth, although not beaching

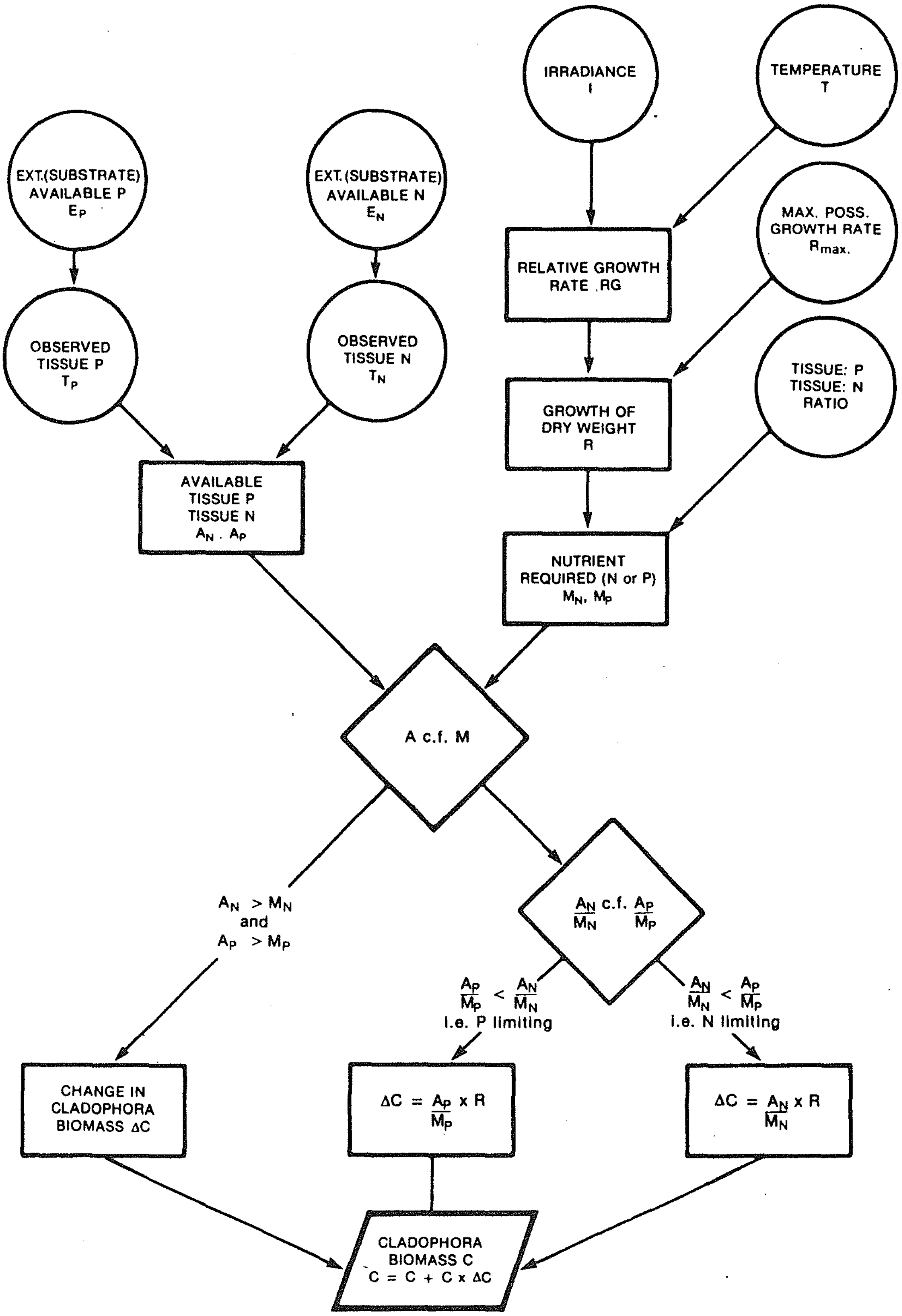


Figure 9.5 : Flow chart of the algebraic Cladophora growth model, GROWMOD

TABLE 9.2

Limits for the rectangular probability distributions for the parameters for Monte Carlo Simulation of the *Cladophora* Growth Model GROWMOD.MONTE

PARAMETER	SYMBOL	DESCRIPTION	RANGE OF VALUES			UNITS
1.	C	*Cladophora* biomass (dry wt.) (gm m^{-2})	50	to	400	$g.m^{-2}$
2.	PAF	bottom PAR fractional value	0.0	to	0.5	dimensionless
3.	FN	environmental nitrogen fractional value	0.0	to	1.0	dimensionless
4.	FP	" phosphorus fractional value	0.0	to	1.0	dimensionless
5.	VMAX	maximum possible growth rate per week	0.0	to	0.3	$week^{-1}$
6.	TN	initial tissue nitrogen concentration	0.04	to	0.041	$\mu g.g^{-1}$
7.	TP	" " phosphorus concentration	0.003	to	0.0035	$\mu g.g^{-1}$
8.	SMP	maximum permissible tissue phosphorus concentration	0.0095	to	0.0105	$\mu g.g^{-1}$
9.	SMN	" " " nitrogen "	0.07	to	0.09	$\mu g.g^{-1}$
10.	PN	nitrogen to tissue dry wt. conversion	0.009	to	0.015	dimensionless
11.	PP	phosphorus to tissue dry wt. conversion	0.0007	to	0.0013	dimensionless
12.	SN	minimum permissible (critical) tissue N concentration	0.009	to	0.015	$\mu g.g^{-1}$
13.	SP	" " " " P "	0.0007	to	0.0013	$\mu g.g^{-1}$
14.	SFL	suspended *Cladophora* loss rate per week	0.0	to	1.0	$week^{-1}$
15.	DR	decomposition rate per week	0.02	to	0.06	$week^{-1}$

and accumulation. All models predict good growth in the well-lit shallows under most conditions, because the effects of wave-induced disturbance of the bed are not considered.

The major GROWMOD programs are outlined below:

GROWMOD. TISMONT This program computes growth rate on the basis of *observed* field tissue nutrient concentrations, and is run as a Monte Carlo simulation. The model applies to 1 m^2 of *Cladophora* bed at any estuarine site supporting a viable *Cladophora* population.

GROWMOD. MONTE This program is substantially similar to TISMONT, and incorporates the added refinement of a substrate-to-tissue nutrient incorporation step. This refinement permits simulations of potential *Cladophora* growth within 1 m^2 at any site within the estuarine system for which a weekly nutrient and water column light time-series are available.

GROWMOD. COMP computes *Cladophora* biomass variation, migration and loss for all sites within the estuarine system, thus simulating the total estuarine population of *Cladophora*. This model incorporates a site-to-site biomass interaction matrix, which estimates biomass transfer by flotation and drift from one site to another, and its eventual loss, if appropriate.

Each of the above Monte Carlo models also exists in a simpler, deterministic form, which have been used mainly for the testing of modifications to the models. The structure and assumptions of the GROWMOD models are explained in the following sections.

9.6.1 The Light-Temperature-Growth Interaction

Values of light- and temperature-related coefficients have been taken from published data (Gordon *et al.* 1980, McComb *et al.* 1980) on the physiology of *Cladophora*. Idealised growth-temperature curves are assumed (Figure 9.6a) and growth is calculated as dry weight gain or loss.

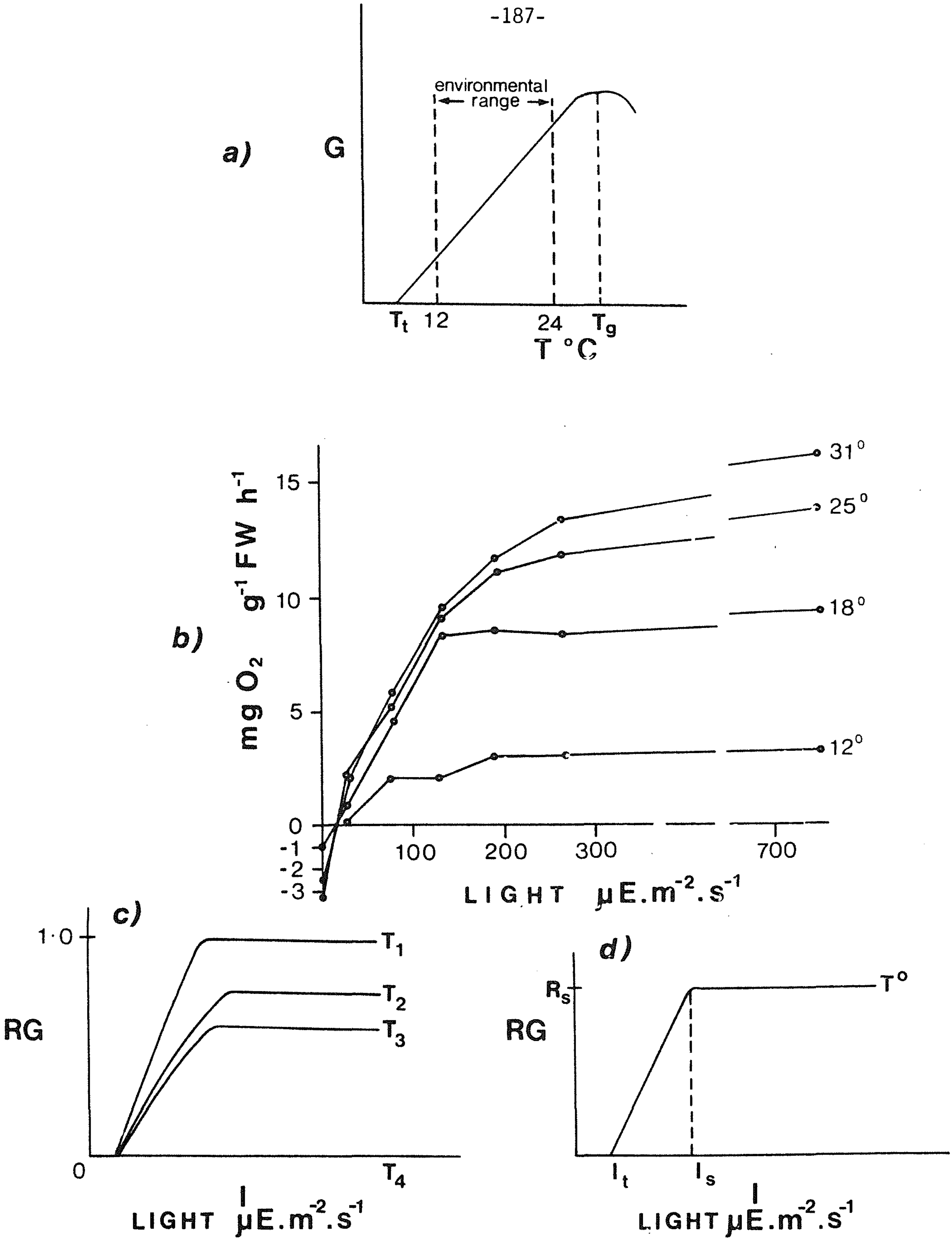


FIGURE 9.6 The light-temperature-growth interaction.
(a) Idealized temperature-growth relationship;
(b) Relationship between photosynthesis (as oxygen production) light and temperature (from Gordon *et al.* 1980);
(c) Idealized relationship between relative growth, temperature and light;
(d) The idealized relationship between relative growth and light at a fixed temperature.
See text for explanation of terms.

