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OXYGEN BALANCE IN AN AUSTRALIAN STREAM

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The University of New South Wales

Water Research Laboratory

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OXYGEN BALANCE IN AN AUSTRALIAN STREAM

by

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7. SUPPLEMENTARY NOTES

8. ABSTRACT Factors influencing the dissolved oxygen balance in a stream are examined within the context of the Australian environment. A mathematical description of the dissolved oxygen balance is developed using empirical equations extracted from the literature to supplement a hybrid of the basic kinetic formulations proposed by Dobbins (1964) and O'Connor (1967).

A computer model of the dissolved oxygen balance (OXSTRAL) has been constructed and shown to have considerable value as a means for predicting dissolved oxygen levels. Application of OXSTRAL is illustrated using data collected from Perisher Creek, an alpine stream located in the Kosciusko National Park.

As a result of the Perisher Creek investigations the need to conduct a sensitivity analysis of the model in order to assess the significance of natural variations and/or errors in the data input was evident. The principles underlying the sensitivity analysis are discussed and the value of the analysis as a method for ascertaining data requirements is demonstrated by example.

10. KEY WORDS dissolved oxygen, streams, numerical analysis, mathematical models, sensitivity, Perisher Creek, water pollution

11. CLASSIFICATION	12. NUMBER OF PAGES Approx. 130	13. PRICE

Acknowledgements

Preface

This report, representing work undertaken by the School of Chemical Engineering and the Water Research Laboratory of the University of New South Wales, is in two sections.

Part 1 describes a method to evaluate the significance of variables in the dissolved oxygen balance equation.

Part 2 is a detailed description of an attempt to simulate the dissolved oxygen distribution in an alpine stream and was submitted by J.K. Tuck to the School of Chemical Engineering as part of the requirement for the Degree of Master of Applied Science in Environmental Pollution Control.

PART 1

A SENSITIVITY ANALYSIS OF THE DISSOLVED OXYGEN BALANCE IN AN AUSTRALIAN STREAM

by

J.K. Tuck

and

R.G. Bowrey

Abstract

Following the use of a dissolved oxygen model in the investigation of the dissolved oxygen dynamics of an alpine stream (Part 2) the need to conduct a sensitivity analysis of the model in order to assess the significance of natural variations and/or errors in the data input was evident.

This section (Part 1) briefly describes the development of the numerical model (described in detail in Part 2) and then establishes the principles underlying the sensitivity analysis. The value of the analysis as a method for ascertaining data requirements is demonstrated by example.

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1. Introduction

The Australian national parks and wildlife reserves are generally virgin areas of bushland having an evolved ecology which responds to natural environmental changes in a way which ensures the survival of the established ecosystems.

As urban populations increase and existing recreational facilities become inadequate, the population is placing a greater emphasis on the national parks and wildlife reserves as a source of relaxation. Unfortunately the surge of interest in these areas is threatening the ecology in a variety of ways, one of which is the disruption of the purification mechanisms of natural streams due to the increased pollution loads, mainly in the form of partly treated sewage effluent.

It is unrealistic to attempt to completely prohibit development of these regions. Past experience has shown that unregulated development often leads to the eventual destruction of these assets so it is essential that integrated planning and environmental investigations be the forerunner to the establishment of recreational areas in parks and reserves.

To assist in the planning of development in bushland areas a computer program has been developed to simulate the dissolved oxygen distribution in a stream for typical Australian conditions. This program can be used to estimate the likely effect that a particular set of circumstances will have on a given stream. By determining the sensitivity of the model to variable movement one is able to identify the significant variables affecting the dissolved oxygen balance.

2. The Dissolved Oxygen Balance in a Stream

The dissolved oxygen distribution along the length of a polluted stream is a dynamic quantity dependent mainly on the formation of a balance between (a) the removal of oxygen by the biological oxidation of carbonaceous and in some instances nitrogeneous material and the respiration of aquatic flora, and (b) the addition of oxygen by atmospheric reaeration and photosynthesis.

The rate of biological oxidation of the carbonaceous material is generally interpreted as a first-order reaction in which the rate of oxidation is proportional to the remaining concentration of unoxidised substance. The effect of an increase in temperature is to increase the rate of bacterial activity and molecular contact such that the rate of biological oxidation is increased by 4.7% for each $1^{\circ}C$ rise in temperature (Nemerow, 1974). In addition, Theriault (1927) and Zanomi (1967) have reported that the ultimate biological oxygen demand is also temperature dependent increasing by approximately 2% per degree in the $20^{\circ}C$ region.

Where partly treated wastes are discharged into the stream and the stream temperature is in excess of $25^{\circ}C$ biological oxidation in the

form of nitrification may become important, and in some instances may dominate all other processes. In most temperate streams nitrification will not be apparent for ten or so days' flow time from the source of the pollution and even then may well be of little significance.

In some streams processes additional to carbonaceous and nitrogeneous oxidation may promote further oxygen depletion. Often these processes create a critical deficit at a fixed location independent of other parameters. For example, the deposition of suspended organic material will be followed by an increase in the benthal oxygen demand and a reduction in the oxygen content of the water in the region of deposition. Another source of oxygen depletion occurs where fixed plants or benthal algae are present. The respiration of this flora, particularly at night can result in a significant lowering of the oxygen level.

The rate of addition of oxygen by atmospheric reaeration is dependent on the hydraulics, the dissolved oxygen deficit (relative to the saturation level) and the temperature of the stream. An increase in turbulence caused by an increase in stream velocity or bed roughness, or a decrease in stream depth, will increase the rate of reaeration, A lower than 'normal' rate of reaeration will occur if the level of oxygen saturation is reduced due to a low barometric pressure (as would occur in alpine locations) or an elevated stream temperature. However, it should be noted that higher water temperatures increase the rate of molecular diffusion of gaseous oxygen in the surface film of water, and thus counteract the effect of reduced solubility.

The final contributing factor to the oxygen balance, the production of oxygen by photosynthesis, is dependent largely on the plant or algae biomass and the availability of light, which is influenced by the season, the topography, the atmospheric conditions and the turbidity of the water. Changes in the rate of photosynthesis may result in considerable fluctuations in the dissolved oxygen content of the stream.

3. Ecological Changes

High nutrient loadings, although not necessarily creating dissolved oxygen deficiences in the first instance, may in time lead to a state of ecological deterioration of the aquatic environment characterised by the replacement of a highly complex system of interdependent aquatic flora and fauna by a less diverse, more independent range of monocultures. This deterioration, generally known as eutrophication, leads to water quality problems, particularly where excessive weed growth, induced by the high nutrient levels, generates large diurnal changes in the dissolved oxygen level.

Consequently it is important to incorporate possible ecological changes, particularly changes in weed and algal densities, into the sensitivity analysis. An interesting example of an attempt to represent biological phenomena in a dynamic form is given by Fisher (1977) in a discussion of an ecosystem approach to the planning of Westernport Bay, Victoria.

4. The Oxygen Sag Curve

The dissolved oxygen balance between oxygen supply and deoxygenation in a stream is often expressed in the form of a plot of dissolved oxygen level as a function of streamflow time or distance downstream from a source of pollution. A detailed discussion of the significant aspects of this relationship is given in Part 2, Section 3.1, pp. 10-22.

5. Established Models

One of the first studies of the dissolved oxygen balance was the classical study of Streeter and Phelps (1925). This study considered carbonaceous oxidation and reaeration to be the only important factors. Other authors, notably Dobbins (1964), Camp (1963) and O'Connor (1967) recognised the limitations of the equation and so expanded the oxygen balance to include other sources and sinks of dissolved oxygen such as photosynthesis, sedimentation, bottom scour, surface runoff, nitrification and benthal demand.

6. Model Design Suitable for Australian Streams

A comprehensive equation has been formulated for Australian streams as outlined in Part 2, Section 5.2, p. 44 and, with reference to the nomenclature on page 6, takes the following form:-

$$D = \frac{K_1}{K_2 - K_r} \left(L_o - \frac{L_a}{K_r}\right) (e^{-K_r t} - e^{-K_2 t}) + \frac{K_3 N_o}{K_2 - K_3} (e^{-K_3 t} - e^{-K_2 t})$$

$$+ D_o e^{-K_2 t} + \frac{B_r}{K_2} (1 - e^{-K_2 t}) - \left(\frac{Ph2 - Pr2}{K_2}\right) (1 - e^{-K_2 t})$$

$$+ \frac{K_1 L_b}{K_2 K_r} (1 - e^{-K_2 t}) \tag{5.10}$$

7. The Computer Program (OXSTRAL)

See Part 2, Section 6, pp 45-56.

8. Sensitivity Analysis

In order to assess the significance of natural variations and/or errors in data used in the dissolved oxygen balance equation (represented by equation 5.10) it is necessary to determine the partial derivative of the dissolved oxygen level, C, with respect to all of the variables. Because of the complexity of equation (5.10) it is easier to do this numerically using the following technique.

Assume that

$$C = f(x_i)$$

where C, the dissolved oxygen level is equal to the difference between the saturation level and D, the deficit.   Therefore -

$$\frac{\partial C}{\partial x_j} = \frac{f\left((xr_i, x_j(1+c))\right) - f(xr_i, x_j(1-c))}{2 c x_j}$$

$$= s_j$$

where xr_i is the reference value of x_i, $j \neq i$,

and c is an arbitrarily selected increment.

Therefore the increment in C caused by an increment in x_j (expressed in terms of reduced variables $\frac{\Delta C}{C_0}$, $\frac{\Delta x_j}{x_j}$) is given by:

$$\Delta C / C_0 \cong \frac{\Delta x_j}{x_j} \frac{\partial C}{\partial x_j} \frac{x_j}{C_0} = \frac{x_j}{C_0} s_j \Delta x_j / x_j$$

Therefore if $x_j s_j / C_0$ is known the effect of say a 10% change in x_j can be seen to produce a $(10 x_j s_j / C_0)\%$ change in C.

Since $\qquad C = f(x_i)$

$$dC = \sum_1^n \frac{\partial C}{\partial x_i} dx_i$$

Therefore the cumulative effect of a $p_i\%$ variation in x_i is given by

$$\sum_1^n p_i x_i s_i / C_0$$

One disadvantage of this numerical approach is that the values of s_j can depend on the values of x_i selected. However, since one can normally make reasonable estimates of or alternately carry out some preliminary measurements it should not be difficult to select appropriate values which can be updated if this analysis indicates a strong dependence of C on a particular variable.

Analysis of the components of equation (5.10) indicates that C is for the most part dependent on 18 variables. Using typical values of these variables and c = 0.05, the results shown in Table 1 were obtained. Because of the diurnal variations in the stream environment the results are shown for typical day and night conditions.

For the stream and environmental conditions described by Table 1 it is apparent that a 10% increase in the value of the ultimate oxygen demand (L) would cause less than 0.4% decrease in C whereas a 10% decrease in solar insolation would lead to a 5% decrease in C. Therefore it is important to measure solar insolation accurately and to closely monitor its natural variations whereas a reasonably accurate value of ultimate BOD is good enough and moderate natural variations are of little significance.

It should be stressed that the results in Table 1 are to demonstrate the technique and that the program should be run using values of xr_i applicable to the stream under consideration before making judgements concerning that stream.

Table 1: Sensitivity of Variables in the Dissolved Oxygen Model based on a Sample Data Input

Variable	xr_i	Units	$\dfrac{x_j s_j / C_o}{I_o = 350}$	$\dfrac{x_j s_j / C_o}{I_o = 0}$
k_1	0.35	days^{-1}	-0.034	-0.034
k_3	2.50	days^{-1}	-0.084	-0.084
L	250.00	mg/l	-0.034	-0.034
N	100.00	mg/l	-0.084	-0.084
I_o	350.00	cal/cm^2/day	0.426	-
b_5	0.03	-	-0.002	-0.002
C_o	10.00	mg/l	0.781	0.781
k_4	0.05	days^{-1}	0.00	0.00
a_3	0.135	-	0.501	-
a_4	0.850	-	1.616	-
b_1	0.001	-	-0.112	-0.112
b_2	0.300	-	-0.077	-0.077
P_b	690.0	in. of Hg	0.018	0.018
a_5	0.03	-	-0.001	-0.001
T	12.0	^{o}C	-0.252	-0.110
X	1000.0	m	-0.118	-0.118
Q	0.175	m^3	-0.0794	0.124
M	125.0	g/m^2	-0.112	-0.112
B_r	0.005	g/m^2/h	0.00	0.00

9. Conclusions

The sensitivity analysis is a valuable method of ascertaining the significance of natural variations and/or errors in the data input to a numerical model of the dissolved oxygen balance. Undertaking such an analysis should be viewed as a prerequisite to the design of a data collection program needed for the more comprehensive study of dissolved oxygen distribution along the length of a stream.

10. Nomenclature

a_3, a_4, a_5)
b_1, b_2, b_5)
coefficients in the relationships describing the rate of oxygen production by photosynthesis and the rate of oxygen consumption by plant and benthal respiration.

B_r	benthal oxygen demand
c	sensitivity analysis increment
C	dissolved oxygen level at time t
C_o	dissolved oxygen level at t = 0
D	dissolved oxygen deficit at time t
D_o	dissolved oxygen deficit at t=0
D	dissolved oxygen deficit at time t
e	Naperian logarithm base (=2.718)
i	1, n
I_o	solar radiation intensity (insolation)
j	1, n
K_1	rate constant for carbonaceous oxidation
K_2	reaeration coefficient
K_3	rate constant for nitrogeneous oxidation
K_4	coefficient for the removal/addition of B.O.D. by sedimentation/resuspension
K_r	$K_1 + K_4$
L	ultimate carbonaceous oxygen demand (U.B.O.D.)
L_a	rate of addition of U.B.O.D. along the reach
L_b	rate of U.B.O.D. addition from benthal deposits
M	biomass of rooted plants
n	number of independent variables
N	ultimate nitrogeneous oxygen demand at time t
N_o	ultimate nitrogeneous oxygen demand at t = 0
p	percentage change in x
Ph_2	oxygen production due to photosynthesis
Pr_2	oxygen consumption by plant respiration
P_b	barometric pressure
Q	streamflow
s	$\partial C / \partial x_j$
t	time

T	stream temperature
x	independent variable
xr	reference value of x

11. References

Fisher, I.H. (1977) An Ecosystem Approach to the Planning of Water Pollution Control, Environmental Engineering Conference, 1977, Canberra 15-17 June 1977. The Institution of Engineers, Australia, National Conference Publication No. 77/4.

Nemerow, N.L. (1974). Scientific Stream Pollution Analysis. New York, McGraw-Hill.

Further references are listed in Part 2.

Part 2

A METHOD TO PREDICT THE DISTRIBUTION OF
DISSOLVED OXYGEN IN AUSTRALIAN STREAMS

by

J.K.Tuck

Preface

This study, partly funded by the Australian Water Resources Council, was undertaken to develop a method to predict the distribution of dissolved oxygen in Australian streams and is part of a wider investigation of water quality problems arising from human visitation in the National Parks of New South Wales.

The need for such an investigation became evident during the course of preliminary work carried out by the School of Chemical Engineering of the University of New South Wales in conjunction with the National Parks and Wildlife Service. Investigations (Stinson 1974) have shown that Perisher Creek, which flows through the popular ski resort area of Perisher Valley in the Kosciusko National Park suffers from severe bacterial contamination. Using Perisher Creek as the focal point, a program to investigate the various health and ecological effects resulting from the pollution of National Park streams was formulated.

This report represents a critical aspect of the investigation program. By developing a method to predict the dissolved oxygen levels of such streams over an established range of conditions, it will be possible to determine the degree of pollutant control required to avoid ecological damage to the stream.

Abstract

Factors influencing the dissolved oxygen balance in a stream have been examined within the context of the Australian environment. A mathematical description of the dissolved oxygen balance has been developed using empirical equations extracted from the literature to supplement a hybrid of the basic kinetic formulations proposed by Dobbins (1964) and O'Connor (1967).

A computer model of the dissolved oxygen balance (OXSTRAL) has been constructed and shown to have considerable value both as a means for predicting dissolved oxygen levels and for evaluating the most significant parameters affecting the dissolved oxygen distribution. Application of OXSTRAL was illustrated using data collected from Perisher Creek, an alpine stream located in the Kosciusko National Park.

The most significant conclusions of this study are that -

(i)   OXSTRAL presents itself as a convenient method of assessing data requirements and frequency of measurement;

(ii)   providing sufficient field data are available the satisfactory prediction of dissolved oxygen levels for a variety of hydrological and climatological conditions is possible using OXSTRAL;

(iii) dissolved oxygen levels in Perisher Creek will be maintained at satisfactory levels providing aquatic growth and the inflow of oxygen-deficient surface or groundwater do not greatly exceed present levels.

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Nomenclature

a	the interfacial area/unit volume	cm^{-1}
a_3	photosynthesis coefficient	-
a_4	" "	-
a_6	" "	-
a_8	" "	-
a_5	benthal demand coefficient	-
AK_4	coefficient for the removal of BOD by sedimentation or the addition by resuspension	$days^{-1}$
A_r	oxygen production due to atmospheric reaeration	$g/m^2/h$
b_5	benthal demand coefficient	-
B_r	quantity of oxygen consumed by mud deposit	$g/m^2/h$
C_o	initial oxygen concentration	mg/l
C	oxygen concentration after time t	mg/l
C_s	dissolved oxygen concentration at saturation	mg/l
Ch	mean chlorophyll content	mg/l
D_o	initial dissolved oxygen deficit ($C_s - C_o$)	mg/l
D	dissolved oxygen deficit at time t	mg/l
D_m	coefficient of molecular diffusion	ft/day
D_B	rate at which oxygen is removed by benthal and plant respiration less that supplied by photosynthesis	mg/l/day
e_c	extinction coefficient	m
F	Froude number ($= \overline{V}/\sqrt{gH}$)	-

H	mean depth of flow	m
I	intensity of solar radiation at the water surface	$cal/cm^2/h$
I_o	mean daily solar intensity	$cal/cm^2/day$
K_1	rate constant for biological oxidation (20^oC)	$days^{-1}$
$(K_1)_T$	value of K_1 at T^oC	$days^{-1}$
K_2	reaeration coefficient, natural log base	$days^{-1}$
k_2	reaeration coefficient, common log base	$days^{-1}$
$(K_2)_T$	reaeration coefficient at T^oC	$days^{-1}$
K_r	BOD removal coefficient (K_1+AK_4)	$days^{-1}$
K_3	nitrification rate coefficient	$days^{-1}$
K_L	liquid film coefficient	cm/s
L	ultimate biological oxygen demand at time t	mg/l
L_o	initial ultimate biological oxygen demand (20^oC)	mg/l
$(L_o)_T$	initial ultimate biological oxygen demand at T^oC	mg/l
L_f	film thickness	ft.
L_a	rate of addition of BOD along the reach, including the addition of BOD with run-off, the diffusion of partly degraded waste from the benthal layer and the scour and resuspension of bottom deposits	$mg/l/day$
m	biomass of rooted plants	g/m^2
N	ultimate nitrification demand at time t	mg/l
N_o	initial ultimate nitrification demand	mg/l

N_h number of hours in the day during which a process is active   h

Ph_1 oxygen production due to photosynthesis $g/m^2/h$

Ph_2 oxygen production due to photosynthesis   mg/l/day

Pr_1 oxygen consumption by plant respiration $g/m^2/h$

Pr_2 oxygen consumption by plant respiration   mg/l/day

r average rate of renewal of the liquid film h^{-1}

R hydraulic radius   m or ft

S_h number of hours sunshine   h

t time of flow   days

T stream temperature ^{o}C

t_a nitrification lag time   days

$\bar{U}$ mean stream velocity   ft/day

$u*$ shear velocity   ft/s

V mean stream velocity   ft/s or m/s

X_r length of reach   m

Z dissolved oxygen meter reading   % Sat.

$\theta_{1,k}$ temperature coefficient for the determination of $(K_1)_T$ -

$\theta_{1,L}$ temperature coefficient for the determination of $(L_o)_T$ -

θ_2 temperature coefficient for the reaeration coefficient   -

θ_3 temperature coefficient for the nitrification coefficient   -

1. Introduction

The national parks and wildlife reserves were chosen as the most suitable areas in which to carry out water quality investigations. These areas cover a broad spectrum of the Australian landscape, ranging from the hot arid Sturt National Park to the Alpine Kosciusko National Park. Consequently, a wide variety of streams and climatic conditions are represented. Since the parks provide recreational activity for many thousands of people some streams will be subjected to urban type pollution and possible ecological disruption, if not continuously then on a seasonal basis. These factors, together with the ability to draw upon the resources of the National Parks and Wildlife Service of N.S.W. have influenced the development of the current study.

The management of water quality in a stream is usually based on the maintenance of adequate dissolved oxygen levels along its length. The minimum dissolved oxygen level for the maintenance of aquatic life is discussed in detail in Chapter 2 and for most purposes it can be fixed at 5 mg/l. The concentration of dissolved oxygen along the length of a stream is dependent on a number of environmental factors, the most important being organic waste type and quantity; stream flow; oxygen deficit; stream temperature; dilution due to groundwater and tributary inflow; and the photosynthetic production of oxygen and respiration of aquatic plant life and algae. A detailed description of the processes affecting the supply and depletion of oxygen can be found in Chapter 3.

Polluted streams are usually characterised by a decline followed by a recovery in the dissolved oxygen level along the length of the stream. The initial decrease in level occurs due to the greater rate of oxygen removal by biological oxidation than can be supplied by re-aeration. The rate of biological oxidation is directly proportional to the quantity of organic material present and consequently decreases with flow time. The minimum deficit will be that point at which the rate of supply of oxygen by reaeration equals the rate of consumption by biological oxidation. Thereafter the reaeration process dominates and the dissolved oxygen deficit is gradually reduced.

The processes which determine the dissolved oxygen balance in a stream have been subject to extensive investigation by numerous research workers overseas. A review of this work is contained in Chapters 3 - 6. It is expected that most of the empirical results are applicable to Australian conditions although empirical equations relating to the oxygen demand of benthal deposits and the photosynthesis and respiration of aquatic plants may require further investigation.

The dissolved oxygen balance for Australian conditions will be developed according to an understanding of those processes affecting the dissolved oxygen level in Australian streams. A computer program (OXSTRAL) based on a mathematical model will be used to simulate the balance between the supply and depletion of oxygen and where necessary will incorporate empirical relationships determined by other research workers. In addition to the carbonaceous oxidation and atmospheric reaeration processes, the effects of plant respiration, photosynthesis, nitrification, benthal demand and dilution

from groundwater and tributary inflow will be included in the analysis.
In this way the model will cater for a wide range of possible conditions,
not only within the confines of a single stream but also from one
stream to another.

Basically OXSTRAL will be structured so as to carry out a
number of successive oxygen balances. The stream will be divided
into predetermined increments and the calculated output of each section
will serve as part of the data for the adjoining downstream section.
The length of each section or reach will be chosen according to how
well parameter uniformity is maintained within the reach. The diss-
olved oxygen profile, or oxygen sag curve for the stream and the
temporal variation of associated variables will be found by integration
of the successive reaches.

Continuation of the present study will involve the collection of
data from a number of national parks in N.S.W. for the purposes of
refinement and verification of the computer model. The current study
will be limited to the development of the model and will outline those
areas where more elaborate data collection techniques may be
warranted. Limited model verification will be possible using field
data collected from Perisher Creek, an alpine stream which flows
through the Perisher Valley in the Kosciusko National Park. The
sensitivity of the computed dissolved oxygen distribution to changes
in input data will also be determined. This information will indicate
the significance of each parameter in the dissolved oxygen balance and
the accuracy to which it is to be evaluated.

2. Australian Stream Characterisation

2.1 Physical Characteristics

A prerequisite to the development of a method of dissolved oxygen prediction is to establish the general characteristics of those streams to which the method will find application. Since the method should be adaptable to most Australian stream types the nature of Australian streams needs to be established.

Hydrologically two types of streams are evident on the Australian continent. Streams which are confined to a narrow strip along the northern and eastern coasts and along small stretches of the southern coast may be subject to substantial rainfalls and accordingly stream-flow may be quite high at various times during the year. Those streams located in the dryer central and north-western areas are subject to low rainfall, high evaporation losses and flat topography. These conditions, together with the lack of perennial snowfields result in the prevalance of low streamflows in the summer. In the tropical north and north-east, on the other hand, streamflows tend to be greatest in the summer.

A common characteristic of all Australian streams is that streamflow tends to be quite variable both within a yearly period and over a number of years. This variability increases inland and northwards towards the monsoonal region (Leeper, 1970). The variability is being counteracted in some areas by the construction of new and the enlargment of existing storage areas. This development is allowing more and more water to be diverted inland and at the same time is placing some control over streamflow.

2.2 <u>Possible Sources of Pollution</u>

The quantity of dissolved oxygen in a stream is subject to reduction whenever organic material is introduced into the system. Generally most non-urban natural streams are susceptible to some degree of pollution - if not continuously then at least on a seasonal basis. The organic material is introduced into the stream environment via stormwash, seepage from groundwater, drainage from swamp lands, decaying of aquatic life and in some instances where recreational pursuits are encouraged the organic material may be in the form of partly treated sewage effluent.

2.3 <u>Oxygen Requirements of Aquatic Life</u>

Oxygen requirements of aquatic life have been the subject of numerous investigations by overseas workers. Unfortunately, there is a lack of data on the requirements of Australian freshwater organisms, and guidelines, at least for the present, must be based on overseas criteria.

EIFAC (1973) and Doudoroff and Shumway (1970) have reviewed information relating to the direct lethal action of low dissolved oxygen on freshwater fish and have taken into account the influence of the age of the fish, the water temperature and acclimatisation. Sublethal effects, in relation to fertilisation, embryonic development, respiration, metabolism and swimming performance were also summarised. While most investigations have dealt specifically with the oxygen requirements of fish there seems to be agreement, based on limited data, that aquatic environments with dissolved oxygen levels sufficient

to sustain a fish population will also support invertebrates and aquatic flora (Hart, 1974).

It is generally accepted that a minimum dissolved oxygen content of 5 mg/l is necessary to avoid deleterious effects on the aquatic life of the stream (Doudoroff and Warren, 1962; Tebbutt, 1971; Klein, 1962; and Hart, 1974). However, difficulties arise in formulating criteria. Factors such as pH, CO_2, dissolved solids and more importantly temperature and fluctuating dissolved oxygen concentration tend to interfere with the requirements and uptake of dissolved oxygen by aquatic organisms. Doudoroff and Warren (1962) indicate that the growth rates of fish subjected to fluctuating dissolved oxygen concentrations are dependent on the minimum concentrations occurring at night rather than on the daily mean concentrations.

Temperature is usually the major factor in criteria formulation. The temperature of the water affects both the solubility of oxygen, as shown in Table 1.2 and the metabolic rate of aquatic life. Generally a rise of $10^{\circ}C$ will increase the oxygen requirements two to threefold.

The dissolved oxygen levels for the protection of trout and other aquatic life at various temperatures, as recommended by the E.P.A. (1973) are shown in Table 2.1. It should be noted that where toxic substances are introduced into the stream environment these values

may have to be increased (Hart, 1974). Generally toxicity increases with temperature and with reduced dissolved oxygen levels. Residual chlorine, emanating from the sterilisation of sewage effluent will generally be the major cause for concern. Apart from affecting the performance and health of fish, plant and microbiological life, the presence of chlorine compounds may also inhibit the biological oxidation of waste material in the stream.

Table 2.1:   Recommended Minimal Acceptable Concentrations of Dissolved Oxygen in Fresh Water[1]

Temperature °C	Oxygen Levels for Complete Saturation mg/1	Minimal Levels for Protection of Trout Spawning		Minimal Levels for Protection of Aquatic Life	
		mg/1	% Saturation	mg/1	% Saturation
36.0	7	6.4	91.4	5.8	82.9
27.5	8	7.1	88.8	5.8	72.5
21.0	9	7.7	85.6	6.2	68.9
16.0	10	8.2	82.0	6.5	65.0
7.7	12	8.9	74.2	6.8	56.7
1.5	14	9.3	66.4	6.8	48.6

[1]Source: EPA, 1973
Presented by Hart (1974)

3. The Dissolved Oxygen Balance in a Stream

The dissolved oxygen distribution along the length of a polluted stream can be visualised as a dynamic quantity dependent mainly on the formation of a balance between the removal of oxygen by the biological oxidation of carbonaceous material and the addition of oxygen by atmospheric reaeration and photosynthesis.

The rate of biological oxidation of carbonaceous material is dependent on the ultimate biological oxygen demand and stream temperature. The ultimate biological oxygen demand (UBOD), which expresses the organic content of the stream water in terms of its oxygen depletion potential, decreases with flow time as oxidation progresses. Consequently, the rate of biological oxidation, which is directly proportional to the UBOD decreases. The effect of increasing the stream temperature is to increase the biological oxidation rate geometrically by approximately 2% per $^{\circ}$C (Theriault, 1927). A more detailed explanation of the oxidation process may be found in Section 3.2.1.

Where partly treated wastes are discharged into the stream and/or the stream temperature is approximately 30°C biological oxidation in the form of nitrification may become important, and in some instances may dominate all other processes. In most temperate streams nitrification will not be apparent for ten or so days' flow time from the source of the pollution and even then will generally be of little significance.

In some streams processes additional to carbonaceous biological oxidation and nitrification may promote further oxygen depletion.

Often these processes create a critical deficit at a fixed location, independent of other parameters. For example, the deposition of suspended organic material will be followed by an increase in the benthal oxygen demand and a reduction in the oxygen content of the water in the region of deposition (see Section 3.2.3). Another source of oxygen depletion occurs where fixed plants or benthal algae are present. The respiration of this flora, particularly at night can result in a significant lowering of the oxygen level (see Section 3.2.4).

The rate of addition of oxygen by atmospheric reaeration depends on the turbulence of the water, which in itself is a function of stream velocity, depth and bed roughness; on the difference in partial pressure between the atmospheric oxygen and dissolved oxygen in the stream; and the stream temperature. An increase in turbulence caused by an increase in stream velocity or bed roughness, or a decrease in stream depth,will increase the reaeration rate. A decrease in the reaeration rate will occur if the partial pressure difference is reduced as a consequence of high altitude (as in the case with Perisher Creek) or the temperature is increased, reducing the oxygen saturation level. A more detailed explanation of these processes is contained in Sections 3.3.1, 3.4 and 3.5.

The final contributing factor to the oxygen balance, the production of oxygen by photosynthesis,is dependent largely on the plant or algal biomass and the availability of light, which is influenced by the season, the topography, the atmospheric conditions as well as the turbidity of the water. Changes in the rate of photosynthesis may result

in considerable diurnal and seasonal fluctuations in dissolved oxygen content.   Section 3.3.2 contains a more detailed discussion of the significant parameters affecting photosynthesis.

3.1 The Oxygen Sag Curve

The dissolved oxygen balance between oxygen supply and de-oxygenation in a stream is often expressed in the form of a plot of dissolved oxygen level as a function of streamflow time or distance downstream from the source of pollution.   This curve, commonly termed an 'oxygen sag curve' may be derived either from field meas-urements or from a mathematical model and represents the dissolved oxygen distribution along the length of a stream for a given set of en-vironmental conditions.

Figure 3.1 shows idealised oxygen sag curves for a stream when different amounts of organic wastes are introduced.   The initial dissolved oxygen concentration drops rapidly at the point of pollutant introduction.   If the waste load is in a phase of active decomposition or if the wastes are voluminous as compared to streamflow and con-tain little dissolved oxygen the decline in dissolved oxygen will take the form of an immediate drop.   The rate and extent of further oxygen depletion will depend upon the concentration of organic matter and the rate at which it is oxidised.   The minimum deficit on the oxygen sag curve will be that point at which the rate of supply of oxygen by reaeration equals the rate of consumption of oxygen by
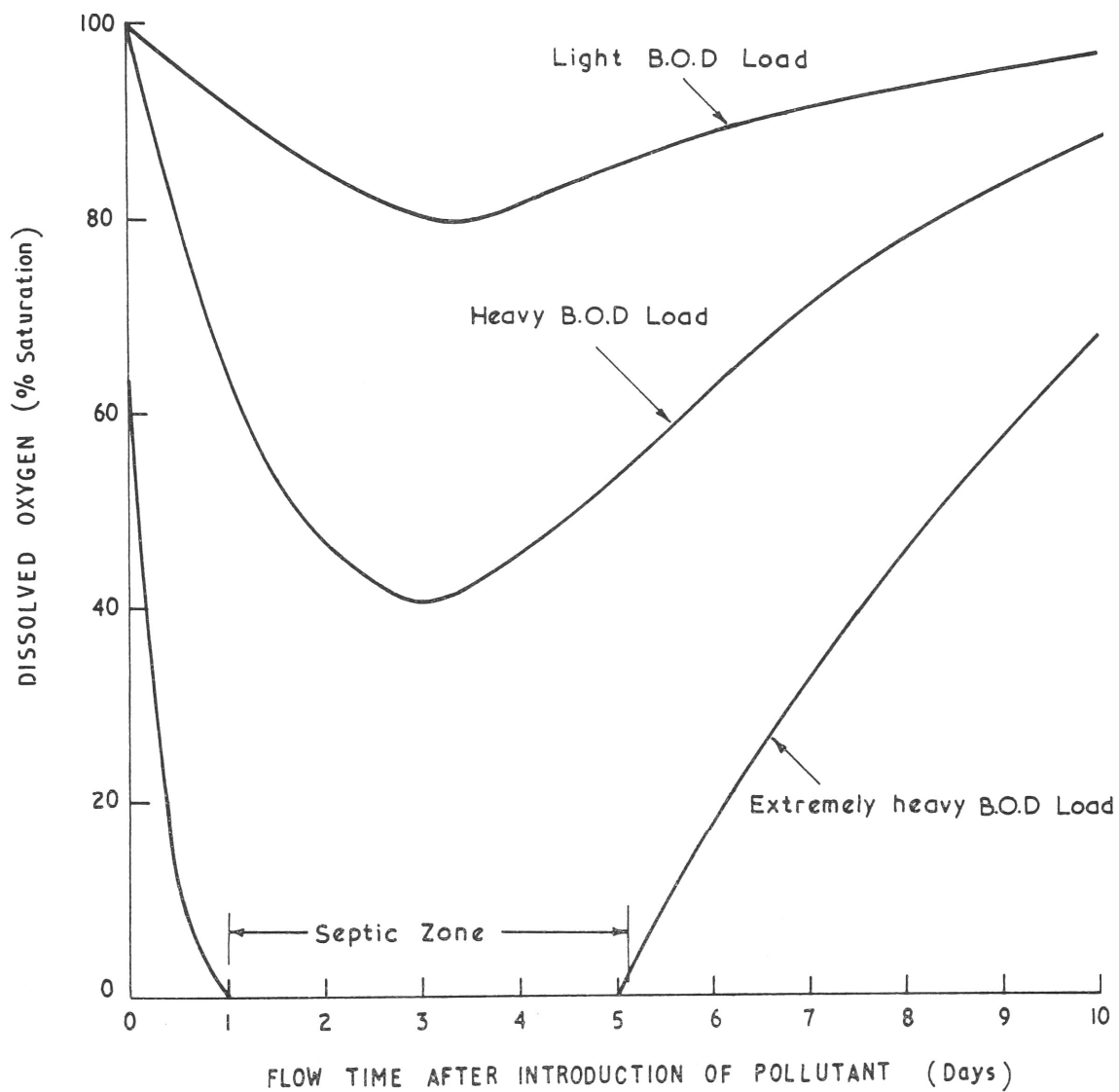
FIGURE 3·1: TYPICAL OXYGEN SAG CURVES

biological oxidation. Thereafter the reaeration process dominates and the dissolved oxygen deficit is gradually reduced. In the case of relatively low concentrations of organic matter the decline in dissolved oxygen concentration is small and recovery is rapid. Higher concentrations of organic matter result in a greater depression in the dissolved oxygen concentration and the length of the stream affected is more extensive. In some instances pollution may be so severe that the dissolved oxygen in a segment of the stream is completely depleted and a septic zone created.

Where partially treated sewage is the main pollutant, the oxygen sag curve described may be modified by the intervention of a succeeding second stage in which nitrification becomes dominant. The oxygen utilisation rate and duration of the nitrification stage will be dependent on a number of environmental factors, as outlined in Section 3.2.2.

The lowest point on the oxygen sag curve should be maintained at a value above 5 mg/1 at all times (Section 2.3) for most Australian streams. The critical period when this condition is most likely to be violated will occur in the warm weather drought season when freshwater flow is low, dilution of pollutants is reduced and where lower stream velocities and turbulence accompany the lower stream-flow such that reaeration efficiency is decreased. The higher stream temperatures decrease the oxygen saturation level which in turn reduces the driving force in the mass transfer of atmospheric oxygen to the water. High stream temperatures also promote an increase in the

rate of biological decomposition resulting in a lower minimum dissolved oxygen level at a distance closer to the point of pollutant discharge. In some alpine localities the critical period may occur in winter when the low streamflow coincides with heavy ice cover. The presence of a heavy ice cover could reduce markedly the surface of the stream available for atmospheric reaeration and could also inhibit photosynthetic oxygen production through a decrease in light penetration. However, to counteract these effects a high oxygen saturation level accompanying the low temperatures will increase the mass transfer rate across the remaining air-water interface, although some dampening of the mass transfer rate will occur due to a geometric decrease in the reaeration rate coefficient of approximately 2.4% per $^\circ$C (Committee on Sanitary Engineering Research, 1961). Information on the degree to which ice cover inhibits reaeration and photosynthesis is scant and further research is necessary before the significance of ice cover as a factor inhibiting reaeration in the Australian Alps can be gauged. However, it should be kept in mind that at low temperatures the rate of biological oxidation will be low and hence the rate of oxygen depletion will be reduced considerably.

3.2 The Depletion of Dissolved Oxygen

Generally the most important process causing oxygen depletion is that associated with the oxidation of carbonaceous material. However, in some streams the circumstances may be such that nitrification of wastes or the respiration of benthal or aquatic plants may be highly significant.

3.2.1 Carbonaceous Oxygen Demand

The carbonaceous oxidation process is a manifestation of the respiratory functioning of micro-organisms. To maintain life and growth micro-organisms consume organic material and dissolved oxygen and respire carbon dioxide in the process. The process is similar to those that characterise biological treatment plants. That is, the oxidation of the organic material proceeds in an overlapping stepwise fashion, the end products of one reaction providing the fresh material for the next reaction.

The rate of oxidation is determined principally by the nature of the organic material and the stream temperature. If the organic material is in solution then the rate of oxidation is likely to be greater than that of a suspended material. The rate of biological oxidation is a function of temperature and will increase with an increase in stream temperature, a rule of thumb being that the reaction rate is doubled for a rise in temperature of $10^{\circ}C$ (Klein, 1962).

One other factor, which is not normally significant but may warrant attention when assessing dissolved oxygen levels close to the source of pollution is that of microbiological population. Evidence presented by Camp (1963) indicates that if the biological oxygen demand at a distance corresponding to one day's travel is to be considered then the initial concentration of bacteria will affect the dissolved oxygen requirement during this period. This is in contrast to the normal five day biological oxygen demand where the initial bacterial count is immaterial to the quantity of dissolved oxygen consumed in the five day period. For example, it has been found

(Camp, 1963) that for a low and a high concentration[1] of the culture aerobacter aerogenes[2] liquid medium the total count and total oxygen utilised after five days was substantially the same.   However, at the end of the first day a considerable difference in bacterial count in the low concentration culture was still evident and oxygen utilised by the low concentration culture was approximately 25% less than that of the high initial count culture.   These results indicate that caution must be applied when applying 5 day B.O.D. data to stream sections which are within one day's travel of the source of pollution and have low bacteria counts.