The symbols in Figure 9.6 are defined as follows:

G = growth rate (g. dry wt. m^{-2} day^{-1});

RG = relative growth rate

R_s = light-saturated relative growth rate

I = irradiance as PAR, $\mu E.m^{-2}.s^{-1}$;

I_t = light compensation point, 15-20 $\mu E.m^{-2}.s^{-1}$;

I_s = photosynthetic saturation point, 250-300 $\mu E.m^{-2}.s^{-1}$;

T = temperature, °C; (including T_1 - T_4)

T_t = minimum growth threshold temperature (developmental zero) ~4°C;

T_g = maximum growth temperature (31°C).

When the light-temperature curves are combined, as, for example, in Figure 9.6b, from Gordon *et al.*, 1980, the empirical data shown in Figure 9.6b may be expressed as relative growth (RG), rather than absolute growth, as shown in Figure 9.6c. The following assumptions are needed for the computation of relative growth rates:

(i) that maximum photosynthesis results in maximum dry matter production i.e., photosynthesis proportional to dry weight gain;

(ii) that maximum growth occurs at T_g, the maximum temperature for growth, and above or at I_s, the photosynthetic saturation point ignoring possible photoinhibition.

Growth rate is then expressed as a proportion (R) of maximum growth rate R_{max} (R_{max} = 0.195 day^{-1}), Gordon *et al.* (1981).

From the data in Figure 9.6b, the following 'lookup table' may be extracted (Table 9.3) relating temperature to saturating light intensities and relative growth rate.

TABLE 9.3

Values of Light-saturated Relative Growth Rate (R_s) Expressed as a Function of Saturating Light Intensity (I_s) and Ambient Temperature (T)

T°C	I_s $\mu E.m^{-2}.s^{-1}$	R_s
12	60	0.15
18	120	0.55
25	200	0.85
31	280	1.00

Note: $0 < R_s < 1$

The idealized relative growth rate (or photosynthesis) - light curve for a particular temperature is shown in Figure 9.6d where the ascending limb of the curve is linear, and the plateau at saturation is flat.

At any temperature not shown in Table 9.3, I_s and R_s are obtained by linear interpolation. The actual relative growth rate (RG) at this temperature and light intensity is obtained by linear interpolation between I_s and I_t. The final product of this analysis is RG or relative growth, i.e. the proportion of total growth possible (assuming no nutrient limitation) under these particular conditions of light and temperature.

9.6.2 Nutrient Uptake, Tissue Nutrient Dynamics and Nutrient Limitation of Growth

The problem of computing nutrient uptake is avoided in the simplest GROWMOD model, which simply uses observed field tissue nitrogen and phosphorus concentrations as input (see Figure 9.4). Relative nutrient limitation is determined by the *minimum* of the calculated relative growth rate from the curves shown in Figure 9.3.

Estimating nutrient uptake and storage from environmental nutrient time-series is complex. *Cladophora* is known to take up nutrients in excess of its immediate requirements ('luxury consumption'), and the relative importance of water column and sediment nutrients to the alga remains ambiguous. If the observed surface time-series of inorganic nitrogen and phosphorus in estuary water are used alone, the modelled *Cladophora* population declines rapidly due to nutrient shortage. This probably means that nutrient cycling is important for the maintenance of the benthic algal population.

There is, however, evidence for a prolonged period of high nutrient availability in the boundary layer of water surrounding the *Cladophora,* since secondary phytoplankton blooms occur in Peel Inlet after the main period of river discharge, and hence nutrient input. It is thought that sedimentation and decomposition of the early winter diatom blooms releases inorganic nutrients for algal growth. A similar phenomenon probably occurs in Cox Bay (or more widely), following the collapse of summer *Nodularia* blooms from Harvey Estuary.

The phytoplankton chlorophyll$_a$ time-series was used to estimate nutrient availability for *Cladophora.* One test of this assumption is the reasonable comparison between observed and simulated tissue nutrient time-series for each site shown in Figure 9.7.

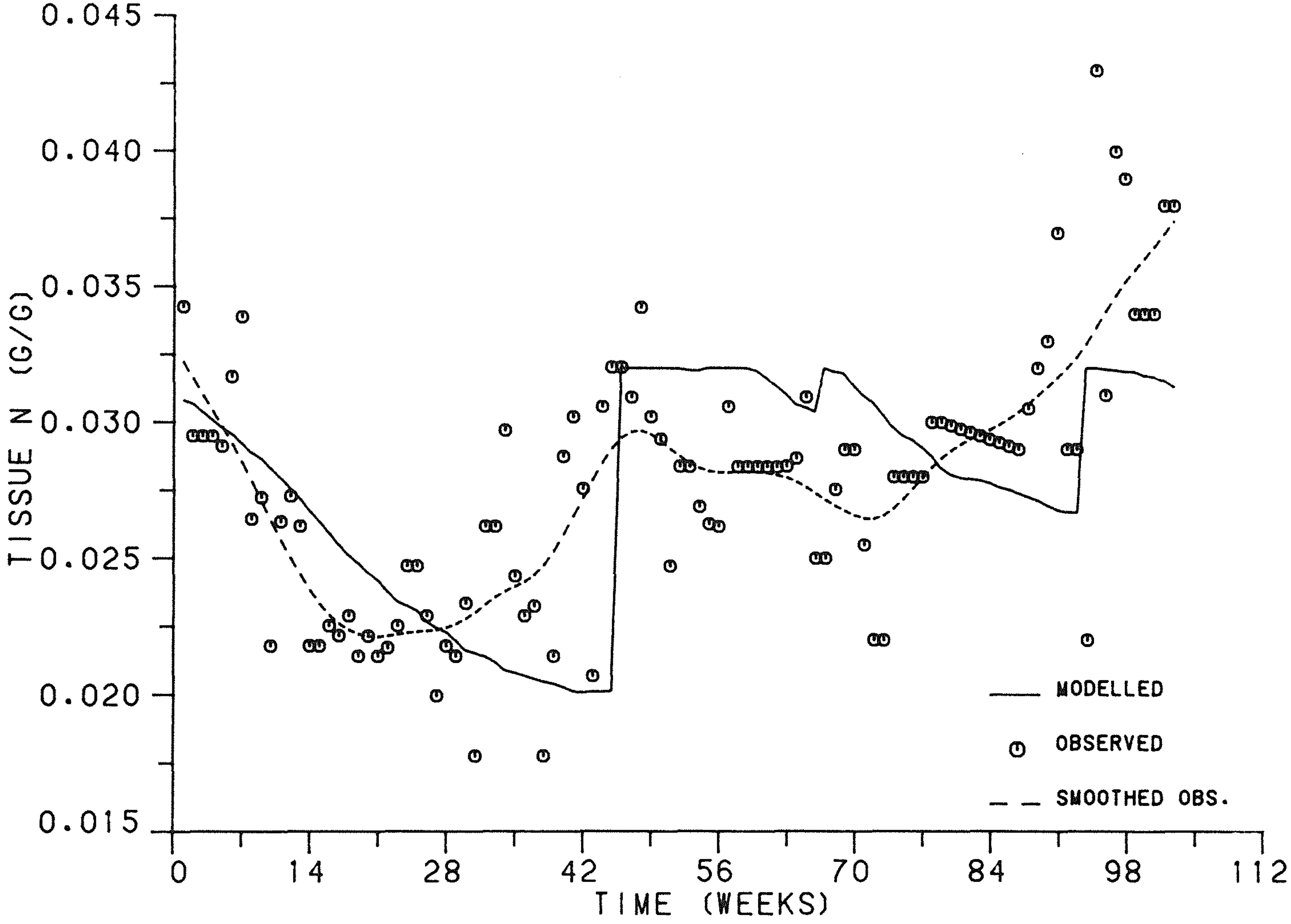
9.6.3 Decomposition and Flotation Losses of Biomass

Decomposition of buried *Cladophora* is a relatively well-known process (Gabrielson, Birch and Hamel 1980). For simplicity, the slope of the measured field *Cladophora* decomposition curve (Figure 9.8) was used as a rate constant for decomposition of all *Cladophora* buried out of contact with light.

Flotation losses were treated stochastically. An algorithm relating the amount of flotation to photosynthetic rate was developed, and then the floating biomass was subjected to a randomly determined, variable loss. In the case of models of 1 m^2 of bed, immigration and settlement of floating *Cladophora* is possible, as well as loss. For the whole inlet simulation, loss and transport show preferred directions, as inferred from the circulation directions in Figure 7.19.

It is possible that flotation due to entrapment of oxygen bubbles from photoshythesis in the algal balls is not the only mechanism

FIGURE 9.7 SITE 4 TISSUE NITROGEN



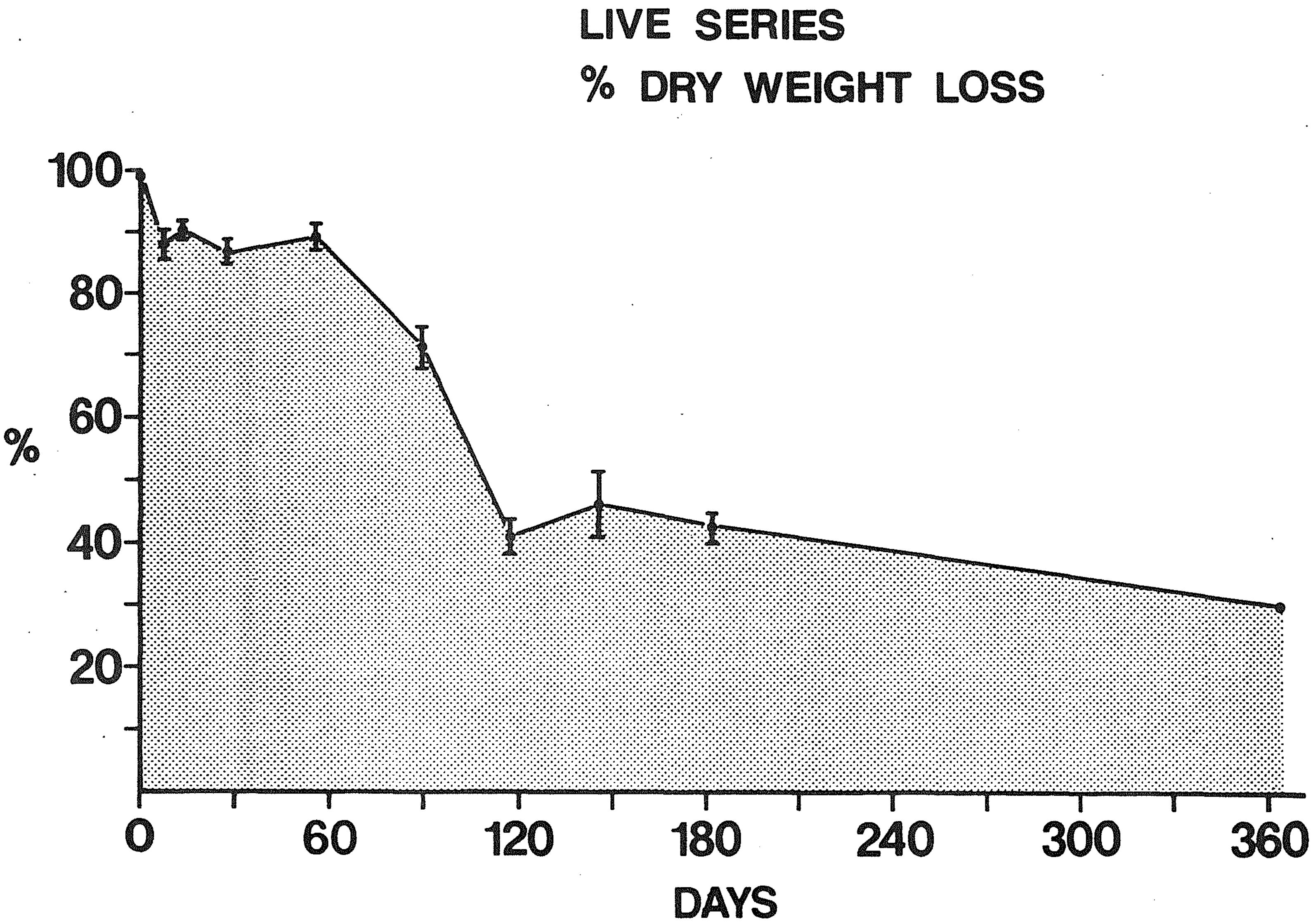

LIVE SERIES
% DRY WEIGHT LOSS
100
80
60
40
20
%
0
60
120
180
240
300
360
DAYS

Figure 9.8

(Gordon *et al.* 1981). Dark starvation of *Cladophora* results in a reduction of specific gravity, which would commonly occur in winter, as well as in buried populations. The present restriction of flotation to periods of photosynthesis may be unrealistic, therefore, since winter beaching of the alga does occur.

Loss, transport and resettling of *Cladophora* are without doubt the most poorly known processes in the life cycle of the alga, but the Monte Carlo simulations at least provide a reasonable method which allows for this uncertainty, and assists in the identification of the magnitude of loss processes in various parts of the estuarine system.

9.7 Simulation Results

Results of the modelling exercises have confirmed the conclusions summarized in Chapter 5, namely phosphorus-limitation of growth, and the importance of adequate levels of light and temperature for growth. The models support the importance of the winter nutrient input to the *Cladophora* beds of eastern Peel Inlet. In the absence of such inputs, tissue N and P concentrations run down, and growth during the following spring and summer is limited. The GROWMOD simulations indicate that decomposition and high export rates of *Cladophora* to the beaches and sea led to the decline of biomass observed during the study. This finding suggests that under conditions of prolonged turbidity (and low water temperature) *Cladophora* losses exceed gains, particularly when nutrient deficiency reduces the alga's ability to respond when conditions for growth ameliorate.

The good flows (and hence high nutrient loading) into the system in 1978 were followed by a summer *Nodularia* bloom in Harvey Estuary, which moved into Peel Inlet and severly reduced the availability of benthic light. This was followed in the winter of 1979 by poor flows and low nutrient availability. This combination of events drove the *Cladophora* population to low levels, and may be the precursor to summer phytoplankton blooms, rather than the domination of Peel Inlet by benthic algae. Alternatively, sedimentation of nutrients to the bottom by *Nodularia* blooms may lead to even greater benthic algal growth after the collapse of the bloom. Tissue nutrient and biomass data from Cox Bay support this hypothesis (Gordon, Birch and McComb

1981). Figure 9.9 shows the pattern of observed and modelled *Cladophora* biomass variation at site 4 over two years of the study. The modelled biomass variation does not show a particularly close agreement with the observed *short-term* variations in biomass. It should be noted, however, that the field measurements of *Cladophora* biomass were subject to great ambiguity and variation, due to the small scale, patchy distribution of the alga in the estuary basin. And we see that the pattern of long-term variation is captured adequately. This provides confidence in the ability of the model to describe the major aspects of *Cladophora* growth dynamics and is consistent with the objectives stated in section 9.5.1.

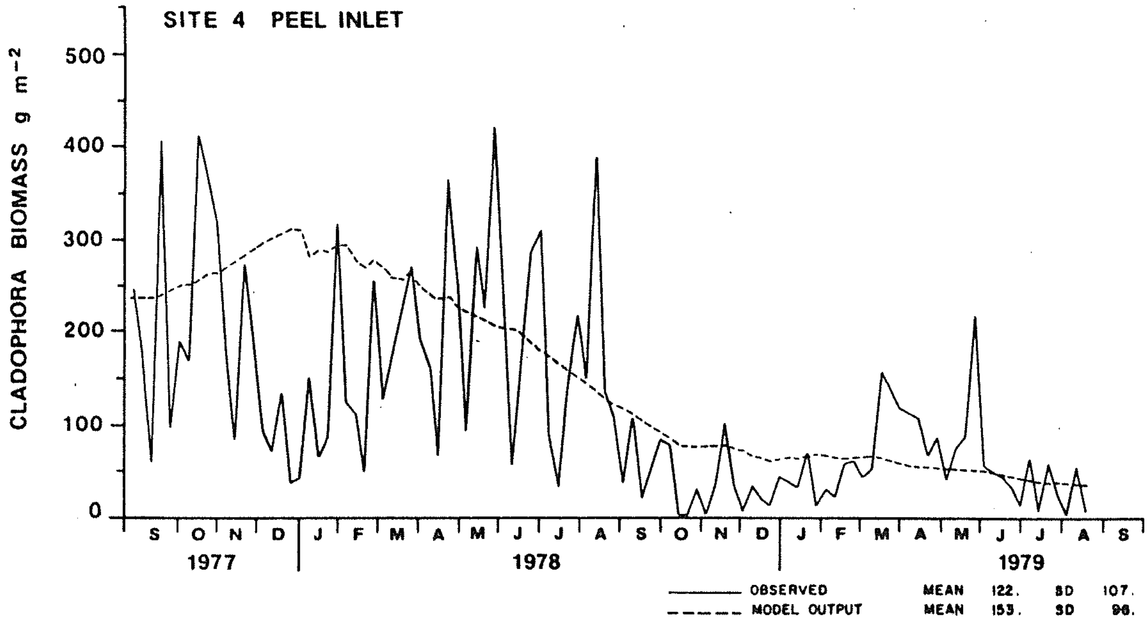


Figure 9.9 Comparison of observed and GROWMOD simulated biomass variation over two years at site 4.

10. THE MANAGEMENT PROBLEM

10.1 Introduction

A clear understanding of the mechanisms causing a particular problem is a pre-requisite for the economical solution of that problem. This study of the Peel-Harvey estuarine system was initiated because the accumulation of algae on the beaches is viewed as a problem, and yet a detailed understanding of the mechanisms causing excessive algal growth and deposition on beaches was not available (e.g. Cross 1974, Hodgkin 1978, 1979). Hodgkin (1979) listed a range of possible causes for the *Cladophora* problem. It is worthwhile restating this list, and commenting on the importance of these listed causes in the light of our current knowledge of the estuarine system.

(i) The peculiar characteristics of the *Cladophora* species involved appear to be an important factor in creating the algal nuisance.

Comment: The ability of *Cladophora* balls to float during active photosynthesis, and possibly as a result of specific gravity reduction due to tissue carbohydrate utilization (Chapter 9) makes *Cladophora* prone to transport in suspension, and to ultimate beaching. Other important macroalgae in the estuarine system (e.g. *Chaetomorpha linum*, *Enteromorpha* sp., *Hypnea* sp.) do not float as easily as *Cladophora*, and appear to be transported onto the beaches far less frequently in this low-energy system. *Cladophora* also tolerates a wide range of salinity (Gordon *et al.*, 1980), which enables it to survive well in this estuarine system, although this characteristic is probably shared by most other resident estuarine plant species.

(ii) Construction of the hills reservoirs has reduced direct river flow to the estuary.

Comment: Hodgkin (1979) states that any flow reduction due to damming has probably been more than compensated for by increased coastal plain runoff due to clearing and agricultural drain construction. Even if the amount of river flushing has been reduced, it should be noted that the rivers now bring the majority of the nutrient load into the Peel-Harvey system (Chapter 8), and have probably always done so. There is little evidence that Winter flows are of any use in removing significant amounts of nutrient already within the system, either mineralised as sediment, or bound as living biomass or detritus. On the contrary, the contemporary high nutrient concentrations in river water (Chapter 8, Humphries 1980) certainly supplement the estuarine nutrient pools, rather than deplete them. This comment is limited to the range of low to average flow conditions observed.

(iii) Growth of Mandurah and associated changes in water usage and sewage disposal have caused the algal problem, at least in the vicinity of the Coodanup flats (Sewell 1978).

Comment: Black and Rosher (1980) have shown that groundwater inflows to the Peel-Harvey system are a negligible component of the estuarine water budget, and they estimate that total nutrient input from groundwater in the 1978 water year was less than 1% of the total. The simple computation in Table 10.1 shows that even if *all* of Mandurah's sewage were diverted directly into Peel Inlet, it would still contribute a relatively small amount of nutrients compared with riverine nutrient inputs in the 1978 water year. Whelan, Barrow and Carbon (1979) investigated the movement of nitrogen and phosphorus from septic tank effluent in sandy soils near Perth, and showed that major losses of N and P occur during movement in groundwater, so that the estimates of possible sewage nutrient input in Table 10.1 are certainly extreme overestimates. Black and Rosher's (1980) measurements of groundwater nutrient concentrations are much lower than those of Whelan *et al* (1979) for septic tank effluent. Further, our knowledge of *Cladophora* nutrition and growth patterns (Chapter 9) strongly suggests that a significant level of continuous nutrient inputs into the Coodanup *Cladophora* growth area (Site 4) is inconsistent with the observed variation in its tissue nutrient concentrations.