Velz (1970) states that streams which drain virgin land normally carry a residual organic load of approximately 1 ppm of BOD_5 during the dry season and up to 2 ppm during high runoff when drainage from swamps occurs.   If sewage effluent from recreational areas is allowed to enter the stream environment the BOD_5 load will be considerably higher and is likely to be present in a cyclic pattern according to both diurnal and seasonal fluctuations in the use of the resort's facilities.

3.2.2 Nitrification

Nitrification represents a series of associated reactions in which ammonia and simple animal compounds are oxidised to nitrite and then to nitrate.   Unlike the carbonaceous reaction which is dominated by a rather persistent group of heterotrophic organisms oxidation of the nitrogenous material is carried out by specialised groups

1.   3,200 and 3,200,000 bacteria per ml.
2.   Aerobacter aerogenes are non fecal coliforms usually found in soil and decaying vegetation.

of organisms which are much more sensitive to environmental conditions.

The oxidation of ammonia to nitrite is carried out by bacteria of the genus Nitrosomonas and the second phase, the conversion of nitrite to nitrate, is carried out by the genus Nitrobacter (Velz, 1970). Although these micro-organisms are widely distributed in nature, the specialised requirements in terms of temperature (i.e. approx. 25-30°C) and pH normally do not permit large populations to dominate the stream environment and consequently nitrification is usually a minor component of the biological oxygen demand.

Nevertheless nitrification may be a significant factor when biologically treated effluents from a recreational area are discharged into the stream environment. Secondary treatment of waste reduces the quantity of easily oxidisable carbonaceous material and ammonia and heat are generated in the process. This encourages the growth of nitrifying bacteria and, where discharge of the treated effluent to a stream results in the effluent constituting a large proportion of the streamflow nitrification will quickly dominate, particularly if the elevated temperatures are maintained in the stream. If the stream temperature and pH are not optimal, nitrification may either be insignificant or occur at a slow rate, commencing at a point downstream corresponding to a lag time of three to ten days (O'Connor, 1967).

Depending on the amount of ammonia in the effluent, the nitrification phase under optimal conditions can depress the dissolved oxygen levels substantially below the level accounted for by the residual carbonaceous B.O.D. of the effluent. In one study by O'Connell and

Thomas (1965) of the Truckee River in Nevada, U.S.A., oxygen consumed in nitrification was found to be approximately five times greater than the carbonaceous oxygen demand. In many regions of Australia, high summer temperatures and low streamflow may provide ideal conditions for the nitrification process to establish itself as the dominant mechanism in the depletion of the dissolved oxygen. Within New South Wales it is interesting to note that streams within the Warrumbungles, Lake Menindee and Sturt National Park areas are likely to be classified as being susceptible to nitrification according to these criteria.

3.2.3 Benthal Decomposition

In addition to the removal of organic wastes by biological oxidation some solid wastes may be removed from a stream by sedimentation. Bottom deposits form in three general ways (Velz, 1958); i.e. by

(i) deposition of heavy solids,

(ii) deposition resulting from the flocculation and coagulation of solids and growths, and

(iii) biological extraction and accumulation of wastes by growths attached to the bottom of the stream.

Flocculation and coagulation of solids is comparable to an activated sludge system in which the growths are dispersed throughout the flowing system. Under certain conditions the growths flocculate and the flocs increase in size until sedimentation occurs. On the other hand the biological extraction and accumulation of wastes is analogous to a trickling filter process, where the organic material is absorbed by the aquatic biota.

The formed bottom deposits, or benthal deposits as they are often termed, undergo a natural purification process involving both aerobic oxidation of surface layers and anaerobic decomposition of lower layers to which oxygen diffusing from the water cannot penetrate. The contribution by the aerobic surface layers to the oxygen demand have been found to be insignificant in fast flowing streams (Tebbutt, 1971). However, if stream velocities are low and benthal deposits are substantial then depletion of oxygen may have a considerable impact on the dissolved oxygen balance of the stream.

Velz (1959) states that if the stream velocity is less than 0.2 m/s deposition of solids can be expected, while velocities greater than 0.3 m/s may cause resuspension. Resuspension of benthal deposits can have undesirable consequences as it may result in the sudden addition of unstable carbonaceous compounds to the streamflow causing excessive oxygen depletion downstream.

Generally speaking, there is no change in benthal oxygen demand with temperature (Rolley and Owens, 1967) although variations in benthal organism growth and type have been observed according to seasonal changes in temperature (Blum, 1972). Observed variations in the benthal oxygen demand along the length of a stream have been found to reflect differences in deposit depth, organic concentration and the area covered.

3.2.4 The Respiration of Plant and Algae

The respiration of aquatic plants and algae can represent a critical factor in establishing the minimum oxygen deficit level of a stream. The process is best analysed within the context of photo-

synthesis and the reader is directed to Section 3.3.2 for a discussion

of the process.

3.3 The Supply of Dissolved Oxygen

Oxygen is supplied continuously to a stream by absorption from

the atmosphere at the stream surface and, where aquatic plants,

plankton or algae are present, by photosynthesis during daylight

hours. Strictly speaking, a process of dynamic interchange involv-

ing absorption and desorption of oxygen occurs at the interface be-

tween the water and air, the rate of absorption being greater than the

rate of desorption if the concentration of the dissolved oxygen is be-

low the saturation level and vice versa.

3.3.1 Atmospheric Reaeration

If for any reason the dissolved oxygen content of a stream falls

below saturation more oxygen will be absorbed at the surface than is

desorbed, and the dissolved oxygen level will again approach satur-

ation if further oxygen depletion is absent.

The process of reaeration takes place in a thin film of water at

the air-water interface but the rate is controlled by the diffusion of

oxygen throughout the main body of water. Consequently any factor

which increases turbulence within the stream will also increase the

rate of reaeration. An increase in flow velocity, a reduction in

stream depth or a roughening of the stream bed are factors which can

cause increased turbulence and increased reaeration.

The interdependence between turbulence and reaeration may be

explained as follows. Turbulent eddies, initially generated at the

bottom by the roughness of the stream bed drift into the main stream

where they are broken up by viscous forces into a succession of smaller
eddies. With an increase in stream velocity the energy contained with-
in the generated eddies promotes both an increase in turbulence at the
air-water interface and greater mixing of the surface and subsurface
layers. Increasing turbulence at the surface not only has the effect
of encouraging greater entrainment of air at the interface but also as
the result of wave and ripple formation the effective water surface area
in contact with the air is expanded. Increasing the water depth causes
greater dissipation of energy so that eddies reaching the surface do not
promote the turbulence that would be evident in shallower depths of
water.

Weed growth can have a pronounced effect on stream turbulence
and reaeration. The presence of the weeds will tend to reduce stream
velocities which in order to preserve streamflow continuity will result
in either a deepening of the stream or an increase in width, depending
on a complexity of factors including the geomorphology of the banks and
bed, stream slope and siltation loading.

Klein (1962) quotes experimental work which shows that the re-
aeration efficiency may be reduced significantly by the presence of
surface active contaminants in the water. The presence of up to 10%
of settled sewage effluent was found to reduce the exchange coefficient
by as much as 60%. On the other hand the presence of well purified
sewage effluent had a relatively small effect. Dobbins (1964) explains
this phenomenon as being a result of the surface active contaminants
in the settled sewage tending to increase the surface tension and thus
decreasing the diffusivity of oxygen into the surface layer. The pres-

ence of detergent in a stream has been observed to have a similar reducing effect on the oxygen diffusivity (Bennett and Rathbun, 1972).

A final factor influencing reaeration is wind. Downing and Truesdale (1955) have found that an increase in reaeration is particularly significant if the wind velocity is greater than 3m/sec. However, since the wind effect is occasional and the added reaeration inconsequential in the assessment of the long term viability of a stream it is usually neglected in dissolved oxygen studies.

3.3.2 Photosynthesis

The oxygen balance of a natural stream may be influenced, often to a significant degree by the metabolic activities of chlorophyll-bearing algae, phytoplankton and aquatic plants. These phototrophes use energy provided by solar radiation to synthesise carbohydrates from carbon dioxide, water nutrients and trace minerals and release oxygen as a byproduct to the surrounding water. At the same time the phototrophes and other aquatic flora require oxygen to meet the continual respiratory need. Consequently there is usually a net gain of oxygen due to photosynthesis during the daylight hours and a decrease at night. In some cases the net gain may be sufficient to cause local supersaturation and venting of oxygen to the atmosphere.

The general equation according to Stumm and Morgan (1962) is

$$106 \; CO_2 + 90 \; H_2O + 16 \; NO_3^- + 1PO_4^{3-} + \Delta E = C_{106} \; H_{180} \; O_{45} \; N_{16} \; P_1 + 154.5O_2 \qquad (3.1)$$

This process may be nutrient (N, P etc.) or CO_2 limited but in polluted water this is unlikely.

Where the mean stream velocity is in excess of 0.3 m/s the development of free-floating phytoplankton is not likely to occur

(O'Connell and Thomas 1965) except perhaps in those areas where the stream widens into stagnant pools of water and sufficient time is available for reproduction. The attached forms of algae and plant life may usually be found in greatest numbers a short distance from the source of pollution. The algae utilise the end products resulting from bacterial decomposition of organic matter or, in the absence of organic matter, the mineral content of the water; in particular the carbon dioxide from bicarbonates, may provide the nutrient supply.

The light energy used in the photosynthetic process is usually considered to be the visible portion of the solar radiation spectrum (4000-7000A^O) which makes up a little more than half of the incident radiation. The availability of this energy is affected by a number of factors, namely the time of day, the season and latitude, the altitude, the formation of shadows by local topography, the degree of cloud cover, the haze in the atmosphere and the turbidity of the water (Brown 1972). All these factors, apart from water turbidity can be estimated by means of a pyrheliometer located in the field.

Turbidity, created by the presence of a suspension of finely divided solids inhibits penetration of light incident on the water surface and so restricts the activity of aquatic flora dependent on light energy. Hart (1974) reports that virtually no light is transmitted beyond a depth of 8 cm when the non-filterable residual concentration reaches 150 mg/l. Owens and Edwards (1966) state that the photosynthetic or euphotic zone is generally assumed to extend to the depth at which the light intensity is 1% of the light intensity at the surface. The measurement of turbidity, using a Sechi disk is used in conjunction with a pyrheliometer to assess the light intensity on the bed of the stream.

Data, presented by Brown (1972) reveal that at low light intensities metabolic response of phototrophes is proportional to light intensity. However, according to the phototrophe type a level of light intensity is reached where increased light does not result in corresponding metabolic increases. At very high light intensities Brown (1972) has shown that increased light may inhibit photosynthesis, presumably by a process of pigment destruction. In areas subject to high solar radiation this phenomenon may be reflected by the lack of phototrophe growth in very shallow stream sections.

Many investigators (Mohlman et al, 1931; Schroepfer, 1942; O'Connell, 1965) have reported large diurnal fluctuations in the concentration of dissolved oxygen in stream and rivers due to the photosynthetic activity of plants and to a much lesser extent of algae. Edwards (1968) and Owens, Knowles and Clark (1969) carried out calculations based on extensive series of respirometric determinations to illustrate the respiratory and photosynthetic effects of plants on the oxygen distribution in a waterway. Calculations, the results of which are shown in Figure 3.2, were made for two daily light intensity distributions and two plant densities of 100 and 500g of dry wt/m^2. Both plant biomass and light intensity were found to be of great influence in the establishment of an oxygen balance in a shallow stream. With high light intensities and fairly low plant populations dissolved oxygen levels did not fall below 100% saturation and for brief periods in the day exceeded 200% saturation. On the other hand, with dense plant populations pronounced deoxygenation occurred during periods of overcast weather and at night. The minimum and maximum light

FIGURE 3·2: CALCULATED EFFECT OF DIFFERENCES IN PLANT DENSITY AND DAILY SUNLIGHT DISTRIBUTIONS ON THE OXYGEN DISTRIBUTION IN A RIVER 0·66 m. DEEP AND WITH A VELOCITY OF 5 cm/sec.

(After Edwards, 1968.)
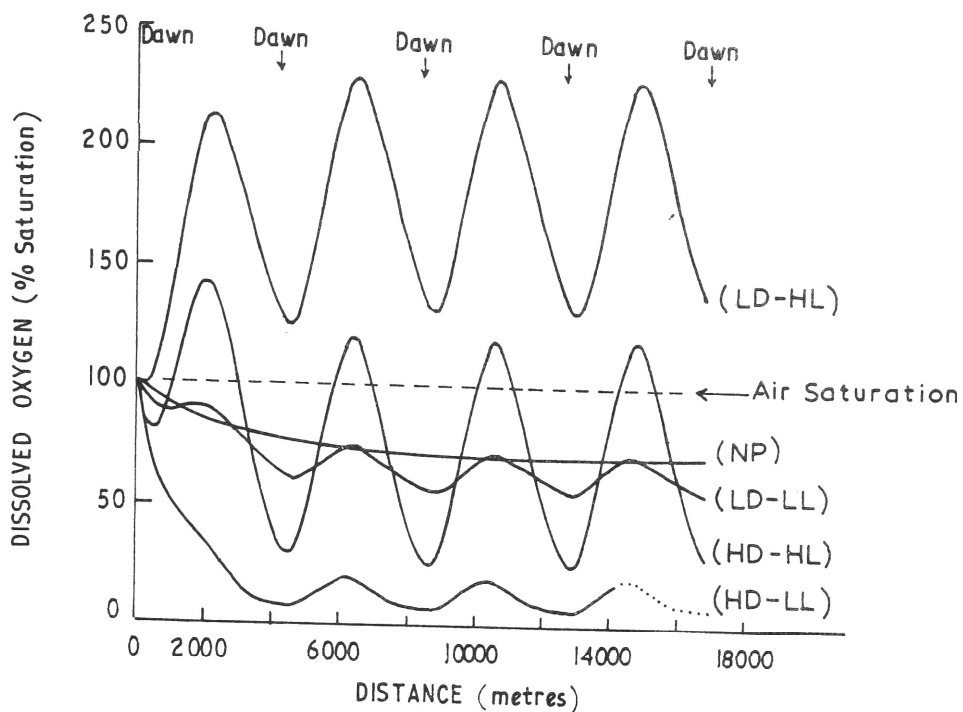
Temperature 15°C.
HL, Bright day

HD, High plant density
LL, Dull day

LD, Low plant density
NP, No plants
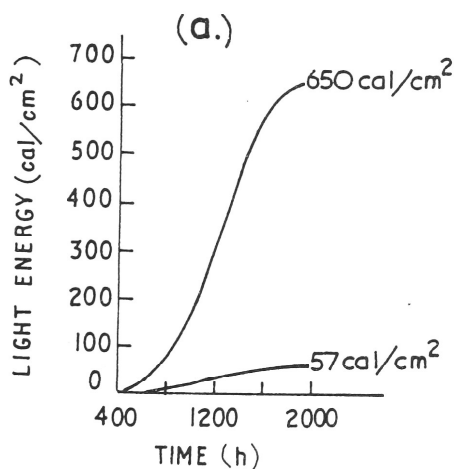
(a.) MINIMUM AND MAXIMUM DAILY LIGHT DISTRIBUTIONS FOR JULY.
(After Edwards, 1968.)
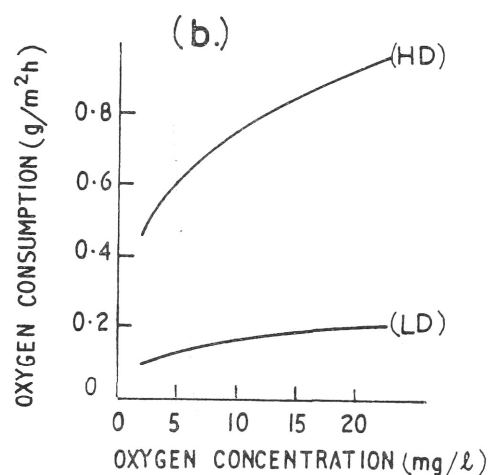
(b.) OXYGEN CONSUMPTION FOR HIGH (HD) AND LOW (LD) DENSITIES OF PLANTS.
(After Edwards, 1968.)

FIGURE 3·3

intensities and respiration rates assumed for these calculations are shown in Figure 3.3.

Obviously heavy growths of algae or rooted vegetation may be of questionable benefit in the maintenance of adequate dissolved oxygen levels. The self shading effect reduces the efficiency of the photosynthetic process whilst the respiratory rate increases in line with increases in biomass. It is most likely that the disadvantages of respiration of the phototrophes at night and during periods of low light intensity will offset the advantages of photosynthesis. This is even more apparent when one considers that although the oxygen produced over a complete diurnal cycle may exceed that consumed by respiration, the mass of water containing the oxygen produced during daylight hours is not the same mass of water from which oxygen is withdrawn to meet night time respiratory demands. As a result significantly large dissolved oxygen deficits will occur. Under such conditions oxygen contributions by photosynthesis cannot be considered an asset where daily minimum rather than the daily mean concentration is critical.

3.4 The Effect of Stream Temperature

An increase in stream temperature affects the dissolved oxygen balance of a stream by lowering the dissolved oxygen saturation level; increasing the reaeration rate coefficient; influencing the species and populations of aquatic life; increasing the metabolic activity of the indigenous aquatic organisms and subsequently the rate of biological oxidation; and increasing the rate of photosynthesis.

At increased temperature levels a stream is capable of holding

at saturation a somewhat lower quantity of dissolved oxygen. The saturation levels at various temperatures are shown in the following table.

Table 3.1: Saturation Levels				
Temp. ^{O}C	0	10	20	30
D.O. mg/l	14.6	11.3	9.1	7.6

The reaeration rate coefficient (defined in Section 4.4) will also increase with temperature, counteracting to some extent the effect of the decrease in the rate of reaeration produced by the reduction in saturation level.

The composition and growth of microbial communities depends largely on the temperature characteristics of the environment. In summer, the higher temperatures increase microbial activity and subsequently oxygen depletion is more intense.

Klein (1962) reports that biological oxidation occurs at four times the rate at 27°C as at 8°C. In the freezing point region very little biological activity takes place. These observations are substantiated by Camp (1963) who, when reporting on the effect of temperature on the generation time of E. coli bacteria states that the organism grows best at 37°C, the temperature of the human body. At lower temperatures of 20°C and 15°C the generation times are respectively four and eight times as long and substantially less oxygen is consumed.

Brown (1972) has shown that at intermediate temperatures light and temperature act together to affect algal activity. Brown cites a case where an increase in water temperature from 20°C to 30°C

lifted the light saturation intensity and increased the algal growth rate by about 50%. He also states that at extremely low or high water temperatures photosynthesis may be severely inhibited. Kniep (1914) has reported that at low temperatures the ratio of photosynthesis to respiration was higher than at elevated temperatures indicating that algae use available energy more efficiently in cooler weather.

The overall effect of temperature on the dissolved oxygen distribution in the presence of pollution will be to promote a greater oxygen deficit when stream temperatures are high. A lowering of stream temperature, as would occur in the winter months, will reduce the likelihood of critical deficits being experienced, although the effects of pollution will extend further downstream.

3.5 The Effect of Atmospheric Pressure

The saturation level of oxygen in water decreases with decreasing atmospheric pressure. The dependence on barometric pressure, P_B, may be expressed in terms of the Henry Law ratio,

$$C_{s_2} = C_{s_1} \frac{P_{B2}}{P_{B_1}} \tag{3.2}$$

where C_s is the oxygen saturation value (mg/l).

For example for a temperature of $20^{\circ}C$ and $P_{B_1} = 760$ mm Hg, $C_{s_1} = 9.1$ mg/l (see Table 3.1). At 1500 metres (5000 ft.) the average barometric pressure is about 640 mm Hg. (from Figure 3.4) and C_{s_2} is calculated as 7.6 mg/l. Hence at 1500 metres not only is there a reduced maximum quantity of oxygen available (of approximately 2.6 mg/l) but also the driving force for the reaeration process, represent-

ed by the dissolved oxygen deficit will be reduced considerably.

Consequently it is apparent that in the evaluation of an oxygen balance at high elevations above sea level the oxygen saturation levels quoted in the literature must be adjusted to values in accordance with the average barometric pressure which prevails at the location of the investigation.   Figure 3.4 shows the average barometric pressure for various elevations above sea level.
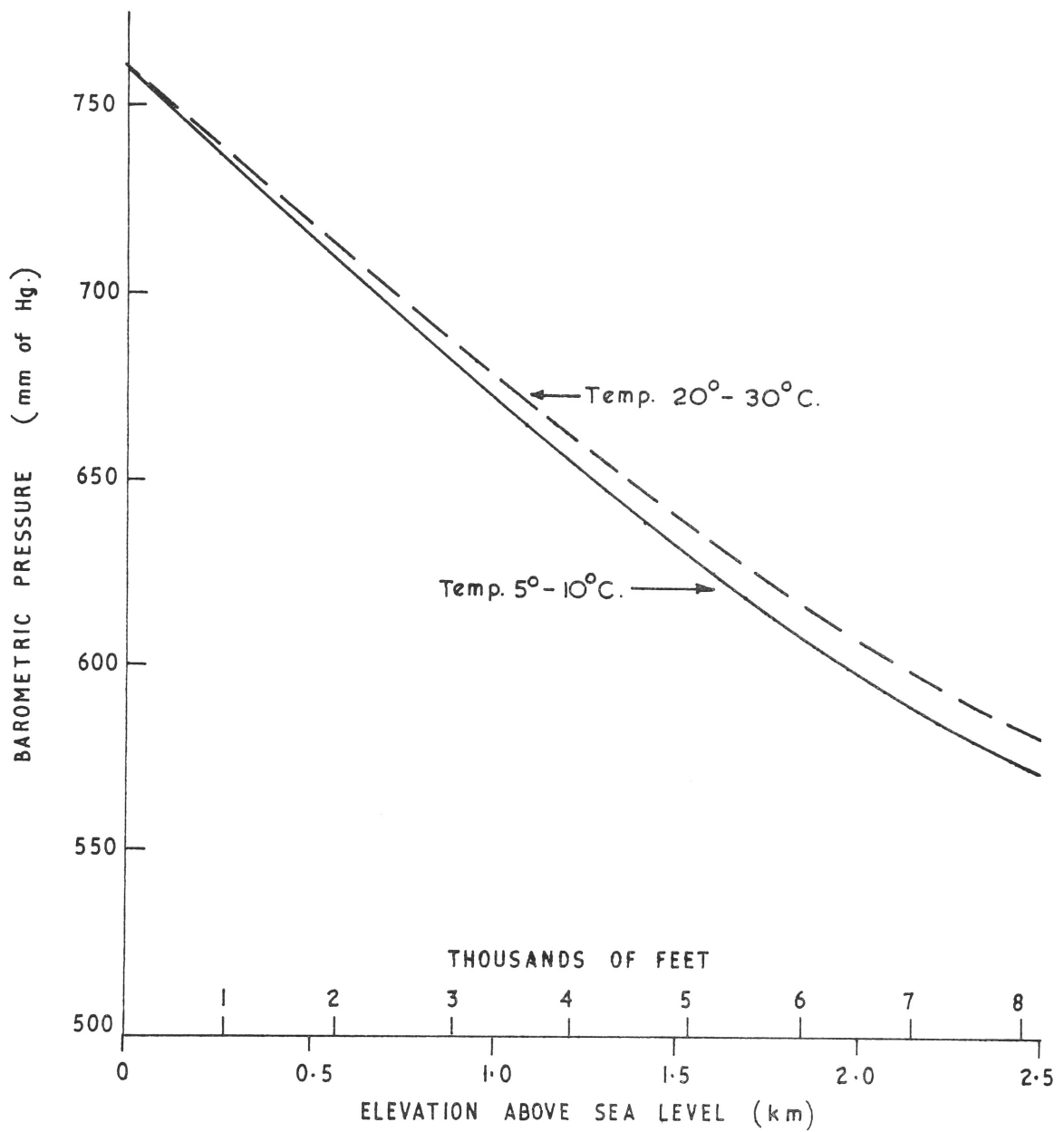
FIGURE 3·4: AVERAGE BAROMETRIC PRESSURE AT VARIOUS ELEVATIONS ABOVE SEA LEVEL.

(After Camp, 1963)

4. The Kinetics of Dissolved Oxygen Depletion and Supply

The kinetics of supply and depletion of dissolved oxygen in a stream have been studied extensively. Some of the processes, such as carbonaceous oxidation, nitrification and benthal demand have been satisfactorily represented by relatively simple first order rate equations. The rate of reaeration is generally accepted as being a function of the oxygen saturation level, stream velocity and depth although the empirical constants expressing reaeration vary widely in the literature. The production of oxygen by photosynthesis and the associated oxygen depletion by respiration are a function of biomass solar radiation, chlorophyll content and stream turbidity. Generally, these parameters are estimated on the basis of field data and not by general empirical equations.

All the above processes are temperature dependent and in most instances, except for perhaps photosynthesis and benthal decomposition, the stream temperature will be a highly significant factor in the computation.

4.1 Carbonaceous Oxidation

The organic waste load is indirectly measured as a function of the amount of oxygen required for the biological oxidation of the material, and is commonly expressed as the biological oxygen demand (B.O.D.). The variation of B.O.D. with time has generally been interpreted as a first-order reaction, dependent on the concentration of oxidisable organic material present but independent of the oxygen concentration, provided it is greater than a critical value ((Phelps 1944),

Theriault (1927), Inkster (1943)). Fair and Geyer (1954) provide a

figure of 4 mg/1 at 20°C for the critical oxygen concentration.

In mathematical terms the rate of biological oxidation is expressed as

$$\frac{dD}{dt} = - \frac{dL}{dt} = K_1 L \qquad (4.1)$$

where D is the dissolved oxygen deficit (mg/1),

L is the ultimate biological oxygen demand (mg/1)

and K_1 is the rate-constant of oxidation (days^{-1}) usually referred to as the deoxygenation coefficient.

Usually the biological oxygen demand of a water sample is determined in the laboratory as a 5 day B.O.D. value. To determine the ultimate biological demand (U.B.O.D. or L_O) the test is extended to approximately 20 days in the presence of a nitrification inhibitor. A relationship between B.O.D. and U.B.O.D. is then determined which will allow the calculation of L_O for a wide range of B.O.D5 levels.

The integrated form of equation (4.1) is

$$L = L_O e^{-K_1 t} \qquad (4.2)$$

where L_O is the initial value of L

and t is the flow time (usually days).

If y is the uptake of oxygen in time t, then the B.O.D. remaining at time t is equal to $(L_O - y)$.

Therefore, $L_O - y = L_O e^{-K_1 t}$

and $y = L_O (1 - e^{-K_1 t})$ $\qquad (4.3)$

Alternatively

$$y = L_o (1 - 10^{k_1 t}) \qquad (4.4)$$

where k_1 is the rate constant to the base 10 (and thus is numerically equal to $K_1/2.303$).

The value of K_1 was determined statistically by Phelps (1944) to be about 0.23 at 20°C for sewage or sewage effluents. However, Ruchhoft, Placak and Ettinger (1948) and other workers (Streeter, (1938), Tebbutt (1971), Camp (1963)) found that K_1 may vary widely, ranging from 0.02 to 0.7 for different samples of sewage.

In the range from 0 to 30°C the deoxygenation constant increases quite rapidly with increasing temperature, the value roughly doubling for a temperature increase of about 15°C (Klein, 1962). Streeter and Phelps (1925) found that the effect of temperature could be adequately expressed by an equation of the form

$$(K_1)_T = K_1 \Theta_{1K}^{(T-20)} \qquad (4.\ )$$

where $(K_1)_T$ is the value of K_1 at any temperature T°C,

K_1 the value at 20°C, and

Θ_{1K} is the temperature coefficient.

Gotaas (1948) found Θ_{1K} to vary with temperature in the following way

5 to 15°C, $\Theta_{1K} = 1.109$

15 to 30°C, $\Theta_{1K} = 1.042$

30 to 40°C, $\Theta_{1K} = 0.967$

These values are substantiated by data from Camp (1963) and Zanoni (1967).

Theriault (1927) and Zanoni (1967) have reported that the biological oxygen demand is also temperature dependent, increasing with

increasing temperatures. Theriault has formulated the following

empirical relation to account for the variation.

$$(L_o)_T = L_o \left[1+0.02 (T - 20) \right] \tag{4.6}$$

where $(L_o)_T$ and L_o are the U.B.O.D. values at T^O and $20^O C$

respectively. This equation indicates an increase in the value of L of

2% for each degree above $20^O C$, and similar decreases for lower

temperatures.

Zanoni (1967) has continued Theriault's work and produced the

following relationship:-

$$(L_o)_T = L_o \left[1 + \Theta_{1L} (T-20) \right] \tag{4.7}$$

where $\Theta_{1L} = 0.0033$ for $2^O C < T < 20^O C$

and $\Theta_{1L} = 0.0113$ for $20^O C < T < 35^O C$

Figure 4.1 taken from Fair and Geyer (1954) and based on data

obtained by Theriault (1927) illustrates the effect of temperature on

the temporal variation in biological oxygen demand.

4.2 Nitrification

Nitrification is an autocatalytic process and may be represented,

according to Whipple (1969) by the equation

$$N = N_o (1 - e^{-K_3(t-t_a)}) \tag{4.8}$$

where N = ultimate nitrification demand at time t (mg/1)

N_o = ultimate nitrification demand (mg/1)

K_3 = nitrification rate coefficient (days^{-1})

t_a = lag time (days)
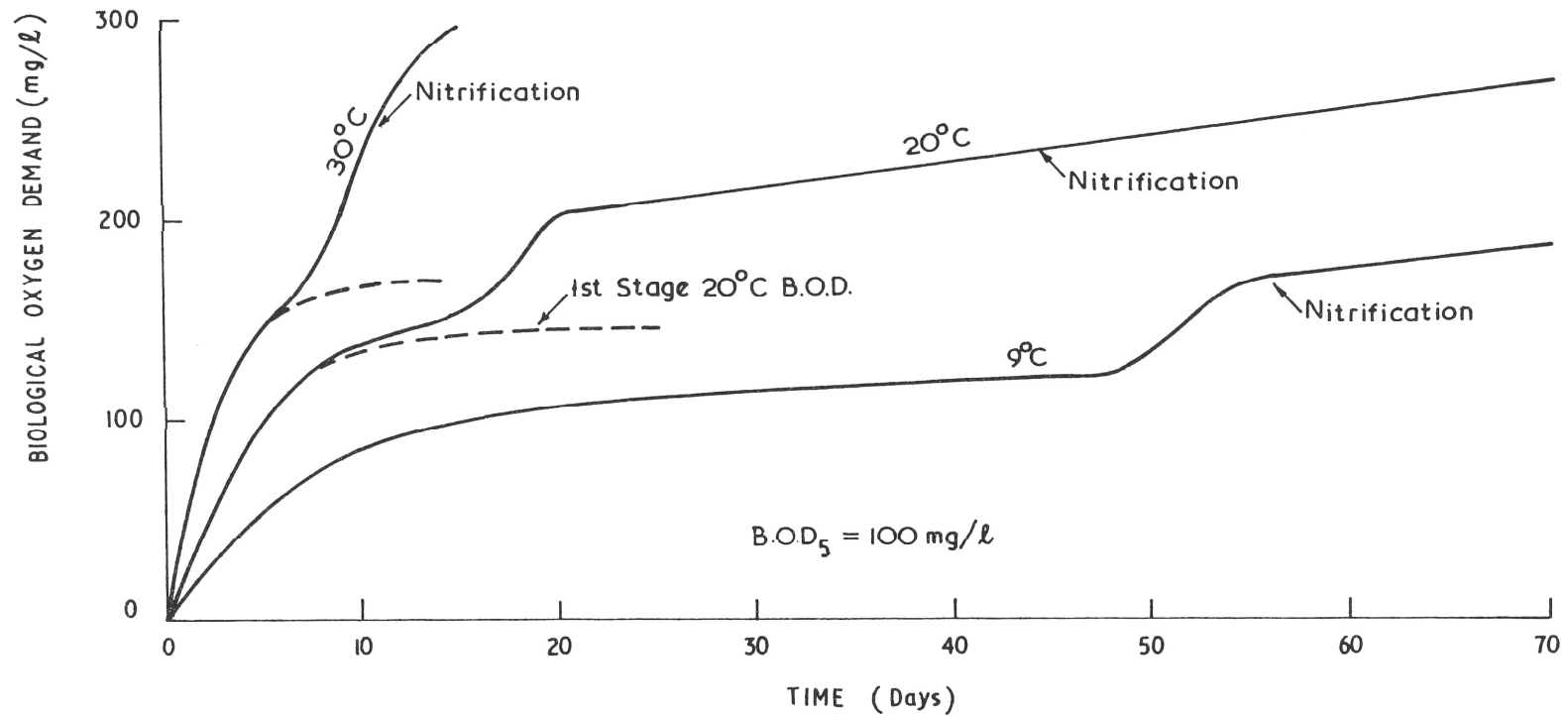
FIGURE 4·1: PROGRESS OF BIOLOGICAL OXYGEN DEMAND (B.O.D) AT 9, 20 AND 30°C. (After Theriault)

The ultimate nitrification demand represents the oxygen required to completely oxidise the ammonia to nitrate.

Klein (1962) states that the value of K_3 increases from about three times that of the deoxygenation constant, K_1, at $5^\circ C$ to about eight times at $30^\circ C$. This relationship will hold so long as the concentration of dissolved oxygen is above about 0.7 to 0.8 ppm. Below this level nitrifying organisms appear to be inhibited.

The temperature dependence of the nitrification coefficient may be expressed in a similar form to the deoxygenation coefficient - temperature relationship (equation 4.5)

$$\text{i.e. } (K3)_T = (K3)_{20} \; \Theta_3^{(T-20)} \tag{4.9}$$

Zanoni (1969) found Θ_3 to be 1.097 for temperatures from $10^\circ C$ to $22^\circ C$ and 0.877 for temperatures from $22^\circ C$ to $30^\circ C$.

4.3 Respiration and Oxidation of Mud Deposits

Edwards and Rolley (1965) investigated benthal deposits and found that the rate of oxygen consumption was independent of sediment depth for depths greater than about 2 cm and that the oxygen consumption of the mud was dependent upon the oxygen concentrations in the overlying water. The relation could be expressed by the empirical equation

$$B_r = a_5 C^{b_5} \tag{4.10}$$

where B_r is the quantity of oxygen consumed ($g/m^2/hr$),

C is the oxygen concentration (mg/l),

and a_5 and b_5 are coefficients averaging 0.033 and 0.6

respectively at $15^\circ C$.

4.4 Atmospheric Reaeration

The absorption of a gas by a liquid may be explained in terms of the two-film theory of Lewis and Whitman (1924). This theory is based on the assumption of the presence of a gas and a liquid film at the interface, through which the gas must pass by molecular diffusion and beyond which the concentration of the gas is uniform. Usually the resistance of the gas film is negligible by comparison with that of the liquid film and only the liquid film need be considered.

The absorption (or extraction) of the gas is a first order rate process, the rate of absorption being proportional to the oxygen deficit. This may be expressed as

$$\frac{dC}{dt} = K_L a (C_s - C) \qquad (4.11)$$

where C = the concentration of the dissolved gas in the body of the liquid at time t (mg/l)

C_s = the concentration of the dissolved gas at the gas-liquid interface, i.e. the saturation concentration (mg/l)

a = the interfacial area per unit of volume of liquid (cm^{-1})

K_L = the liquid film coefficient (cm/s)

Dobbins (1962) has presented experimental evidence to show that where the film is being continuously replaced or renewed, the value of K_L, in feet/day, is represented by

$$K_L = \sqrt{D_m r} \ \ coth \ \sqrt{\frac{r L_f^2}{D_m}} \qquad (4.12)$$

in which r = average rate of renewal of the liquid film $(hours^{-1})$

D_m = coefficient of molecular diffusion (ft^2/day)

L_f = film thickness (feet)

For a given liquid and temperature the value of r is dependent on the physical pattern and speed of mixing and is difficult to measure other than under laboratory conditions.

An alternative approach, developed by Streeter (1925) is to express the rate of solution of atmospheric oxygen in terms of a rate-constant similar in form to the deoxygenation constant. This rate constant, or reaeration coefficient K_2, can be expressed in terms of the film co-efficient as

$$K_2 = K_L/H \tag{4.13}$$

where K_2 is in days^{-1}

and   H is the mean depth of flow in metres

Equation (4.11) can be re-expressed as

$$\frac{dC}{dt} = K_2 (C_s - C) \tag{4.14}$$

or in terms of the oxygen deficit, D (= C_s - C)

$$-\frac{dD}{dt} = K_2 D \tag{4.15}$$

By integration

$$D = D_o e^{-K_2 t} \tag{4.16}$$

in which   D = dissolved oxygen deficit at time t (mg/l)

D_o = initial dissolved oxygen deficit (mg/l)

Equation (4.16) also describes the way in which the concentration of dissolved oxygen will fall if the water happens to be supersaturated (i.e. $C_o > C_s$).

The saturation value of oxygen in water, C_S (mg/l), is influenced by temperature and may be calculated from the following formula (Whipple, 1969).

$$C_S = 14.652 - 0.41022T + 0.007991T^2 - 0.000077774T^3 \qquad (4.17)$$

where T is in $^\circ$C and the atmospheric pressure is 760 mm of mercury.

Investigation of the reaeration coefficient, K_2, has been undertaken by a number of workers.   The technique used has generally been a least squares analysis of field data.   Most workers have found K_2 to be a function of velocity and depth with the general form

$$K_2 = a \; \frac{V^b}{H^c} \qquad (4.18)$$

(Churchill, Elmore and Buckingham (1962), O'Connor and Dobbins (1958), Gameson (1959) and Owens, Edwards and Gibbs (1964)).

Unfortunately, the results that the formulae yield are significantly different due to the wide variations in equation constants.

O'Connor (1958) proposed alternate equations based on the turbulent characteristics of the stream being categorised in terms of the Chezy coefficient, C, which is an hydraulic factor of flow resistance.

For isotropic flow (Chezy C > 17)

$$K_2 = \frac{(D_m \bar{U})^{\frac{1}{2}}}{2.31 \, (H)^{3/2}} \qquad (4.19)$$

and for non-isotropic flow (Chezy C < 17)

$$K_2 = \frac{480 D_m^{0.5} S_e^{0.25}}{H^{1.25}} \qquad (4.20)$$

where $\bar{U}$ = mean stream velocity (ft/day)

H = stream depth (ft.)

S_e = slope of the hydraulic energy line

D_m = molecular diffusivity (ft^2/day)

and Chezy   C = $V/\sqrt{RS_e}$

where   V = mean velocity in feet/sec.

R = hydraulic radius (ft.)

The molecular diffusivity, D_m, may be computed from the equation given by Dobbins (1964), i.e.

$$D_m = 0.00189 \, (1.037)^{T-20} \quad (ft^2/day) \qquad (4.21)$$

where T is the stream temperature (^{o}C)

Krenkel (1973) states that the values obtained using O'Connor's formulations do not always agree with actual observations, and should be used with caution.

Investigations by Krenkel and Orlob (1963) resulted in the following empirical equation for K_2 corrected to a temperature of 20°C

$$K_2 = 1.138 \times 10^{-5} \, D_L \, H^{-2.32} \qquad (4.22)$$

where D_L is the longitudinal mixing coefficient (ft^2/day) and H is the depth of water undergoing reaeration in a laboratory flume (ft).