TABLE 10.1

Comparison of estimated nitrogen and phosphorus loadings (tonnes) into the Peel-Harvey estuarine system during the 1977/78 water year, compared with those due to the hypothetical *direct* input of Mandurah's total sewage effluent.

Source	N (tonnes)	P (tonnes)
Murray River	1153	25
Serpentine River	116	22
Harvey and drains	317	73
Rainfall	4	0.8
Total	1590	121
* Mandurah Sewage	65	13.2
Sewage as % of total	4.09%	10.9%

* Assuming a population size of 12,000, and per capita N input of 5.45 kg year^{-1}, per capita P input of 1.1 kg year^{-1} (Whelan *et al* 1979).

(iv) Construction of training walls along the edge of the Inlet Channel near Mandurah in 1967.

Comment: As Hodgkin (1979) states, it is difficult to see how an *improvement* in tidal exchange can have made the estuary more eutrophic. Construction of the walls have prevented siltation of the mouth of the Inlet channel, and hence it permits continuous exchange with the Indian Ocean under conditions of no river flow. Previously the bar was breached by Winter flows, or by deliberate dredging. Continuous marine exchange may have improved water clarity, and permitted colonization of the Peel Inlet basin by a benthic alga, but it certainly would not have enhanced nutrient availability to the system.

(v) The higher rate of sediment disturbance by powerboat usage has enhanced sediment nutrient release, and hence availability for plant growth.

Comment: Disturbance of sediments may or may not release nutrients. Inspection of the current nutrient time-series of data (Chapter 8) shows that inorganic nutrient levels show little variation, except in Winter when dramatic increases in concentration occur. If boats were a significant cause of water column nutrient enrichment, Summer maxima (or at least peaks) in the nutrient concentrations should occur, rather than the presently observed Winter maxima.

(vi) There has been a contemporary increase in nutrient loadings to the estuaries from the predominantly rural catchments, and that these increases are due to current agricultural practices.

Comment: Artificial fertilizer usage has increased dramatically (Chapter 1, Figure 1.2) and there is strong evidence for a historical increase in estuarine eutrophication, with the coastal plain rivers carrying the major nutrient loads (Humphries 1980, Black and Rosher 1980, Chapter 8). Due to abnormally low river flows in 1979 (Black and Rosher 1980) it has proved difficult to precisely locate the major terrestrial sources of nutrient loading into the inflowing streams, although it seems that phosphorus is predominantly of coastal plain origin, whilst most nitrogen (in a normal to wet year) enters the Murray River in the plateau (wheat-belt) section of its catchment. Oxidised nitrogen is the dominant species of N, and probably comes from nitrogen-fixing pasture legumes. Large nutrient inputs during Winter flows

(Chapter 8) trigger heavy diatom blooms; and these, in addition to flocculation and direct benthic algal nutrient uptake, serve to trap and then sediment nutrients out of the water column, before they are lost to sea. Nutrient budget and phytoplankton uptake analysis (Chapter 8), combined with simulation of *Cladophora* growth dynamics (Chapter 9), shows that the observed levels of riverine nutrient input are sufficient to "explain" the growth and maintenance of the present Peel Inlet *Cladophora* population.

We conclude that the *Cladophora* problem exists in Peel Inlet due to:

(a) the availability of suitable habitat for *Cladophora* growth, primarily sheltered areas for the development of beds which also have an adequate benthic light environment (Chapter 9). The bottom of Harvey Estuary seems both too disturbed and too poorly-lit to support a significant *Cladophora* population;

(b) the relatively regular, but short-lived input of large quantities of essential plant nutrients to Peel Inlet. If high nutrient inputs were relatively continuous, as in Harvey Estuary, phytoplankton would be predicted to dominate Peel Inlet also (see Chapters 8 and 9 for amplification);

(c) the peculiar mechanical properties of *Cladophora*, particularly its ability to float and be transported in conditions of low water column turbulence, make it uniquely able to reach the beaches of Peel Inlet in sufficient quantities to be a nuisance.

Considering the above conclusions, the remainder of this Chapter will outline the management options available to force a decline of the *Cladophora* population, comment on their likelihood of success and, if possible, assess the possibility of deleterious consequences if any particular option is implemented.

10.2 Management Options

There appears to be four major options for the control of benthic macroalgae within Peel Inlet:

- direct removal of algae
- chemical manipulation of growth
- biological control
- reduction of nutrient availability

or some combination of the above. This is summarized in Figure 10.1.

10.2.1 Direct Removal of Algae

(a) Direct removal of beached algae is already practised by the PIMA collection of weed from Coodanup and Navarro beaches, and is unlikely to have any permanent effect for several reasons. Firstly, the algae removed originate by natural losses from the growth areas, although there is some chance that removal from the beaches prevents the return of nutrients released by decomposition to the living populations. Secondly, aerial and ground survey indicates that far greater amounts of algae are found further from shore, and are never removed by human efforts. Bulldozing beached algae also has deleterious effects on shoreline stability, tends to expose the roots of littoral trees, and greatly reduces the amenity of the beach while it is in progress.

(b) Dredging the growth areas to remove the weed, black ooze and superficial sediment may reduce nutrient availability for growth during periods of no river flow, although our most recent analyses indicate that deep sediment nutrients seem relatively unimportant in the annual growth cycle of *Cladophora* (Chapter 9). The role of the black ooze and interalgal water in *Cladophora* nutrition remain obscure at present. Dredging would certainly reduce a major source of stored N and P

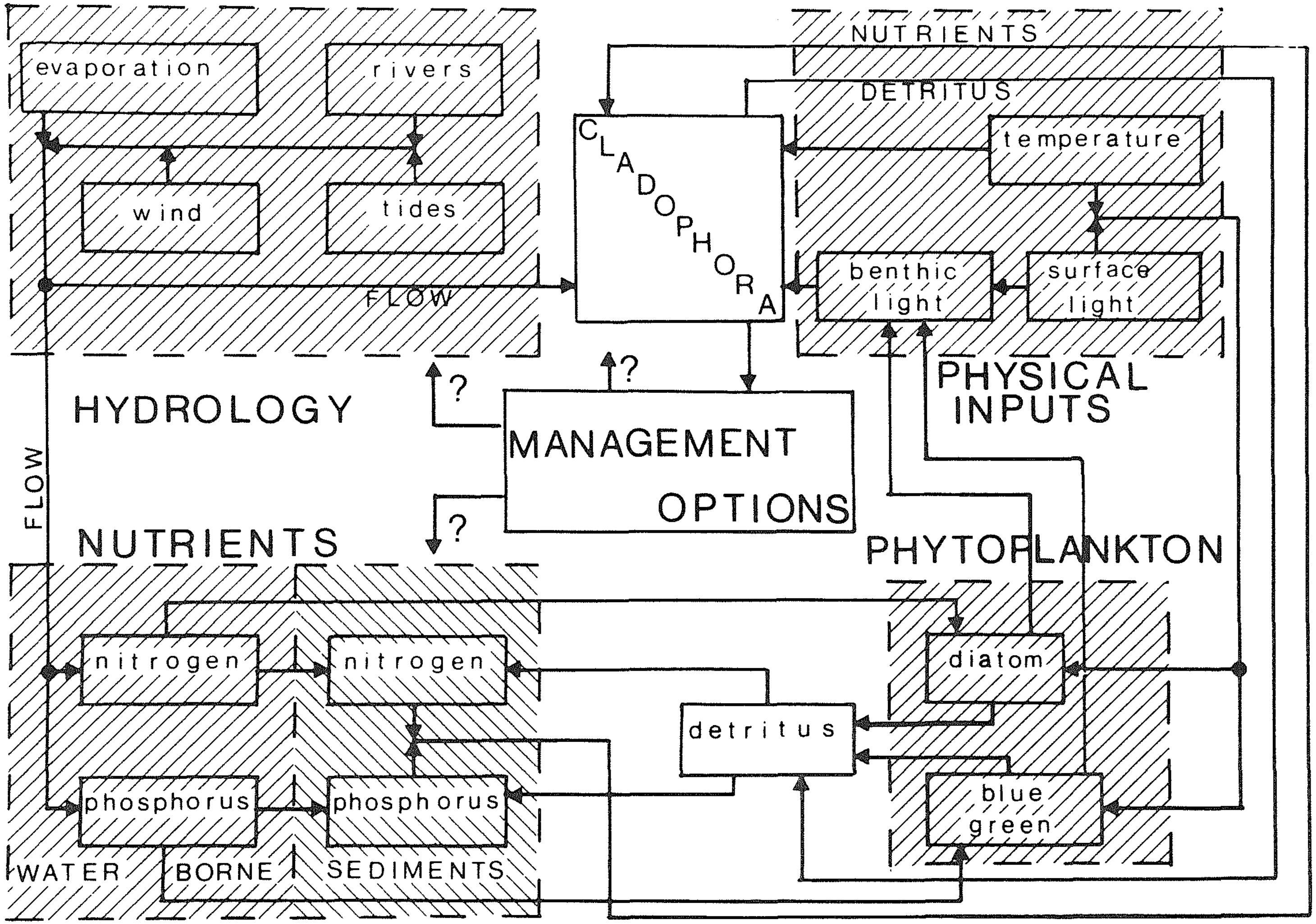


FIGURE 10.1 Weed Management Interactions Network

within the system (Chapter 8), and presumably affect the position of the sediment-water nutrient concentration equilibrium. The effectiveness of this method will depend on whether the findings of the Soil Science group confirm the apparent low importance of deep sediment nutrients for *Cladophora* growth, and on the practical problems of dredging rates and their cost. Further, as with the beach clearing of weed, this solution is not permanent, since riverine nutrient inflows would be expected to replace the dredged sediment nutrients in about 5 to 8 years (Chapter 8, Humphries *et al* 1980).

(c) Harvesting of *Cladophora* for sale as a soil mulch or stock-food additive is a superficially attractive idea, although it would entail considerable product and market development. An ideal harvesting mechanism would prevent or minimize *Cladophora* loss to the beaches, possibly by trapping clean, sediment-free *Cladophora* drift on mesh barrages, and then harvesting the weed from the barrages. The harvesting would probably be seasonal, during Spring and Summer, when the majority of *Cladophora* flotation and drift occurs. The possible advantages of commercial harvesting are: firstly, the operation *might* be financially self-sustaining; and secondly, it would cause minimal ecological changes to the system, because the natural "behaviour" and loss rates of the algae itself could be exploited to assist the harvesting procedure. In addition, harvesting as outlined above would not remove more *Cladophora* than is already lost by flotation and drift, and it should slowly deplete the system of *Cladophora*-bound nutrients, assuming that the present decomposition of weed *in situ* returns some nutrients to Peel Inlet. Of course, the practical success or otherwise of this management option depends upon its economic viability and its further consideration must include a detailed economic assessment (see Section 10.3).

10.2.2 Chemical Manipulation of Growth

Chemical manipulation of *Cladophora* growth with the use of herbicides (e.g. acrolein, paraquat, diquat; Mitchell 1978), or copper sulphate could be expected to have rapid effects, but at the risk of serious ecological damage to the estuarine system, and at a great cost. Another possible chemical treatment involves reducing benthic light availability with the use of soluble substances which strongly absorb the photosynthetically useful wavelengths (e.g. Aquashade). This method, although ecologically safer than herbicides, would require prohibitive amounts of chemical because of the large volume of Peel Inlet, and the great resistance of *Cladophora* to death and decomposition *in situ* (Gordon, ms. Birch and Gabrielson *pers. comm.*,Chapter 9).

10.2.3 Biological Control

Biological control might be applied to suppress *Cladophora* in various ways, either in the form of a specific predator, parasite or disease, or through nutrient competition by more vigourous aquatic plants. The major problems with any proposal for biological control are two-fold. Firstly, any predator or pathogen chosen must be absolutely specific for *Cladophora*, as with the *Cactoblastis-Opuntia* (prickly pear) system. Failure to ensure such specificity would be likely to result in the introduction of a potentially serious pest into the estuaries, as in the case of the ill-considered introduction of cane toads (*Bufo marinus*) to various sub-tropical parts of the world. Secondly, no predators or pathogens of *Cladophora* are known at present, and even if they were, years of evaluation would be required before they could be used.

D. Kidby has suggested that commercially-valuable agar-producing red algae (agarophytes) might be grown in Peel Inlet, in nutrient and light competition with *Cladophora*. This proposal might be worth serious commercial evaluation, but would again require considerable investigation and field trials. Further, agarophyte aquaculture would have to be carried out on a very large scale to seriously compete with *Cladophora*, and the highly seasonal input of nutrients to Peel Inlet would be likely to cause undesirable fluctuations in the productivity of the agarophyte crop.

10.2.4 Reduction of Nutrient Availability

Reduction of nutrient availability to the system has been proposed in a number of ways, which may be summarized under two major headings:

- Reduction of nutrient input.
- Enhancement of nutrient loss.

Neither general strategy is mutually exclusive of the other, so the various proposals are discussed together below.

It has been argued (Black and Rosher 1980, Chapter 8) that the majority of river-borne phosphorus entering the system originates on the coastal plain, whereas in average to wet years at least, most nitrogen comes from the wheatbelt sector of the Murray catchment. Further, much of the nitrogen might originate from pasture legume nitrogen fixation, rather than inorganic nitrogen fertilizer application, although this needs confirmation. This apparent geographic separation of the major N and P sources suggests that different methods are needed to significantly reduce inputs of either element.

Tissue nutrient analyses of *Cladophora* (Birch *et al* 1980; Chapter 9) indicate that phosphorus is relatively more limiting than nitrogen for *Cladophora* growth, and hence phosphorus reduction in the Peel-Harvey system seems more likely to reduce *Cladophora* growth. Also, under eutrophic conditions with relative N-limitation, cyanobacterial N-fixation is likely to occur, as was observed in Harvey Estuary during November 1978 (Huber and Kidby *pers. comm.*), which means that N-limitation is more difficult to achieve.

Three major options are possible for the reduction of nutrient loadings into the Peel-Harvey estuarine system and we will consider them in turn.

(a) Reduction of Soluble Fertilizer Application Rates

During January 1980 the Study Co-ordinator, Ernest Hodgkin, held a workshop to discuss the problem of phosphorus runoff from the coastal plain into the estuarine system (reported by Birch, 1980). The conclusions of that workshop are summarized more fully by Birch, but the main findings are summarized below:

- A survey of fertilizer application practices in the non-irrigated portion of the coastal plain catchment was reported by D. Kidby. Mean application of superphosphate was found to be 18kg/ha, and more work was needed to understand the pattern of P contributions from various parts of the coastal plain.

- J. Giumelli reported a similar farm survey in the irrigated Harvey area. Mean application rates were 38kg P/ha, 38kg N/ha, and 117kg K/ha. The P application rate was considered excessive, and reflected the high profitability of irrigated agriculture, and the relatively low cost of phosphorus fertilizers.

- J. Barrow reported that his research with Coolup Sands agriculture showed that these duplex soils suffer no yield reduction if P application is withheld for up to 3 years, although sulphur application was required annually. He stated that even though some P buildup occurred in Coolup Sands, leaching losses were high, and use of a less soluble (slower-releasing) source of P would be more efficient.

- W. Cox reported P leaching studies of various soil types within the coastal plain catchment, and reported that *no* leaching losses (± 20% accuracy) occurred from Coolup Sands. He stated that surface wash-off of fertilizer occurred, and that the Autumn P application tended to maximize surface P loss during the following Winter rains, particularly in irrigated areas. He suggested that a split Autumn and Spring P application combined with the use of a less soluble form of P (e.g. rock phosphate or dicalcium phosphate) would reduce both availability for plant growth and leaching losses.

There is little published work on the relationship of superphosphate granule size to the susceptability of surface wash-off. Increasing granule size might also reduce phosphorus loss to the drainage system.

There are two important points to note at this juncture. Firstly, the eastern Peel Inlet *Cladophora* population seems to be supplied with nutrients predominantly from the Murray-Serpentine System (Chapters 7, 8; Black and Rosher 1980), so that most attention will have to be given to controlling phosphorus from these rivers. Reduction in P supply to Harvey Estuary will improve water quality there, but is only likely to affect the northern Harvey and Falcon Bay *Cladophora* populations. Secondly, any reduction in P loading by changing agricultural practices is certainly worthwhile, if for no other reason than to conserve phosphorus, but it cannot be expected to quickly reverse the accumulated effects of 40 or more years of phosphorus fertilizer application.

(b) Prevention of Riverine and Drain Discharge into the Estuarine System

The complete prevention of river and drain discharge to the estuarine system would almost certainly cause a rapid reduction on aquatic plant growth in both Peel Inlet and Harvey Estuary; it would take at least a few years to achieve this reduction (Chapter 8), but it could result in greater hypersalinity in Summer than at present.

Table 10.2 contains provisional estimates of the range of annual salinity variation in the absence of river inflow into the system. These estimates were obtained by constraining the minimum water salinity to the marine salinity value of $35^{o}/oo$, and the estimates are based on the salinity models discussed in Chapter 7. These approximate results must be checked later by full constrained estimation, but they provide a reasonable idea of the system flushing characteristics.

The above approach has been applied to all sites in the Peel-Harvey System and the results are given below in Table 10.2. It should be noted that no significance should be read into the nominally smaller maximum salinity at site 7 (50) in relation to sites 2 (53) and 3 (52). The salinity variations at site 7 closely resemble those at site 2 and so the difference here is simply a function of the uncertainty in the estimation of the maximum salinities.

TABLE 10.2

PROVISIONAL ESTIMATES OF SALINITY VARIATIONS IN THE ABSENCE OF FRESH WATER INTRUSION

SITE	SALINITY RANGE (‰)
1	$35 < S < 78$
2	$35 < S < 53$
3	$35 < S < 52$
4	$35 < S < 57$
5	$35 < S < 70$
6	$35 < S < 57$
7	$35 < S < 50$
Average for Peel Inlet	$35 < S < 57$

This estimated salinity range would not be expected to grossly change the significant biological components of the estuarine system in themselves, but the resulting nutrient depletion would most likely lead to reductions in both primary and secondary production.

Diversion or damming of the Harvey River, and thereby reducing P loading due to this source has been proposed but for the reasons given above it seems unlikely that it would have much impact on the Peel *Cladophora* population. There are also proposals to dam the Murray River as a further source of water supply for Perth. Such a dam would capture any nutrients originating in the wheatbelt and hills sections of the catchment (and presumably itself become eutrophic), but would do nothing to reduce estuarine nutrient loads of coastal plain origin.

(c) Increase of Flushing Rates to the Indian Ocean

The above discussion indicates that a substantial diversion of river flow, and hence nutrient load, away from the estuarine system would, at best, be difficult and expensive. It would probably not achieve much suppression of *Cladophora* activity, unless the coastal plain drainage of the Murray-Serpentine system were altered.

Any method which increased nutrient loss to the Indian Ocean might, however, produce a beneficial reduction in *Cladophora*. There are two, possibly mutually inclusive, approaches to this:

- reduce the retention time of nutrients discharged during high river flows;
- increase marine flushing during the period of no river flow.