Thackston and Krenkel (1966) extended this work and derived the following equation for K_2 at 20°C

$$K_2 = 0.000125 \, (1 + \mathbb{F}^{\frac{1}{2}}) \, \frac{\bar{U}_*}{H} \qquad (4.23)$$

where $\mathbb{F}$ = Froude No. = $\bar{U}/\sqrt{gH}$

$\bar{U}_*$ = shear velocity (ft/sec)

H = stream depth (ft.)

Bennett and Rathbun (1972) claim that probably the best field study of the reaeration coefficient has been by Churchill, Elmore and Buckingham (1962). This study involved collecting extensive data in streams supplied from dams, where the water, because of the prolonged storage under conditions of thermal stratification was deficient in dissolved oxygen and contained negligible biological oxygen demand. The equation developed was based on a correlation analysis and has a coefficient of multiple correlation of 0.82. The equation is:-

$$K_2 = 5.026 \ \bar{V}^{\ 0.969} \ H^{-1.673} \tag{4.24}$$

where K_2 is in reciprocal days, $\bar{V}$ is in ft/sec. and H in feet.

Figure 4.2 shows the reaeration coefficient (20°C) as a function of depth for a number of prediction equations. A standard velocity of 1 ft./second and a slope of 0.0001 are used as a basis for calculation. It is obvious that considerable error may result in the prediction of K_2 Apart from differences according to the predictive equation used K_2 is sensitive to changes in depth, being approximately 100 days^{-1} in 0.5 ft. depth of water decreasing to approximately 1 day^{-1} in 1.5 ft. of water. However, sensitivity decreases as depth increases. For example, a change in depth from 1 to 5 ft. results in a decrease in K_2 from approximately 5 to 0.5 days^{-1}.

The reaeration coefficient is affected by temperature due to its dependence on such temperature sensitive parameters as molecular diffusivity, kinematic viscosity and surface tension. It is generally accepted that the effect of temperature is adequately expressed in the form

$$(K_2)_T = K_2 \ \Theta_2^{(T-20)} \tag{4.25}$$
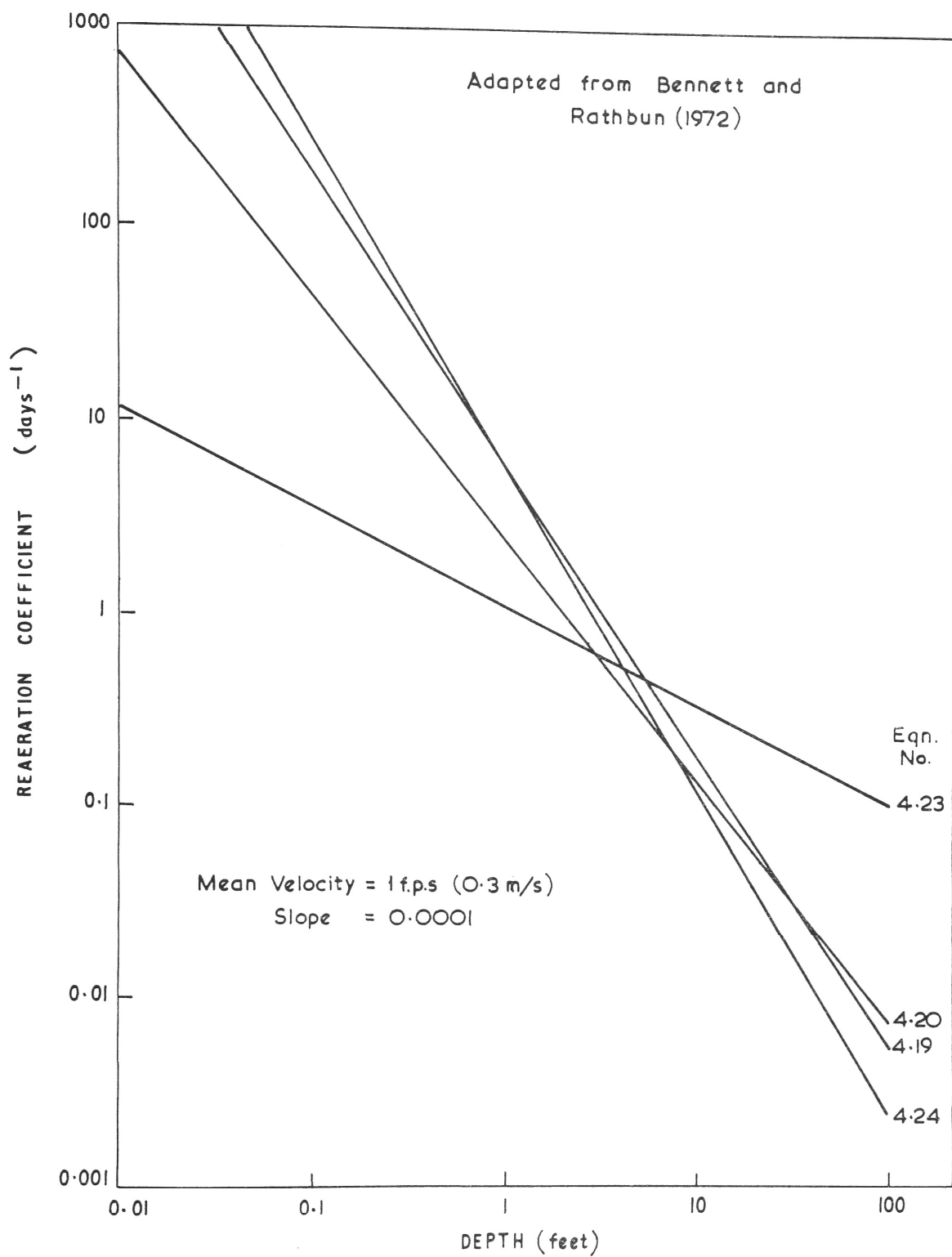
FIGURE 4·2 : REAERATION COEFFICIENT AS A FUNCTION OF DEPTH.

where $(K_2)_T$ is the reaeration coefficient at T^oC

K_2 is the reaeration coefficient at 20^oC

Streeter and Phelps (1925) have found Θ_2 to be equal to 1.0241, a value which was later substantiated by Churchill, Elmore and Buckingham (1962) and the Committee on Sanitary Engineering Research (1961)

i.e. $$K_{2(T)} = K_{2(20)} \times 1.0241^{(T-20)} \tag{4.26}$$

This represents approximately 2% change in K_2 per degree centigrade change near 20^oC. It should be noted that gas solubility in water decreases with increasing temperature, a fact that partially offsets the temperature effect on the rate constant.

4.5 Photosynthesis and Respiration

Since biota type often varies from one location to another, the effectiveness of the general statistical approach to the prediction of oxygen production by photosynthesis and depletion by respiration is reduced considerably. Consequently these two factors are usually determined experimentally at the site of the investigation.

The nature of the relationships to be expected in the field may be gauged by the resultsof Owens, Knowles and Clark (1969) in their study of a non polluted reach of a shallow river (River Ivel, England). It was found that oxygen production was relatively independent of the amount of aquatic weed present within the limits 37-253 g dry weight/ m^2. The relationship between oxygen production and solar radiation (up to 60 cal/cm^2/hr) was found to be represented by -

$$Ph_1 = a_3 I^{a4} \tag{4.27}$$

where Ph_1 = oxygen production $(g/m^2/hr)$

I = intensity of solar radiation at the water

surface $(cal/cm^2/hr)$

and a_3 and a_4 are constants which in this study averaged

0.062 and 0.79 respectively.

Bailey (1967) proposed a more elaborate relationship which

takes into account the additional factors of chlorophyll content, stream

turbidity and stream temperature, i.e.

$$Ph_2 = a_6 \, Ch \, \frac{I_o}{e_c}^{2/3} + a_7 \, T - a_8 H \qquad (4.28)$$

where Ph_2 = photosynthetic oxygen production $(mg/l/day)$

C_h = mean chlorophyll content (mg/l)

I_o = mean daily solar intensity $(cal/cm^2 day)$

e_c = extinction coefficient (m)

T = mean water temperature (^oC)

H = mean water depth (m)

and a_6, a_7 and a_8 are constants.

Photosynthetic production of oxygen only occurs during daylight

hours. Respiration, on the other hand, is a continuous process.

Owens, Knowles and Clark (1969) have presented the following relation-

ship for the respiration of rooted plants.

$$Pr_1 = b_1 \, MC^{b2} \qquad (4.29)$$

where Pr_1 = oxygen consumption $(g/m^2/hr)$

M = biomass of rooted plants $(g \; dry \; wt/m^2)$

C = dissolved oxygen concentration (mg/l)

and b_1 and b_2 are constants and in this instance are quoted

as 0.75×10^{-3} and 0.30 respectively.

The conversion of oxygen production and oxygen consumption values from $g/m^2/hr$ to $mg/1/day$ is accomplished by dividing by the stream depth (metres) and multiplying by the number of hours in the day for which the process actively contributes to the dissolved oxygen balance.

Where the rate of oxygen production or respiration is assessed from field data, the following formulae can be used:

$$Ph_1, Pr_1 = 3600\Delta C \frac{V}{X} H \qquad g/m^2/hr \qquad (4.30)$$

or
$$Ph_2, Pr_2 = 3600\Delta C \frac{V}{X} N_h \qquad mg/1/day \qquad (4.31)$$

where X = reach length (metres)

N_h = number of hours in the day during which the process is active

ΔC = change in O_2 concentration over the reach. (mg/1)

V = stream velocity (m/s)

5. Mathematical Design of the Dissolved Oxygen Model

5.1 Established Models

One of the first studies of the dissolved oxygen balance was the classical study of Streeter and Phelps (1925). This study considered carbonaceous oxidation and reaeration to be the only important factors and neglected other parameters. Other authors, notably Dobbins (1964), Camp (1963) and O'Connor (1967) recognised the limitations of the equation and so expanded the oxygen balance to include other sources and sinks of dissolved oxygen such as photosynthesis, sedimentation, bottom scour, surface runoff, nitrification and benthal demand.

5.1.1 Streeter and Phelps Model

The fundamental Streeter and Phelps equation assumes that only two major processes are involved. That is, the biodegradable waste and dissolved oxygen are being removed along the length of the stream and the oxygen is being replaced by reaeration at the surface. Other factors such as nitrification, photosynthesis and respiration of aquatic flora have been considered negligible.

Consequently the rate of change of dissolved oxygen deficit is expressed as a summation of equations (4.1) and (4.15)

$$\text{i.e.} \quad \frac{dD}{dt} = K_1 L - K_2 D \qquad (5.1)$$

By substituting equation (4.2) into (5.1) and integrating the solution is

$$D = \frac{K_1 L_0}{K_2 - K_1} \left[\exp(-K_1 t) - \exp(-K_2 t) \right] + D_0 \exp(-K_2 t) \qquad (5.2)$$

where

D = the dissolved oxygen deficit at the downstream end of

reach (mg/1)

L_O = ultimate B.O.D. at the upstream end of reach (mg/1)

D_O = the dissolved oxygen deficit at the upstream end of

reach (mg/1)

K_1 = deoxygenation coefficient (day^{-1})

t = time of flow in the reach (days)

Additional assumptions inherent in the Streeter and Phelps

equation are:-

(i) The initial pollution load is added at the upstream end of the

reach and thereafter is affected only by biological oxidation and not by

the addition of either organic material or dilution flow along the reach.

(ii) The streamflow is steady and uniform along the length of

the reach.

(iii) The process for the reach as a whole is a steady state pro-

cess, the conditions at every cross section being unchanged with time.

(iv) The B.O.D. and oxygen are uniformly distributed over each

cross section, thus permitting the equations to be written in one

dimensional form.

5.1.2 Dobbins Model

Dobbins (1964) expanded the Streeter-Phelps equation to include;

(i) the removal of B.O.D. by sedimentation or absorption on the

stream bed;

(ii) the removal of dissolved oxygen from the water by diffusion

into the benthal layer and by respiration of algae and plants;

(iii) the addition of B.O.D. along the reach by runoff and by scour of bottom deposits, and

(iv) the addition of dissolved oxygen by photosynthesis.

The effect of longitudinal dispersion in redistributing the B.O.D. and D.O. in natural streams was examined and assumed to be negligible compared with the other terms.

The following equations were derived

$$L = L_o e^{-(K_1 + AK_4)} + \frac{L_a}{K_1 + AK_4} \left(1 - e^{-(K_1 + AK_4)^t}\right) \tag{5.3}$$

and

$$D = \frac{K_1 \left(L_o - \frac{L_a}{K_1 + AK_4}\right) \left(e^{-(K_1 + AK_4)^t} - e^{-K_2 t}\right)}{K_2 - (K_1 + AK_4)}$$

$$+ D_{oe}^{-K_2 t} + \left(\frac{D_B}{K_2} + \frac{K_1 L_a}{K_2 (K_1 + AK_4)}\right)\left(1 - e^{-K_2 t}\right) \tag{5.4}$$

where

L_a = rate of addition of B.O.D. along the reach, including the addition of B.O.D. with runoff ,the diffusion of partly degraded waste from the benthal layer into the water,and the scour and resuspension of bottom deposits (mg/1/day)

AK_4 = coefficient for the removal of B.O.D. by sedimentation or the addition by resuspension (days^{-1})

D_B = rate at which oxygen is removed by benthal and plant respiration less that supplied by photosynthesis (mg/1/day).

For the B.O.D. equation, B.O.D. may either decrease or increase along the reach depending on whether L_o is greater or less than $L_a/(K_1 + K_3)$.

5.1.3 Camp Model

Camp (1965) proposed a model to include photosynthensis and benthal demand in the following manner:-

$$\frac{dD}{dt} = (K_1 L - K_2 D) - P_{h_2} \qquad (5.5)$$

where P_{h_2} is the oxygen production in the euphotic zone by photosynthesis (mg/l/day).

This equation is the same as the Streeter and Phelps equation when $P_{h_2} = 0$. The rate of change of L may be determined by means of a development similar to that of Streeter and Phelps (Eqn.5.2).

i.e.
$$\frac{dL}{dt} = -(K_1 + AK4)L + L_a \qquad (5.6)$$

where L_a is the rate of addition of B.O.D. to the overlying water from bottom deposits (mg/l/day).

The integral of equation (5.6) is

$$L = \left[L_o - \frac{L_a}{(K_1+AK4)} \right] e^{(K_1 + AK4) t} + \frac{L_b}{(K_1 + AK4)} \qquad (5.7)$$

The differential equation (5.5) may be integrated after substitution of L to give the general equation

$$D = \frac{K_1}{K_2 - K_1 - AK4}\left[L_o - \frac{L_a}{K_1 + AK4} \right]\left[e^{-(K+AK4)t} - e^{-K_2 t} \right]$$

$$+ \frac{K_1}{K_2}\left[\frac{L_a}{K_1 + K_3} - \frac{P_{h2}}{K_1} \right](1 - e^{-K_2 t}) + D_o e^{-K_2 t} \qquad (5.8)$$

In essence this formulation is similar to that of Dobbins. Some small differences exist in terms of parameter definition.

5.1.4 O'Connor Model

O'Connor (1967) developed a general dissolved oxygen balance in which the oxygen demand of the waste was divided into the requirements for both the carbonaceous material and the nitrogeneous material.

i.e. $D = \dfrac{K_1 L_0}{K_2 - K_r} (e^{-K_r t} - e^{-K_2 t}) - \dfrac{K_3 N_0}{K_2 - K_3} (e^{-K_3 t} - e^{-K_2 t})$

$- D_0 (e^{-K_2 t}) + \dfrac{BR(P_{h_2} - P_{r_2})}{K_2} (1 - e^{-K_2 t})$ (5.9)

where

N_0 = the ultimate oxygen demand due to the oxidation of

NH$_2$ and nitrites in the stream - (mg/l)

K_3 = nitrification coefficient (days^{-1})

BR = the benthal oxygen demand - (mg/l/day)

$(P_{h_2} - P_{r_2})$ = net production of photosynthetic oxygen (mg/l/day)

K_r = B.O.D. removal ceofficient - $K_1 + AK_4$ (days^{-1})

5.2 Model Design Suitable for Australian Streams

Apart from photosynthesis and plant and benthal respiration both nitrification and runoff (or groundwater inflow) are parameters which may have a significant effect on the dissolved oxygen balance in Australian conditions. A comprehensive equation covering all the significant factors can be formulated by combining the Dobbins and O'Connor equations (equations 5.4 and 5.9) to give

$D = \dfrac{K_1}{K_2 - K_r} (L_0 - \dfrac{L_a}{K_r}) (e^{-K_r t} - e^{-K_2 t}) + \dfrac{K_3 N_0}{K_2 - K_3} (e^{-K_3 t} - e^{-K_2 t})$

$+ D_0 e^{-K_2 t} + \dfrac{BR}{K_2} (1 - e^{-K_2 t}) - \dfrac{P_{h_2} - P_{r_2}}{K_2} (1 - e^{-K_2 t})$

$+ \dfrac{K_1 L_b}{K_2 - K_r} (1 - e^{-K_2 t})$ (5.10)

It should be noted that L_b has been created by redefining L_a so as to include only the addition of waste from the benthal deposits and not from runoff or groundwater inflow. These two factors are treated with alternative logic within the computer program so as to include the dilution effect as well as the B.O.D. addition.

6. OXSTRAL Computer Program

The computer program for the computation of dissolved oxygen levels in Australian streams using equation (5.10) has been written in Fortran 11. The amount of storage required and the running time is dependent on the number of stream segments chosen for the simulation. Segment lengths should be chosen based on maximising hydraulic and biological uniformity within each segment.

6.1 Operation and Program Logic (Refer to Flow Chart - Fig. 6.1 and Tables 6.1 and 6.2).

The stream is subdivided into reaches of uniform depth, velocity and streamflow. Beginning at the head of the stream the dissolved oxygen formulation is used to determine the downstream deficit for each reach since the deficit at the bottom of one reach is also the initial deficit at the top of the next reach.

The general data list for the program (data cards 1-3) characterises the ultimate oxygen demand, the initial oxygen level, the air pressure, the rates of deoxygenation associated with each oxidation process and the photosynthesis and respiration constants. Data card 3 indicates the number of segments (M) and the segment number at which nitrification becomes important (N).

Data for each segment is supplied in the remaining data cards and includes stream temperature, velocity, depth, streamflow, plant biomass and benthal demand. The B.O.D. temperature and oxygen content of tributary, overland or groundwater inflow as well as the biological oxygen demand from diffused or resuspended benthal waste are also quantified.

The main program commences with the calculation of flow time in the segment under consideration followed by the computation of the carbonaceous oxidation coefficient, reaeration coefficient and nitrification coefficient at the stream temperature.

The ultimate biological oxygen demand at the stream temperature is then calculated from knowledge of the B.O.D. completion factor (i.e. B.O.D. ultimate at 20°C/B.O.D.$_5$ at 20°C), the temperature coefficient and the stream temperature. The downstream U.B.O.D. is then calculated from first order kinetics, using the deoxygenation coefficient and flow time.

The rate of oxygen production by plant photosynthesis, oxygen depletion by plant and benthal respiration and the oxygen saturation level (taking into account atmospheric pressure) are calculated according to empirical formulae (equations 4.27, 4.29, 4.10, 4.17 and 3.2 respectively). These components are then substituted into the dissolved oxygen balance equation and the downstream dissolved oxygen level calculated.

Dilution by runoff, groundwater or tributary inflow is assessed and the downstream B.O.D. and oxygen level modified accordingly.

The computation loop is continued as many times as there are segments at the end of which the results are tabulated for each segment.

```
                    ┌─────────────────────────────────────┐
                    │          INITIAL VALUES             │
                    │  T(1), TT(1), FM(1), PH(1), PR(1)   │
                    │  BR(1)                              │
                    └─────────────────────────────────────┘
                                     │
                                     ▼
                    ┌─────────────────────────────────────┐
                    │         DATA CARD INPUT             │
                    │  DC1 - AK120, AK320, BOD20, CBOD    │
                    │        ODN, SR, SHRS, BETA5         │
                    │  DC2 - C(1), AK4, ALPHA3, ALPHA4,   │
                    │        BETA 1, BETA 2, AP, ALPHA5   │
                    │  DC3 - M,N                          │
                    └─────────────────────────────────────┘
                                     │
                                     ▼
                            ⟨    2          ⟩
                            ⟨   I = 1, M    ⟩
                                     │
                                     ▼
                    ┌─────────────────────────────────────┐
                    │         DATA CARD INPUT             │
                    │         (D.C.'s 4 TO(M+4))          │
                    │  TW(I), V(I), H(I), X(I), FS(I)     │
                    │  BM(I), TWM(I), CM(I), BA(I)        │
                    │         BIOM(I)                     │
                    └─────────────────────────────────────┘
                                     │
                                     ▼
                                   ( 2 )
                                     │
                                     ▼
            ┌────────────────────────────────────────────────┐
            │   DATA CHANGES FOR SENSITIVITY ANALYSIS         │
            └────────────────────────────────────────────────┘
                                     │
                                     ▼
                            ⟨   10          ⟩
                            ⟨  I=1, M-1     ⟩
                                     │
                                     ▼
            ┌────────────────────────────────────────────────┐
            │   TIME INTERVAL AND CUMULATIVE TIME            │
            │   T(I+1)=(X(I+1)-X(I))/V(I)/(3600.0*24.0)     │
            │         TT(I+1)=TT(I)+T(I+1)                  │
            └────────────────────────────────────────────────┘
                                     │
                                     ▼
            (α₁)                   (α₂)
```

$$T(I+1)=(X(I+1)-X(I))/V(I)/(3600.0*24.0)$$
$$TT(I+1)=TT(I)+T(I+1)$$

FIGURE 6·1: OXSTRAL FLOW CHART

FIGURE 6·1 - Continued

THETA3 = 0.877

NITRIFICATION COEFFICIENT
$AK3(I) = AK320*THETA3**(TW(1)-20.0)$

$TW(I) - 20.0$

$>$

$\leqslant$

THETA2 = 0.0033

THETA2 = 0.0113

CARBONACEOUS OXYGEN DEMAND COMPONENT
$B(1)=CBOD*BOD20*(1.0+THETA2*(TW(1)-20.0))$
$B(I+1)=B(I)*EXP(-AK1(I)*T(I+1))$

$CDX = 24.0/(H(I+1)+H(I))/2.0$

PHOTOSYNTHESIS COMPONENT
$PH(I+1)=ALPHA3*(SR/SHRS)**ALPHA4*SHRS/(H(I+1)+H(I))/2.0$

PLANT RESPIRATION COMPONENT
$PR(I+1) = BIOM(I)*BETA1*C(I)**BETA2*CDX$

BENTHAL RESPIRATION COMPONENT
$BR(I+1)=ALPHA5*C(I)**BETA5*CDX$

FIGURE 6·1 – Continued

FIGURE 6.1 - Continued

α_1 α_6

$BEN = BR(I+1)/AK2(I)*(1.0-EXP(-AK2(I)*T(I+1)))$

$PHO = (PH(I+1)-PR(I+1))/AK2(I)*(1.0-EXP(-AK2(I))*T(I+1))$

$ADB = AK1(I)*BA(I)/(AK2(I)*AKR)*(1.0-EXP(-AK2(I)*T(I+1)))$

D.O. BALANCE
$C(I+1) = CS(I)-ORG-ANIT-ATM-BEN+PHO-ADB$

INPUT FROM MERGING STREAMS
$FM(I+1) = FS(1+I)-FS(I)$

$>$ $FM(I+1) - 0.0$

$\leqslant$

$FM(I+1) = 0.0$

$B(I+1) = (B(I+1)*FS(I)+BM(I+1)*CBOD$
$*FM(I+1))/(FS(I)+FM(I+1))$
$C(I+1) = (C(I+1)*FS(I)+CM(I+1)*$
$*FM(I+1))/(FS(I)+FM(I+1))$

10

α_7

FIGURE 6·1 - Continued

α_7

INPUT DATA SUMMARY

AK120, AK320, BOD20, CBOD, ODN, SR, SHR5, BETA5

C(1), AK4, ALPHA3, ALPHA4, BETA1, BETA2,

AP, ALPHA5

X(I), V(I), H(I)TW(I), FS(I), BM(I), TWM(I)

CM(I), BIOM(I), BA(I)

OUTPUT DATA SUMMARY

TT(I), X(I), B(I), PH(I), PR(I), C(I), CS(I)

FIGURE 6·1 - Continued

6.2 Definition of Input and Output Variables

The following tables give a brief description of all input and output variables. The variables are presented in order of their presence in the program. Units, the probable range of values (based on a survey of the literature) and relevant equation numbers are included wherever applicable.
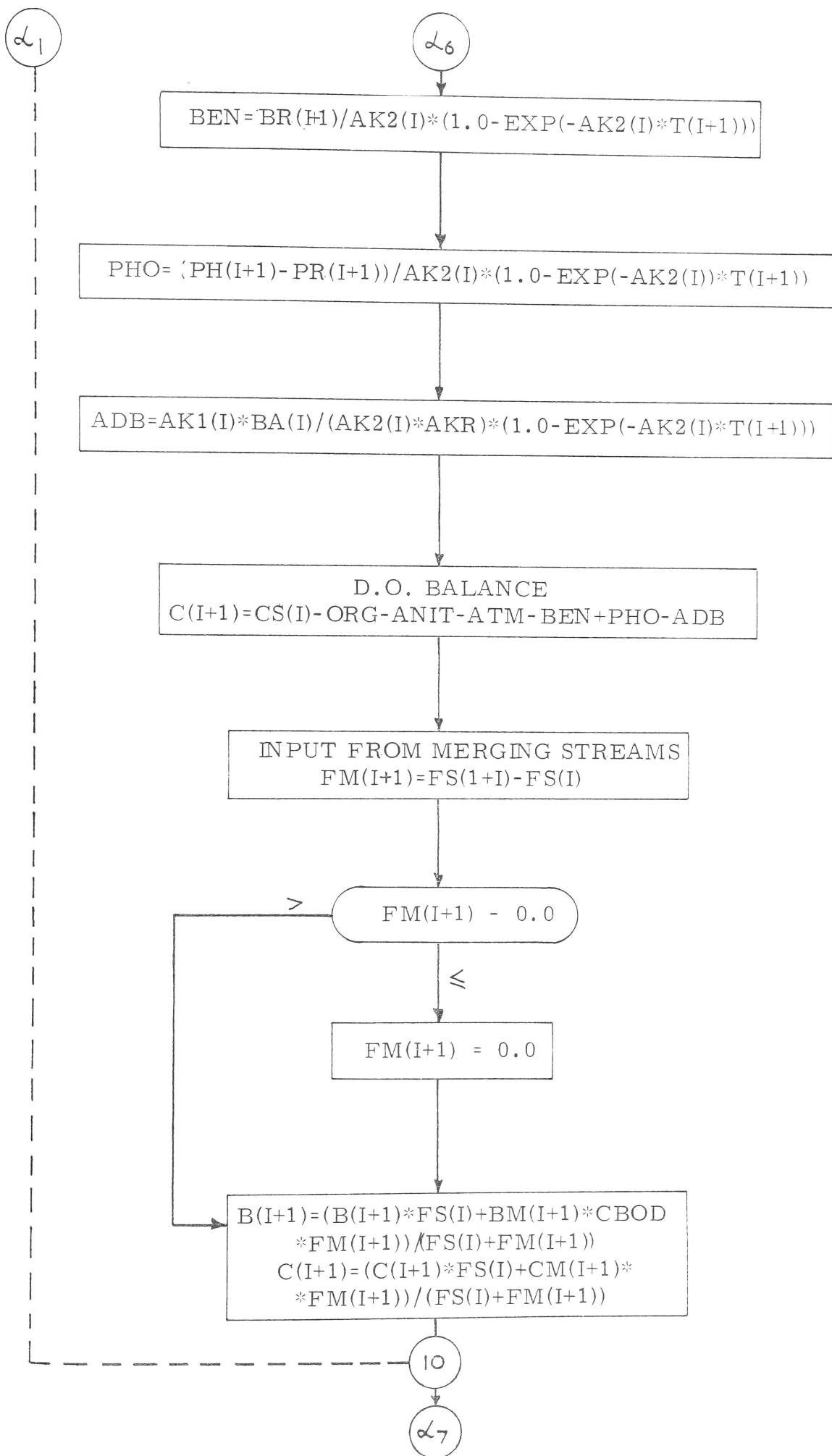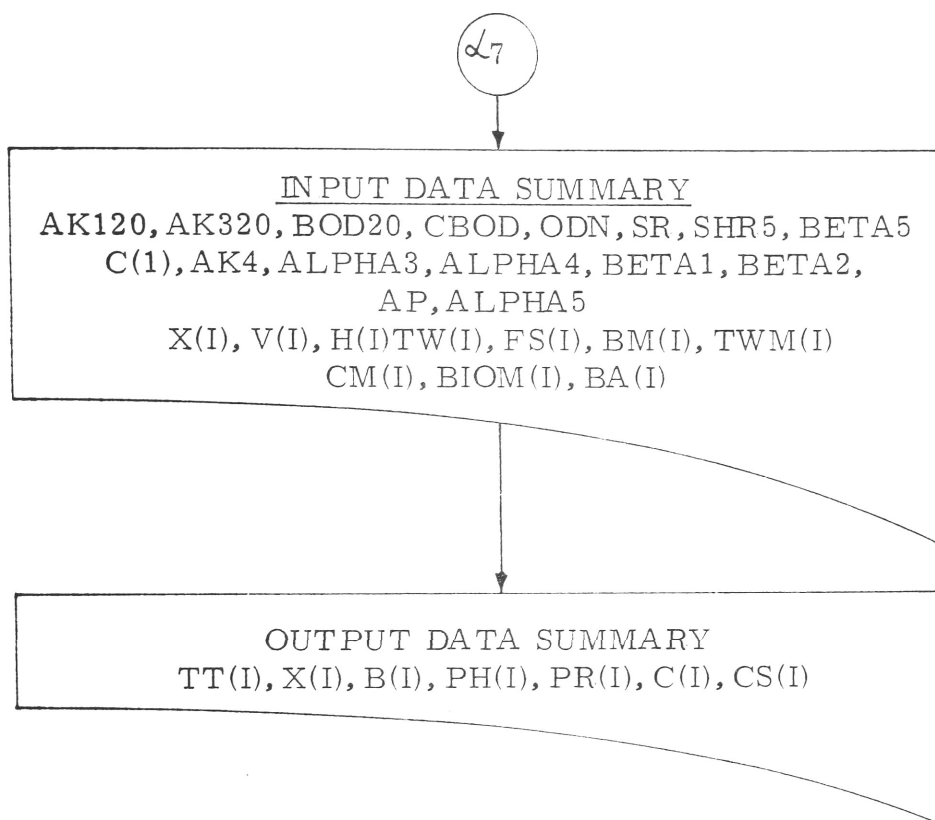
Table 6.1: Input Variables for OXSTRAL

Variable	Definition	Units	Range
AK4	Coefficient for the removal of B.O.D. by sedimentation or the addition by re-suspension eqns. 5.3, 5.4	$days^{-1}$	0-0.1
ALPHA3	Photosynthesis constant eqn. 4.27	-	0.006-0.27
ALPHA4	Photosynthesis constant eqn. 4.27	-	0.424-1.26
ALPHA5	Benthal respiration coeff. eqn. 4.10	-	0.033
AK120	Deoxygenation rate coefficient at $20^{\circ}C$ - eqn. 4.1	$days^{-1}$	0.02-0.7
AK1(I)	Deoxygenation rate coefficient at $TW(I)^{\circ}C$ - eqn. 4.5	$days^{-1}$	0-1
AK2(I)	Reaeration coefficient at TW(I) eqn. 4.26	$days^{-1}$	0.5-100
AK3(I)	Nitrification coeff. at TW(I) eqn.4.9	$days^{-1}$	
AK320	Nitrification rate coefficient at $20^{\circ}C$ eqn. 4.8	$days^{-1}$	0-5
AP	Atmospheric air pressure eqn. 3.2	in. of Hg	600-700
B(1)	Ultimate B.O.D. at TW (I) eqn.4.2	mg/l	0-100
B(I)	Unsatisfied U.B.O.D. at TW(I) eqn.4.2	mg/l	0-100
BR(I)	Benthal oxygen demand - eqn. 4.10	$g/m^2/h$	0.005-0.5

Variable	Definition	Units	Range
BA(I)	Rate of addition of B.O.D. by re-suspension or scour of benthal deposits - eqn. 5.10	mg/l/day	0-100
BM(I)	Merging stream $B.O.D._5$	mg/l	0-100
$BOD2_O$	Initial stream BOD_5	mg/l	0-500
BIOM(I)	Biomass of rooted plants - eqn. (4.29)	g/m^2	0-250
BETA1	Plant respiration constant eqn.(4.29)	-	0.75×10^{-3}
BETA2	Plant respiration constant eqn. (4.29)	-	0.3
BETA5	Benthal respiration coeff. eqn.(4.10)	-	0.6
C(1)	Initial d.o. concentration	mg/l	0.30
C(I)	d.o. level in segment (I)	mg/l	0.30
CS(I)	Saturation value of oxygen in water- eqn. (4.17)	mg/l	7-14.6
CM(I)	Merging stream d.o. concn.	mg/l	0-30
CBOD	BOD completion factor (UBOD/BOD_5)	-	1-2
DN(I)	Unsatisfied nitrification demand at TW(I)	mg/l	0-100
FS(I)	Streamflow	m^3/s	0+
FM(I)	Merging streamflow	m^3/s	0+
H(I)	Stream depth	m	0.03 -3
I	Reach number	-	-
M	Number of data collection points	-	-
N	Reach number at which nitrif-ication begins	-	-
ODN	Ultimate oxygen demand due to nitrification at $20^{\circ}C$	mg/l	0-100

Variable	Definition	Units	Range
PH(I)	Oxygen production due to photo-synthesis - eqn.(4.27)	mg/l/day	0-1.0
PR(I)	Oxygen consumption due to rooted plants - eqn.(4.29)	mg/l/day	0-0.5
SR	Solar radiation intensity - eqn. (4.27)	$cal/cm^2/$ day	50- 700
SHRS	Number of sunshine hours	-	0-12
TW(I)	Stream temperature	^{o}C	0-35
TWM(I)	Merging stream temperature	^{o}C	0-35
T(I)	Flow time in segment	days	0.01+
TT(I)	Cumulated flow time	days	0.01+
THETA1	Deoxygenation temp. coeff. eqn. (4.5)	-	0.96 -1.1
THETA2	BOD temp. coeff. - eqn.(4.7)		0.9- 1.1
THETA3	Nitrification temp.coeff.eqn.(4.9)	-	0.88 -1.1
V(I)	Stream velocity	m/s	0.05- 2.0
X(I)	Distance from datum point	m	-

Table 6.2: Output Variables for OXSTRAL

Variable	Definition	Units	Range of Values
B(I)	Unsatisfied BOD at TW(I)	mg/1	0-100
BR(I)	Rate of benthal deposit respiration	mg/1/day	0-0.5
C(I)	Dissolved oxygen concentration	mg/1/day	0-30
CS(I)	Oxygen saturation level	mg/1	7-14.6
PH(I)	Rate of oxygen production by photosynthesis	mg/1/day	0-1.0
PR(I)	Oxygen consumption due to rooted plants	mg/1/day	0-0.5
TT(I)	Flow time from head of stream	days	0.1+
X(I)	Flow distance from head of stream	m	-

6.3:   Data Requirements

Parameter	Source and/or Reference
AK120	From empirical formulae (e.g. eqn. 4.24) or field measurements.
AK4	In situ or laboratory analysis.
ALPHA3	In situ analysis (Owens, Knowles and Clarke, 1969).
ALPHA4	In situ analysis (Owens et al 1969).
AK320	Laboratory analysis.
BETA 1	Field measurements (Owens et al, 1969).
BETA 2	Field measurements (Owens et al, 1969).
BIOM(I)	Survey and laboratory analysis.
BR(I)	Survey or from empirical eqn. 4.10.
BA(I)	Survey and laboratory analysis.
BM(I)	Survey and laboratory analysis.
BOD20	Survey and laboratory analysis.
C(1)	Survey using D.O. Meter.
CBOD	Laboratory analysis.
CM(I)	Survey with D.O. meter.
FS(I)	From velocity and cross sectional areas.
H(I)	Survey with meter rule.
M	Total number of segments, selected according to uniformity.
N	Segment in which nitrification commences.
ODN	Survey and laboratory analysis.
SR	In situ measurement using a pyrheliometer.
SHRS	Observation

Parameter	Source and/or Reference
TWM(I)	Survey with thermometer.
TW(I)	Survey with thermometer.
V(I)	Survey with a current meter.
X(I)	Locality maps.

6.4 <u>OXSTRAL LISTING</u>

```
C        JON TUCK/DISSOLVED OXYGEN   IN AUSTRALIAN STREAMS
         DIMENSION B(10),V(10),H(10),PH(10),C(10),BR(10),T(10),TT(10)
         DIMENSION TW(10),AK1(10),CS(10),AK2(10),X(10),PR(10),AK3(10)
         DIMENSION FS(10),BM(10),FM(10),TWM(10),CM(10),BA(10),BIOM(10)
         DIMENSION DN(10)
C        INITIAL VALUES
         T(1)=0.0
         TT(1)=0.0
         FM(1)=0.0
         PH(1)=0.0
         PR(1)=0.0
         BR(1)=0.0
C        DATA INPUT
     5 FORMAT (8F10.3)
         READ 5,AK120,AK320,BOD20,CBOD,ODN,SR,SHRS,BETA5
         READ 5,C(1),AK4,ALPHA3,ALPHA4,BETA1,BETA2,AP,ALPHA5
     6 FORMAT(2I10)
         READ 6,M,N
C        M=NO. OF DATA CARDS =NO. OF DATA COLLECTION POINTS
C         N=NITRIFICATION SEGMENT
         DO 2 I=1,M
C        WATER TEMP.(DEG.C),STREAM VEL.(M/S),STREAM DEPTH(M),DIST.FRO.
C        MEAS. PT. TO START(M),STREAMFLOW(CUM/S),MERGING BOD(MG/L),
C        MERGING TEMP(DEGC),MERGING DO(MG/L)
     1 FORMAT(8F10.2)
         READ 1,TW(I),V(I),H(I),X(I),FS(I),BM(I),TWM(I),CM(I)
     7 FORMAT(2F10.2)
         READ 7,BA(I),BIOM(I)
     2 CONTINUE
         DO 606 K=1,9
         IF(K-1)607,607,608
   608 IF(K-2)607,609,610
   609 ALPHA4=0.3
   610 IF(K-3)607,611,612
   611 DO 801 I=1,M
         TW(I)=5.0
   801 CONTINUE
   612 IF(K-4)607,613,614
   613 DO 802 I=1,M
         V(I)=0.2
   802 CONTINUE
   614 IF(K-5)607,615,616
   615 DO 803 I=1,M
         BIOM(I)=100.0
   803 CONTINUE
   616 IF(K-6)607,617,618
   617 DO 804 I=1,M
         TW(I)=25.0
   804 CONTINUE
   618 IF(K-7)607,619,620
   619 DO 805 I=1,M
         H(I)=0.1
```

```
 605  CONTINUE
 620  IF(K-8)607,621,622
 621  DO 806 I=1,M
      FS(I)=0.05
 806  CONTINUE
 622  IF(K-9)607,623,607
 623  BOD20=100.0
      ODN=100.0
      C(1)=4.0
      AK320=4.0
      DO 807 I=1,M
      TW(I)=20.0
      V(I)=0.2
      BIOM(I)=100.0
      BA(I)=5.0
      H(I)=0.1
      FS(I)=0.05
 807  CONTINUE
 607  MP1=M-1
      DO 10 I=1,MP1
C     MEAN TIME INTERVAL AND CUMULATIVE TIME/HRS
      DX=X(I+1)-X(I)
      T(I+1)=DX/(V(I+1)+V(I))/(3600.0*24.0*2.0)
      TT(I+1)=TT(I)+T(I+1)
C     KINETIC COEFFICIENTS
      IF(TW(I)-15.0)101,101,102
 101  THETA1=1.109
      GO TO 105
 102  IF(TW(I)-30.0)103,103,104
 103  THETA1=1.042
      GO TO105
 104  THETA1=0.967
 105  AK1(I)=AK120*THETA1**(TW(I)-20.0)
      AK2(I)=5.026*((V(I)+V(I+1))/0.61)**0.97/((H(I+1)+H(I))/0.61)
     X**1.67*1.0241**(TW(I)-20.0)
      IF(TW(I)-22.0)301,301,302
 301  THETA3=1.097
      GO TO 305
 302  THETA3=0.877
      GO TO 305
 305  AK3(I)=AK320*THETA3**(TW(I)-20.0)
C     CARBONACEOUS  O2 DEMAND COMPONENT
 200  IF(TW(I)-20.0)201,201,202
 201  THETA2=0.0033
      GO TO 205
 202  THETA2=0.0113
 205  B(1)=CBOD*BOD20*(1.0+THETA2*(TW(1)-20.0))
      B(I+1)=B(I)*EXP(-AK1(I)*T(I+1))
C     PHOTOSYNTHESIS COMPONENT
      CDX=12.0/(H(I+1)+H(I))
      PH(I+1)=ALPHA3*(SR/SHRS)**ALPHA4*SHRS/(H(I+1)+H(I))/2.0
C     PLANT RESPIRATION AND BENTHAL COMPONENT
      BR(I+1)=ALPHA5*C(I)**BETA5*CDX
      PR(I+1)=BIOM(I)*BETA1*C(I)**BETA2*CDX
C     DISSOLVED OXYGEN CALCULATION
      CS(1)=14.652-0.41022*TW(1)+0.007991*TW(1)**2.0-0.000077774*TW(1)
     X**3.0
      CS(I+1)=14.652-0.41022*TW(I+1)+0.007991*TW(I+1)**2.0-0.000077774
     X*TW(I+1)**3.0
      CS(1)=CS(1)*AP/760.0
```

```
      CS(I+1)=CS(I+1)*AP/760.0
C     EQN. ADAPTED AFTER O CONNOR AND DOBBINS
      AKR=AK1(I)+AK4
      ORG=AK1(I)/(AK2(I)-AKR)*(B(I)-BA(I)/AKR)*(EXP(-AKR*T(I+1))
     X-EXP(-AK2(I)*T(I+1)))
      IF(M-N)401,405,405
  401 ANIT=0.0
      GO TO 406
  405 DN(1)=ODN
      DN(I+1)=DN(I)*(1.0-EXP(-AK3(I)*T(I+1)))
      ANIT=AK3(I)*DN(I)/(AK2(I)-AK3(I))*(EXP(-AK3(I)*T(I+1))-EXP
     5(-AK2(I)*T(I+1)))
  406 ATM=(CS(I)-C(I))*EXP(-AK2(I)*T(I+1))
      BEN=BR(I+1)/AK2(I)*(1.0-EXP(-AK2(I)*T(I+1)))
      PHO=(PH(I+1)-PR(I+1))/AK2(I)*(1.0-EXP(-AK2(I))*T(I+1)))
      ADB=AK1(I)*BA(I)/(AK2(I)*AKR)*(1.0-EXP(-AK2(I)*T(I+1)))
      C(I+1)=CS(I+1)-ORG-ANIT-ATM-BEN+PHO-ADB
C     INPUT FROM MERGING STREAMS
      FM(I+1)=FS(I+1)-FS(I)
      IF(FM(I+1)-0.0)3,3,4
    3 FM(I+1)=0.0
    4 B(I+1)=(B(I+1)*FS(I)+BM(I+1)*CBOD*FM(I+1))/(FS(I)+FM(I+1))
      C(I+1)=(C(I+1)*FS(I)+CM(I+1)*FM(I+1))/(FS(I)+FM(I+1))
   21 FORMAT(8F10.3)
      PRINT 21,T(I),X(I),B(I),PH(I),BR(I),C(I),CS(I),PR(I)
      PRINT 21,CS(I),ORG,ANIT,ATM,BEN,PHO,ADB,AK2(I)
   10 CONTINUE
   30 FORMAT (1H0,10X,38HDISSOLVED OXYGEN IN AUSTRALIAN STREAMS)
      PRINT 30
C     INPUT DATA SUMMARY
  501 FORMAT(1H0,5X,5HAK120,4X,5HAK320,5X,5HBOD20,6X,4HCBOD,5X,3HODN,8X,
     X2HSR,6X,4HSHRS,6X,5HBETA5)
      PRINT 501
  502 FORMAT(8F10.3)
      PRINT 502,AK120,AK320,BOD20,CBOD,ODN,SR,SHRS,BETA5
  503 FORMAT(1H0,5X,4HC(1),5X,3HAK4,7X,6HALPHA3,5X,6HALPHA4,5X,5HBETA1,5
     XX,5HBETA2,5X,2HAP,7X,6HALPHA5)
      PRINT 503
      PRINT 502,C(1),AK4,ALPHA3,ALPHA4,BETA1,BETA2,AP,ALPHA5
   70 FORMAT(1H0,5X,4HDIST,8X,3HVEL,6X,5HDEPTH,5X,4HTEMP,5X,4HFLOW,5X,
     X4HMBOD,5X,5HMTEMP,7X,3HMDO,7X,4HBIOM,5X,5HBODAU)
      PRINT 70
      DO 80 I=1,M
   90 FORMAT(10F10.2)
      PRINT 90,X(I),V(I),H(I),TW(I),FS(I),BM(I),TWM(I),CM(I),BIOM(I),
     XBA(I)
   80 CONTINUE
C     OUTPUT DATA SUMMARY
   40 FORMAT(1H0,5X,4HTIME,3X,9HFLOW DIST,5X,4HUBOD,5X,5HPHOTO,5X,
     X7HPLANT.R,5X,2HDO,5X,6HSAT DO)
      PRINT 40
      DO 50 I=1,M
   60 FORMAT(7F10.3)
      PRINT 60,TT(I),X(I),B(I),PH(I),PR(I),C(I),CS(I)
   50 CONTINUE
  606 CONTINUE
      CALL EXIT
      END
```

6.5 Simulation of Measured Dissolved Oxygen Levels

The capacity of OXSTRAL to simulate the dissolved oxygen distribution in a stream is illustrated in Section 6 of Chapter 7.

6.6 Sensitivity Analysis

Because of the complexity of the dissolved oxygen balance a rigorous statistical analysis of the effect of errors and variations in parameters cannot be performed within the scope of this report. Nevertheless the relative significance of errors and variations in the data and parameters of the dissolved oxygen equation can be assessed using a technique known as the sensitivity analysis.

The sensitivity analysis involves observing the behaviour of the computer output (in this instance the dissolved oxygen distribution) as one parameter or parameter group is varied whilst all others are kept constant. The sensitivity of the system to the parameter is taken to be the change in output per unit change in the parameter. The use of this technique has an obvious advantage. For a stream with certain basic hydrological and biological characteristics those parameters which are insignificant and those which require accurate measurement are revealed. Maximisation of the accuracy of the computer program and the rationalisation of data collection techniques follow.

The use of the sensitivity analysis technique is illustrated in Section 6 of Chapter 7.

7. Perisher Creek

7.1 Introduction

Water samples taken from Perisher Creek have indicated a high level of bacterial contamination (Stinson, 1974). Additional information, in the form of dissolved oxygen data collected in situ and computed dissolved oxygen levels will be used to investigate the possible deterioration in stream water quality and provide the basis for possible remedial action.

7.2 The Nature of the Stream

Perisher Creek is located in Perisher Valley, a winter tourist resort in the Kosciusko National Park, approximately 528 Km south of Sydney.

The stream, shown in Figure 7.1, has its beginnings in a marsh area at the summit of Perisher Gap to the west of Perisher Village. It gradually increases in width as it meanders its way down the alpine slope. In some sections the stream disappears altogether beneath a continuous cover of vegetation and peat. Upon reaching the floor of the valley the stream generally becomes wider and shallower and velocities decrease. As the stream flows through the Perisher Village its meandering nature becomes more prominent. However, once clear of the Village the width of the stream increases further and the meandering becomes less evident. The stream flows without change until a few hundred metres beyond Barrakee Lodge where it is subjected to a considerable gradient as it drops 100 or so metres down to the site of the weir. At this
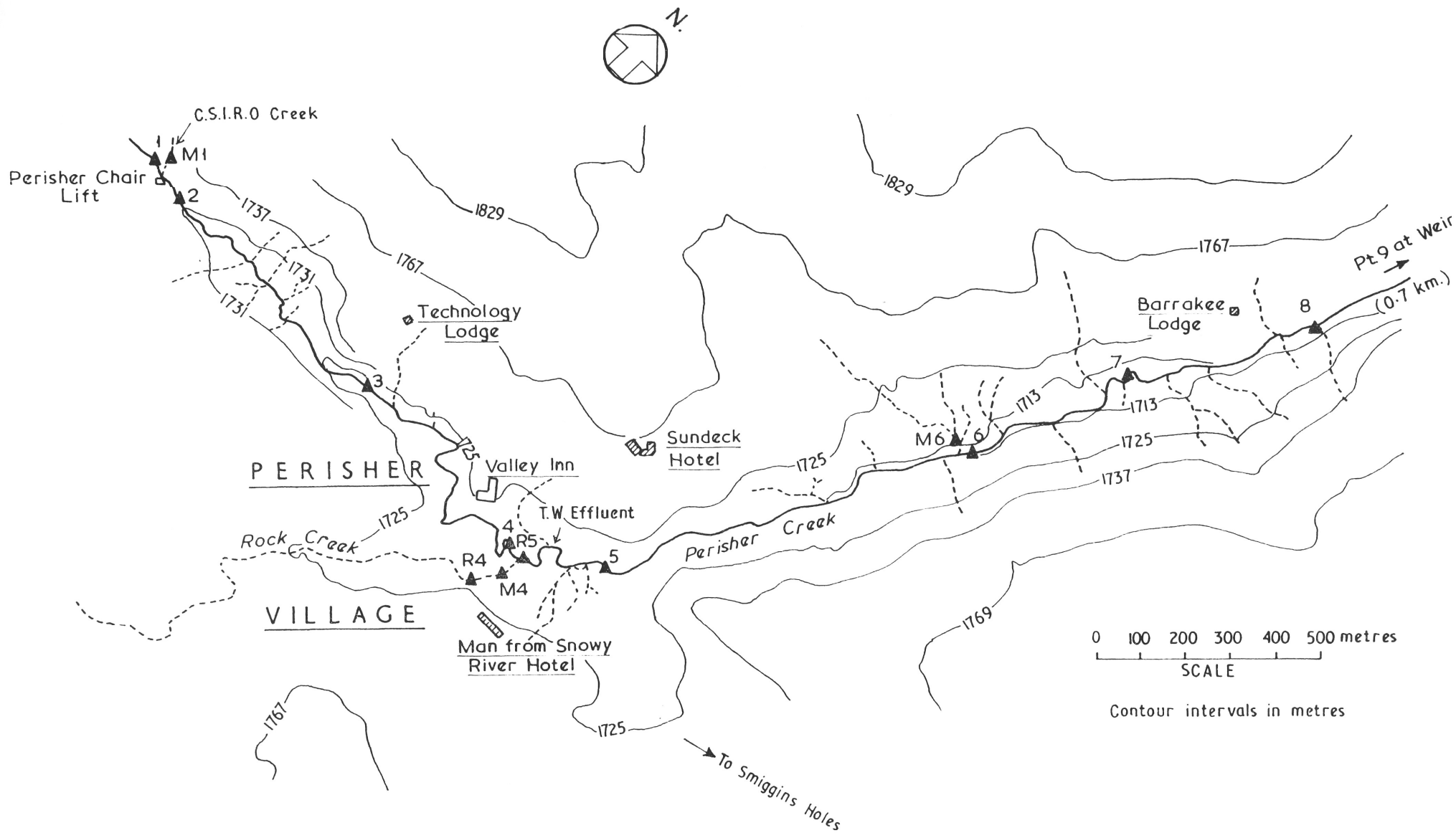
FIGURE 7·1: LOCALITY MAP

point the stream is piped approximately 4 Km to Guthega Dam.

7.3 Factors Affecting the Dissolved Oxygen Balance of Perisher Creek

7.3.1 Climate

Perisher Valley is subject to relatively mild, dry summers. In the winter and spring low temperatures may lead to heavy snow-falls in the valley.

7.3.2 Precipitation and Streamflow

During winter, precipitation falls predominantly as snow. The snow cover usually begins to form in the highest part of the area in April or May, and by June all mountains and valleys may be covered. The snow coverage tends to reach a maximum in August; after that the snowmelt begins and may last for 3 to 4 months. Except for some drifts at high elevations, all snow has usually disappeared by late December.

The streamflow reflects the precipitation except that there is an average time lag of two to three months between the occurrence of precipitation as snow in the winter and its melting during the spring. The hydrological cycle may be regarded as commencing in March when the flows in Perisher Creek will be at its lowest following the end of the spring snowmelt and the comparatively dry summer and early autumn. During April or May increased rain and snow will increase stream discharge. However, with the onset of winter the flows are reduced with the increasing snowfalls and freezing temperatures. The bulk of the annual runoff occurs in spring when high flows are sustained by the melting of the snow pack

and a continuance of precipitation which may last until the middle of December. During the months January to March, streams in the Snowy Mountains are mainly fed from groundwater sources (Snowy Mountains Authority, 1966).

A typical yearly hydrograph for Perisher Creek has been generated from data given by the Snowy Mountains Authority (1966, 1971), and is shown in Figure 7.2. The dry months of January, February and March are shown on an expanded scale in Figure 7.3. As shown the minimum dry weather flow in the late summer is about 1 cusec (0.03 m^3/s). However, flows as low as 0.7 cusecs (0.02 m^3/s) have been recorded in other years (Snowy Mountains Council, 1975). In this dry period precipitation losses are high. Much of the water is retained in the soil and vegetation mat and later lost by transpiration and evaporation. Some percolates to the subsoil and replenishes the groundwater storage, which is a major contributor to the maintenance of dry period flow.

Diurnal fluctuations in streamflow have been reported (Snowy Mountains Authority, 1966). These fluctuations, caused by changes in temperature may be present throughout the year. Up to 400% diurnal variation during the thaw period and up to 100% in the summer have been recorded. The winter variations are the result of melting by direct insolation in the day followed by freezing of the snow at night. Summer fluctuations reflect the diurnal variation in the evapotranspiration rate which is also dependent on solar radiation.
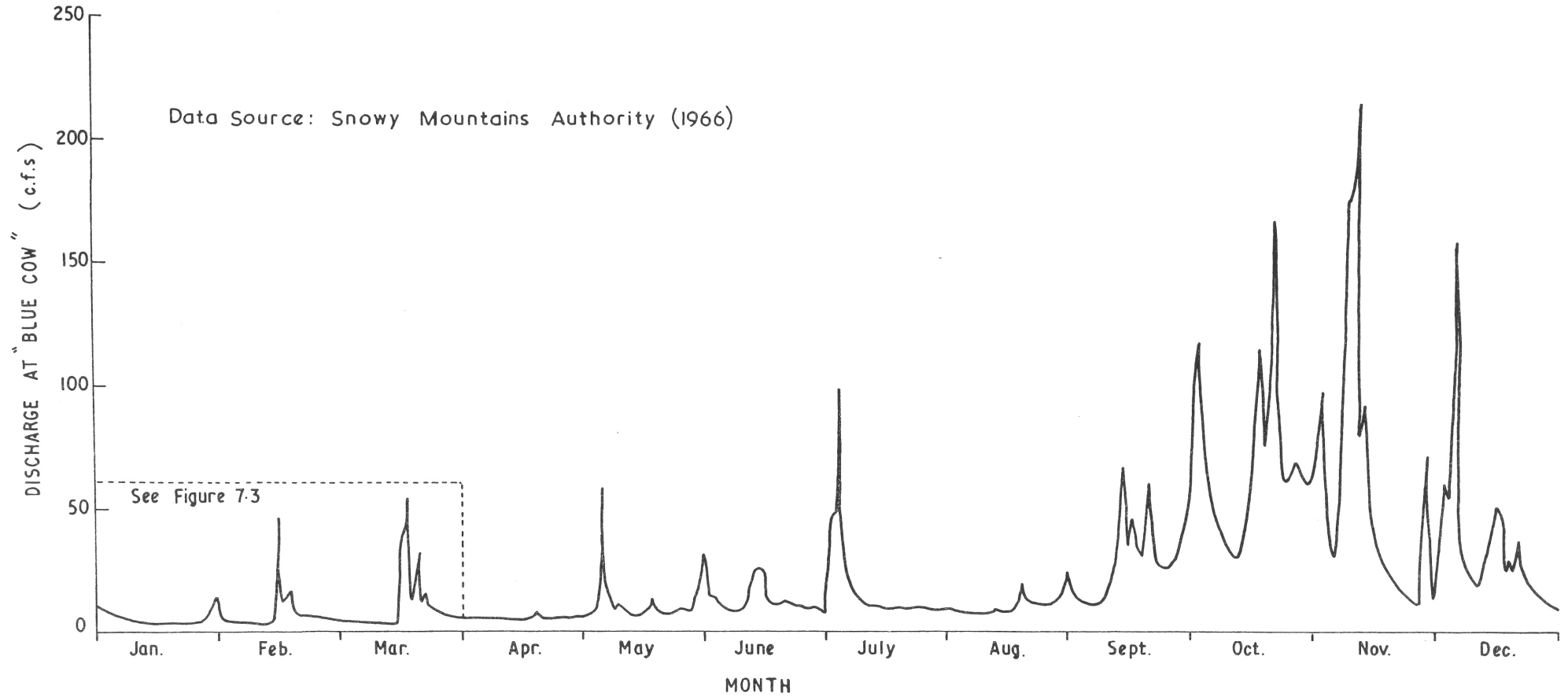
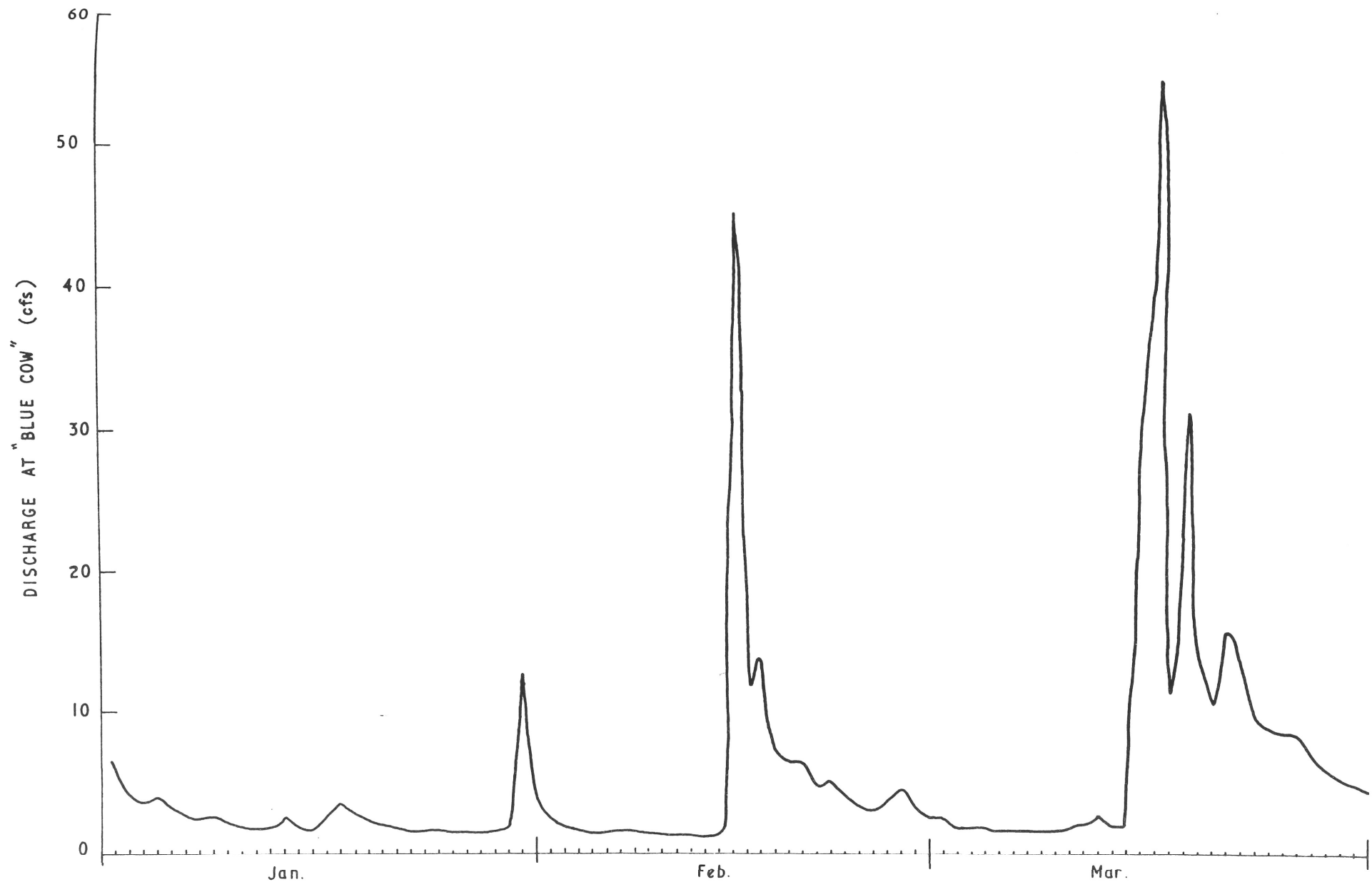FIGURE 7·2: PERISHER CREEK HYDROGRAPH FOR THE YEAR 1966.

FIGURE 7·3: PERISHER CREEK HYDROGRAPH FOR THE MONTHS JAN-MARCH, 1966.

7.3.3 Groundwater Flow

Water received as rain or snow on the alpine summits rarely
flows over the surface (Coster, 1959). Water enters the soil and
moves downwards into the deeply weathered substrate to reappear in
the valley below or in a lower catchment area. Some of the water
reappears as hillside springs, usually marked by the presence of
bogs. Perisher Creek is thought to originate in such a bog at the
summit of Perisher Gap.

The relation of underground water flow to streamflow is depict-
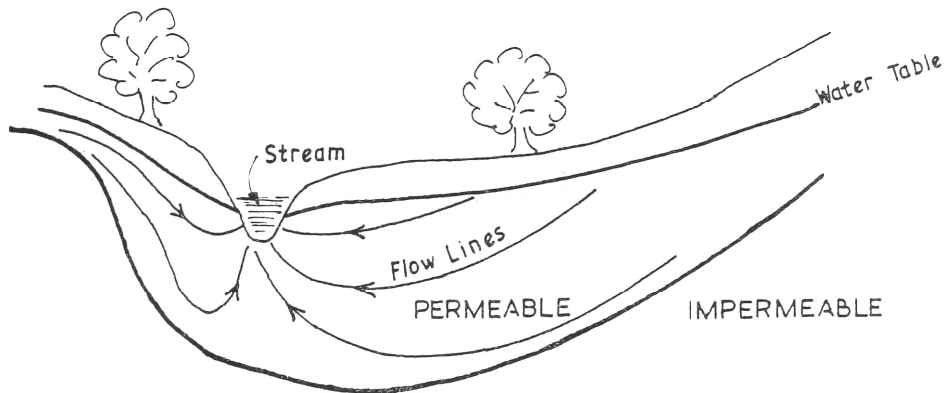ed in the figure below.

FIGURE 7·4: GROUNDWATER FLOW

The underground flow forms the base flow of perennial streams
such as Perisher Creek. In some instances the water table may
encroach on the surface soil forming extensive marsh and swamp
areas. Large amounts of water may be lost by evapo-transpiration
and the remaining water may stagnate, producing foul odours and
creating a source of pollution.

Generally, groundwater received by a stream is inferior in

quality to surface runoff. Dissolved gases in groundwater are mainly CO_2 and N_2 although H_2S is sometimes present. The oxidation of organic matter to CO_2 during the infiltration process may result in a low dissolved oxygen level. The carbon dioxide produced assists in the slow leaching of minerals from soil, rock and vegetation and may result in the groundwater being of measurable salinity. This process may be assisted by the weathering of mineral constituents and the conveyance of the soluble components to the groundwater basin.

From Figure 7.3 the groundwater flow into Perisher Creek is approximately 1-2 cusecs (0.03 - 0.06 m^3/s) in dry weather.

7.3.4 Pollution

Bacterial analysis of samples taken from Perisher Creek indicate high coliform and fecal coliform levels (Stinson, 1974). The coliforms are introduced to the stream by rotting vegetation and fecal pollution of warm and cold blooded animals, whilst fecal coliforms are introduced exclusively by fecal pollution of warm blooded animals. Fecal coliforms do not survive for long periods outside the body; hence their presence indicates recent fecal pollution.

Natural pollution of the stream in the form of organic material from decaying vegetation may have been accelerated by the development of the area as a tourist resort. The mat of surface vegetation may suffer damage by trampling during the summer season. Thus decaying organic material may be generated and may gradually leach into the stream.

The fecal pollution is believed to be introduced to the stream in two ways. A sewage treatment plant in the Village screens, aerates and clarifies raw sewage and then discharges the waste to the stream. If chlorination of the waste is carried out, the micro-biological hazard is removed. However, the biological oxygen demand, although temporarily suppressed, is not removed. The second source of pollution emanates from the large number of septic tanks in the area. The septic tank often does not provide adequate treatment, particularly at lower temperatures when active digestion is inhibited. The septic tank effluent, whilst low in suspended solids, still has a high B.O.D. and bacterial content. If the disposal trenches are damaged the effluent may seep into the groundwater table and eventually into the stream. Alternatively, low lying marsh areas may receive the seepage, depleting them of oxygen to create anaerobic foul odoured areas. A flash rainstorm could result in a flushing of the marsh land such that the stream receives a sudden influx of low quality water having a low dissolved oxygen and a highly putrescible organic content.

7.3.5 Plants and Photosynthesis

The banks of Perisher Creek are stabilised by grasses. Within the stream almost no aquatic weed is present although seasonal growths of benthal algae have been observed.

7.4 Field Data

Field data were collected on 11th and 12th May 1974 and 28th and 29th January 1975. The measuring point locations and general

reach characteristics are described in Table 7.1 and Figure 7.1.

Table 7.1:   Reach Characteristics

Data Collection Point Number	Approx. Flow Distance from Perisher Chairlift – m	Elevation – metres	Description of the Reach between Data Collection Point
1	0	1734	Narrow, fast flowing, sand and stone bed, no algae or weed. CSIRO Creek junction.
2	100	1731	
3	825	1725	Stream widens; meanders.
			Stream widens, meanders. In May algae observed.
4	1550	1719	
			Algae (May), less meandering, sewage inflow Rock Creek inflow.
5	1920	1716	
			Algae (May). Several tributary inflows.
6	2830	1713	
			Algae (May). Several tributary inflows.
7	3550	1713	
			Algae (May). Several tributary inflows.
8	3820	1709	
			Rapids as stream drops to lower elevation.
9	5000	1585	
M1	-	1734	Measuring point located in CSIRO Creek. Narrow, fast flowing.
M4	-	1719	Measuring point located in Rock Creek. Wide, algae present.
M6	-	1713	Measuring point located in tributary near Pt. 6

7.4.1 11-12th May 1974.

The May study, the results of which are shown in Tables 7.2

and 7.3, was exploratory in nature. A limited number of dissolved

oxygen and temperature measurements were taken to assess both

the operational characteristics of the dissolved oxygen meter in the

field and the general level of dissolved oxygen in the stream.

Table 7.2: Field Measurements of 11th May 1974[i]

Data Collection Point No.	Position Description	Temp. $^{\circ}C$	Meter Reading z	D.O %Sat.	D.O. Level mg/1
1	Junction Perisher and CSIRO Creek	4.5	79	97	10.2
2	100m downstream of chairlift	4.2	81	99	10.5
3	Opposite Technology Lodge [ii]	4.2	82	100	10.5

Notes: (i) Weather overcast, atmospheric pressure = 620 mm Hg

(ii) Algal growth evident downstream from Point 3

Table 7.3: Field Measurements of 12th May 1974[i]

Data Collection Point No.	Position Description	Temp. $^{\circ}C$	Meter Reading	D.O. %Sat.	D.O Level mg/1
1	Junction Perisher and CSIRO Creek (chairlift)	4.3	82	100	10.6
3	Across from Technology Lodge (ii)	3.5	85	104	11.0
4-5	At foot bridge	3.5	87.5	107	11.4

Notes: (i) Weather sunny, atmospheric pressure = 620 mm Hg

(ii) Algal growth evident downstream

Table 7.4 shows the change in dissolved oxygen level over a distance of 243 metres in the Rock Creek tributary. This reach contained large amounts of weed and algal growth and the streamflow was of the same order of magnitude as the upstream sections of Perisher Creek (approx. 0.1 m^3/s). It is assumed that the increase in the level of dissolved oxygen is due to the production of oxygen by photosynthesis. Atmospheric reaeration will not contribute to the increase. In fact, since the stream is supersaturated with oxygen, desorption of oxygen to the atmosphere will occur.

Table 7.4: Effect of Photosynthesis (12th May - Rock Creek)

Position	Temp. ^{o}C	Meter Reading z	D.O. Level mg/1	D.O. Level mg/1
R4 - Road Bridge	$4\frac{1}{4}$	85.5	105	11.0
R5 - Junction with Perisher	4	87.0	107	11.2

Note: av. velocity = 0.3 m/s

av. depth = 0.2m

approx. distance R4-R5 = 200m

7.4.2 28th-29th January 1975

More extensive measurements, shown in Tables 7.5 and 7.6 were taken in January and included such stream parameters as cross-sectional area, depth, velocity, as well as water temperature and dissolved oxygen. Night readings of water temperature and dissolved oxygen were collected in addition to the day readings. In this way it was hoped that the effect of photosynthesis on dissolved oxygen levels could be quantified.

Table 7.5: Field Measurements of 28th Jan. 1975 - Weather Slightly Overcast

	Parameter	Measuring Point Location											
		1	2	3	4	5	6	7	8	9	M1	M4	M6
Day Readings	Cross-sectional area m^2	0.53	0.08	0.05	0.20	0.42	0.51	-	125	0.37	-	0.22	0.20
	Depth - m	0.53	0.12	0.25	0.20	0.21	0.16	-	0.50	0.1	-	0.22	0.26
	Velocity - m/s	0.07	1.1	0.7	0.37	0.26	0.31	-	0.12	0.52	-	0.38	0.1
	Streamflow m^3/s	0.04	0.08	0.04	0.07	0.109	0.16	-	0.15	0.17	-	0.08	0.02
	Stream Temp. ^oC	11	11	12.7	17.2	17.5	16.5	-	17.0	14.2	-	17.0	15.5
	z	70	82	82	95	98	94	-	100	91	-	99	89
	D.O.% Satn.	86	100	100	116	120	115	-	123	111	-	121	109
	D.O. Mg/l	7.7	9.0	8.8	9.2	9.4	9.2	-	9.6	9.3	-	9.6	9.0
Night Readings	Stream Temp. ^oC	8.5	8.0	9.0	10.0	-	-	11.5	-	10.0	-	11.5	-
	z	80	79	76	76	-	-	75	-	82	-	70	-
	D.O.% Satn.	98	97	93	93	-	-	92	-	100	-	86	-
	D.O. Mg/l	94	93	8.8	8.5	-	-	8.2	-	9.2	-	7.7	-

Table 7.6: Field Measurements of 29th Jan. 1975 - Weather Clear, No Cloud

Parameter		Measuring Point Location											
		1	2	3	4	5	6	7	8	9	M1	M4	M6
Day Readings	Cross-sectional area - m^2	0.40	0.14	0.54	0. .0	0.40	0.53	-	0.17	-	0.05	0.33	0.20
	Depth	0.40	0.30	0.54	0.20	0.20	0.15	-	0.12	-	0.08	0.22	0.24
	Velocity - m/s	0.06	0.57	0.17	0.14	0.33	0.33	-	0.5	-	0.2	0.13	0.10
	Streamflow m3/s	0.02	0.08	0.09	0.04	0.13	0.17	-	0.08	-	0.01	0.04	0.02
	Stream Temp. ^oC	12.5	12.5	16.0	18.0	18.5	17.0	-	18.0	14.5	11.0	18.0	17.5
	z	83	85	90	96	100	100	-	102	96	80	104	93
	D.O.% Satn.	102	104	110	118	123	123	-	125	118	98	127	114
	D.O. Mg/l	8.9	9.1	8.9	9.1	9.2	9.6	-	9.6	9.6	8.8	10.1	9.0
Night Readings	Stream Temp.	10.0	9.0	9.0	11.0	12.0	-	13.5	-	12.0	-	13.5	-
	z	82	83	78	81	82	-	79	-	84	-	79	-
	D.O.% Satn.	100	102	96	99	100	-	97	-	103	-	97	-
	D.O. Mg/l	9.2	9.6	9.0	9.0	8.8	-	8.2	-	9.3	-	8.3	-

The methods used in the collection of data were relatively simple and reliable. Cross sectional area and depth were evaluated with a metre rule and stream velocity by either timing the movement of a surface float or from the digital readout of a vane type current meter ("Ott - Meter"). Stream temperature and percentage saturation of dissolved oxygen were measured using a portable dissolved oxygen meter (see Appendix B for full description). Since the meter was calibrated at 760 mm Hg atmospheric pressure and the average atmospheric pressure at Perisher was 620 mm Hg, the D.O.% Sat. meter reading (z) was multiplied by a correction factor of 1.225 (see Section 3.5) to obtain the per cent saturation at 620 mm Hg. The absolute dissolved oxygen levels were evaluated from the % saturation and temperature measurements using a nomogram supplied with the dissolved oxygen meter.

7.5 Interpretation of Field Data

7.5.1 Data Collected on 11th and 12th May 1974

Figure 7.5 shows the dissolved oxygen and water temperature distribution recorded in autumn. Stream temperature is relatively static at approximately $4^{o}C$ on both days. On the overcast day (11th May) an oxygen level close to saturation appeared to be maintained along the length of the stream. On the sunny day (12th May) the percentage saturation increased from 100% at the chairlift to a supersaturated value of 107% at a distance of 2000 metres. This increase in oxygen level can only be attributed to photosynthesis.

The effect of atmospheric reaeration will be to counteract the increase due to photosynthesis. For example, if a flow velocity of 0.3 m/s and an average depth of 0.2m are assumed (see Figures 7.7,
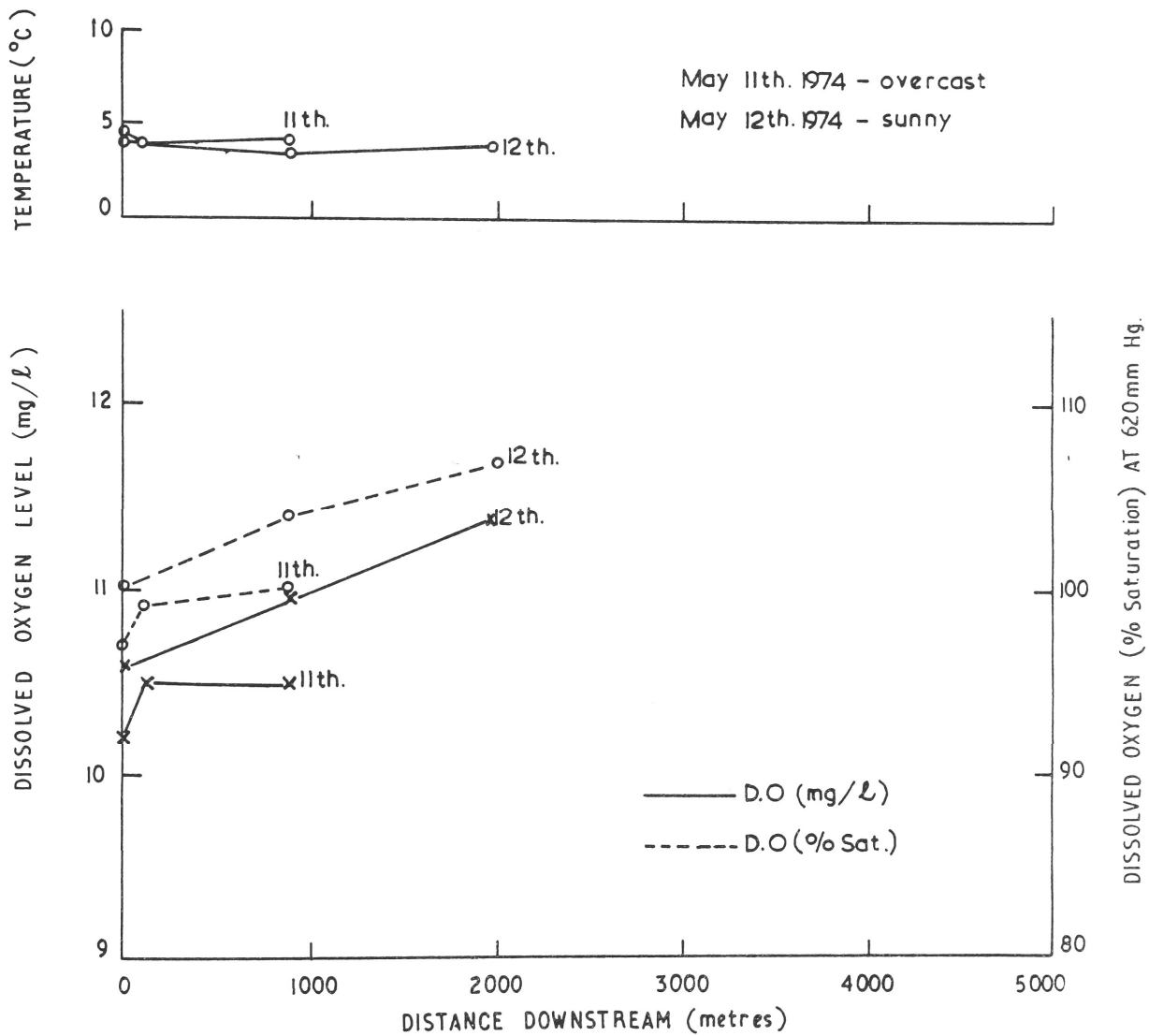
FIGURE 7·5: DISSOLVED OXYGEN AND
TEMPERATURE DISTRIBUTION –
11th. & 12th. MAY, 1974.

7.8, 7.12 and 7.13), then reaeration coefficient can be estimated to

be approximately 10 days^{-1} (Figure 4.2). Based on a mean dissolved

oxygen excess of 0.4 mg/l, the rate of oxygen desorption is calculated

to be 4 mg/l/day (equation 4.14). Over a distance of 2000 metres

(equivalent to 0.08 days flow time) the desorption is approximately

0.3 mg/l. Consequently for the same reach the net oxygen production

by photosynthesis (Ph_2-Pr_2) on 12th May is calculated by substituting

C=1.1 mg/l (i.e. 11.4-10.6+0.3 mg/l) into equations 4.30 and 4.31.

By this method (Ph_2-Pr_2) is found to be 4.8 mg/l/day (based on 8 hours

sunshine) or, in terms of (Ph_1-Pr_1), 0.1 g/m^2/h. In comparison similar

calculations using the Rock Creek data (Table 7.4) result in values of 5.3

mg/l/day or 0.2 g/m^2/hr. The larger oxygen production in Rock Creek

was to be expected since the growth of plant and algae was far more

extensive than in Perisher Creek.