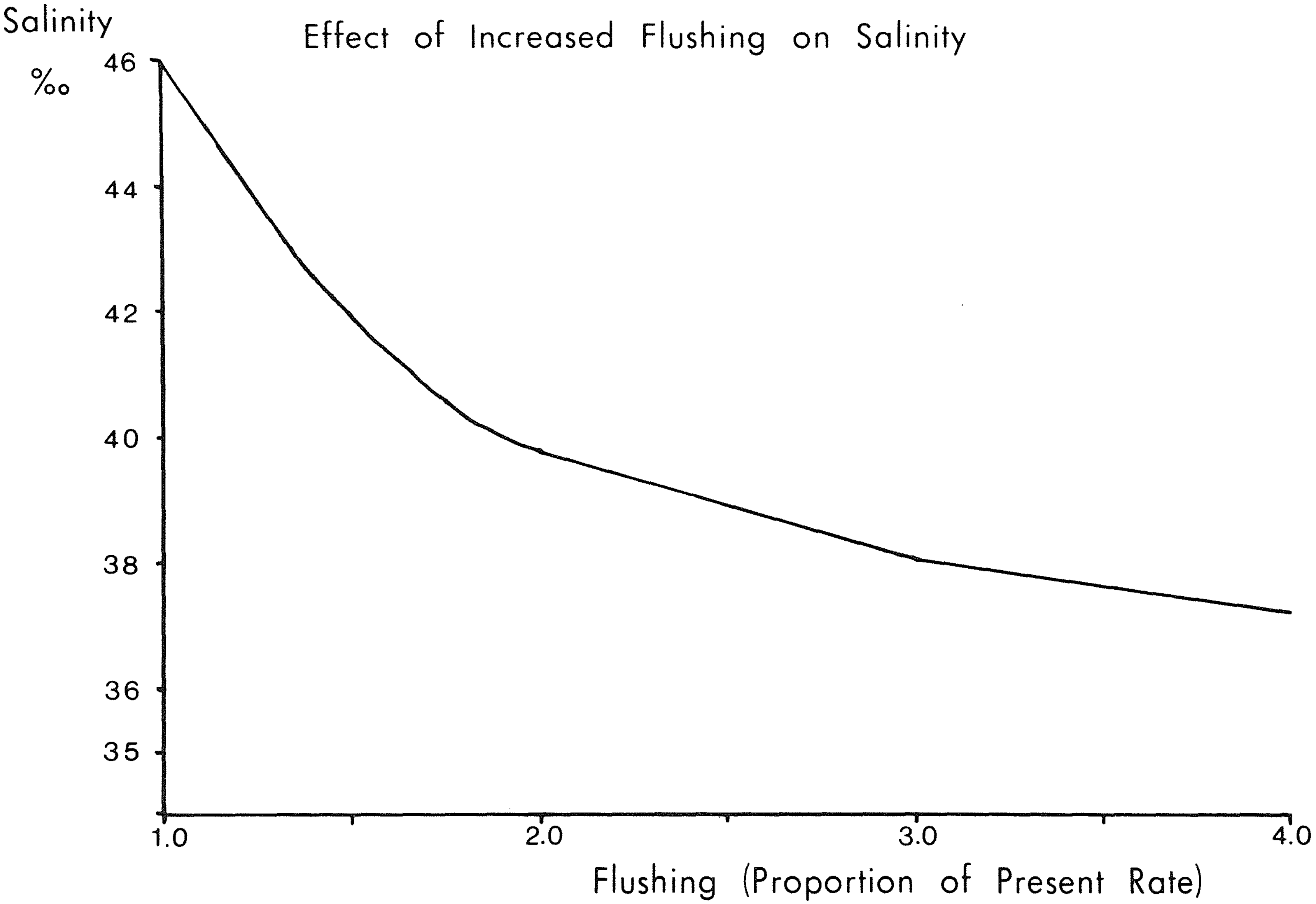
A simple analysis which attempts to estimate the effect of "short circuiting" Murray and Serpentine flows more directly to sea via a channel dredged across the northern shallows suggests that there could be up to 1/3 increase in flushing rate through such a bifurcated channel system than through the present system. It can also be shown that, on the basis of the salinity analysis presented in Chapter 7, this increase in flushing rate should result in a small decrease in maximum Summer salinities in the Inlet: for example, we estimate that maximum salinities at Site 4 (Coodanup) in the case of no river flow should reduce from the level of $53^{o}/oo$ predicted in Chapter 7 to about $50^{o}/_{oo}$ and, for a year such as 1978, the maximum salinity should reduce from the recorded levels of $46^{o}/_{oo}$ to about $43^{o}/oo$. Of course, more substantial modifications to the Inlet Channel could further increase flushing rate with consequent reductions in peak Summer salinities. Figure 10.2, for example, shows the estimated reductions in peak Summer salinities as a function of increasing flushing rate above present levels.

In addition to the reduction of maximum Summer hypersalinity, it has been suggested that the Murray-Serpentine channel would serve to flush weed accumulations out to sea. Neither Cyclone "Alby" nor river flows of the 1978 Winter noticeably disturbed weed banks within Peel Inlet or in the delta channels themselves, so it seems that only exceptionally high flows would be likely to achieve any degree of weed bank mobilization, if any at all.

Perhaps the greatest potential advantage of improved communication to the sea would be the enhancement of marine flushing and hence nutrient loss to the ocean, so that dissolved water column nutrients would be expected to more closely approach marine values. The effects of simulated nutrient reductions on *Cladophora* growth are discussed in Chapter 9.

Another more capital intensive possibility is to attempt improvement of flushing by introducing marine water into the south end of Harvey Estuary, as suggested by Imberger (*pers. comm.*). We investigated this possibility and simple analysis

FIGURE 10.2 Estimated Effect of Increased Flushing on Salinity



suggests that functional factors associated with this required an 8km long channel and would demand high energy expenditure which would almost certainly render such a scheme impractical. Again, these calculations need to be confirmed by more detailed engineering analysis, as would any other such engineering solution.

10.3 Economic Aspects : Cost-Benefit Analysis

It is important in assessing the physical management options for the control of the *Cladophora* problem (as for an assessment of any other public works programme) that the analysis go beyond pure technical feasibility in order to address the issues of the costs and benefits flowing to society from these physical management options. This is the province of economic analysis, in particular cost-benefit analysis, which seeks to identify that project, among a series of alternative uses of funds, which will maximise "net social benefit". The net social benefit of a project is defined as the difference between the social benefits of the project and its social costs. Consequently, the correct measurement of these benefits and costs is the central concern of cost-benefit analysis.

The results of a cost-benefit analysis are seldom definitive in the sense that a recommendation to proceed with a particular course of action is produced over which no disagreement can be expressed. This occurs because the results of the analysis depend on the assumptions made in it and these assumptions often deal with complex issues of human behaviour. If these assumptions are made explicit, as they should be, then the results can be discussed in relation to the underlying assumptions and the sensitivity of the results to changes in these assumptions can be examined.

Thus, cost-benefit analysis does not take the place of the decision maker, whose final role it is to decide on a project, since his judgements on the inputs to the analysis will be vitally important. Rather the function of cost-benefit analysis is to provide the decision maker with better information on which to base his decision and to help him identify the best alternative in a given situation. Even if the results are only roughly indicative of the relative differences in benefits and costs between alternative projects (as is often the case) some indication of these differences is better than none and can lead to better decisions being made on behalf of society.

As mentioned above, the correct measurement of the benefits and costs of a project forms the core of cost-benefit analysis. Without going into great detail, project benefits are measured by summing over all individuals affected by the project, the "willingness to pay" of each individual. Project costs are measured by opportunity costs: the income foregone by proceeding with the given project rather than the next best alternative. The measurement of both benefits and costs presents problems which are now briefly outlined.

In order to compare benefits and costs, both must be measured in the same units. The unit commonly chosen is money although any other numeraire could be used. Money is chosen since it is the usual medium of exchange in the community and therefore conveys more information on the relative values of different goods than would other possible numeraires. Various objections have been raised to the use of money to evaluate project benefits, especially where those benefits do not usually command a market price such as views of pleasant scenery and so on. These arguments are discussed in detail in Reynolds and Ulph (1979) and Ulph and Reynolds (1980). Suffice to say here that the evaluation of benefits in money terms is possible in principle, at least for the sort of benefits flowing from any management alternative undertaken to ameliorate the problems presented by *Cladophora* in the Peel-Harvey System.

The key problem in evaluating benefits in practice is to obtain a true valuation from the individuals concerned (i.e. to induce them to state their real value for the benefit). Commonly, this is done in a personal interview framework with the questioning designed to ensure that respondents do reveal their true benefit valuations. Lack of space prevents a detailed presentation of the different methodologies used. Freeman (1979) presents a good summary. One of the simplest methods is to ask respondents to nominate how much they would be willing to pay in, say, increased local government service charges in order to obtain some benefit. This approach is outlined below for possible use in analysing *Cladophora* management alternatives.

As far as the appropriate measurement of costs is concerned, difficulties arise when the resources to be used in the project are otherwise unemployed or underemployed. For example, some of the labour used may have previously been out of work. If this is the case, then appropriate adjustments can be made in the analysis to ensure that the project costs used truly reflect social costs.

A cost-benefit analysis takes future, as well as present, costs and benefits into account. The means of including future costs and benefits in a current decision is by *discounting* them to reflect the fact that individuals typically prefer to receive benefits now rather than later. Using any positive rate of discount means that future benefits and costs exert less influence on the analysis of the project than do present benefits and costs. Now, the discount rate used can have an important effect on the results of the analysis. A higher discount rate will tend to favour projects which incur low initial costs but which have higher operation and maintenance costs while a lower discount rate tends to favour projects with high initial costs and lower running costs. Because of the importance of the discount rate used it is important first, that the choice of the rates to be used is made in conjunction with the relevant decision makers; and second, that the results of the analysis be subjected to a stochastic sensitivity test using a range of discount rates to examine the robustness of the conclusions.

We now turn to discussing cost-benefit analysis as it might be applied to the assessment of alternatives for reducing the *Cladophora* problem in the Peel-Harvey System. The first step in any cost-benefit analysis is to identify clearly the sorts of costs and benefits to be measured. As far as costs are concerned, these can only be defined and examined after detailed engineering proposals have been established so they will not be discussed further here. However, some general comments can be made on the approach which would be needed to evaluate the benefits of any measures taken to relieve the *Cladophora* problem in Peel-Harvey.

Ideally, as a result of the modeling exercises undertaken, the effects of any management alternative on the *Cladophora* population should be identified. For example, decreasing the phosphorus input to the Peel Inlet from the Murray River by a certain percentage per annum might be shown to cause a consequent percentage decrease in *Cladophora* levels over each year. This is the *physical benefit* of the management programme which must then be expressed in terms of benefits which accrue to individuals in society.

This reduction in *Cladophora* levels could be expected to yield two sorts of benefits. First is what might be called a *production benefit*. For example, high levels of *Cladophora* in the Inlet result in excessive contamination of the beaches and the PIMA, responding to local pressure, have initiated programs of beach cleaning using bulldozers to collect the material and trucks to carry it away. Thus any amelioration of the *Cladophora* problem will lead to decreased local authority expenditures and a reduction in say, the local rates. Evaluating this benefit would involve questioning the local authority officials and ascertaining the savings that could accrue from reduction in *Cladophora*. Another example might be the effect of such reductions on the fishing industry. High *Cladophora* levels can cause disruptions to nets and so any reduction in algal levels could decrease the costs of the fishing industry with more net hauls per unit time together with less net breakage. Evaluating this benefit would involve questioning fishermen on the details of their operations in high algal concentration conditions and ascertaining corresponding information for the reduced algal levels resulting from any management initiatives.

Some production benefits may arise less directly: for example, the dredging of a diversion channel as discussed in section 10.2.4 may be beneficial not only in increasing flushing rates but also in providing better access for boats into the Inlet, and such benefits could be set against the high capital costs involved. Similarly, if excessive fertilizer usage is occurring then improved management practices will mean that substantial benefits could accrue both in reduction of farm costs and from conservation of fertilizers.

The second, and probably major, class of benefits to be evaluated might be termed *aesthetic benefits*. Here would be included the benefits of improving the smell and appearance of the area as well as the benefits of improving the comfort and convenience of negotiating beaches covered in less decaying algae than before.

A survey of the population affected by the *Cladophora* nuisance would be necessary to determine the level of this benefit. A sample of the population, perhaps stratified by distance from the inlet (on the assumption that the magnitude of the problem varies inversely with distance between the inlet and place of residence) would need to be drawn. Possible sample frames would be state electoral rolls, Australian Bureau of Statistics Census Collector District figures, or maps of the residential areas affected. Potential respondents would then be asked how much they would be willing to pay to have the *Cladophora* levels reduced by say 75%. In order to present this question in a realistic framework, the question could be posed in terms of a local government rate increase which could reasonably be presumed to be the means for financing any *Cladophora* management programme.