7.5.2 Data Collected on 28th January 1975·

Streamflow, depth, velocity, temperature and dissolved oxygen

data are presented graphically in Figures 7.6 to 7.10.

Figure 7.6 indicates that the streamflow at the weir (5000m) was

approximately 0.15 m^3/s (5.3 cusecs). This figure is considerably

higher than the predominant dry weather flow of approximately 0.03 -

0.06 m^3/s (1-2 cusecs) shown in the hydrograph for the 'Jan.-Mar.

1966' period (Figure 7.3). The streamflow profile shown in Figure

7.6 indicates a sharp increase in streamflow at the chairlift followed

by a decrease in streamflow as the stream flows towards the Village

(1500m). The sharp increase is explained in terms of streamflow

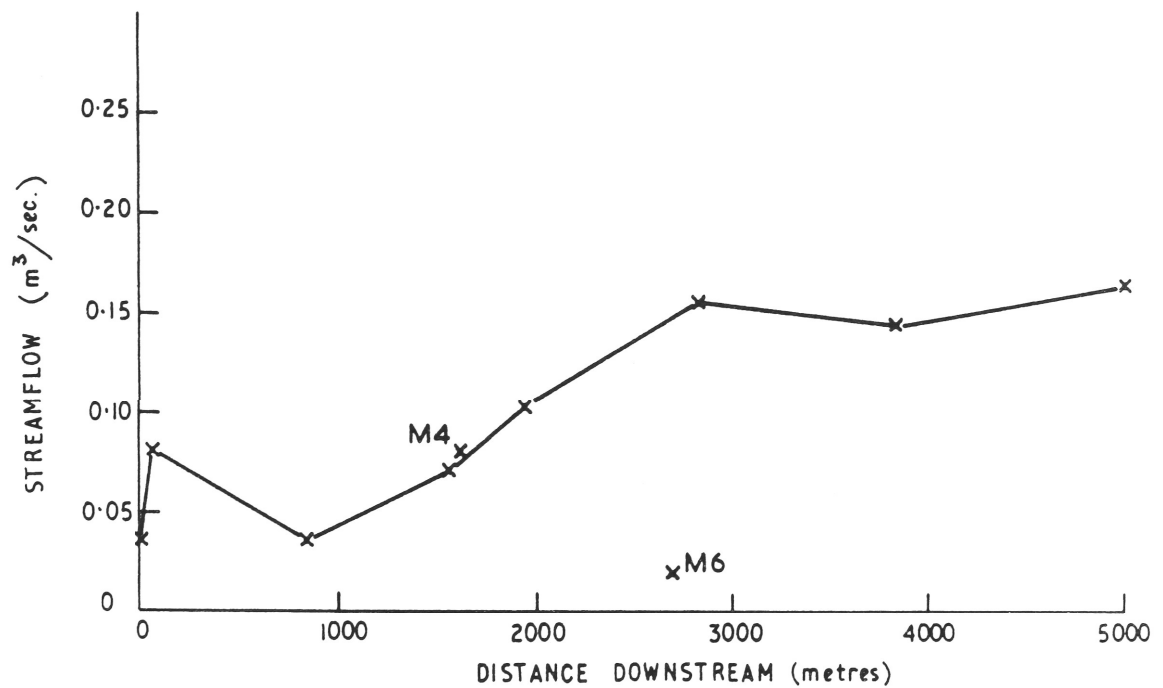contribution from the CSIRO Creek tributary merging with Perisher

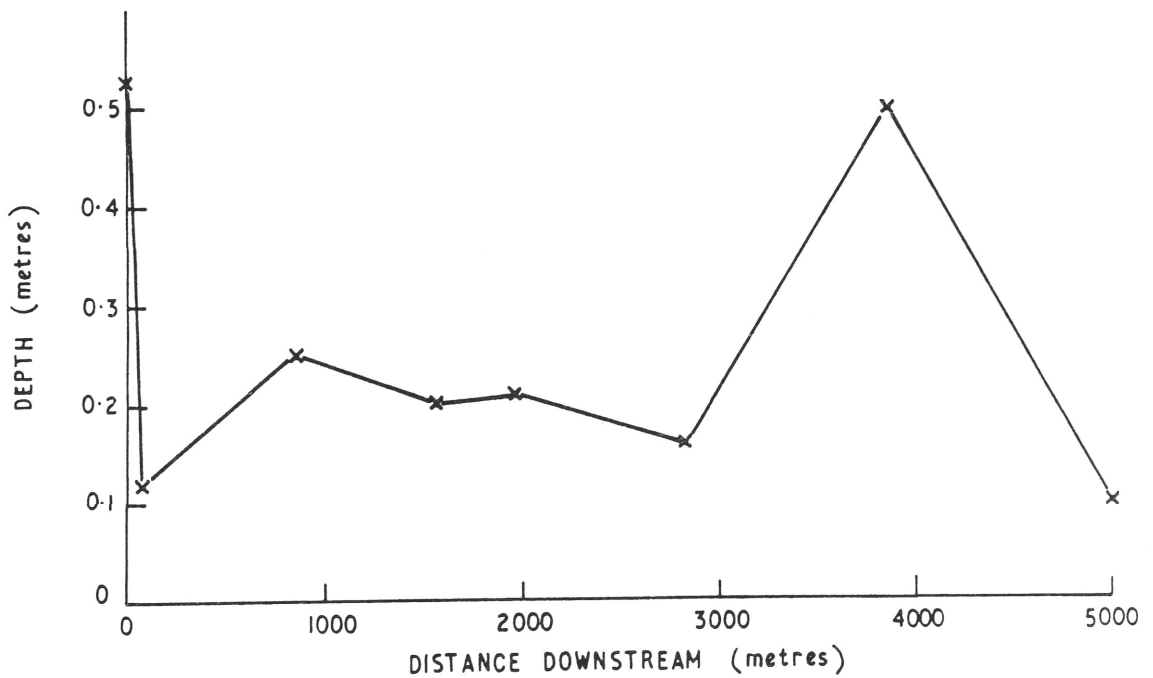FIGURE 7·6: STREAMFLOW DATA FOR 28th. JAN. 1975.

FIGURE 7·7: DEPTH DATA FOR 28th. JAN. 1975.

Creek at the chairlift. The decrease in streamflow suggests that seepage into the groundwater basin or the surrounding marsh area is occurring in this particular section of the stream. An increase in the flow from the Village downstream is due to the mergence of the Rock Creek tributary and flow of waste water from the sewage treatment plant (1600m downstream).

A plot of stream depths, shown in Figure 7.7 indicates that for an 0.15 m^3/s streamflow stream depth is approximately 0.2m except in localised areas, such as around the chairlift and at the 4000 metre mark, where 0.5m depths were recorded (compare with Figure 7.12).

The velocity profile of Figure 7.8 shows high velocities of up to 1 m/s at the junction of CSIRO and Perisher Creeks, gradually decreasing as stream width increases to an 0.2 - 0.3 m/s range between the Village (1600m) and Barrakee Lodge (4000m). At the weir the velocity is measured at 0.5 m/s, although it is possible that significantly higher velocities may have occurred between Barrakee Lodge and the weir due to the substantial slope in this reach. The low velocity recorded at the 3880 metre mark corresponds to the exceptional depth measurement, in Figure 7.7, of 0.5m.

Temperature distribution shown in Figure 7.9 shows an increase from 11 to 17°C between the chairlift and Rock Creek, followed by substantial stability. The temperature increase is presumably due to solar heating (which increases its influence as the stream widens) and heat conduction from the atmosphere. Comparison of this temperature profile with that of Figure 7.5 reveals differences deserving explanation. The differences in temperature at the head of
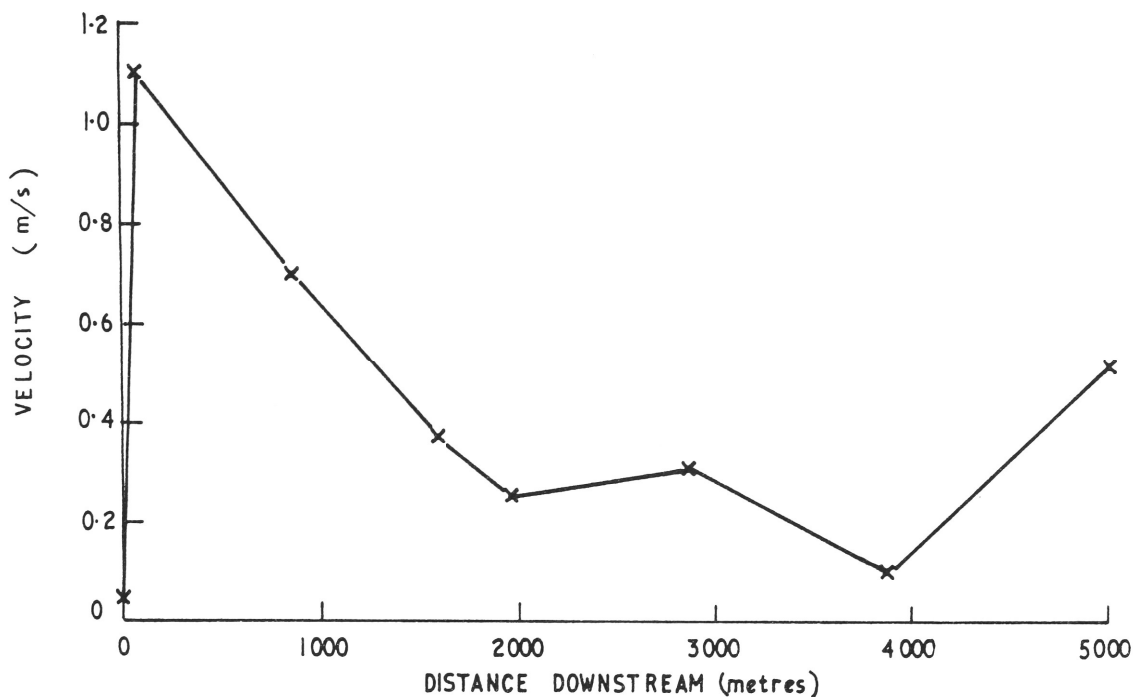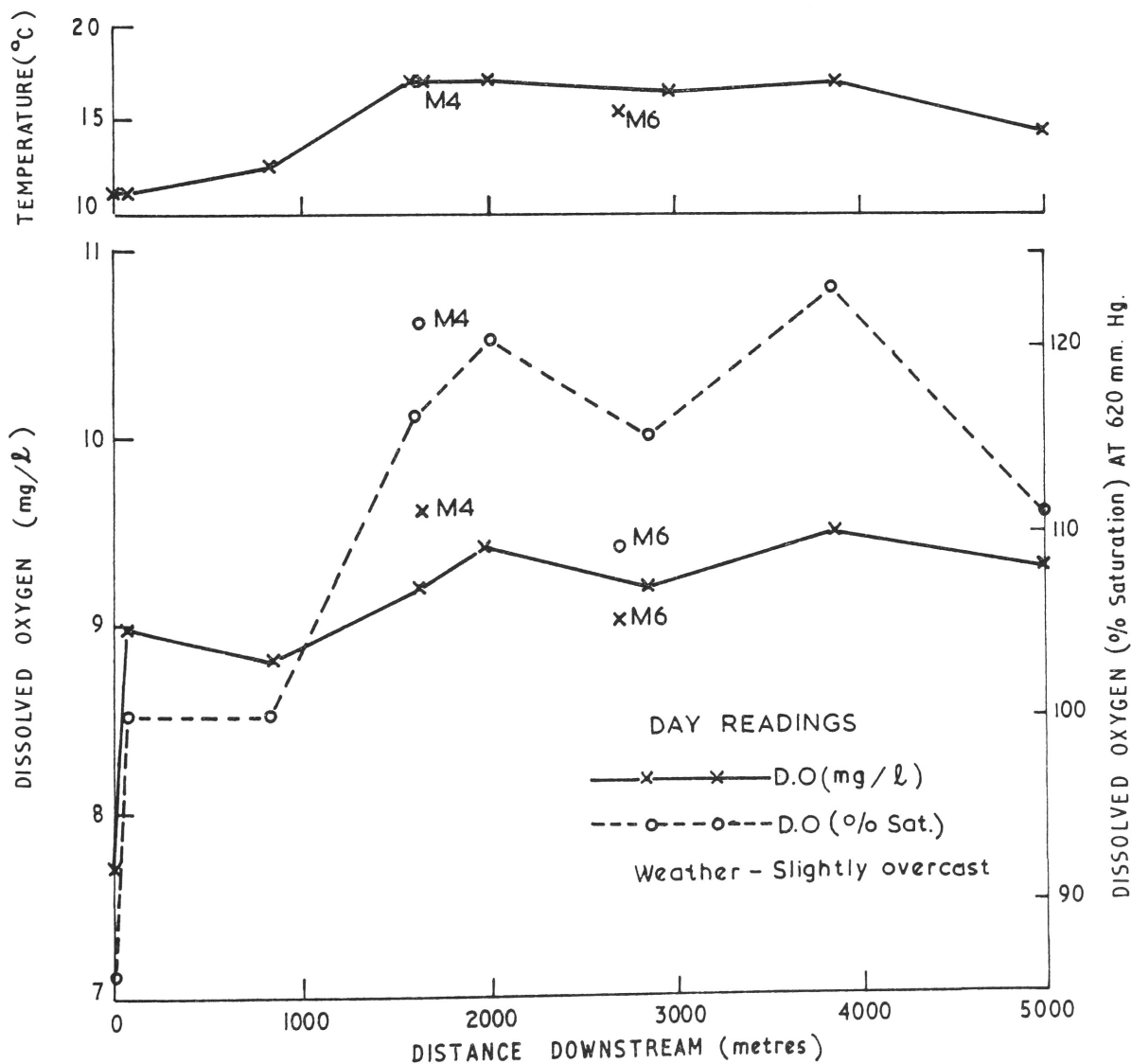
FIGURE 7·8: VELOCITY DATA FOR 28th. JAN. 1975.

FIGURE 7·9: STREAM TEMPERATURE AND DISSOLVED OXYGEN DISTRIBUTION FOR 28th. JAN. 1975 - DAY READINGS.

the stream of $4^{\circ}C$ on 11th and 12th May and $11^{\circ}C$ on 28th January reflect differences in groundwater temperature arising presumably from differences in precipitation and subsurface temperatures. The failure of stream temperature to rise with flow time on 11th and 12th May may be due to a significantly higher streamflow at this time of year (recent precipitation had occurred).

The dissolved oxygen distribution in terms of percentage saturation and absolute concentrations is also shown on Figure 7.9. The percentage saturation rises from 86 to 100% over a very short distance from the chairlift. This rapid aeration is most likely due to high turbulence in this reach (velocities are high) and the mixing with aerated water from CSIRO Creek. The level remains at 100% for approximately 1000 metres and then increases rapidly to levels exceeding 100%. As previously mentioned, an increase in stream temperature is experienced at the same time. Since the saturation concentration decreases with increasing temperature a state of supersaturation develops. The mergence of Rock Creek, with a saturation level of 121%, increases the supersaturation further. Since absolute dissolved oxygen levels do not increase dramatically, photosynthesis, although probably active, does not in this instance appear to be a major contributor to the oxygen balance. A depression in dissolved oxygen level after the mergence of a less aerated tributary at 2700m suggests that a major cause of dissolved oxygen fluctuation is the mergence and mixing of tributary flows.

Figure 7.10 shows temperature and dissolved oxygen measurements taken during the night (11 pm - 1 am). Stream temperatures are several degrees lower than the corresponding day temperatures.
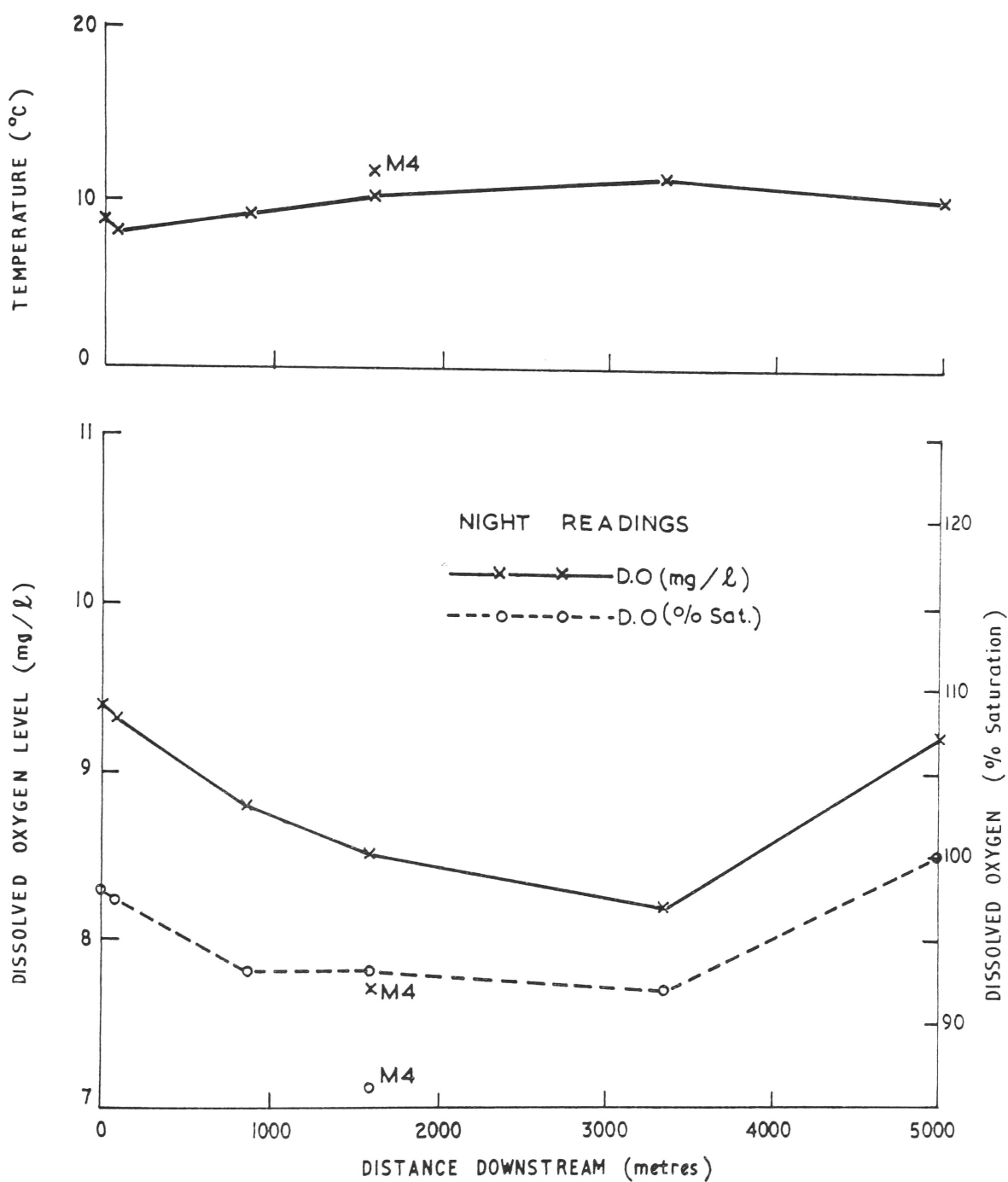
FIGURE 7·10: STREAM TEMPERATURE AND DISSOLVED OXYGEN DISTRIBUTION FOR 28th. JAN. 1975 - NIGHT READINGS.

A slight increase in temperature is evident as one progresses downstream although not to the degree observed during the day. It is assumed that the increase in stream temperature represents conduction of heat from the atmosphere to the water.

The dissolved oxygen distribution shows a definite decrease along the length of the stream. In terms of per cent saturation a sharp decrease from 98% to 93% occurs within 1000 metres of the chairlift. This decrease probably is the result of mixing with unsaturated groundwater and tributary flow rather than respiration, since flow times in this region are relatively short. The depressed oxygen level is maintained up to the 3,300 metre mark. However, a sharp increase to 100% was measured at the weir.

This increase between 3300 and 5000 metres is due to the high rate of reaeration produced during the rapid, turbulent descent from 1700 to 1580 metres (see Table 7.1). The absolute dissolved oxygen profile reveals a steady decrease in dissolved oxygen content along the length of the stream followed by an increase in the level at the weir. These observations indicate the presence of respiration activity, although some of the decrease will be due to the mixing with unsaturated tributary water and ground water. For example, water from Rock Creek was measured as having 8% less dissolved oxygen than Perisher Creek.

Production of oxygen by photosynthesis and depletion by respiration may be estimated by the method described in Section 7.5.1. Considering the reach between 900m and 1550m on Figure 7.9 the oxygen desorption to the atmosphere is calculated to be 7 mg/l/day and the

'oxygen production due to photosynthesis less oxygen depletion due to respiration' is of the order of 0.2 $g/m^2/h$ (9 mg/l/day based on 8 hours sunshine). Respiration without photosynthesis (Figure 7.10) was calculated to be 0.2 $g/m^2/h$ (24 mg/l/day) over the same reach That is to say P_{h1}, the gross oxygen production, is approximately 0.4 g/m/h and P_{r1} is approximately 0.2 $g/m^2/h$.

A final observation concerns the presence of algal and weed growths in tributaries. In Figure 7.9 Rock Creek (M4) has a higher dissolved oxygen content than Perisher Creek, presumably because of a larger biomass concentration. Subsequently the oxygen content in Perisher Creek is elevated further at the confluence of the two streams. At night (Figure 7.10) Rock Creek has a lower dissolved oxygen content due to a greater rate of respiration and the oxygen level in Perisher Creek is lowered accordingly at the confluence.

7.5.3 Data Collected on 29th January 1975

Streamflow data shown in Figure 7.11 has similar minimum and maximum values to the data of the previous day (Figure 7.6). A similar general increase in streamflow with distance is apparent and a decrease in streamflow before the Village is also in agreement with the previous results. However, the marked decrease in streamflow at the 4000 metre mark is not in agreement and it is suspected that an error in measurement may have occurred. It is noted that on both days the streamflows in Rock and Perisher Creeks correspond remarkably well in spite of a changing flow profile in the upper
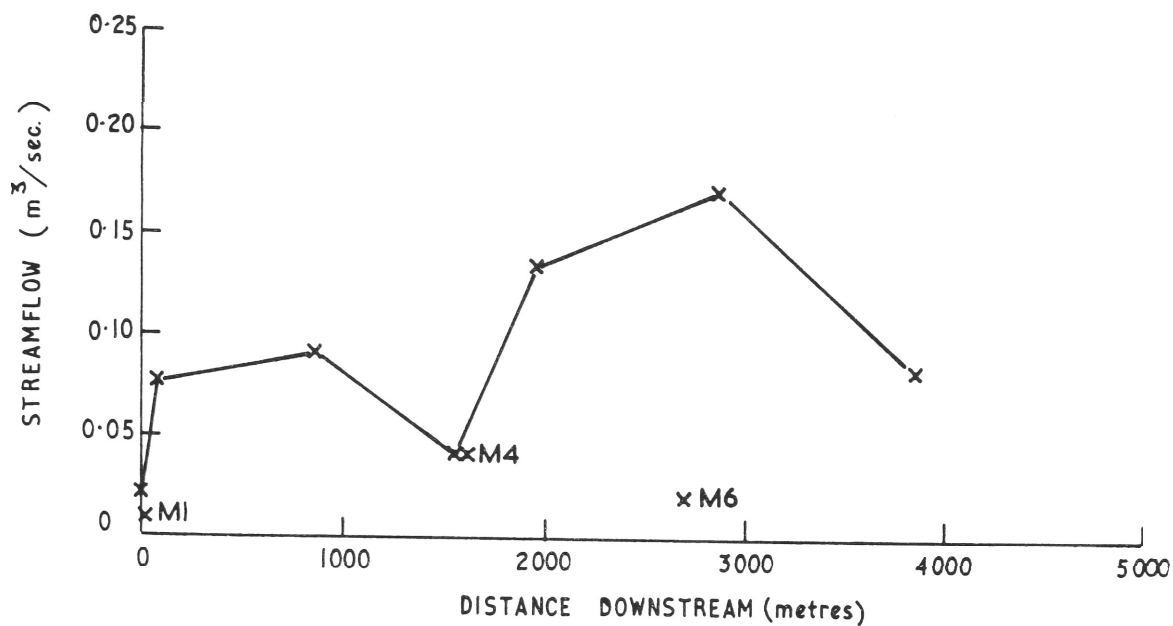
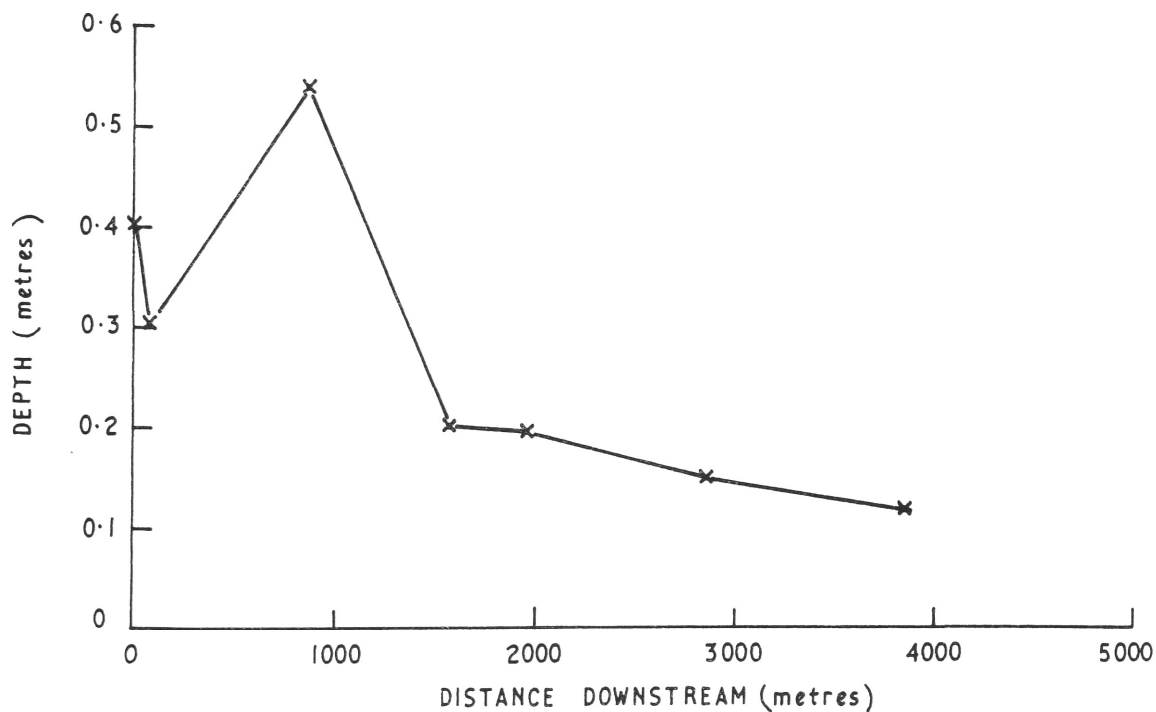FIGURE 7·11: STREAMFLOW DATA FOR 29th. JAN. 1975.

FIGURE 7·12: DEPTH DATA FOR 29th. JAN. 1975.

reaches of Perisher Creek. This phenomenon strengthens the con-cept that both streams draw on a common groundwater reservoir. It is of some interest to note that the streamflow of CSIRO Creek accounts for less than 20% of the increase in streamflow at the chair-lift. It seems likely that at this point the groundwater influx may be quite high. A similar situation is evident downstream of the Village. The streamflow in Rock Creek is insufficient to account for the over-all increase in streamflow recorded at the 2000 metre mark. This is in contrast to the results of the previous day (Figure 76) where a loss of streamwater to the surrounding groundwater basin was observed in this reach.

Figure 7.12 shows the variation in depth along the length of the stream. Comparison with Figure 7.7 illustrates the variability en-countered in any one reach.

The velocity distribution (Figure 7.13) indicates velocities to be lower in the upper reaches and higher in the lower reaches than on 28th.

Stream temperatures, shown in Figure 7.14, are generally higher than on 28th. This is most likely due to a greater abundance of solar energy being available for the heating of the stream water. As obs-erved on 28th, the temperature increases gradually in the upper reaches as exposure time and stream width increase.

The per cent saturation of dissolved oxygen shown on the same figure indicates supersaturated conditions for the length of the stream. An initial value of 102% (8.9 mg/l) is followed by a gradual
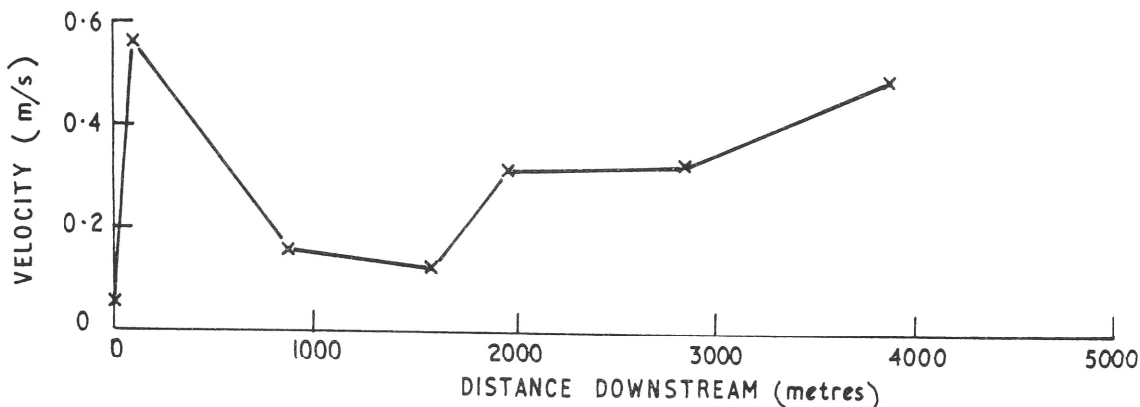
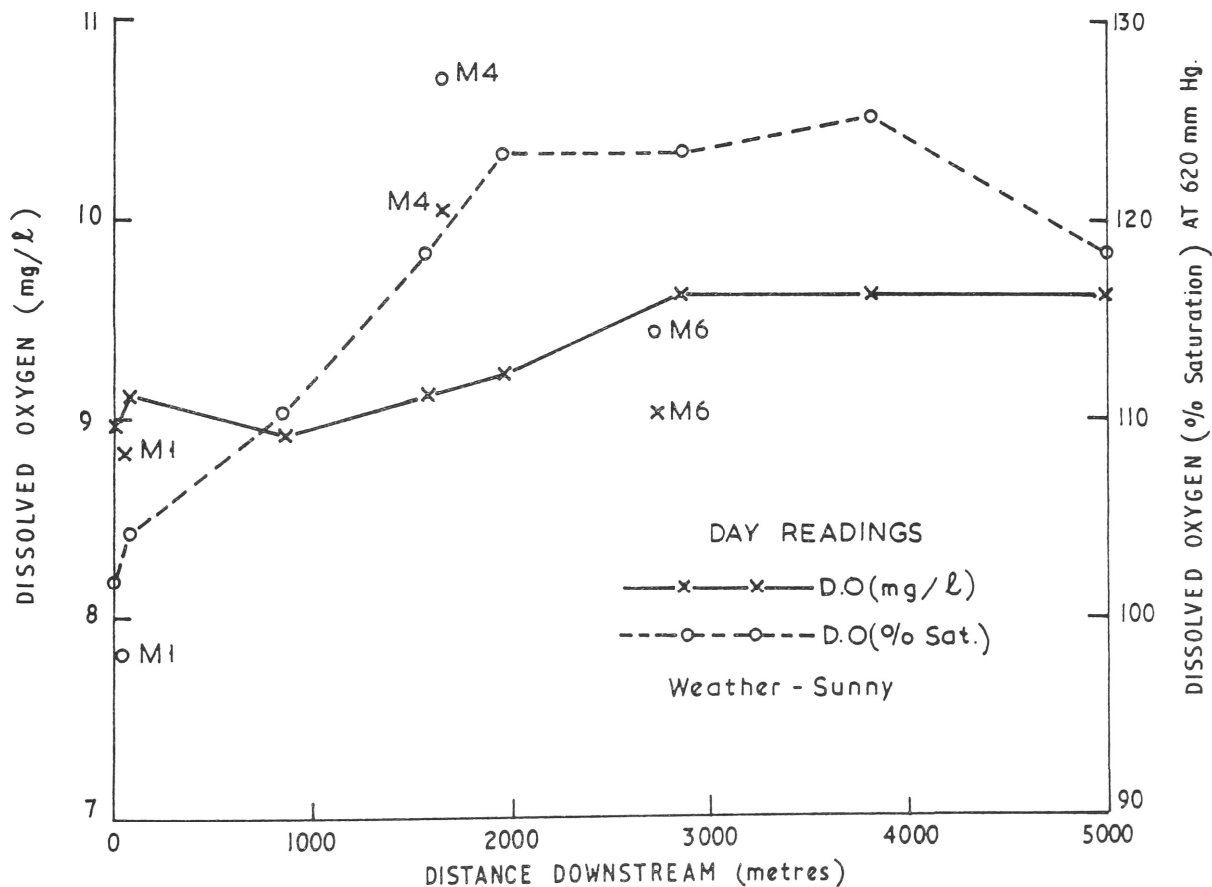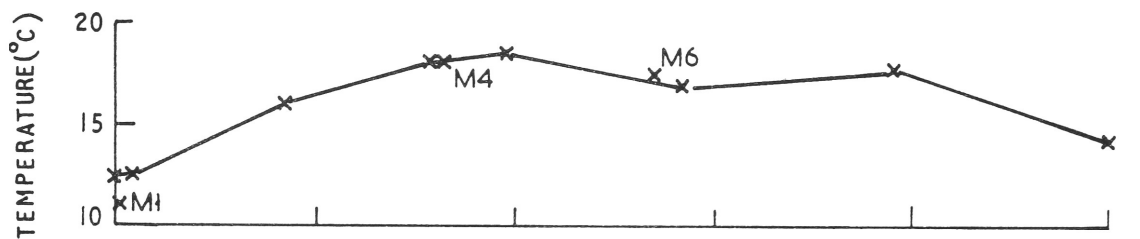FIGURE 7·13: VELOCITY DATA FOR 29th. JAN. 1975.

FIGURE 7·14: STREAM TEMPERATURE AND
DISSOLVED OXYGEN DISTRIBUTION
FOR 29th. JAN. 1975 - DAY READINGS.

increase as the stream temperature increases. A steady value ranging from 123 to 125% (approx. 9.5 mg/l), slightly greater than that measured on the previous day, was reached at the 2000 metre mark. The average absolute oxygen level climbed from 9 mg/l in the first 2,500 metres to 9.6 mg/l thereafter. These levels are generally only marginally higher than the results of 28th (Figure 7.9). It should be noted that dissolved oxygen levels are extremely high in Rock Creek and will contribute to the general increase of dissolved oxygen in Perisher Creek.

Measurements made in the night of 29th are shown in Figure 7.15. As observed during the previous night, stream temperature increases gradually from the chairlift to reach a maximum of $13^{\circ}C$ about 3000 metres from the chairlift.

Per cent saturated dissolved oxygen varies from 96 to 103%, a slightly higher range to that observed on 28th. The decline in the per cent saturation level is less evident due to the larger temperature range experienced ($4^{\circ}C$ in contrast to $3^{\circ}C$ on the evening of 28th). Nevertheless the effect of plant and algal respiration is reflected in the decline of absolute dissolved oxygen concentration from 9.6 mg/l at the chairlift to 8.2 mg/l at a distance of 3,300 metres.

Considering the reach lying between 850m and 1550 m net oxygen production ($Ph_1 - Pr_1$) is calculated to be 0.12 $g/m^2/hr$ and respiration (Pr_1) in the 2000m to 3350m reach is 0.1 $g/m^2/h$. Ph_1 is thus calculated to be approximately 6.2 $g/m^2/h$. These estimations are based on a reaeration rate of 5 mg/l/day.
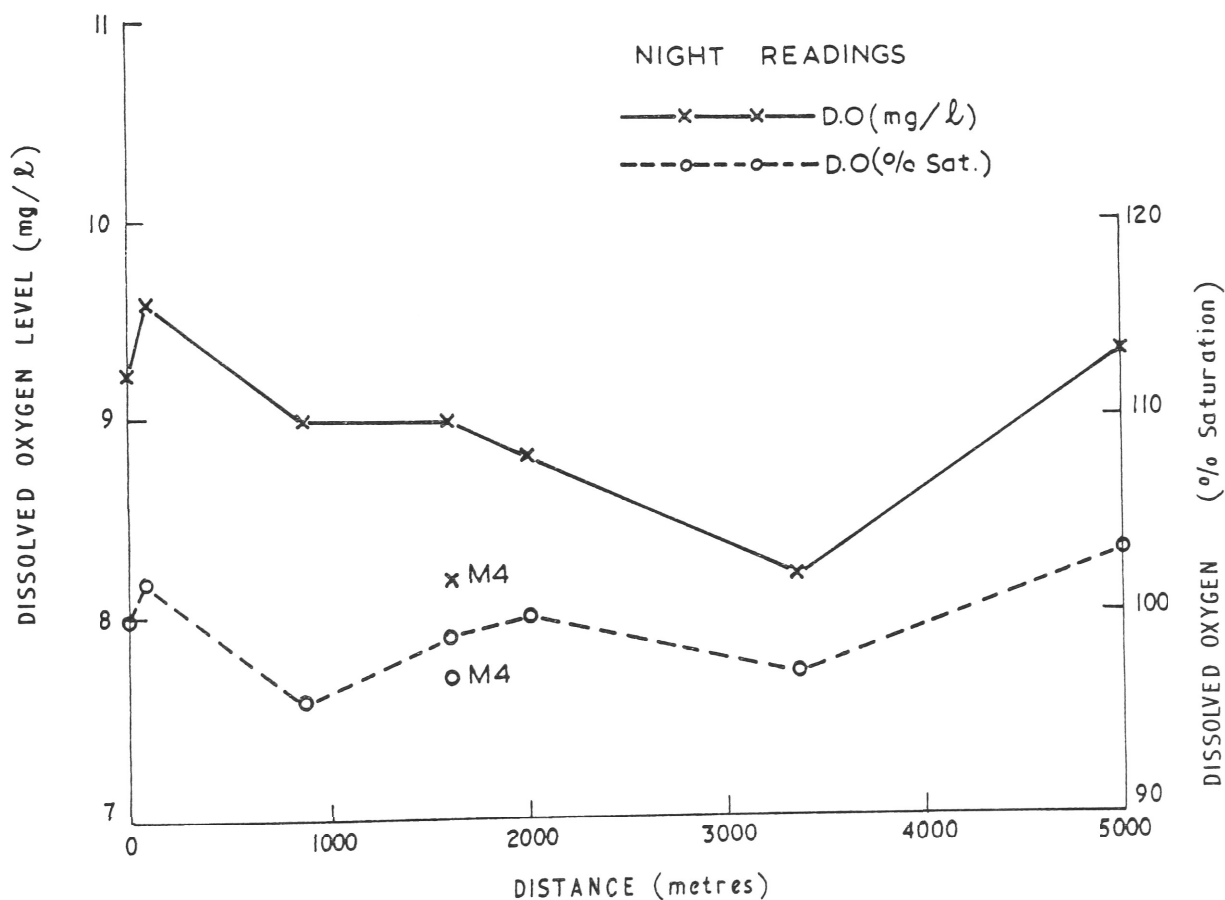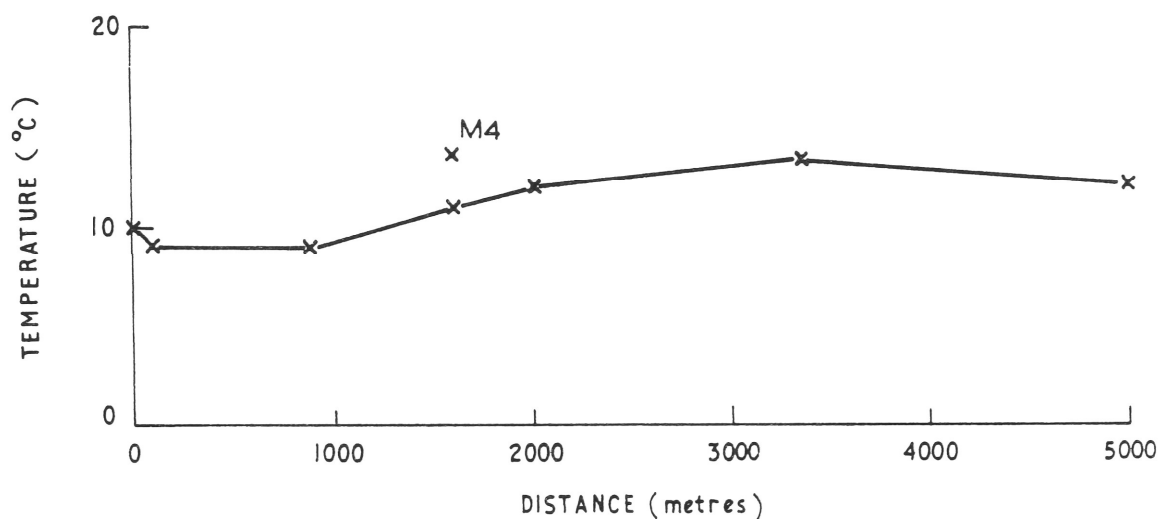
FIGURE 7·15: STREAM TEMPERATURE AND
DISSOLVED OXYGEN DISTRIBUTION
FOR 29th. JAN. 1975 – NIGHT READINGS.