A different approach would be needed in surveying any day visitors to the area, i.e. those recreationers who do not live in the area but visit the inlet on a short term basis. Here the question could be posed in terms of (increased) boat launching fees or beach user fees or even (higher) parking fees (in effect beach user fees). The day user questionnaire would be administered to a sample of users chosen on some random basis.

The benefit evaluation surveys would best be conducted over a fairly wide time span encompassing periods when the *Cladophora* problem is evident and periods when it is not. This would avoid any upward or downward bias which might arise in the results depending upon whether the alga were present or not when respondents were interviewed.

Resulting from such surveys, an approximate value for the benefits of varying levels of reduction in *Cladophora* can be derived. These different values can then be compared to the costs of the management programmes which, if undertaken, would reduce *Cladophora* levels by the relevant amounts. In this way, it can be established on the basis of the benefits and costs of the various management alternatives which, if any, should be undertaken.

Since social cost-benefit analysis of the kind described above seems the only viable and relatively objective way of assessing the relative merits of different management alternatives, we have previously advised that such analysis should be part of the present Study. Unfortunately this has not been possible within the unavoidable funding constraints. *However, we urge that a thorough social cost-benefit exercise be initiated as soon as possible and certainly before any management decisions are taken.*

10.4 Conclusions

In conclusion, we feel that from a physico-biological standpoint, the most promising management alternative proposed to date is the introduction of better management practices in regard to the use of agricultural fertilizers together with some modification to the input channel, such as construction of a Murray-Serpentine diversion channel across the northern flats, provided this seems justified from a total cost-benefit standpoint. There is reasonable evidence that this would reduce input nutrient supply to some extent, divert a fraction of the remaining Winter nutrient inflow directly to sea with little return to the estuaries (Black and Rosher 1980), and enhance nutrient loss during periods of no river flow. The system should then tend towards oligotrophy (= nutrient shortage), and perhaps approximate its condition in the 1940's and 1950's. The major difference between this new state and the previously oligotrophic conditions would be that Peel Inlet would be somewhat more marine, and could be expected once again to support a relatively diverse biota (Treloar 1978), although possibly a lower total biomass than at present.

We recommend that this management approach should receive further consideration in the form of more detailed analysis, engineering feasibility studies and, as we discussed in the previous section, a thorough evaluation in social cost-benefit terms.

REFERENCES

ATKINS, R.P., GORDON, D.M., McCOMB, A.J. and PATE, J.S. (1977) *Botanical Contribution to the Peel-Harvey Estuarine Study.* Report to the Estuarine-Marine Advisory Committee, W.A. Dept. Conservation and Environment.

BACH, S.D., and JOSSELYN, M.N. (1978) Mass blooms of the alga *Cladophora* in Bermuda. *Mar. Poll. Bull.* 9, 34-37.

BARRETT, J.F., COALES, J.F., LEDWICH, M.A., NAUGHTON, J.J., and YOUNG, P.C. (1973) Macro-economic modeling: a critical appraisal. Proc. IFAC/IFORS Conference on *Dynamic Modeling and Control of National Economics,* IEE: London.

BEER, T., and BLACK, R. (1979) Water exchange in Peel Inlet, Western Australia. *Aust. J. Mar. Freshwater Res.,* 30, 135-141.

BEER, T., and YOUNG, P.C. (1980) On the characterisation of longitudinal dispersion in natural streams. Rep. No. AS/R42 (1980), Centre for Resource and Environmental Studies, Australian National University.

BIRCH, P.B. (1980) Phosphorus Export from Coastal Plain Catchments into the Peel-Harvey Estuarine System, Western Australia. *Dept. of Conservation and Environment Bulletin,* No. 99.

BIRCH, P.B., GORDON, D.M., and McCOMB, A.J. (1981) The nitrogen and phosphorus nutrition of *Cladophora* in the Peel-Harvey Estuarine System, W.A. *Botanica Marina* (in press).

BLACK, R.E., and ROSHER, J.E. (1980) The Peel Inlet and Harvey Estuary System Hydrology and Meteorology. *Dept. of Conservation and Environment Bulletin,* No. 89.

CHOW, V.T., ed. (1964) *Handbook of Applied Hydrology.* McGraw-Hill: New York.

COLLINS, P.D.K. (1974) *Murray River Basin, Surface Water Resources Survey.* Public Works Dept., Western Australia.

CROSS, W.J. (1974) A look at the pollution problems of Peel Inlet. *Aust. Mar. Sci. Ass. Bulletin,* 48, 7-9.

DELL, B. (1976) *Cladophora,* eutrophication and the Peel Inlet. *The Western Australian Naturalist.* 13(7), 172-173.

ELLIS, J., KANAMORI, S., and LAIRD, P.G. (1977) Water pollution studies on Lake Illawarra. *Aust. J. Mar. Freshwater Res.,* 28, 467-477.

FITZGERALD, G.P. (1970) Aerobic lake muds for the removal of phosphorus from lake waters. *Limnol. Oceanog.,* 15, 550-555.

FLEMING, G. (1975) *Computer Simulation Techniques in Hydrology.* Elsevier Environment Series: New York.

FOGG, G. (1966) The extracellular products of algae. *Oceanog. Mar. Biol. Ann. Rev.,* 4, 195-212.

FREEMAN, A.M. (1979) *The Benefits of Environmental Improvement,* Johns Hopkins University Press: Baltimore.

GABRIELSON, J.O. (1981) The Sediment Contribution to Nutrient Cycling in the Peel-Harvey Estuarine System. *Dept. of Conservation and Environment Bulletin,* No. 96.

GABRIELSON, J.O., BIRCH, P.B., and HAMEL, K.S. (1980) The Decomposition of *Cladophora. Department of Conservation and Environment Bulletin,* No. 92.

GODFREY, J.S. (1977) A scheme for studying Peel-Harvey Inlet, private communication to Dept. of Conservation and Environment.

GORDON, D.M., BIRCH, P.B., and McCOMB, A.J. (1980) The effect of light, temperature and salinity on photosynthetic rates of an estuarine *Cladophora. Botanica Marina,* 23, 749-755.

GORDON, D.M., BIRCH, P.B., and McCOMB, A.J. (1981) The ecology of *Cladophora* in the Peel-Harvey Estuarine System. *Dept. of Conservation and Environment Bulletin,* No. 91.

GREENAWAY, M., HUMPHRIES, R.B., and BIRCH, P.B. (1979) A simulation of *Cladophora* growth. Working Paper (Ms.), Centre for Resource and Environmental Studies, Australian National University.

HARRIS, D.O. (1971) Growth inhibitors produced by the green algae *Volvocaceae. Arch. Microbiol.,* 76, 47-50.

HEALEY, F.P. (1974) Inorganic nutrient uptake and deficiency in algae. *CRC Critical Reviews in Microbiology*, 3, 69-113.

HEALEY, F.P. (1978) Physiological indicators of nutrient deficiency in algae. *Mitt. Internat. Verein. Limnol.,* 21, 34-41.

HODGKIN, E.P. (1978) Progress reports on the Peel-Harvey Estuarine System Study, *Dept. of Conservation and Environment Bulletin,* No. 52.

HODGKIN, E.P. (1979) Seminar on Peel-Harvey Estuarine System Study, Department of Conservation and Environment, W.A.

HODGKIN, E.P., and LENANTON, R.C. (1980) Estuaries and coastal lagoons of South Western Australia, in B. Nielson and A. Cronin (eds.), *Nutrient Enrichment in Estuaries,* Humana Press: New Jersey.

HODGKIN, E.P., and VICKER, E. (1977) *A History of Algal Pollution in the Estuary of the Swan River,* Department of Conservation and Environment, W.A. (unpublished manuscript).

HODGKIN, E.P., BIRCH, P.B., BLACK, R.E., and HUMPHRIES, R.B. (1981) The Peel-Harvey Estuarine System Study (1976-1980). Report No.9, Dept. of Conservation and Environment, W.A.

HOLLING, C.S. (1978) *Adaptive Environmental Assessment and Management.* (Wiley for IIASA): New York.

HORNBERGER, G.M., and SPEAR, R.C. (1980) Eutrophication in Peel Inlet - I: The problem-defining behaviour and a mathematical model for the phosphorus scenario, *Water Res.*, 14, 29-42.

HUBER, A.L. (1980) Cyanobacteria and nitrogen fixation in the Peel-Harvey Estuarine System, *Dept. of Conservation and Environment Bulletin*, No. 94.

HUMPHRIES, R.B. (1978) Preliminary investigations of benthic algal distribution in the Peel Inlet Basin, Working Paper No. AS/WP4, Centre for Resource and Environmental Studies, Australian National University.

HUMPHRIES, R.B. (1979) Data based plant growth modeling of Peel Inlet: an introduction. Working Paper No. AS/WP9, Centre for Resource and Environmental Studies, Australian National University.

HUMPHRIES, R.B. (1980) Is eutrophication increasing in Peel-Inlet? Part 1: An analysis of river load-flow relationships. Working Paper No. AS/WP15, Centre for Resource and Environmental Studies, Australian National University.

HUMPHRIES, R.B., and HENDERSON, A. (1980) Is eutrophication increasing in Peel Inlet? Part 2: An analysis of salinity-nutrient concentration relationships. Working Paper No. AS/WP15, Centre for Resource and Environmental Studies, Australian National University.

HUMPHRIES, R.B., and GREENAWAY, M. (1979) A suggested structure for a simplified *Cladophora* growth model. Working Paper (Manuscript), Centre for Resource and Environmental Studies, Australian National University.

HUMPHRIES, R.B., and MICHELL, P.A. (1978) Peel-Harvey dye tracer/salinity studies, Part 1: Salinity/Rhodamine WT tracer study, Mandurah Channel and Peel Inlet, and Part 2: Rhodamine WT tracer study, Murray River. Working Paper, AS/WP1, Centre for Resource and Environmental Studies, Australian National University.

HUMPHRIES, R.B., BEER, T., and YOUNG, P.C. (1980) Weed management in the Peel Inlet of Western Australia, in *Water and Related Land Resource Systems*, Y. Haimes and J. Kindler (eds.), 95-103. Pergamon: Oxford.

IMBERGER, J. (1976) Dynamics of a longitudinally stratified estuary, *Proc. 15th Int. Conf. Coastal Engineering*, Hawaii, 3108-3123.

IMBERGER, J., BERMAN, T., CHRISTIAN, R.R., HAINES, E.B., WHITNEY, D.E., HANSON, R.B., POMEROY, L.R., WIEGERT, R.G., and WIEBE, W.J. (manuscript). The influence of water motion on the distribution and transport of materials in a salt marsh estuary. Submitted to *Limnology and Oceanography*.