7.6 Analysis Using OXSTRAL

The computer program developed in Chapter 6 can be used to simulate the dissolved oxygen distribution in Perisher Creek and to evaluate, by means of a sensitivity analysis, the effects of variations in hydraulic and climatic parameters, constants and coefficients.

7.6.1 Simulation of Field Data

Using the calculated rates of oxygen production by photosynthesis and depletion by plant respiration, described in Section 7.5, the values of solar radiation intensity (SR/SHRS) and plant biomass (BIOM) were calculated and found to be 150 $cal/m^2/day$ and 35 g/m^2 respectively, based on field data of 28th January 1975 (equations 4.27 and 4.29).

Figures 7.16 and 7.17 for which the input and output data are shown in Tables 7.7 and 7.8 show a good correlation between field and computed data. Using the same calculated values of solar radiation intensity and plant biomass and substituting the hydraulic data collected on 29th January, 1975, the Figures 7.18 and 7.19 were formulated (input and output data shown in Tables 7.9 and 7.10). Although the correlation is not as good, particularly at the 1500m location, the error of 0.5 to 1 mg/l is not extreme.

7.6.2 Sensitivity Analysis for Perisher Creek

The sensitivity analysis involved observing the variations in dissolved oxygen output as a function of variations in input data. The parameter or parameter group, the input variation, the maximum output variation and the sensitivity are shown in Table 7.11. Figures 7.20 to 7.28 indicate the magnitude of variation in dissolved oxygen

Table 7.7: Input and Output Data for 28th January 1975 Day Simulation.

DISSOLVED OXYGEN IN AUSTRALIAN STREAMS

AK120	AK320	BOD20	CBOD	CDN	SR	SHRS	BETA5
.300	.010	0.000	1.300	0.000	150.000	10.000	.600

C(1)	AK4	ALPHA3	ALPHA4	BETA1	BETA2	AP	ALPHA5
7.800	.007	.100	.600	.001	.300	620.000	.033

DIST	VEL	DEPTH	TEMP	FLOW	MBCD	MTEMP	MDO	BIOM	BODAD
0.00	.10	.53	11.00	.04	5.00	14.00	9.00	35.00	1.00
91.00	1.10	.12	11.00	.08	5.00	14.00	9.00	35.00	1.00
823.00	.70	.25	13.00	.04	5.00	14.00	9.00	35.00	1.00
1554.00	.37	.20	17.00	.07	5.00	17.00	9.00	35.00	1.00
1920.00	.26	.21	17.00	.10	15.00	14.00	9.00	35.00	1.00
2835.00	.31	.16	16.00	.10	5.00	15.50	9.00	35.00	1.00
3809.00	.40	.15	17.00	.15	5.00	14.00	9.00	35.00	1.00
4500.00	.40	.10	16.00	.15	5.00	14.00	9.00	35.00	1.00
5029.00	.52	.10	14.00	.16	5.00	14.00	9.00	35.00	1.00

TIME	FLOW DIST	UBOD	PHOTO	PLANT.R	DO	SAT DO
0.000	0.000	0.000	0.000	0.000	7.800	8.976
0.000	91.000	3.250	3.905	1.196	8.593	8.976
.002	823.000	3.249	6.861	2.164	8.372	8.564
.006	1554.000	4.641	5.641	1.765	8.403	7.636
.010	1920.000	9.095	6.192	1.940	8.870	7.636
.019	2835.000	9.073	6.861	2.185	9.361	8.007
.027	3809.000	8.203	8.189	2.650	9.206	7.636
.032	4500.000	8.192	10.155	3.269	9.421	8.007
.035	5029.000	8.080	12.693	4.115	9.711	8.371

Table 7.8: Input and Output Data for 28th January, 1975 Night Simulation.

DISSOLVED OXYGEN IN AUSTRALIAN STREAMS

AK120	AK320	BOD20	CBOD	UDN	SR	SHRS	BETA5
.300	.010	0.000	1.300	0.000	0.000	10.000	.600

C(1)	AK4	ALPHA3	ALPHA4	BETA1	BETA2	AP	ALPHA5
9.400	.007	0.000	.790	.001	.300	620.000	.053

DIST	VEL	DEPTH	TEMP	FLOW	MBOD	MTEMP	MDO	BIOM	BODAD
0.00	.10	.53	8.50	.04	5.00	10.00	9.00	50.00	1.00
91.00	1.10	.12	8.00	.08	5.00	10.00	9.00	50.00	1.00
823.00	.70	.25	9.00	.04	5.00	10.00	9.00	50.00	1.00
1554.00	.37	.20	10.00	.07	5.00	10.00	9.00	20.00	1.00
1920.00	.26	.21	10.50	.10	15.00	10.00	9.00	20.00	1.00
2835.00	.31	.16	10.50	.10	5.00	10.00	9.00	20.00	1.00
3809.00	.40	.15	11.00	.15	5.00	10.00	9.00	20.00	1.00
4500.00	.60	.10	10.00	.15	5.00	10.00	9.00	20.00	1.00
5029.00	.52	.10	10.00	.16	5.00	10.00	9.00	20.00	1.00

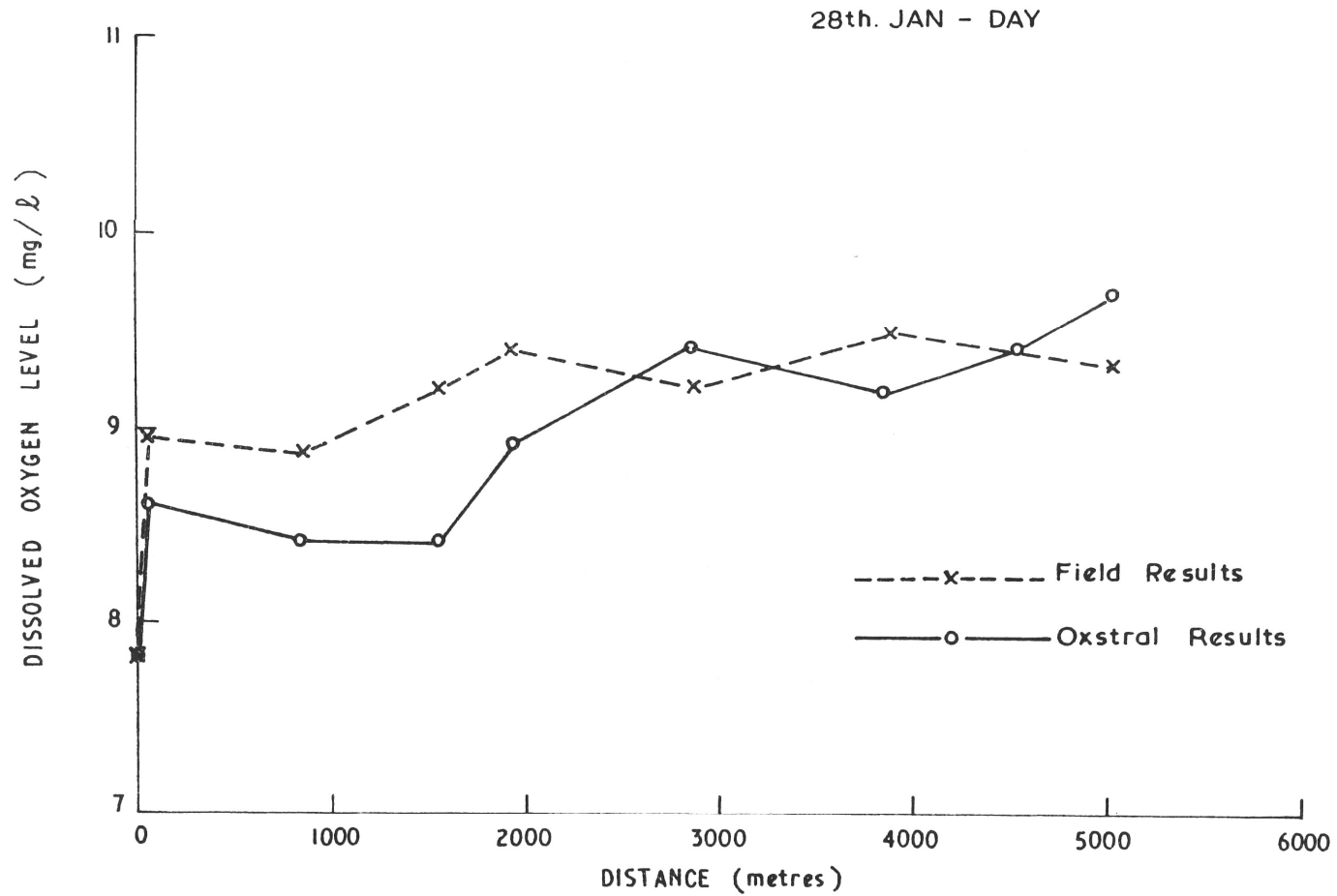| TIME	FLOW DIST	UBOD	PHOTO	PLANT.R	DO	SAT DO
0.000	0.000	0.000	0.000	0.000	9.400	9.540
0.000	91.000	3.250	0.000	1.807	9.123	9.660
.002	823.000	3.249	0.000	3.147	8.779	9.422
.006	1554.000	4.641	0.000	2.558	8.619	9.194
.010	1920.000	9.098	0.000	1.117	8.559	9.084
.019	2835.000	9.088	0.000	1.235	8.413	9.084
.027	3809.000	8.220	0.000	1.466	8.488	8.976
.031	4500.000	8.210	0.000	1.823	8.673	9.194
.034	5029.000	8.106	0.000	2.294	8.685	9.194

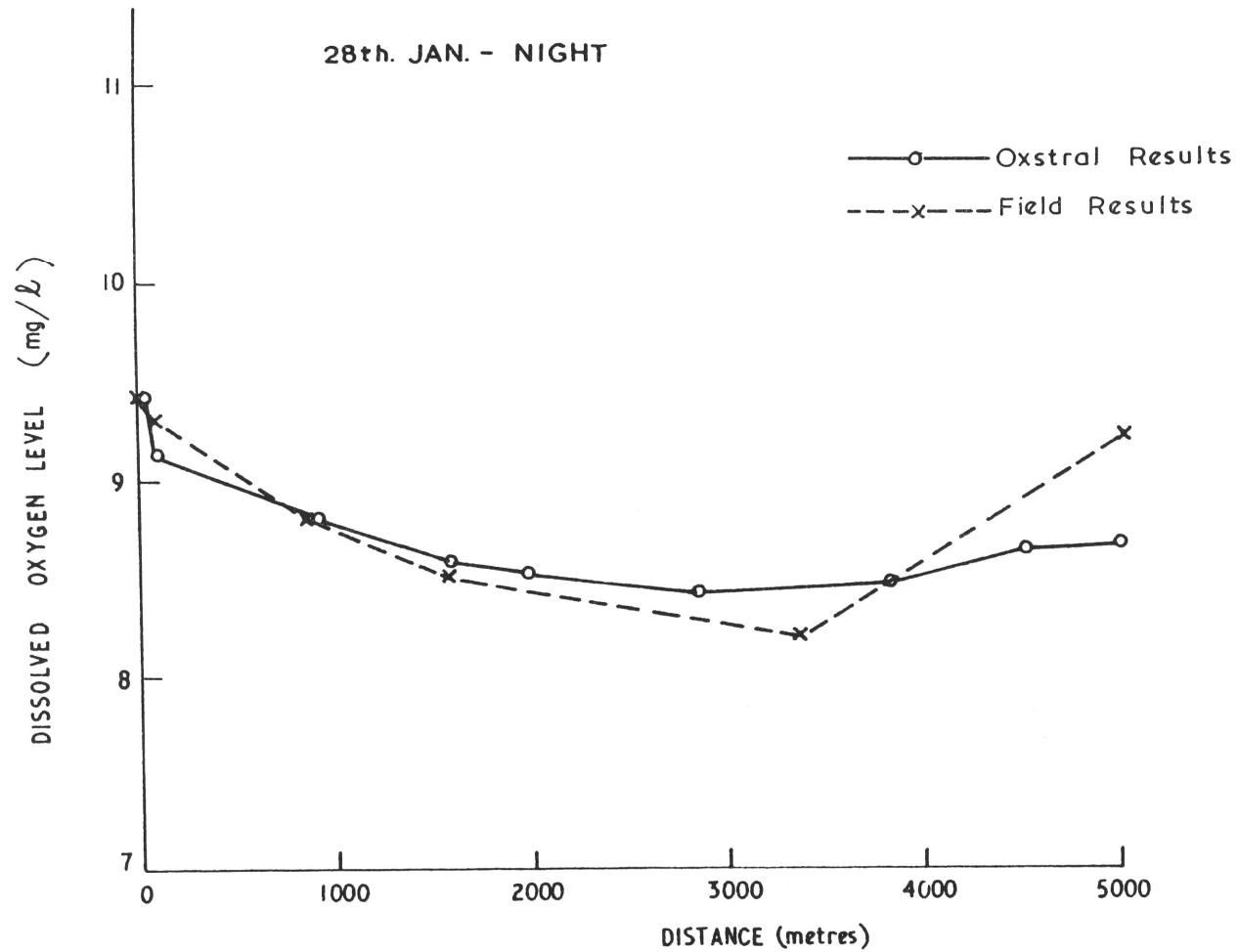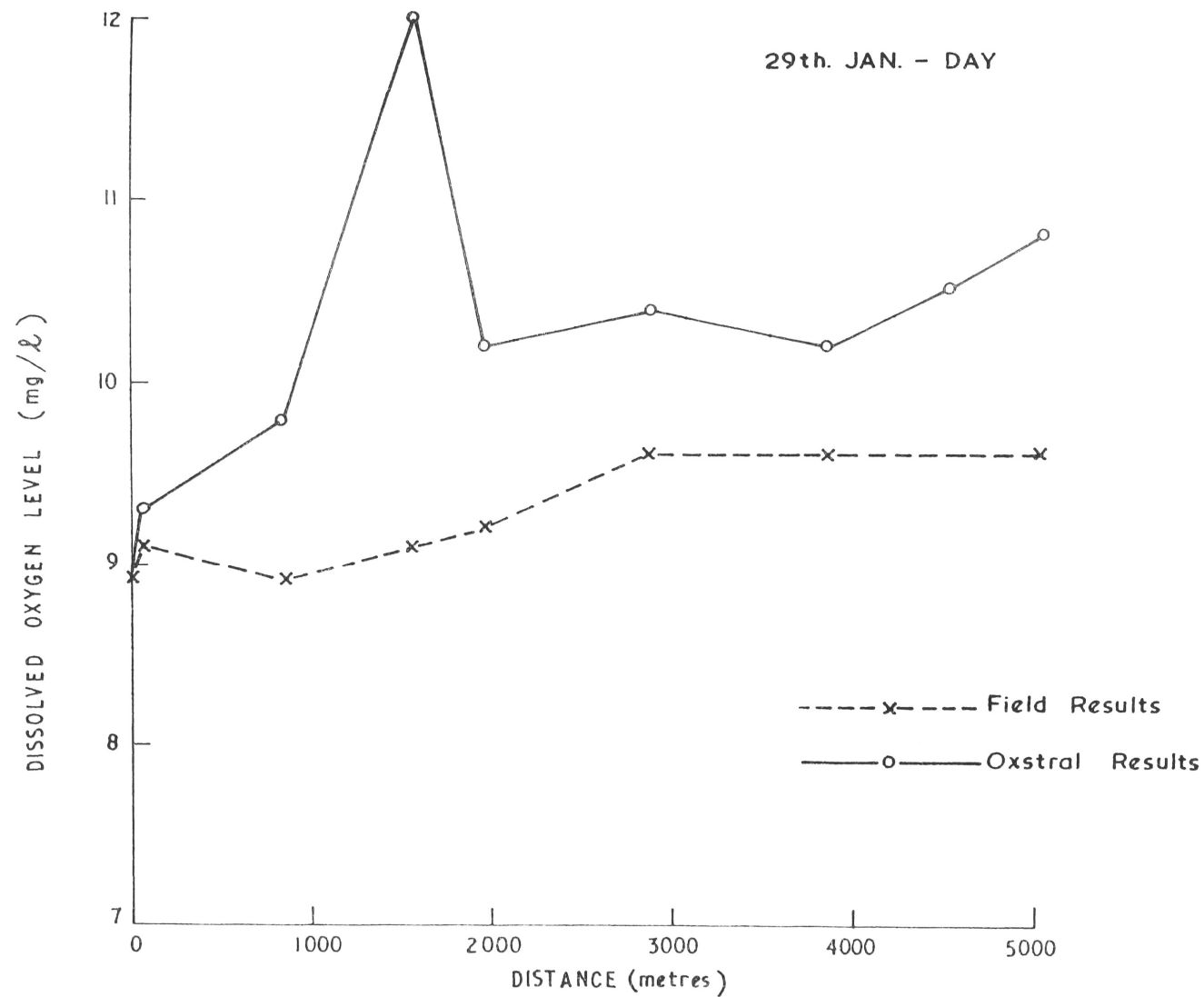FIGURE 7·16: SIMULATION OF "DAY" DISSOLVED OXYGEN LEVELS FOR 28th. JAN. 1975.

FIGURE 7·17: SIMULATION OF "NIGHT" DISSOLVED OXYGEN LEVELS FOR 28th. JAN. 1975.

Table 7.10: Input and Output Data for 29th January 1975 Night Simulation.

DISSOLVED OXYGEN IN AUSTRALIAN STREAMS

AP 120	AK320	BOD20	CBOD	GDN	SR	SHRS	BETA5
.800	.010	0.000	1.300	0.000	0.000	10.000	.600

T(1)	AK4	ALPHA3	ALPHA4	BETA1	BETA2	AP	ALPHA5
9.000	.100	0.000	.790	.001	.300	620.000	.100

DIST	VEL	DEPTH	TEMP	FLOW	MBOD	MTEMP	MDO	BIOM	BODAD
0.00	.06	.40	10.00	.02	10.00	12.00	9.00	35.00	1.00
100.00	.57	.30	9.00	.08	10.00	12.00	9.00	35.00	1.00
825.00	.17	.54	9.00	.09	10.00	12.00	9.00	35.00	1.00
1550.00	.14	.20	11.00	.04	10.00	12.00	9.00	35.00	1.00
1920.00	.33	.20	12.00	.13	10.00	12.00	9.00	35.00	1.00
2830.00	.33	.15	12.00	.17	10.00	12.00	9.00	35.00	1.00
3809.00	.50	.12	13.50	.08	10.00	12.00	9.00	35.00	1.00
4500.00	.50	.12	13.00	.08	10.00	12.00	9.00	35.00	1.00
5000.00	.50	.12	12.00	.08	10.00	12.00	9.00	35.00	1.00

TIME	FLOW DIST	UBOD	PHOTO	PLANT.R	DO	SAT DO
0.000	0.000	0.000	0.000	0.000	9.200	9.194
0.000	100.000	9.750	0.000	1.167	9.015	9.422
.006	825.000	10.106	0.000	.967	8.673	9.422
.020	1550.000	10.093	0.000	1.085	7.404	8.976
.024	1920.000	12.103	0.000	1.914	8.350	8.766
.032	2830.000	12.305	0.000	2.268	8.297	8.766
.039	3809.000	12.294	0.000	2.934	7.818	8.467
.044	4500.000	12.280	0.000	3.243	7.826	8.564
.046	5000.000	12.281	0.000	-.244	7.942	8.766

Table 7.9: Input and Output Data for 29th January, 1975 Day Simulation.

DISSOLVED OXYGEN IN AUSTRALIAN STREAMS

AK120	AK320	BOD20	CBOD	ODN	SR	SHRS	DETA5
.300	.010	0.000	1.300	0.000	150.000	10.000	.600

C(1)	AK4	ALPHA3	ALPHA4	BETA1	BETA2	AP	ALPHA5
8.900	.100	.100	.790	.001	.300	620.000	.100

DIST	VEL	DEPTH	TEMP	FLOW	MBOD	MTEMP	MDO	BIOM	BODAD
0.00	.06	.40	12.50	.02	10.00	16.00	9.00	35.00	1.00
100.00	.57	.30	12.50	.08	10.00	16.00	9.00	35.00	1.00
825.00	.17	.54	16.00	.09	10.00	16.00	9.00	35.00	1.00
1550.00	.14	.20	18.00	.04	10.00	16.00	9.00	35.00	1.00
1920.00	.33	.20	18.50	.13	10.00	16.00	9.00	35.00	1.00
2830.00	.33	.15	17.00	.17	10.00	16.00	9.00	35.00	1.00
3809.00	.50	.12	18.00	.08	10.00	16.00	9.00	35.00	1.00
4500.00	.50	.12	16.00	.08	10.00	16.00	9.00	35.00	1.00
5000.00	.50	.12	14.50	.08	10.00	16.00	9.00	35.00	1.00

TIME	FLOW DIST	UBOD	PHOTO	PLANT.R	DO	SAT DO
0.000	0.000	0.000	0.000	0.000	8.900	8.664
0.000	100.000	9.750	6.067	1.156	9.329	8.664
.006	825.000	10.104	5.055	.977	9.884	8.007
.020	1550.000	10.069	5.739	1.128	12.065	7.671
.024	1920.000	12.094	10.617	2.216	10.194	7.591
.032	2830.000	12.280	12.134	2.408	10.362	7.836
.039	3809.000	12.264	15.729	3.137	10.185	7.671
.043	4500.000	12.250	17.695	3.510	10.476	8.007
.046	5000.000	12.241	17.695	3.540	10.847	8.277

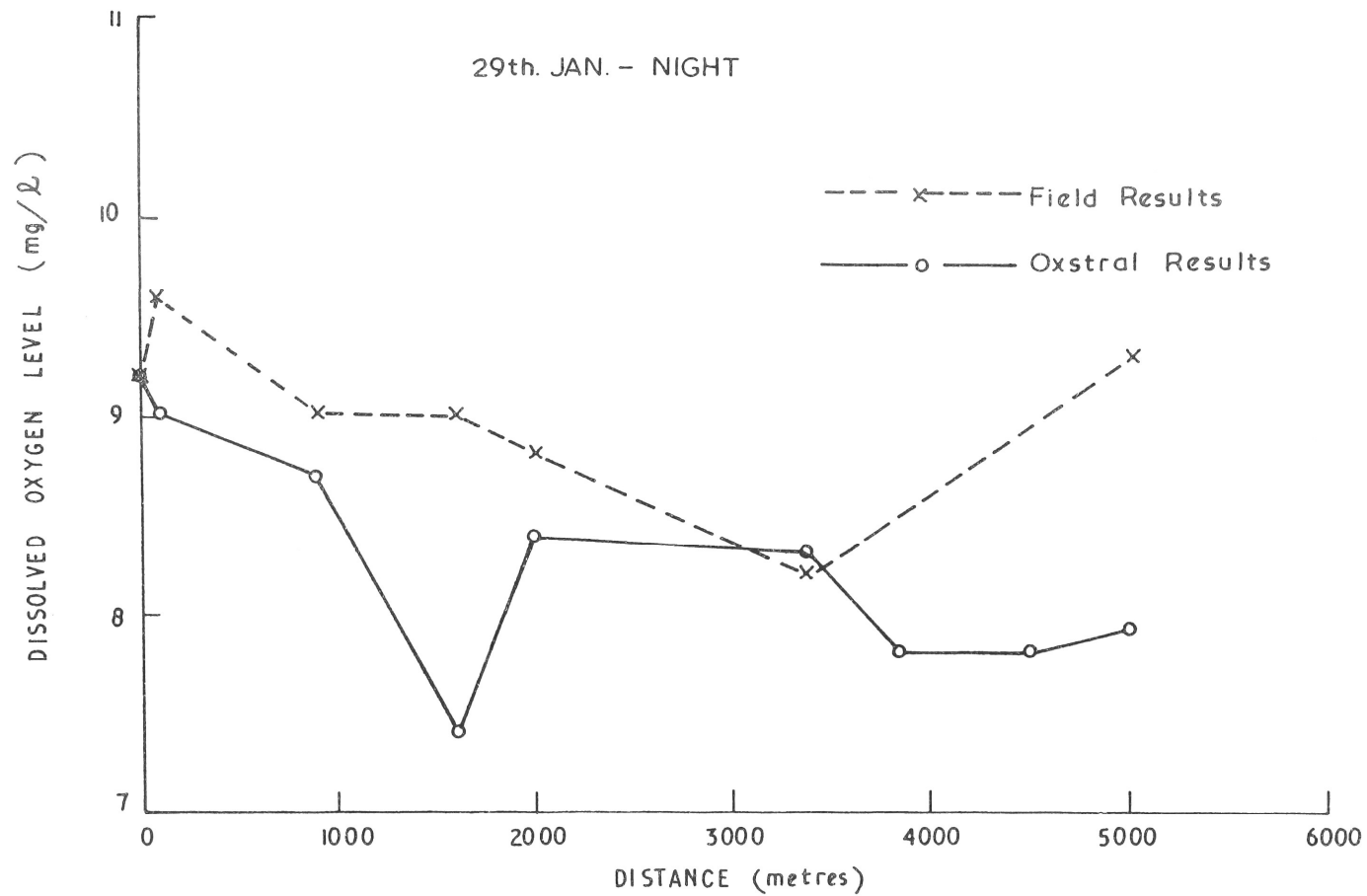FIGURE 7·18: SIMULATION OF "DAY" DISSOLVED OXYGEN LEVELS FOR 29th. JAN. 1975.

FIGURE 7·19: SIMULATION OF "NIGHT" DISSOLVED OXYGEN LEVELS
FOR 29th. JAN. 1975.

Table 7.11: Parameter Sensitivity

Parameter	Range of Variation	Maximum Deviation of D.O. Profile (mg/l)	Sensitivity[1]
TW(I)	Incr. 10°C - 25°C	-ve 1.2	0.07
	Decr. 10°C - 5°C	-ve 0	0.08
V(I)	Decr. 0.5-0.2 m/s	-ve 0.4	1.3
BIOM(I)	Incr. 40-100 mg/m^2	-ve 1.2	0.02
H(I)	Decr. 0.2 - 0.1m	+ve 1.2	12
FS(I)	Decr. 0.14-0.05 m^3/s	-ve 1.0	20
BOD20	Incr. 0-100 mg/1.	-ve 0.2	0.002
ODN	Incr. 0-100 mg/1	-ve 0.1	0.001
BA(I)	Incr. 0-100 mg/1	-ve 0.001	0
CM(I)	Incr. 9-11	2	1
	Decr. 9-7	2	1
TWM(I)	Incr. 12-16°C	No meas. change	0
AK120	Incr. 0.3-0.7	-ve 0.04	0.1
AK320	Incr. 0.01-5.0	No meas. change	0
AK4	Decr. 0.007-0	No meas. change	0
ALPHA5	Incr. 0.033-0.2	0.4	2.35
BETA 2	Incr. 0.3-0.5	0.3	1.5
AP	Incr. 620-640	+ve 0.1	.005
BIOM(I)	Incr. 20-35mg /m^2	-ve 0.3	0.02
	Incr. 20-60	-ve 0.4	0.01-
	Incr. 40-100	-ve 1.2	0.02
	Incr. 35-250	-ve 2.3	0.01
SR	Incr. 150-350	+ve 1	0.05
	Incr. 150-700	+ve 2.2	0.04

1. Sensitivity = Change in D.O. level/unit change in Parameter Input
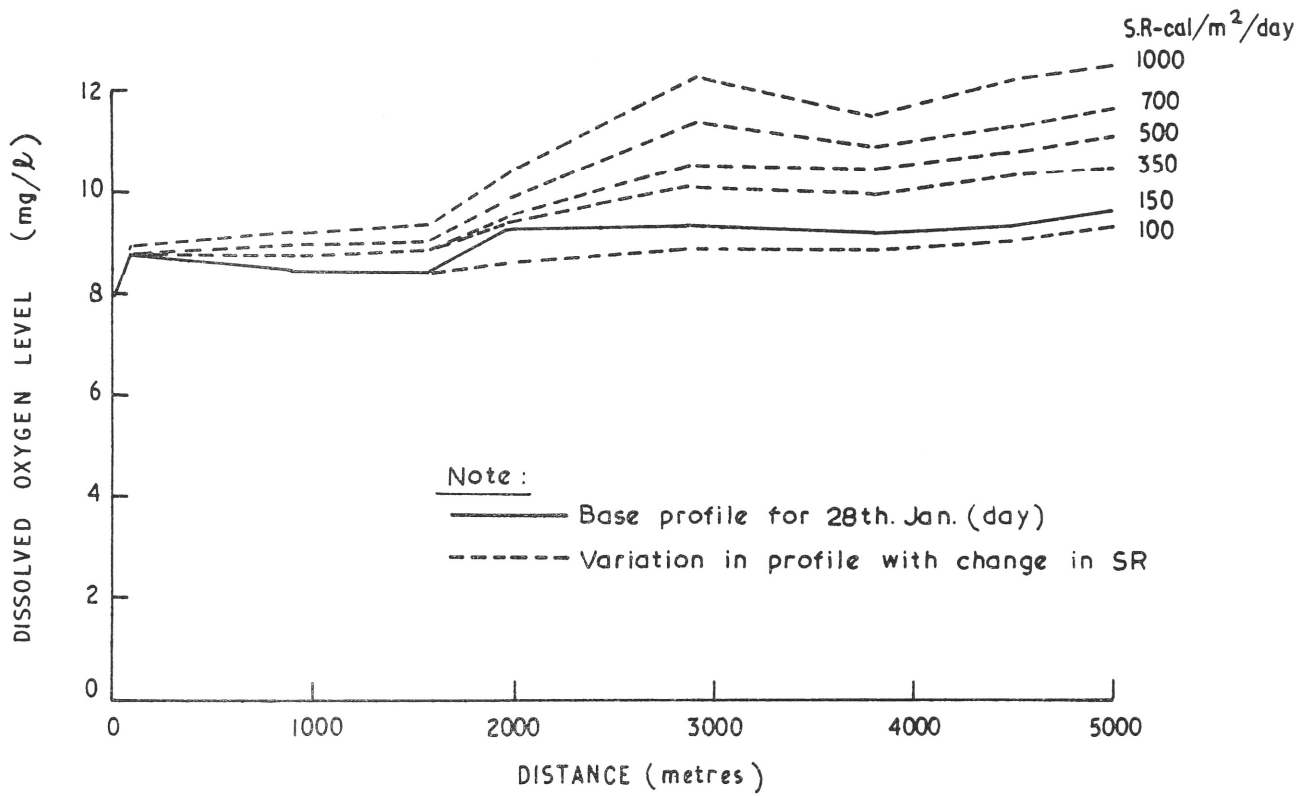
FIGURE 7·20: VARIATION IN D.O PROFILE WITH SR.
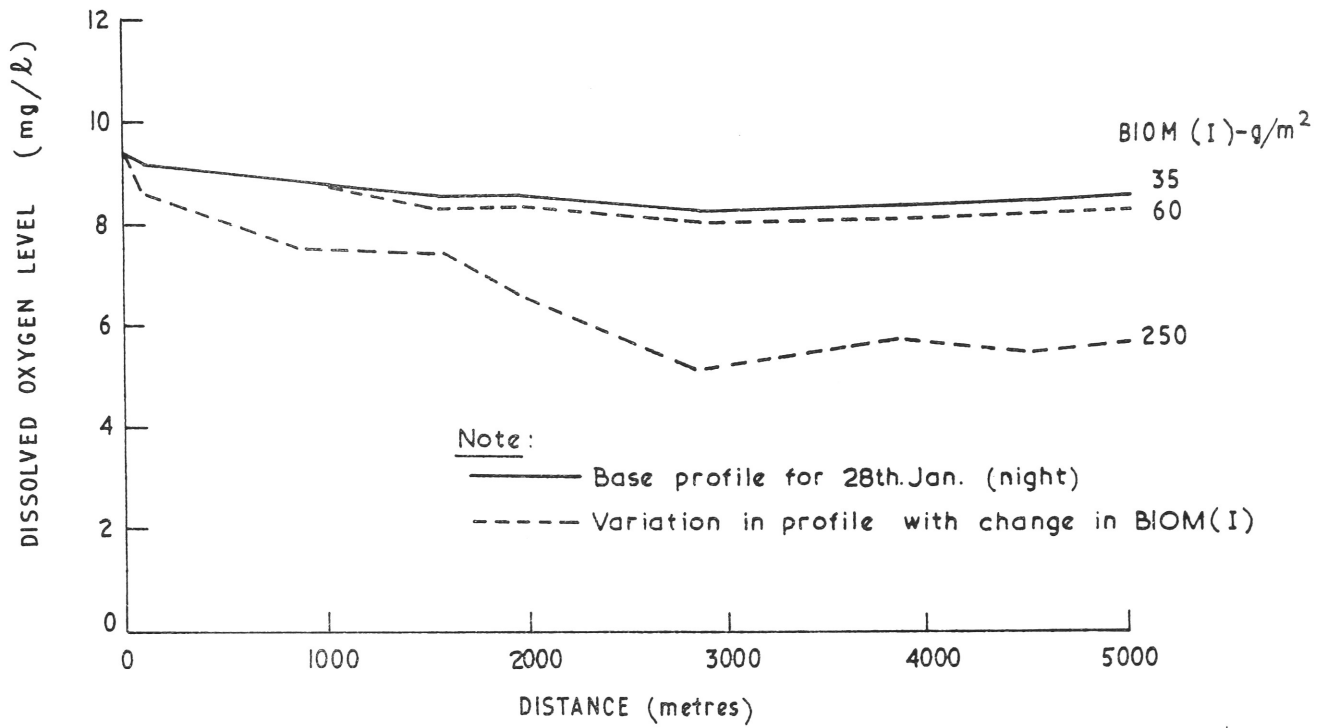
FIGURE 7·21 : VARIATION IN D.O PROFILE WITH BIOM (I)
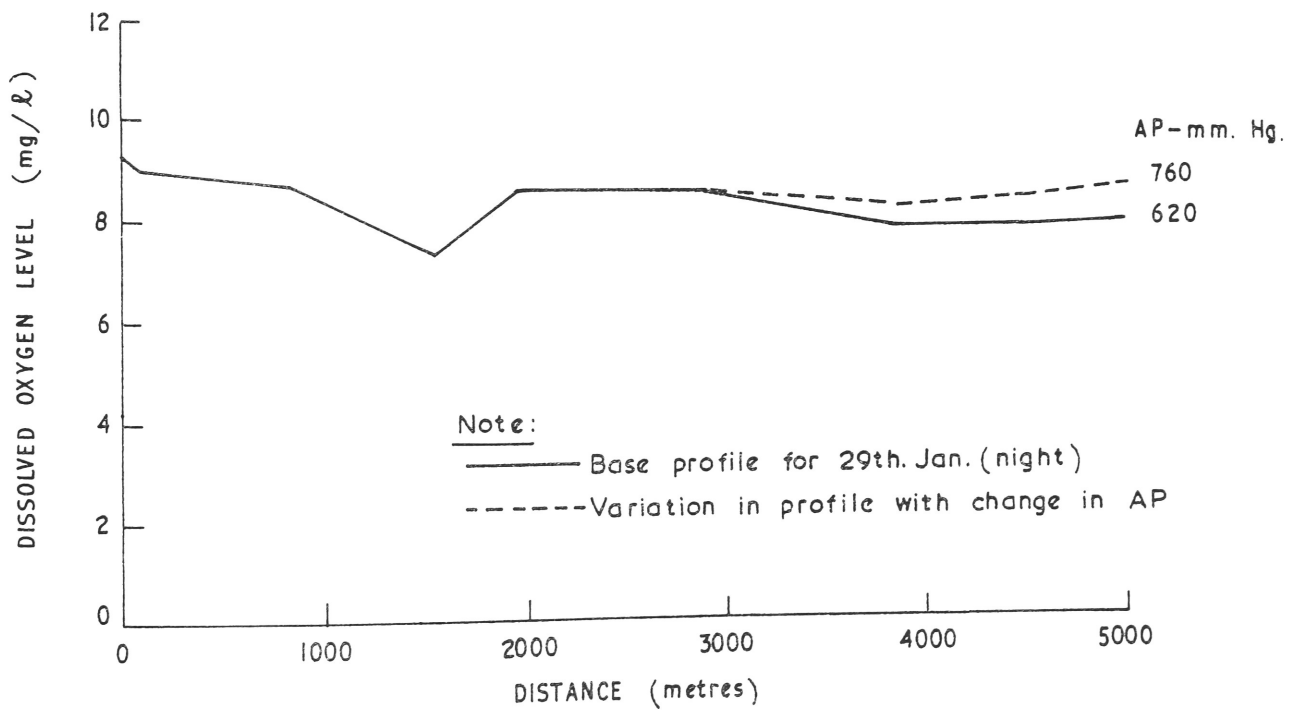
FIGURE 7·22: VARIATION IN D.O PROFILE WITH AP
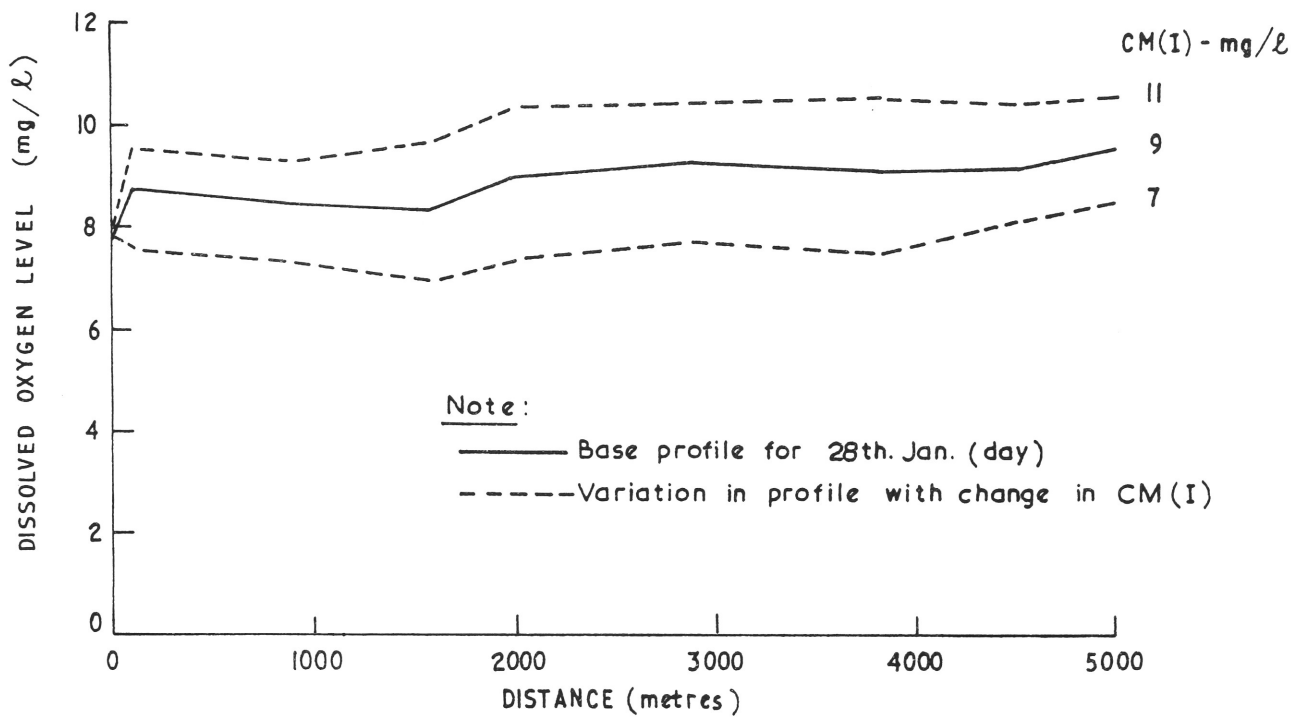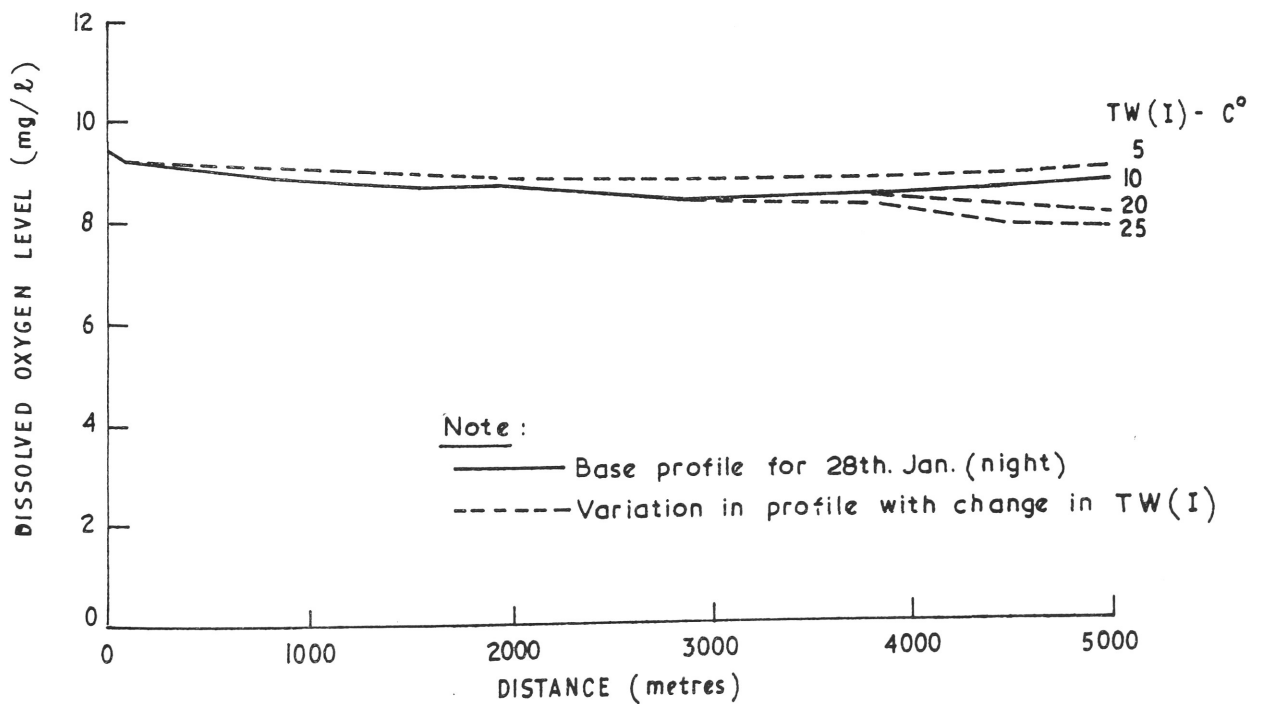
FIGURE 7·23 : VARIATION IN D.O PROFILE WITH CM(I)
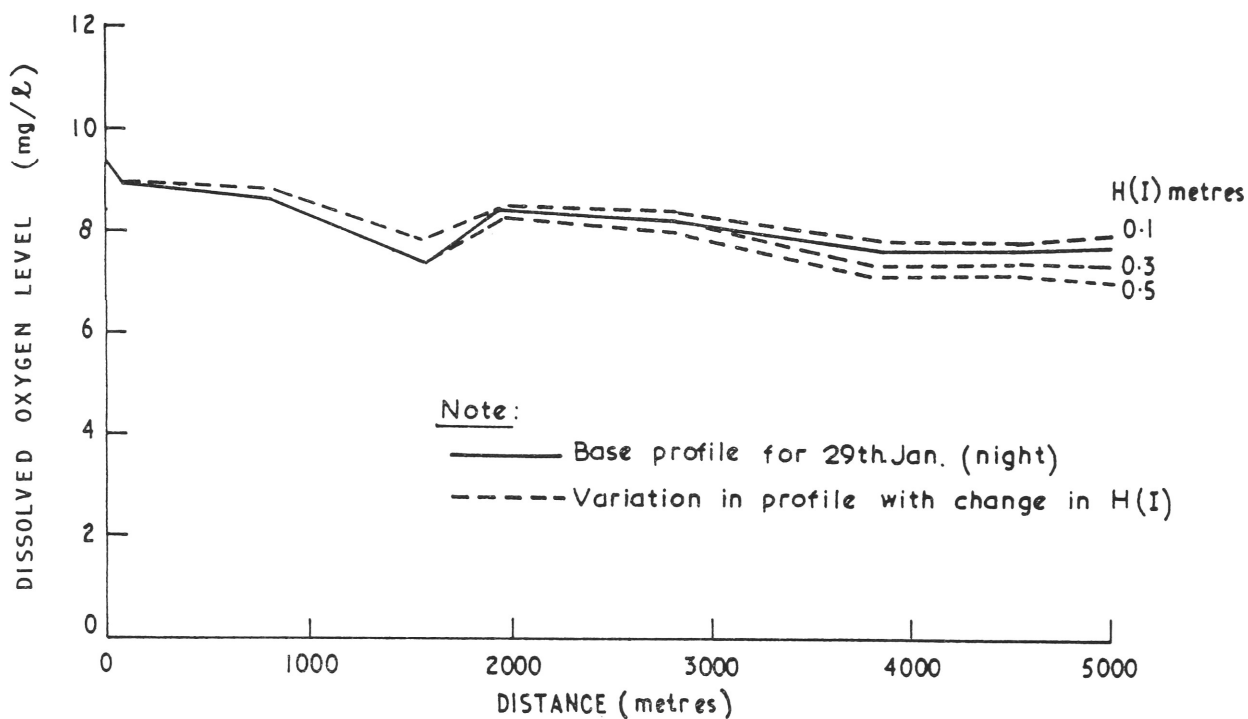

FIGURE 7·24 : VARIATION IN D.O PROFILE WITH TW(I)
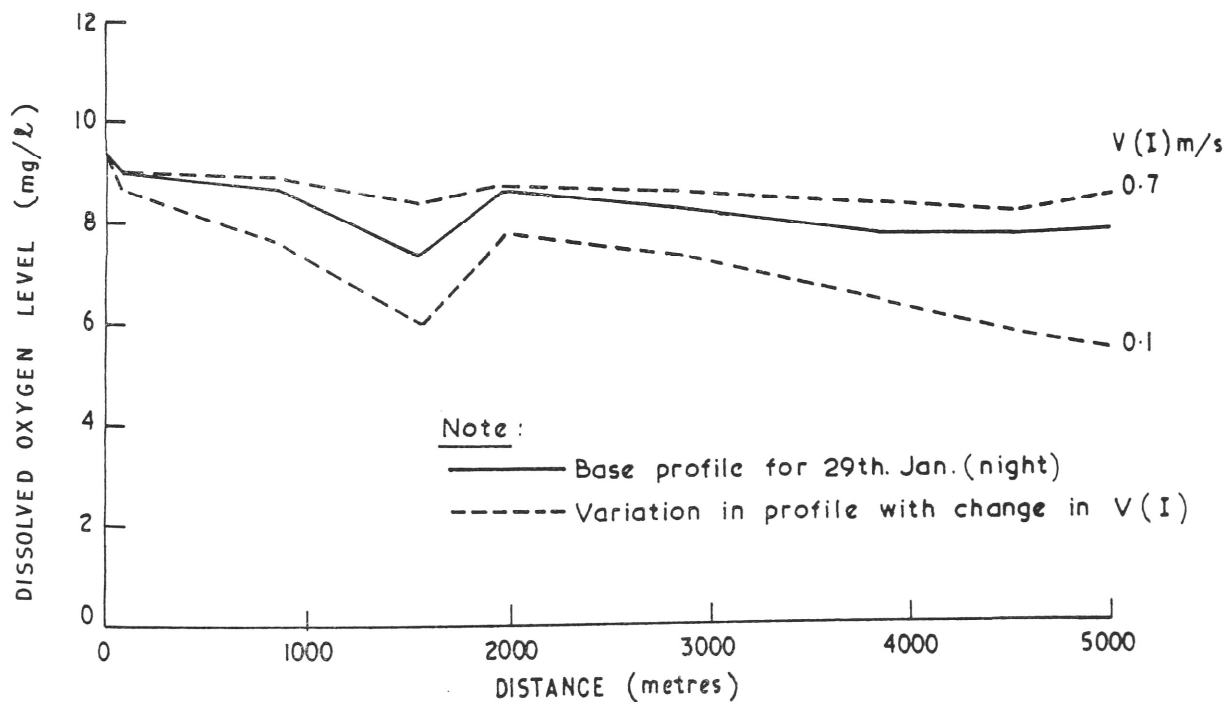
FIGURE 7·25: VARIATION IN D.O PROFILE WITH H(I)
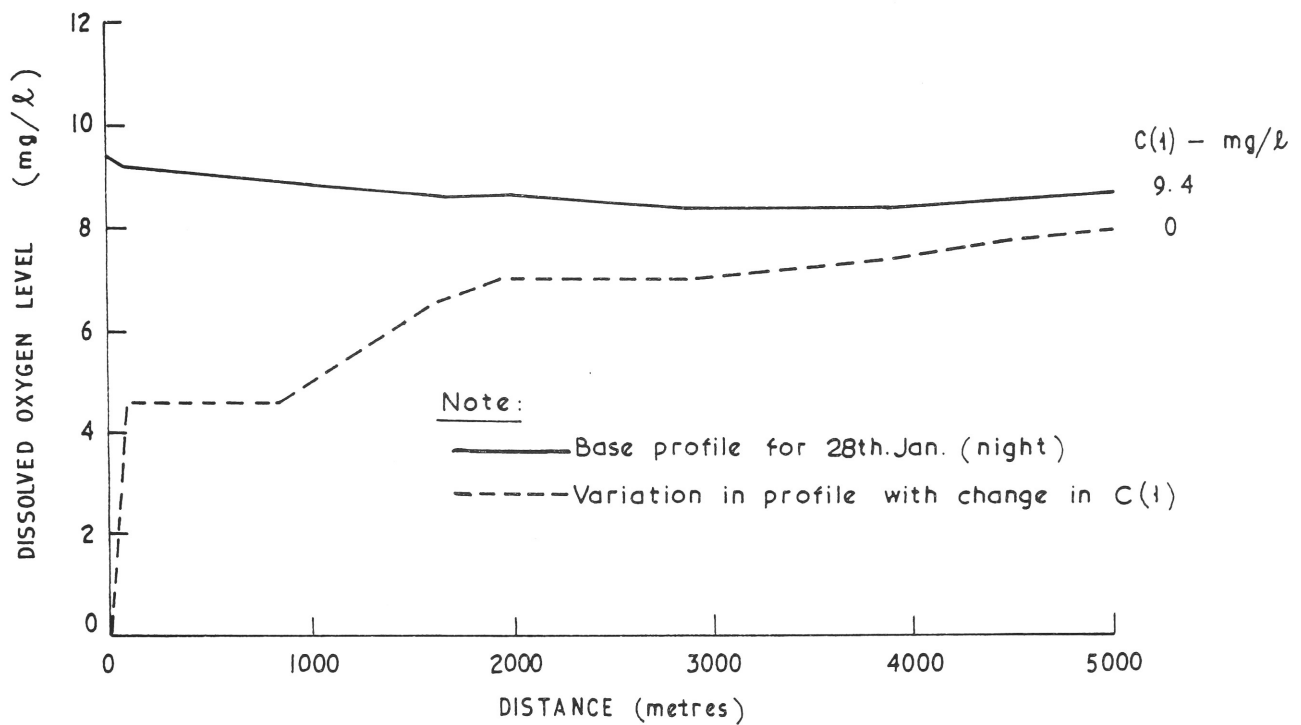

FIGURE 7·26: VARIATION IN D.O PROFILE WITH V(I)
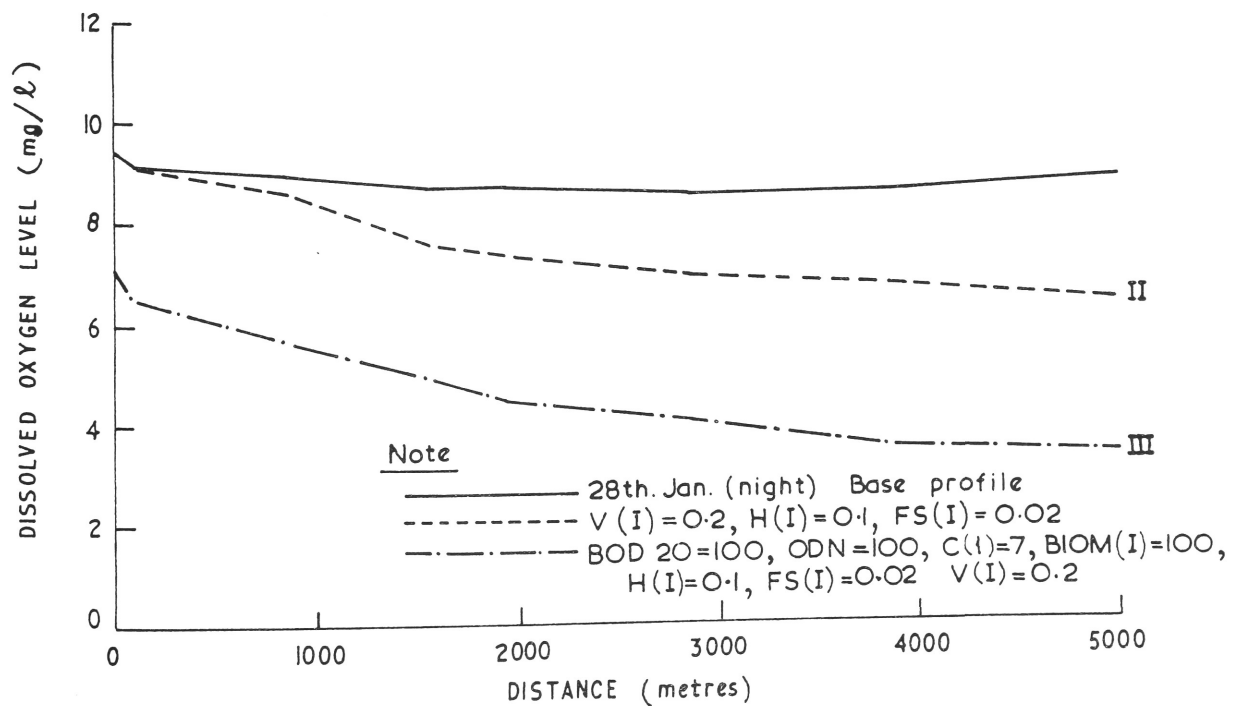
FIGURE 7·27: VARIATION IN D.O PROFILE WITH C(1)=0

FIGURE 7·28: VARIATION IN D.O PROFILE WITH
PARAMETER GROUPINGS

levels over the expected input range for those parameters of major influence.

7.7 Discussion of Results

7.7.1 Field Results

The components of the dissolved oxygen balance which were demonstrated to be significant from the field testing of Perisher Creek are:-

1. Atmospheric reaeration.

2. The production of oxygen by the photosynthesis of algae.

3. The depletion of oxygen by respiration of algae.

4. The dilution effect caused by the influx of tributary and groundwater flow.

5. Stream temperature.

Deoxygentation due to the oxidation of carbonaceous material will be insignificant due to the short flow times (less than 8 hours) and generally low stream temperatures prevalent throughout the year.

The oxygen exchange resulting from reaeration has been calculated in Section 7.5 as part of the calculations required to estimate oxygen production and depletion by photosynthesis and respiration respectively. For the specific reaches examined the rate of reaeration was found to lie between 4 and 7 mg/l/day based on a reaeration coefficient (K_2) of 10 days^{-1}. The reaeration coefficient was estimated from Figure 4.2, assuming a stream depth of 0.2m and a velocity of 0.3m/s. Considerable error associated with the estimation of K_2 restricts the accuracy to which the rate reaeration can be determined.

Higher rates of reaeration than those calculated in

Section 7.5 will be induced by greater turbulence (and

in some instances by cascading of the stream) in at least two

reaches where the terrain is of steep slope.   The first reach extends

100m from the chairlift.   The stream in this section is narrow and

subject to relatively high stream velocities.   Velocity and turbulence

are promoted even further by the inflow of tributary water of equiv-

alent flow magnitude (CSIRO Creek).   As illustrated in the day

readings of 28th January (Figure 7.9) any initial deficit at the head of

this reach is rapidly reduced and the dissolved oxygen level brought

up to the saturation level.

The second reach lies between Barrakee Lodge (1710 m.elev.)

and the weir (1600 m elev.).   In this reach (commencing at a distance

of 3400 m from the chairlift) the deficit produced by the nocturnal

respiration of algae is substantially reduced as indicated by the in-

crease in the absolute dissolved oxygen level from 8.2 mg/l to

approximately 9.3 mg/l (Figures 7.10 and 7.15).   An examination of

the day-time dissolved oxygen levels over the same reach (Figures

7.9 and 7.14) suggests that the increased turbulence is also effective

in de-aerating stream water which has become supersaturated as a

result of photosynthesis.

The complementary processes of photosynthesis and respiration

of algae are shown to be perhaps even more significant than reaeration

in the dissolved oxygen balance.   The significance of these activities

is apparent from the diurnal variations shown in Figure 7.29.   During

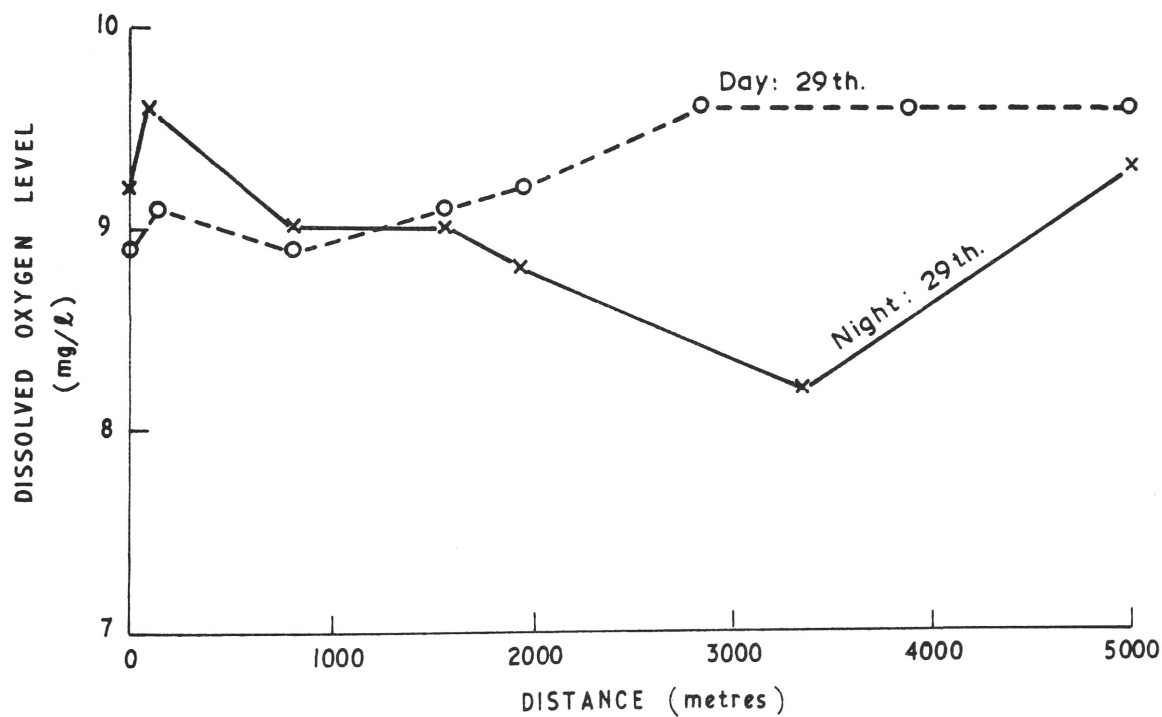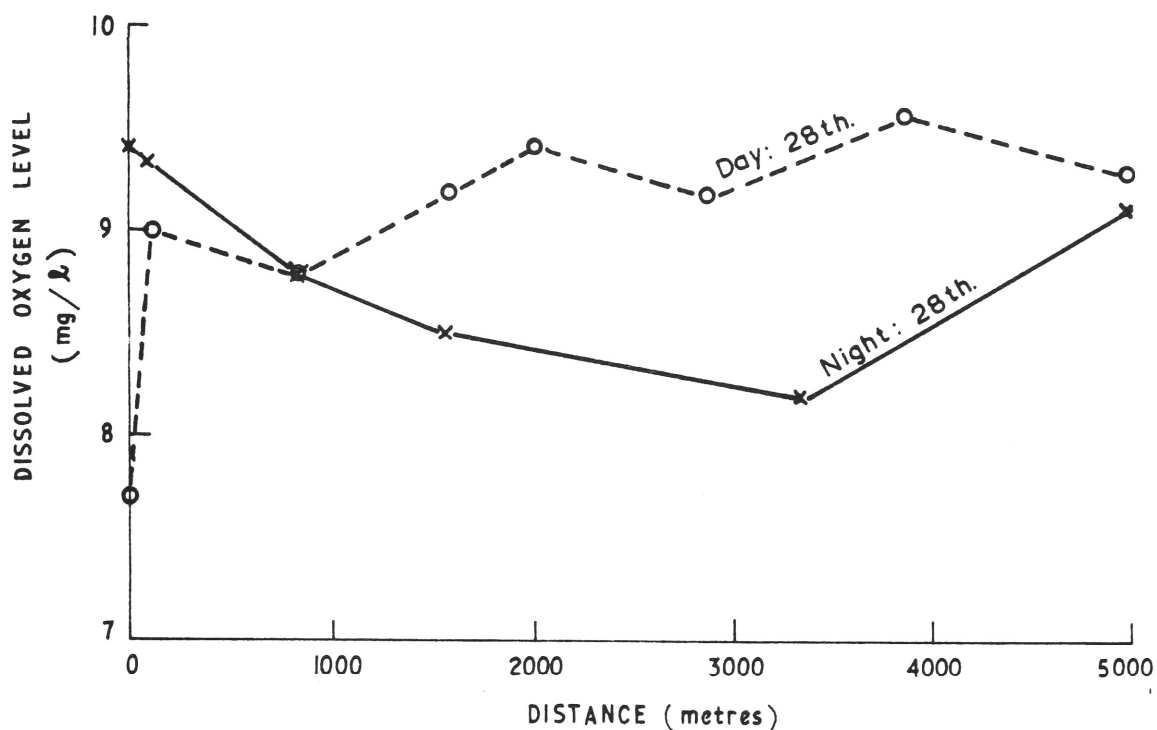daylight hours a nett production of oxygen by photosynthesis elevates

FIGURE 7·29: DIFFERENCES BETWEEN DAY AND NIGHT ABSOLUTE D.O LEVELS.

dissolved oxygen levels into the supersaturated region (Figures 7.9 and 7.14) whilst at night in the absence of photosynthesis, the removal of oxygen by the respiration of algae creates a deficit. For the January testing period the deficit was less than 15% of the saturation level and did not create any concern. Nevertheless it should be noted that the rates of oxygen production/depletion by photosynthesis and respiration outlined in Section 7.5 are not necessarily indicative of the order of magnitude to be expected in the field all year round. Variations may occur on a seasonal basis according to changes in stream temperature, algal biomass and, in the case of oxygen production by photosynthesis, the availability of light.

The influx of tributary and groundwater flow along the length of Perisher Creek was found to be a major factor in the establishment of dissolved oxygen levels. Apart from the adjustment in dissolved oxygen level resulting from the mixing of waters having different oxygen content the accompanying increase in stream velocity and flow rate will affect other parameters. In particular reaeration is likely to increase whilst the contribution to the oxygen balance by photosynthesis and respiration will be less significant.

A reach where extraneous water is of particular interest exists between the chairlift (0 metres distance) and the village (2000 metres distance). Fluctuations in streamflow (Figures 7.6 and 7.11) indicate that a dynamic flux exists between the stream and the large marsh basin, bounded by the 1725 metre contour and shown in Figure 7.30. It is hypothesised that groundwater flow from the surrounding alpine areas converges into this basin. Depending on the evapotranspiration
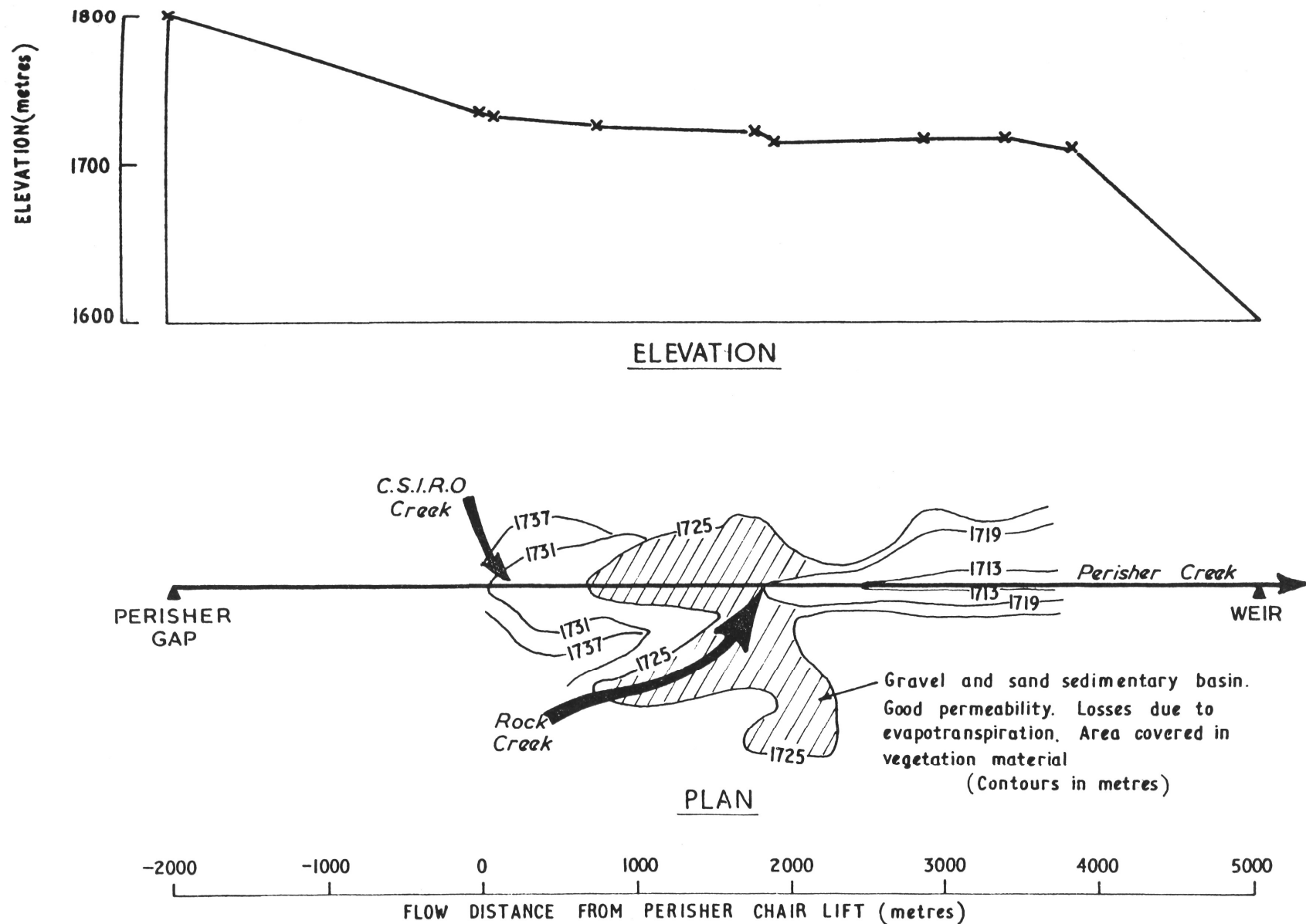
FIGURE 7·30: PLAN AND ELEVATION OF DRAINAGE AREA

rate in the basin, the position of the groundwater table and the stream-flow in Perisher Creek, water will either be transferred from the stream to the basin or vice versa.

Stream temperature was observed to be particularly important in the determination of the initial dissolved oxygen level. Figure 7.31, showing a comparison of diurnal dissolved oxygen levels and temperatures suggests that the lower nocturnal temperatures and subsequently higher saturation levels lead to initial dissolved oxygen concentrations above those recorded during the daylight hours.

7.7.2 OXSTRAL Results

Figures 7.16 - 7.19 show that the dissolved oxygen profile in Perisher Creek is satisfactorily reproduced using the dissolved oxygen model (OXSTRAL). Although the profiles for the 28th January show excellent agreement with the field results it should be noted that the solar radiation and biomass parameters were selected so as to give a computed profile in the same range as the field profile. The profiles for 29th January were derived by substitution of new hydraulic data into the program. The discrepancy between the field and computed results for 29th is thought to be the result of a number of interrelated factors. The computed day results, shown in Figure 7.18, are generally about 0.5 mg/l higher than the field results. Although no supporting evidence is available, it would seem plausible that the difference is due to a difference in oxygen production by photosynthesis. Since 29th was observed to be sunnier than 28th (that is less haze and less cloud) this explanation relies on the asser-
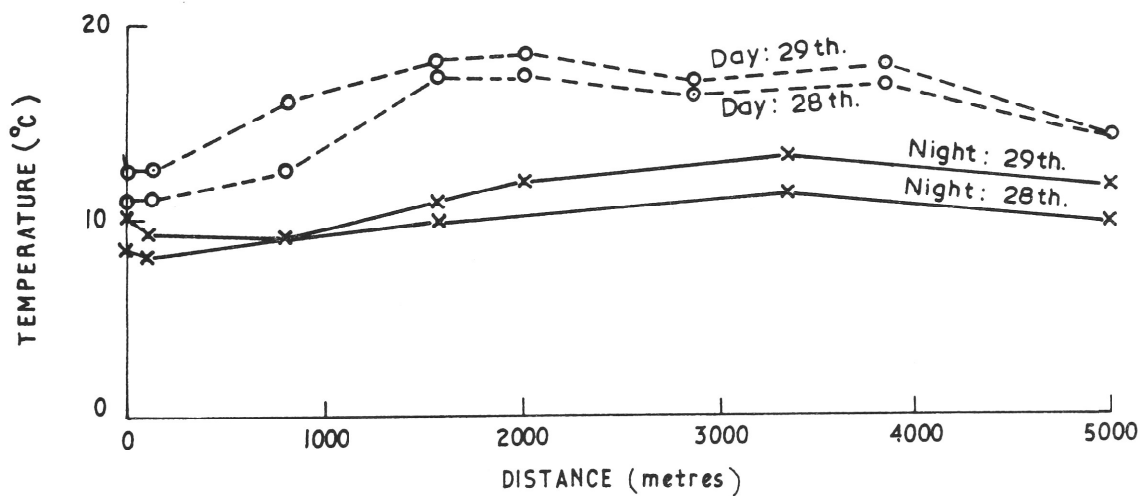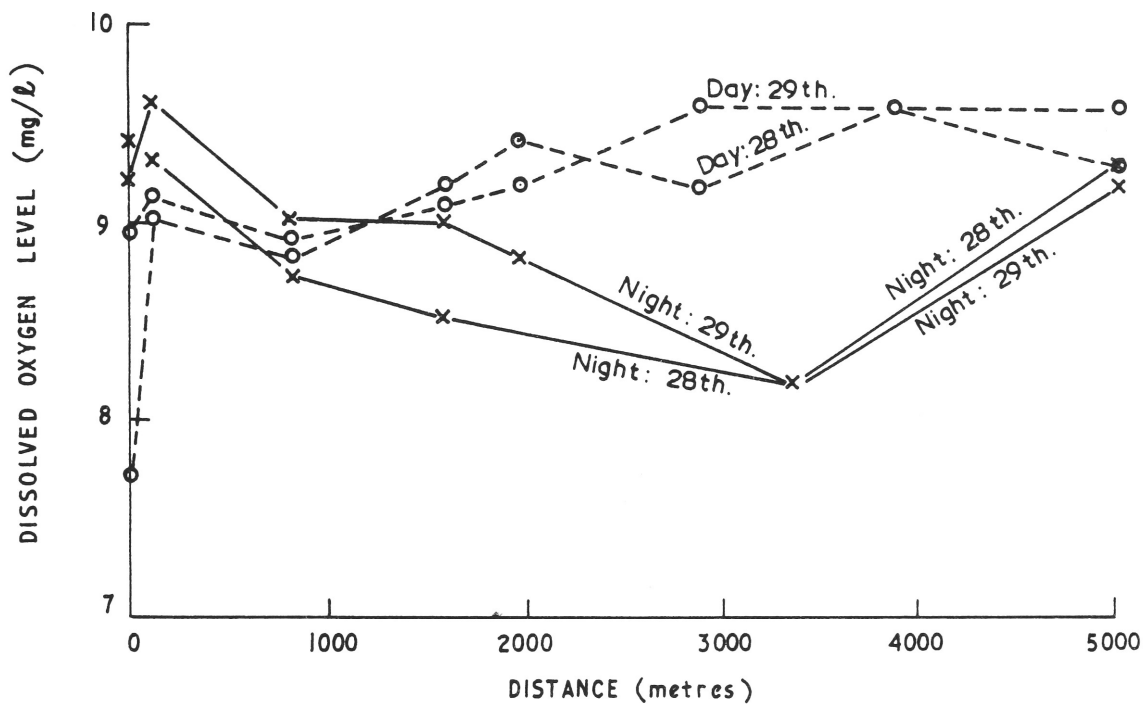
FIGURE 7·31: DISSOLVED OXYGEN LEVEL AND TEMPERATURE COMPARISON.

tion by Brown (1972) that at high light intensities photosynthesis is inhibited (see Section 3.3.2). The sharp rise at the 1550m location is most likely due to the use of velocity and depth data which does not represent the true nature of the reach. Comparison of the depth and velocity profiles for the two days (Figures 7.7, 7.8, 7.12 and 7.13) suggest that the velocity reading and depth reading at the 850 and 1550m locations may be untypically low and high respectively. Characterisation of the reach by an untypically low velocity would have caused the residence time of water in the reach to be excessive, resulting in the exaggerated levels of oxygen production by photosynthesis. This phenomenon is also apparent in the night results (Figure 7.19). A similar increase in residence time and subsequent overestimation of algal and plant respiration would have resulted in the 'exaggerated' decline in dissolved oxygen level at the 1550 location. It can also be hypothesised that in the steep section between 4000m and 5000m the velocities are higher (and depths lower) than interpolated, again resulting in an excessive depression of the dissolved oxygen profile.

The sensitivity analysis confirms earlier comments (Section 7.7.1) that plant and algal photosynthesis and respiration and the inflow of tributary and groundwater flow will be significant parameters. Figures 7.20 and 7.21 show the effect on the dissolved oxygen profile of altering the solar radiation and plant biomass. Both factors were found to influence the dissolved oxygen distribution, although not in a dominating way. It was estimated that the biomass level in Perisher Creek was less than 20-50 g/m^2 of stream bed. The sensitivity

analysis indicated that a critical dissolved oxygen level of 5 mg/l would only be approached if the biomass was five to ten times as dense (i.e. > 250 g/m^2). The possibility of such a situation developing is remote although some growth in aquatic biomass could occur if nutrient supplies increased as a result of increased pollution.

The effect of atmospheric pressure shown in Figure 7.22, is significant when considering a range of 100 mm Hg or more. Generally it will be sufficient to know the approximate atmospheric pressure as fluctuations of less than 50 mm Hg pressure will have minimal influence on the dissolved oxygen profile.

Tributary and groundwater inflow into Perisher Creek is substantial. The sensitivity analysis, shown in Figure 7.23 indicates that the dissolved oxygen level of the inflow will have a major effect on the stream quality. Consequently this parameter should receive considerable attention in any future analysis of the stream.

Figure 7.24 shows that stream temperature fluctuations of less than 5 centigrade degrees will not alter the dissolved oxygen level by more than 0.2 mg/l. However, seasonal changes in temperature, in the order of 15-20 degrees may affect dissolved oxygen levels downstream of Perisher Village by as much as 1 mg/l. The small effect of changes in temperature on the dissolved oxygen profile is attributed to the short flow times involved which prevent the attainment of steady state conditions. In particular, temperature induced changes in the reaeration coefficient will not be of sufficient duration to be of any significant consequence in the overall dissolved oxygen balance. However, it is likely that in practice seasonal changes in temperature will affect the dissolved oxygen level of the surface and groundwater

inflow and this will then have a major effect on the oxygen distribution.

Variations in depth over the range likely to be encountered in Perisher Creek shown in Figure 7.25 have a relatively small effect on the dissolved oxygen profile. Generally errors associated with the measurement of depth will only be important in terms of streamflow calculations where oxygen deficient surface or groundwater requires accurate assessment.

Figure 7.26 shows that variations in velocity can have a significant effect on the dissolved oxygen profile. Velocities in excess of those measured on 29th January do not increase dissolved oxygen levels greatly. However, a decrease in stream velocity to a uniform 0.1 m/s results in a marked decline in the nocturnal dissolved oxygen levels. This effect can be explained mainly in terms of a lower velocity increasing the residence time and allowing algal respiration to dominate, although some of the effect can be attributed to a decrease in the rate of atmospheric reaeration. Alternatively one can expect a decrease in velocity to elevate dissolved oxygen levels during the day due to the dominance of oxygen production by photosynthesis. It should be noted that in Figure 7.26 the increase in the dissolved oxygen level at the 2000 m distance is due to the inflow of higher quality groundwater and tributary flow.