JAKEMAN, A.J., and YOUNG, P.C. (1979) Refined instrumental variable methods of recursive time-series analysis, Part II: multivariable systems. *Int. J. Control*, 29, 621-644.

JANNSON, A.-M. (1974) Community structure, modelling an simulation of the *Cladophora* ecosystem in the Baltic Sea. *Contrib. Asko Lab. (No. 5)*. University of Stockholm, Sweden, (130pp.).

JANNSON, A.-M. (1975) Systems analysis and simulation of the green algal belt *(Cladophora)* in the Baltic. *Proc. 3rd Baltic Symposium on Marine Biology*, 239-247.

KALDOR, J.M. (1978) The estimation of parametric change in time-series models. M.A. Thesis, Centre for Resource and Environmental Studies, Australian National University.

KEEFER, T.N. (1976) Comparison of linear systems and finite difference flow-routing techniques. *Wat. Resources Res.*, 12, 997-1006.

KITTLER, J., and YOUNG, P.C. (1973) A new approach to feature selection based on the Karhunen-Loeve Expansion, *Pattern Recognition*, 5, 335-352.

KJERFVE, B. and MCKELLAR, H.N.Jr. (1980) Time series measurements of estuarine material fluxes. Estuarine Perspectives. Academic Press (in press).

LIKENS, G.E. (ed.) (1972) Nutrients and eutrophication: the limiting nutrient controversy. *Proc. Special Symposium Amer. Soc. Limnology and Oceanography*, Lawrence, Kansas.

LUKATELICH, R.J. (1978) Phytoplankton of the Peel-Harvey estuarine system. Honours Thesis. Dept. of Botany, University of Western Australia.

LUKATELICH, R.J., and McCOMB, A.J. (1980) The control of phytoplankton populations in the Peel-Harvey Estuarine System. *Dept. of Conservation and Environment Bulletin*, No. 93.

MITCHELL, D.S. (1978) Aquatic weeds in Australian inland waters. Dept. of Environment, Housing and Community Development. AGPS: Canberra.

MOSHIRI, C.A., and CRUMPTON, W.G. (1978) Certain mechanisms affecting water column-to-sediment phosphate exchange in a bayou estuary. *J. Wat. Pollut. Control. Fed.*, 50, 392-394.

McCOMB, A.J., ATKINS, R.P., BIRCH, P.B., GORDON, D.M., and LUKATELICH, R.J. (1980) Eutrophication in the Peel-Harvey Estuarine System, Western Australia. In B. Nielson and A. Cronin (eds.), *Nutrient Enrichment in Estuaries.* Humana Press: New Jersey.

OGATA, K. (1970) *Modern Control Engineering.* Prentice Hall: New Jersey.

PHILIP, J.R. (1975) Some remarks on science and catchment prediction, in *Prediction in Catchment Hydrology*, T.G. Chapman and F.X. Dunin (eds.). Aust. Acad. of Science: Canberra.

POPPER, K.R. (1959) *The Logic of Scientific Discovery*, Hutchinson: London.

PRICE, R.K. (1975) *Flood Routing Studies, Flood Studies Report, Volume III, Nat. Environ. Res. Council.* White Friars Press: London.

PROVIS, D.G. and RADOK, R. (1979) Sea-level oscillations along the Australian coast. *Aust. J. Mar. Freshwater Res.*, 30, 295-301.

REYNOLDS, I.K., and ULPH, A.M. (1979) An economic approach to national parks. *Search,* 10, 433-438.

ROCHFORD, D.J. (1951) Studies In Australian estuarine hydrology. Introductory and comparative features. *Aust. J. Mar. Freshwater Res.,* 2, 1-116.

SCHULZ, R. (1979) Water quality monitoring survey of the Mandurah Peel Inlet-Harvey Estuary. Report 21, Govt. Chem. Labs. W.A.

SEWELL, P.L. (1978) Weed pollution in the Peel Inlet, Western Australia, Internal Report, Div. of Land Resources Management, CSIRO, W.A.

SMITH, R. (1980) Buoyancy effects upon longitudinal dispersion in wide well-mixed estuaries, *Phil. Trans. Roy. Soc.,* A296, 467-496.

SPEAR, R.C. (1970) Application of Kolmogorov-Renyi statistics to problems of parameter uncertainty in systems design, *Int. J. Control,* 11, 771-778.

SPEAR, R.C., and HORNBERGER, G.M. (1978) Eutrophication in Peel Inlet: the analysis of behaviour and sensitivity of a poorly defined system, Rep. No. AS/R18, Centre for Resource and Environmental Studies, Australian National University.

SPEAR, R.C., and HORNBERGER, G.M. (1980) Eutrophication in Peet Inlet II. Identification of critical uncertainties via generalized sensitivity analysis. *Water Res.,* 14, 43-49.

STEEDMAN, R.K., and CRAIG, P.D. (1979) Numerical model study of circulation and other oceanographic aspects of Cockburn Sound. Report to the W.A. Dept. Conservation and Environment, R.K. Steedman & Associates, Subiaco, W.A.

STEVENSON, L.H., CHRZANOWSKI, T.H., and KJERFVE, B. (1980) Short term fluxes through major outlets of the north inlet marsh in terms of adenosine 5' - triphosphate, in P. Hamilton and K.B. McDonald (eds.), *Estuarine and Wetland Processes with Emphasis on Modelling.* Plenum Press: N.Y. (653 pp.).

THISSEN, W. (1978) Investigations into the World 3 Model: overall behaviour and policy conclusions, *IEEE Trans. Systems, Man and Cybernetics.* SMC-8, 172-182.

TRELOAR, J.M. (1978) Sediments, depositional environments and history of sedimentation in Peel Inlet, W.A., M.Sc. Thesis, Geology Dept., Univ. of Western Australia.

ULPH, A.M., and REYNOLDS, I.K. (1980) An economic evaluation of national parks, Rep. No. R/R4, Centre for Resource and Environmental Resources, Australian National University.

VOLLENWEIDER, R.A. (1968) Scientific fundamentals of eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Report DAS/CS1/68.27, (192 pp.), Organisation for Economic Cooperation and Development, Paris.

WEINMANN, P.E., and LAURENSON, E.M. (1977) Modern methods of flood routing. *Proc. of the Aust. Inst. Engnrs. Hydrology Symposium*, Brisbane, 136-140.

WELCH, E.B. (1980) *Ecological Effects of Waste Water*. Cambridge University Press.

WETZEL, R.G. (1975) *Liminology*. W.B. Saunders Company: Philadelphia.

WHITEHEAD, P.G., and YOUNG, P.C. (1979) Water quality in river systems - Monte Carlo analysis, *Water Resources Res.*, 15, 451-459.

WHITEHEAD, P., HORNBERGER, G., and BLACK, R. (1978) Effects of parameter uncertainty in a flow routing model. Rep. No. AS/R25, Centre for Resource and Environmental Studies, Australian National University.

WHELAN, B.R., BARROW, N.J., and CARBON, B.A. (1979) Movement of phosphate and nitrogen from septic tank effluent in sandy soils near Perth, Western Australia, in C.R. Lawrence and R.J. Hughes, (eds.). *Proc. of the Groundwater Pollution Conference*, Perth. *(Australian Water Resources Council Conference Series No. 1)*, 391-401.

YOUNG, P.C. (1968) Regression analysis and process parameter estimation: ... a cautionary message. *Simulation*, 10, 209-128.

YOUNG, P.C. (1974) Recursive approaches to time-series analysis. *Bull. Inst. Math. Appl.*, 10, 209-224.

YOUNG, P.C. (1975) The computer as a tool in socio-economic and environmental systems analysis, General Paper No. AS/GP1, Centre for Resource and Environmental Studies, Australian National University.

YOUNG, P.C. (1976a) The Peel-Harvey Estuarine System Study: Preliminary proposal for a systems contribution by Applied Systems Group, Centre for Resource and Environmental Studies, Australian National University.

YOUNG, P.C. (1976b) Some observations on instrumental variable methods of time-series analysis, *Int. J. Control*, 23, 593-612.

YOUNG, P.C. (1978) A general theory of modeling for badly defined systems, in *Modeling, Identification and Control in Environmental Systems*, G.C. Vansteenkiste (ed.), North Holland/American-Elsevier: Amsterdam/New York.

YOUNG, P.C. (1980) Mining and the natural environment: systems analysis and mathematical modelling, in S.F. Harris (ed.) *Social and Environmental Choice: the impact of uranium mining in the Northern Territory*. CRES Monograph 3, ANU Press: Canberra.

YOUNG, P.C. (1981) The validity and credibility of models for badly defined systems, to appear in M.B. Beck and G. van Straten (eds.), *Uncertainty and Forecasting of Water Quality*, IIASA/Pergamon: Oxford). Presented at *Task Force Mtg., Int. Inst. for App. Syst. Analysis (IIASA)*, Vienna, 1980).

YOUNG, P.C., and JAKEMAN, A.J. (1979) Refined instrumental variable methods of recursive time-series analysis, Part I: single input-single output systems. *Int. J. Control*, 29, 1-30.

YOUNG, P.C., and KALDOR, J.M. (1978) Recursive estimation: a methodological tool for investigating climatic change, Rep. AS/R14 (being revised) Centre for Resource and Environmental Studies, Australian National University.

YOUNG, P.C., and RENNIE, G. (1976) The modelling activities associated with the Western Port Bay Study, Rep. No. AS/R7, Centre for Resource and Environmental Studies, Australian National University.

YOUNG, P.C., SHELLSWELL, S.H., and NEETHLING, C.G. (1971) A recursive approach to time-series analysis, Report No. CUED/B-Control/TR16, Dept. of Eng., University of Cambridge, England.

YOUNG, P.C., NAUGHTON, J.J., NEETHLING, C.G., and SHELLSWELL, S.H. (1973) Macro-economic modeling: a case study, in *Identification and System Parameter Estimation,* P. Eykhoff (ed.), American Elsevier: Amsterdam, 145-166.

YOUNG, P.C., and WATERCRES Team (1977) The Peel-Harvey Estuarine System Study: initial suggestions for basic data collection programme and a proposal for additional special experiments, Centre for Resource and Environmental Studies, Australian National University.

YOUNG, P.C., HORNBERGER, G., and SPEAR, R. (1978) Modelling badly defined systems: some further thoughts, in P.G. Whitehead (ed.), *Simulation Modelling, Techniques and Applications. Proc. of SIMSIG-78: Simulation Conference, Australian National University,* Canberra.

YOUNG, P.C., JAKEMAN, A.J., McMURTRIE, R. (1980) An instrumental variable method for model order identification, *Automatica,* 16, 281-294.