Figures 7.27 and 7.28 illustrate the type of dissolved oxygen profiles one could expect under extreme circumstances. In Figure 7.27 complete deoxygenation of the stream water at the chairlift (0 metres) is followed by rapid reaeration such that the critical level

is exceeded within 2000 metres of travel.   Figure 7.28 shows that
with minimum dry weather flow when velocities, depths and stream-
flow are at their lowest values, the minimum night level exceeds
6 mg/1 (curve II).   It is only when one considers the unlikely sit-
uation of the stream being highly polluted, having considerable weed
and algal growth and being subject to the same drought flow that the
dissolved oxygen level drops below the recommended 5 mg/1 level
(curve III).   A situation such as this would occur only after consider-
able visual deterioration of the stream had occurred and is consequently
a highly unlikely occurrence.

8. <u>Conclusions</u>

Based on the experience gained in assessing the field data collected in Perisher Creek it is concluded that the computer program, OXSTRAL, provides a valuable means of predicting dissolved oxygen levels in Australian streams. By carrying out a sensitivity analysis the significant parameters affecting the oxygen balance may be isolated for a particular stream. This information is invaluable in the planning of extensive field investigations, since prior knowledge of the significant parameters can save time and reduce expenditure.

An assessment of the field data taken from Perisher Creek indicates that the concentration of dissolved oxygen along the length of the stream will probably exceed the critical value of 5 mg/l at all times of the year, the main reasons being that temperatures are generally low, ensuring low rates of oxidation and high oxygen saturation levels, and the flow time is short. The sensitivity analysis supports this view although at the same time reveals the need for some caution due to the limited nature of the field data. The only possible (although unlikely) situation which may lead to unsatisfactory dissolved oxygen levels is that in which drought streamflow is accompanied by low quality tributary or groundwater inflow, high stream temperature and high density plant and algal growth. The high density growth of plant and algae would be the critical factor and as this could only occur as a result of gross ecological change it is likely detection and rectification of the situation would occur at an early stage.

The only other area of concern lies in the establishment of the critical dissolved oxygen level. Although the consensus of opinion is that 5 mg/l is the minimum acceptable level, Hart (1974) recommends values as high as 9.3 mg/l for the protection of trout spawning where toxic substances are present (Table 2.1). It is conceivable that if chlorine is introduced into Perisher Creek during the course of waste treatment the critical dissolved oxygen level may need to be increased.

9. <u>Recommendations</u>

It is recommended that:-

(i) further refinement of OXSTRAL be made as more data comes to hand in the course of the continued study of Perisher Creek and other National Park streams. In particular more information should be sought in regard to the production of oxygen by plant and algal photosynthesis and the associated depletion of oxygen by respiration;

(ii) any further study of Perisher Creek should establish, on a seasonal basis, the quality of groundwater and tributary inflows, the distribution of algae along the length of the stream, and examine these two factors in terms of their influence on the dissolved oxygen distribution;

(iii) data be gathered during those periods when dissolved oxygen levels are likely to be lowest, i.e. during the summer nights when stream temperature is high, photosynthesis is absent, algal respiration is high and streamflow is low; and at night during spring thaw or after a light rainfall when the inflow of low quality water may be substantial.

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APPENDIX A

METHODS TO EVALUATE MODEL PARAMETERS

After a preliminary study of the stream an assessment of the principal parameters affecting dissolved oxygen should be made. Data allowing evaluation of the principal parameters should be sought both from field measurements and by laboratory analyses in the manner described in the following sections.

A1: Sampling Procedure

When critical conditions are being studied, sampling should be undertaken at a time when streamflow is low and if possible relatively stable.

Krenkel (1973) states that generally sampling locations should include one station just above each major waste discharge and other stations at about half to one day intervals below the waste sources. In those instances where parameters other than dissolved oxygen or B.O.D. levels are being investigated (e.g. reaeration coefficient, streamflow etc.) the sampling locations may be chosen at shorter intervals.

Sampling once daily and once nightly will be sufficient in most cases. However, if streamflow, waste discharge or photosynthesis are found to fluctuate widely, it may be necessary to sample continuously to establish the daily cycle of variation.

A2: Flow Distances

Flow distances may be ascertained from topographical maps of the area.

A3: **Stream Velocities**

Stream velocities may be measured directly using a current meter or timing the movement of a tracer, or indirectly from stage-discharge ratings and cross-sectional area measurements.

A4: **Flow Time**

The flow time in a reach is calculated by dividing the flow distance in the reach by the mean stream velocity in the reach.

A5: **The Ultimate BOD Level (L_O) and the Deoxygenation Coefficient (K_1)**

Values of L_O and K_1 can be estimated in a number of ways. A summary of techniques and approaches follows.

Clark (1968) reports that polluted water samples may be satisfactorily transported to the laboratory for BOD analysis if packed in ice. BOD analysis (Winkler method) is carried out within 24 hours of sampling the BOD value will show a difference of less than 10% of that which would have been obtained if analysis had occurred immediately after sampling (Clark, 1968). Accordingly, an allowance for the sample deterioration may be made, particularly if sample handling procedure is standardised.

The BOD value obtained represents the amount of oxygen consumed in mg/l of waste water over a period of 5 days at $20^{O}C$ under laboratory conditions. The value measured is dependent not only on the nature and amount of the organic materials present but also on the microorganisms and their environment in the BOD bottle.

The ultimate BOD value (UBOD), required in the kinetic formulation is estimated by establishing a relationship with the BOD_5

value, based on information from long-term BOD tests extending to 10 or more days. These long-term BOD tests can also provide a means of determining the deoxygenation coefficient, K_1. The method, outlined by Whipple (1969), involves observing the oxygen uptake of stream samples at $20^\circ C$ as a function of time. L_O can be calculated from equation (4.3) where $t_2 = 2t_1$

$$\text{i.e. } X = L_O (1 - e^{-K_1 t_1}) \tag{A1}$$

$$Z = L_O (1 - e^{-K_1 t_2}) = L_O (1 - e^{-2K_1 t_1}) \tag{A2}$$

From Equation (A1)

$$e^{-K_1 t_1} = 1 - \frac{X}{L_O}$$

Substituting into (A2)

$$Z = L_O \left(1 - \left(1 - \frac{X}{L_O}\right)^2\right)$$

$$\text{i.e. } L_O = \frac{X^2}{2X - Z} \tag{A3}$$

K_1 can be calculated from equations A1 and A2

$$\text{i.e. } \frac{X}{Z - X} = \frac{(1 - e^{-K_1 t_1})}{e^{-K_1 t_1} - e^{-K_1 t_2}}$$

$$= \frac{1 - e^{-K_1 t_1}}{e^{-K_1 t_1} (1 - e^{-K_1 t_1})}$$

$$\text{i.e. } \log \frac{X}{Z - X} = K_1 t_1$$

$$\text{i.e. } K_1 = \log \frac{X}{Z - X} / (t_2 - t_1) \tag{A4}$$

Krenkel (1973) has expressed the opinion that the rate constant is dependent on environmental conditions and is not adequately rep-resented within the confinement of a BOD bottle. Krenkel also states that K_1 is not only affected by mixing, but by deposition,

absorption and scour which may occur along the stream length.
These factors may be taken into consideration by measuring the
BOD_5 at successive downstream locations, and then determining the
rate constant from the slope of a plot of the log (BOD_5) versus time
of passage.

The most accurate method of finding L_O and K_1 from a series
of observations of the oxygen demand, y, exerted over a period of
time, t, is to use the "method of moment " developed by Moore,
Thomas and Snow.   This method involves relatively simple calcul-
ations, followed by referral to the appropriate graphs given in the
paper.

A more convenient method, derived by Thomas involves plotting
$(t/y)^{1/3}$ against t on ordinary graph paper.   A straight line is ob-
tained in which the intercept on the y axis is (A) and the slope (B)
are defined by the equation,

$$A = (K_1 L_O)^{1/3} \qquad\qquad (A4)$$
$$\text{and} \quad B = (K_1)^{2/3}/ \ 6 L_O^{1/3} \qquad\qquad (A5)$$

from which

$$K_1 = 1.13 \ B/A \qquad\qquad (A6)$$
$$L_O = 1/K_1 A^3 \qquad\qquad (A7)$$

A6: <u>The Rate of Addition of BOD along the Reach (L_a) and the</u>
<u>Rate Coefficient to Account for the Removal or Addition of</u>
<u>BOD by Deposition or Resuspension (AK4)</u>

The rate of addition of BOD along a reach may be computed by
reference to the Dobbins equation (Section 5.1.2).

$$L - \frac{L_a}{(K_1 + AK_4)} = \left[L_O - \frac{L_a}{(K_1 + AK_4)} \right] 10^{-(K_1 + AK_4)t} \qquad (5.3)$$

The carbonaceous deoxygenation coefficient (K_1) and the BOD profile (i.e. a tabulation of L versus time) are determined by laboratory analysis. If L is found to decrease along the reach faster than the rate of reduction due to oxidation (i.e. $L < L_O e^{-K_1 t}$) then AK_4 may be assumed to be positive, i.e. the reduction of BOD due to sedimentation is greater than any addition of BOD to the stream from the benthal deposit or other sources. It is then assumed that $L_a - 0$ and so the effective value of AK_4 may be computed from equation (5.3).

If L is found to decrease, remain constant or increase along the reach but exceeds the value predicted by carbonaceous deoxygenation (i.e. $L > L_{Oe}^{-K_1 t}$) then the rate of addition of BOD along the reach exceeds the removal by sedimentation. It is then assumed that $AK_4 = 0$ and L_a is computed from equation (5.3).

A7: The Reaeration Coefficient (K_2)

Wherever possible the reaeration coefficient should be directly determined in situ rather than relying on empirical formulations. In this way normally unaccountable factors affecting turbulence are encompassed.

The two basic methods for the determination of K_2 in the field are the disturbed equilibrium technique and the tracer technique.

A7.1: The Disturbed Equilibrium Technique

This technique is described by Gameson and Truesdale (1959) and Klein (1962). It entails the measurement of two different levels of dissolved oxygen concentration at the upstream and downstream ends of the reach. The upstream dissolved oxygen deficit is obtained

usually by adding sodium sulphite and a cobalt catalyst to the stream
($O_2 + 2SO_3^{2-} \rightleftharpoons 2SO_4^{2-}$). Precautions should be made to assure that
the sulphite is completely mixed with the flow and that the reaction
has proceeded to completion before the flow enters the study reach.
If velocity, stream temperature and reaeration coefficient are assumed
constant for the reach during the period of the experiment, then, from
equation 4.16

$$K_2 = \frac{1}{t} \ln \frac{(C_s - C_1)}{(C_s - C_2)} \qquad (A8)$$

where C_1 and C_2 are d.o. concentrations at two stations
downstream of the reagent addition with time of flow between them of
t days.

If oxygen is liberated by photosynthesis or consumed by respir-
ation, it can also be shown from equation (4.16) that providing the
rates of these processes remain constant during the measurement,

$$K_2 = \frac{1}{t} \ln \frac{(C_1' - C_1)}{(C_2' - C_2)} \qquad (A9)$$

where C_1' and C_2' are the steady concentrations at the two
stations before the addition of the reducing agent, and C_1 and C_2 are
as previously defined.

A7.2 Tracer Technique

This technique described by Bennett and Rathbren (1972) and
Tsivoglou (1968) uses an instantaneous injection of three tracers at a
point upstream from the reach over which the reaeration coefficient
is to be measured. The tracers are (1) a fluorescent dye the pur-
pose of which is to enable field personnel to follow the movement of
the tracers; (2) tritiated water, which is used as a conservative dis-

persion tracer, and (3) the radioactive tracer gas Krypton-85, which is used to measure the gas transfer capacity of the flow. Samples of stream water are removed from the flow as the dye peak passes the upstream end and again as it passes the downstream end of the reach. The transfer capacity of the flow for the tracer gas is obtained from the relative concentrations of the gas and tritiated water tracers at the two ends of the reach. Tsivoglou (1968) showed that

$$\frac{\left[\dfrac{C_G^*}{C_L^*}\right]_b}{\left[\dfrac{C_G}{C_L}\right]_a} = e^{-K_2Gt} \tag{A10}$$

where C^* is concentration; t is flow time. The subscripts a and b refer to the upstream and downstream stations respectively, the subscripts G and L refer respectively to the Krypton and tritium tracers and the term K_{2G} is the gas transfer coefficient of the tracer gas.

K_{2G} can be converted to a reaeration coefficient, K_2, by means of the gas-transfer ratio determined by Tsivoglou (1968). He found that the average ratio of the rate of Krypton desorption to the rate of oxygen absorption was 0.83. Hence,

$$K_2 = \frac{K_{2G}}{0.83} \tag{A11}$$

Generally the tracer technique is preferred to the disturbed equilibrium technique. The measurement of 'concentration' using scintillation detectors is very accurate, and because only ratios of the counts are used, determination of the counting efficiency is not necessary. This is reflected in a comparison of accuracy of the

two methods reported by Bennett and Rathbun (1972). The expected root-mean-square error for the tracer technique is 15% and for the disturbed equilibrium method an error of up to 115% can be expected.

The disadvantages to using the radioactive tracer technique are minimal when investigating streams with discharges less than $6 \text{ m}^3/\text{s}$. For larger flows stringent precautions against radiation exposure may be necessary because of the larger amounts of tracer necessary.

A8: Rate of Photosynthetic Oxygen Production and Respiration

Several procedures have been developed for the measurement of photosynthetic and respiration effects in natural streams. These include the light and dark bottle technique, the upstream-downstream method, the finite difference method and the plastic dome method.

A8.1: Light and Dark Bottle Technique

The light and dark bottle technique described by Camp (1963), Whipple (1969) and Bennett and Rathbun (1972) involves dividing a water sample into two parts; one part is placed in a transparent glass bottle and the other in an opaque bottle. Both bottles are suspended in the stream at the sampling point for a period of time, usually from 24 hours to several days. At the end of the period the bottles are analysed for their dissolved oxygen concentrations. The loss of oxygen from the dark bottle represents BOD while the change in oxygen in the light bottle is a result of both BOD and photosynthesis. The oxygen production due to photosynthesis is taken as the difference between the dissolved oxygen concentrations over a 24 hour period.

The technique described thus far considers the activity of plank-
ton and not benthal growths and rooted plants, which are more likely
to dominate in the natural stream environment. Under these circum-
stances the light and dark technique involves using one opaque and one
clear glass bell jar. Camp (1963) describes the method used as
follows: The bell jars are placed open side down in contact with the
bental deposit. A flow of water is to be passed through the bell
jars at a constant rate so as to produce a decrease or increase in
dissolved oxygen content which can be measured with accuracy. The
quality of this water should be that it is of the same temperature and
mineral content as the natural stream water but its BOD and plankton
count should be negligible. The opaque jar test should yield the ox-
ygen demand of the deposit and the clear glass jar should include the
compensating effects of photosynthesis.

Criticisms of the light and dark bottle method usually concern
the high surface/volume ratio in the container, the lack of turbulence
and the absorption of radiation by the glass. These three factors
could result in the enclosed biological system changing to such an
extent that it no longer represents the natural stream environment.

A8.2 The Upstream-Downstream Method

The rate of photosynthesis and respiration at any time during
the day can be estimated using the upstream-downstream method
developed by Odum (1956) and described by Bennett and Rathbun (1972),
Klein (1962) and O'Connell and Thomas (1965). The concentration of
dissolved oxygen is measured at two stations in the stream at fre-
quent intervals throughout the day and night, and from the resulting

values the change in concentration in the water flowing between the stations is plotted against time.

The graphical representation is typified by Figure A1. The constant diurnal rate of respiration is indicated by the minimum night time value. The area between the horizontal respiration line for the period between sunrise and sunset represents the total daily oxygen production by photosynthesis.

The mathematical basis for the procedure is the dissolved oxygen balance written in the form

$$q = \frac{dC}{dt} = p - r + K_2D - K_1L + a_o \qquad (A12)$$

where q (i.e. $(\frac{dC}{dt})$) = rate of change of d.o. content, $mg/m^3/day$

$\qquad\qquad$ p $\quad$ = rate of oxygenation due to photosynthesis $mg/m^3/day$

$\qquad\qquad$ r $\quad$ = rate of respiration, $mg/m^3/day$

$\qquad\qquad$ $K_2 D$ $\quad$ = rate of reaeration, $mg/m^3/day$

$\qquad\qquad$ K_1L $\quad$ = rate of carbonaceous deoxygenation $mg/m^3/day$

$\qquad\qquad$ a_o $\quad$ = rate of addition of d.o. by drainage, $mg/m^3/day$

It is assumed that respiration occurs at the same rate in the day during active photosynthesis as at night and that other factors such as the exchange coefficient, BOD, streamflow and the addition of dissolved oxygen by drainage remain constant. Therefore it follows that the rate of photosynthetic oxygen production in $mg/m^2/day$ ($p \times$ depth) is
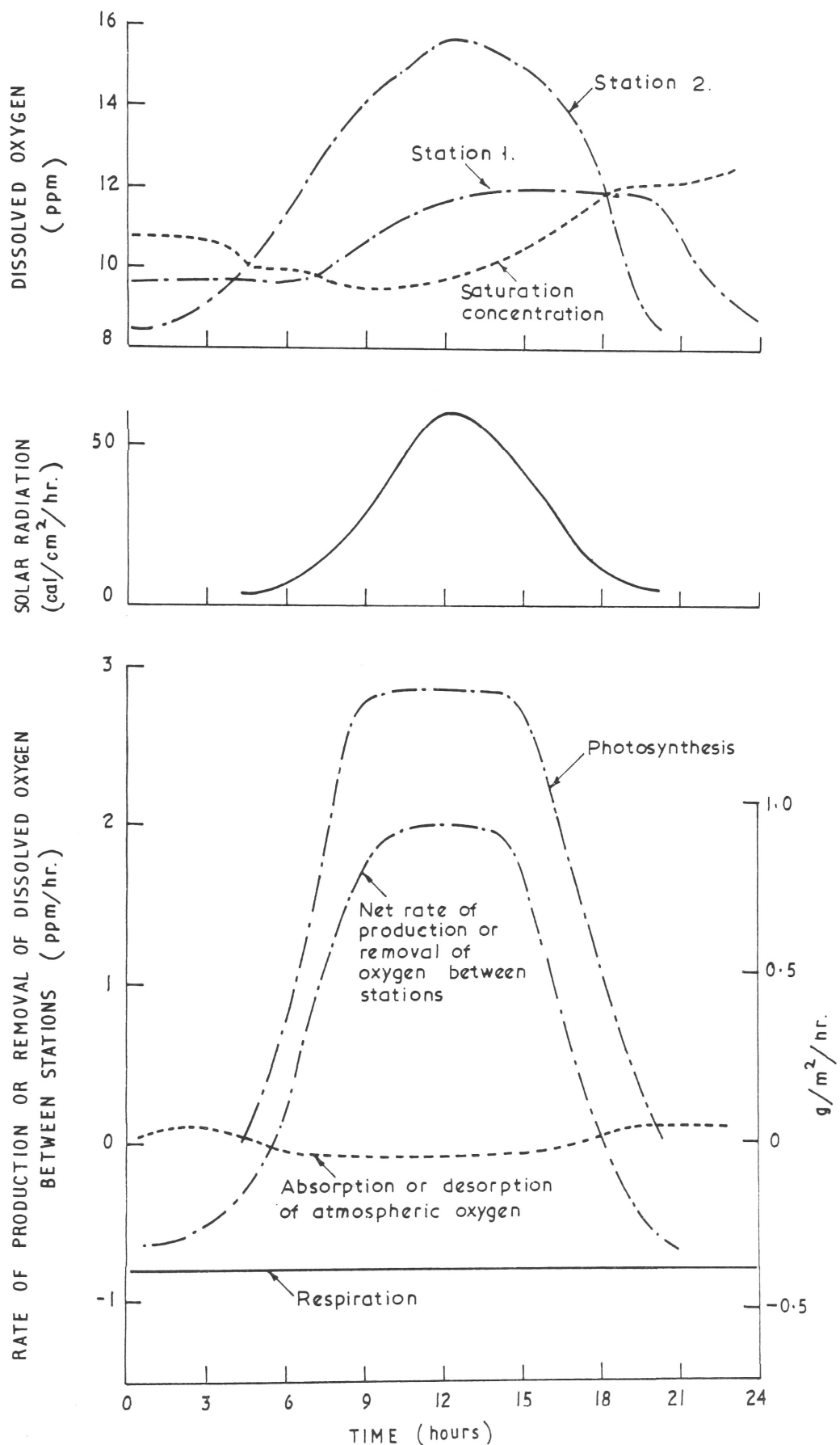
FIGURE A1: DIURNAL VARIATIONS IN DISSOLVED OXYGEN IN A STREAM FOR DETERMINATION OF THE RATES OF RESPIRATION AND PHOTOSYNTHESIS. (After Klein, 1962.)

$$P = H \int_{t_1}^{t_2} (q_2 - q_1) \, dt$$

$$= \frac{F}{A_s} \int_{t_1}^{t_2} (\Delta C_2 - \Delta C_1) \, dt \qquad (A13)$$

where $P = pH$

H is the stream depth (metres)

F is the volumetric water flow rate

A_s is the surface area of the reach

and ΔC is the d.o. concentration difference between the

upstream and downstream stations and the subscripts 1 and 2 refer

respectively to the time at which sunrise occurs and the time of

evening at which q (or ΔC) returns to the sunrise value.

A8.3 The Finite Difference Procedure

This method, described by O'Connell and Thomas (1965) in-

volves the determination of the net oxygen contribution by photo-

synthetic activity $(P_{h2} - P_{r2})$ by solution of the dissolved oxygen

balance equation,

i.e. $\quad \dfrac{dC}{dt} = (P_{h2} - P_{r2}) + K_2 D - K_1 L - N \qquad (A14)$

Therefore $(P_{h2} - P_{r2}) = \dfrac{dC}{dt} - K_2 D + K_1 L + N$ mg/l $\qquad (A15)$

The reaeration $(K_2 D)$, deoxygenation $(K_1 L)$ and nitrification(N)

terms are determined according to methods previously described.

For evaluation of the derivative term, samples are collected at

selected intervals and locations and a series of curves, showing

D.O. level as a function of time are plotted. The slope of the re-

lationship represents the rate of change of oxygen concentration $(\frac{dC}{dt})$.

The solution of the dissolved oxygen balance will depend on plant and algal biomass and solar radiation intensity. Quantitative assessment of oxygen production due to photosynthesis will be presented as a function of both the time of day and the location along the length of the stream.

The major disadvantage of the finite difference procedure lies in the accumulation of errors which will accompany the evaluation of the other terms in the dissolved oxygen balance, and particularly in the evaluation of the reaeration coefficient.

A9: Nitrification

The values of the ultimate nitrification demand and the rate constant (equations (4. 8) and (4. 9)) can be obtained in several ways. Indirectly estimation of the parameters can be achieved by measuring the production of nitrate in the stream. This must be done under steady state conditions. The measured concentrations of nitrate can be converted into the equivalent amount of oxygen required to produce it through oxidation of ammonia. A plot of oxygen consumed by nitrification versus time can be prepared.

Another method is to obtain a sample of stream water and observe its oxygen uptake as a function of time with and without the addition of a nitrification inhibitor. If the inhibited curve (organic matter oxidation only) is subtracted from the inhibited curve (organic matter and ammonia oxidation), a curve of oxygen utilised by ammonia

oxidation will result.   A more detailed description of the method is

given by Whipple (1969).

APPENDIX B

DISSOLVED OXYGEN METER

An 'E.I.L. Portable Dissolved Oxygen Meter-Model 1520, Electrode Model 152' was used in the investigation of dissolved oxygen levels in Perisher Creek. Details of the instrument and its operation are presented in the following sections.

B1 Description

The instrument consists of a cylindrical electrode (approx. $5\frac{1}{2}$" x 1" in size) connected to a direct read-out meter by a length of signal transmission cable. Both dissolved oxygen, expressed as a percentage of the saturation value, and stream temperature, are measured.

The oxygen electrode (Mackereth type) relies on oxygen diffusing through a semi-permeable polythene membrane covering the electrode, and being reduced at the cathode to give a current proportional to the oxygen partial pressure. The electrode is cylindrical and consists of a central lead anode surrounded by a hollow perforated silver cathode. Both the anode and cathode are covered in permeable polythene membrane and the volume between is filled with electrolyte. The membrane allows gaseous diffusion but not liquid or ionic diffusion.

Since the output current of the electrode varies with temperature, automatic temperature compensation is provided by a thermistor situated above the silver cathode. This thermistor is also used for measuring stream temperature.

The meter has three oxygen ranges: 0-200%, 0-100% and

0-50% saturation of oxygen. One hundred per cent saturation represents the partial pressure of oxygen in water saturated with air at 760 mm Hg pressure. The temperature scale covers the range -5 to +35°C.

B2 Calibration

Calibration of the instrument involves calibration of the temperature scale followed by a calibration of the dissolved oxygen scales. The procedure is detailed in the manual of 'Operating Instructions' supplied with the instrument.

It should be noted that if the atmospheric pressure deviates significantly from 760 mm Hg pressure the 100% saturation value will be denoted by the following meter reading:

$$\frac{\text{Atmospheric Pressure (mmHg)} - \text{SWVP}}{760 - \text{SWVP}} \times 100 \ \%$$

where SWVP = saturated water vapour pressure at the

temperature of calibration (mmHg)

The manufacturers suggest that the calibration procedure be repeated weekly if the instrument is in general use.

B3 Operation

The electrode is immersed in the stream water being examined. After a period of one minute, this being the 0-90% response time for temperature compensation, a reading can be taken from the selected scale.

Two points should be noted

(a)   The water must be moving past the electrode at a minimum rate of 10 cm/s to avoid oxygen depletion in the vicinity of the electrode.

(b)   A correction for salinity must be applied when making deter-
minations in saline water

$$\text{i.e. } (\% \text{ SAT})_{\text{actual}} = (\% \text{ SAT})_{\text{measured}} - \frac{2.65 \times S}{33.5 + T} \times \frac{(\% \text{ SAT})_{\text{measured}}}{100}$$

where S is the salinity (pp thousand)

and T is the water temp (^{O}C)

(Meter operating instructions)

Values of oxygen concentration (ppm) may be obtained from %
saturation values and stream temperature readings using the histo-
gram supplied with the instrument.

B4 Performance

The instrument specifications state that the dissolved oxygen
reading is accurate to 1% initially after calibration. Verification of
the accuracy should be carried out using the Winkler method, a chem-
ical method based on the fact that, in alkaline solution, the dissolved
oxygen oxidises manganous ion to manganic ion which, in turn, ox-
idises iodine ion to free iodine in quantities equivalent to the amount
of oxygen present.   Care has to be taken to ensure that oxygen con-
tamination of the sample, particularly the sample of low d.o. level,
does not occur during the process of analysis.   Attempts were made
to assess the accuracy of dissolved oxygen measurement by simul-
taneously comparing the readings of two identical instruments. Diff-
iculty occurred in the calibration of one of the instruments and con-
sequently readings showed a difference of approximately 8%. Never-
theless linearity was preserved over a wide range and no single
reading showed a deviation of more than 3% from the mean value.
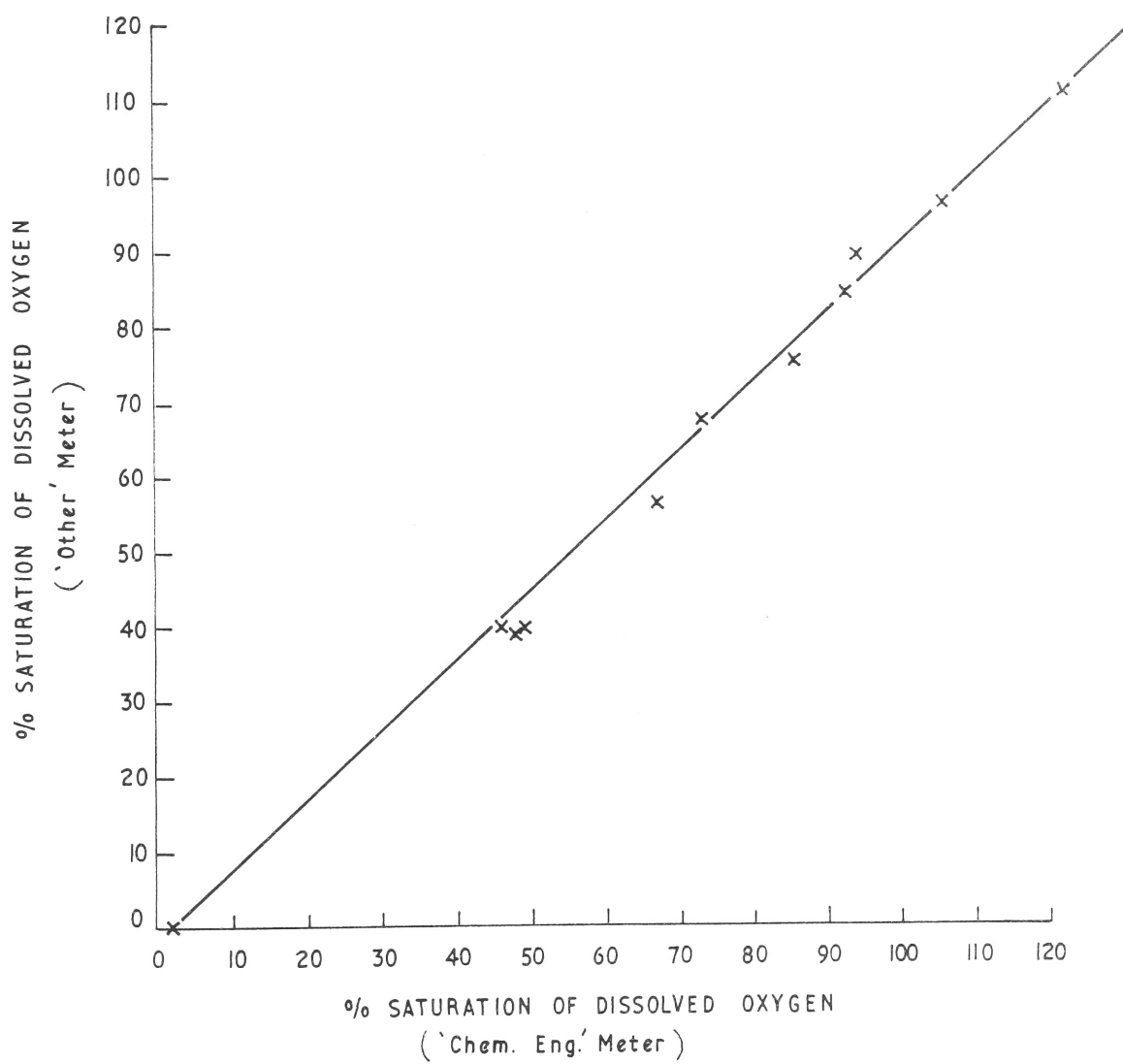Figure B1 depicts the results obtained.

FIGURE B1: COMPARISON OF D.O METER READ-OUTS.

The specifications for temperature are that the accuracy is $\pm$ 1°C initially after calibration. Comparison of thermometer and meter read-out, shown in Figure B2 confirm this specification.

Unfortunately the automatic temperature compensation is not ideal. Although untested, the instrument specifications state that the error in the dissolved oxygen reading due to differences in sample temperature will not exceed $\pm$ 5% for a $\pm$ 10°C change from the original calibration temperature.

The response time for 90% of the final d.o. reading is stated by the manufacturers to be approximately 75 seconds. Laboratory measurements shown in Figure B4 indicate that the 90% digure may be obtained within 30 seconds. However, up to 3 minutes may be necessary for 99% of the final reading.

The effect of stream velocity on the meter reading is shown in Figure B5. These results indicate that at 10 cm/s the reading will be within 1% of the final value. A flow velocity of 20 cm/s will enable 100% read-out.

Instrument drift is specified at less than 2% per day and about 5% per week. Laboratory measurements indicated a weekly figure of approximately 3%.
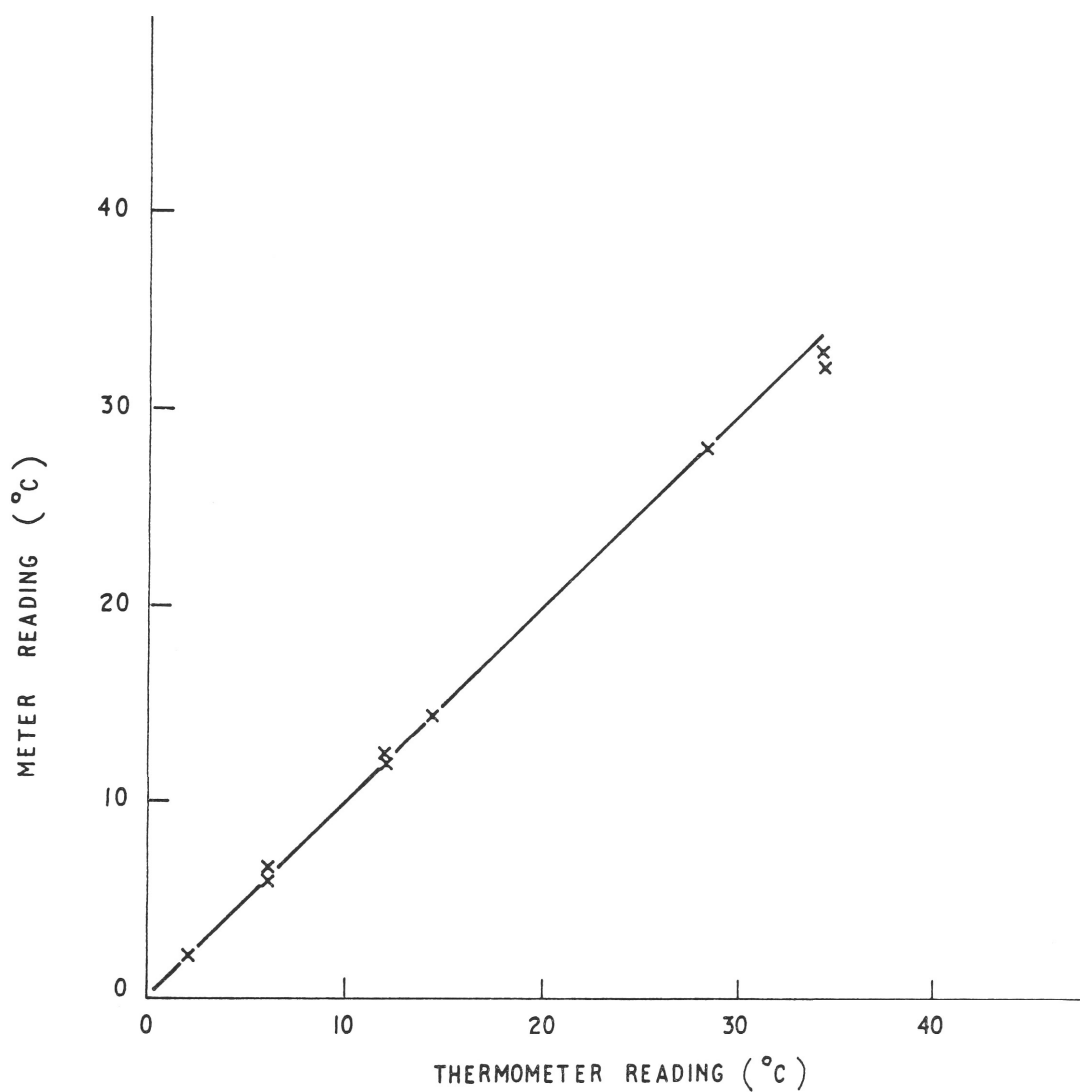
FIGURE B2: COMPARISON BETWEEN 'METER' AND 'THERMOMETER' READINGS OF WATER TEMPERATURE.
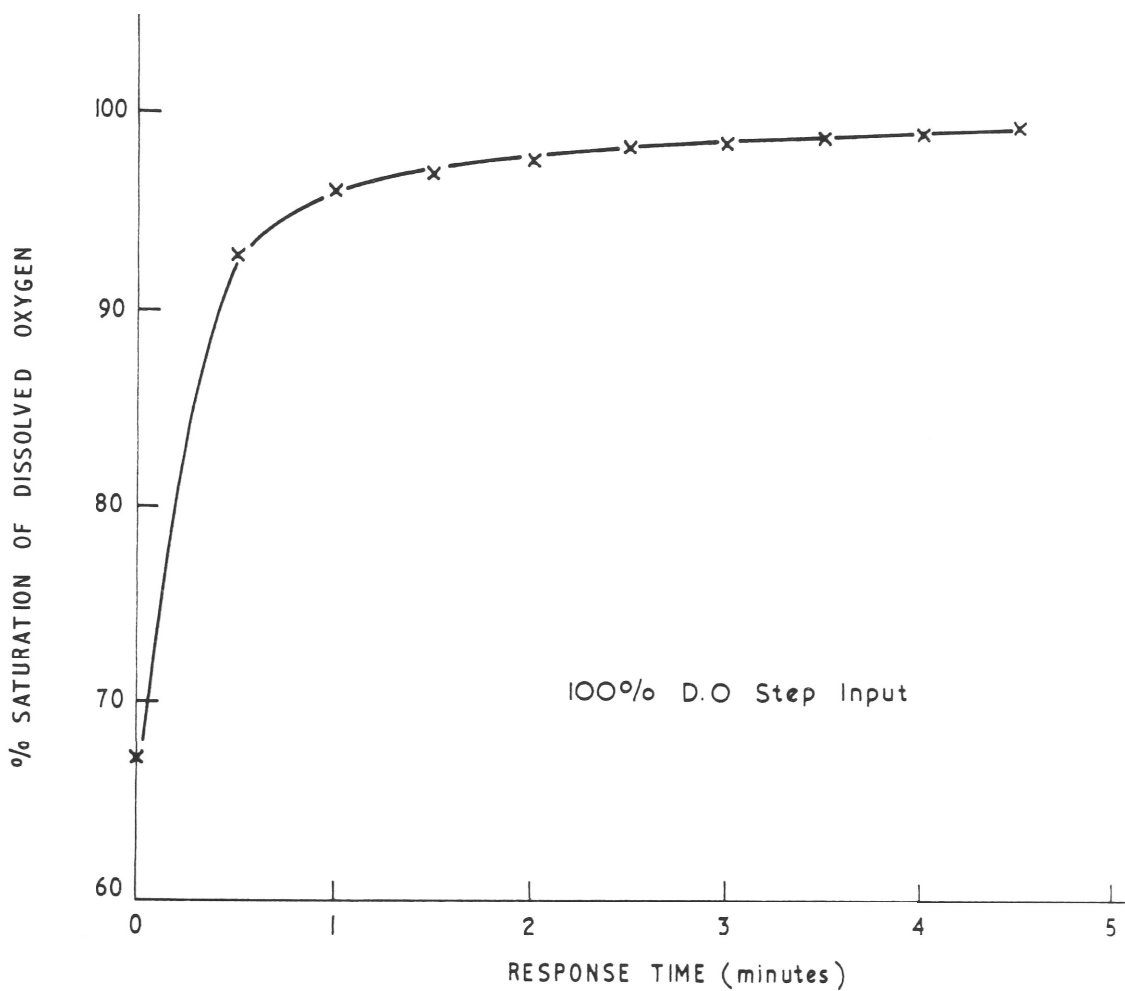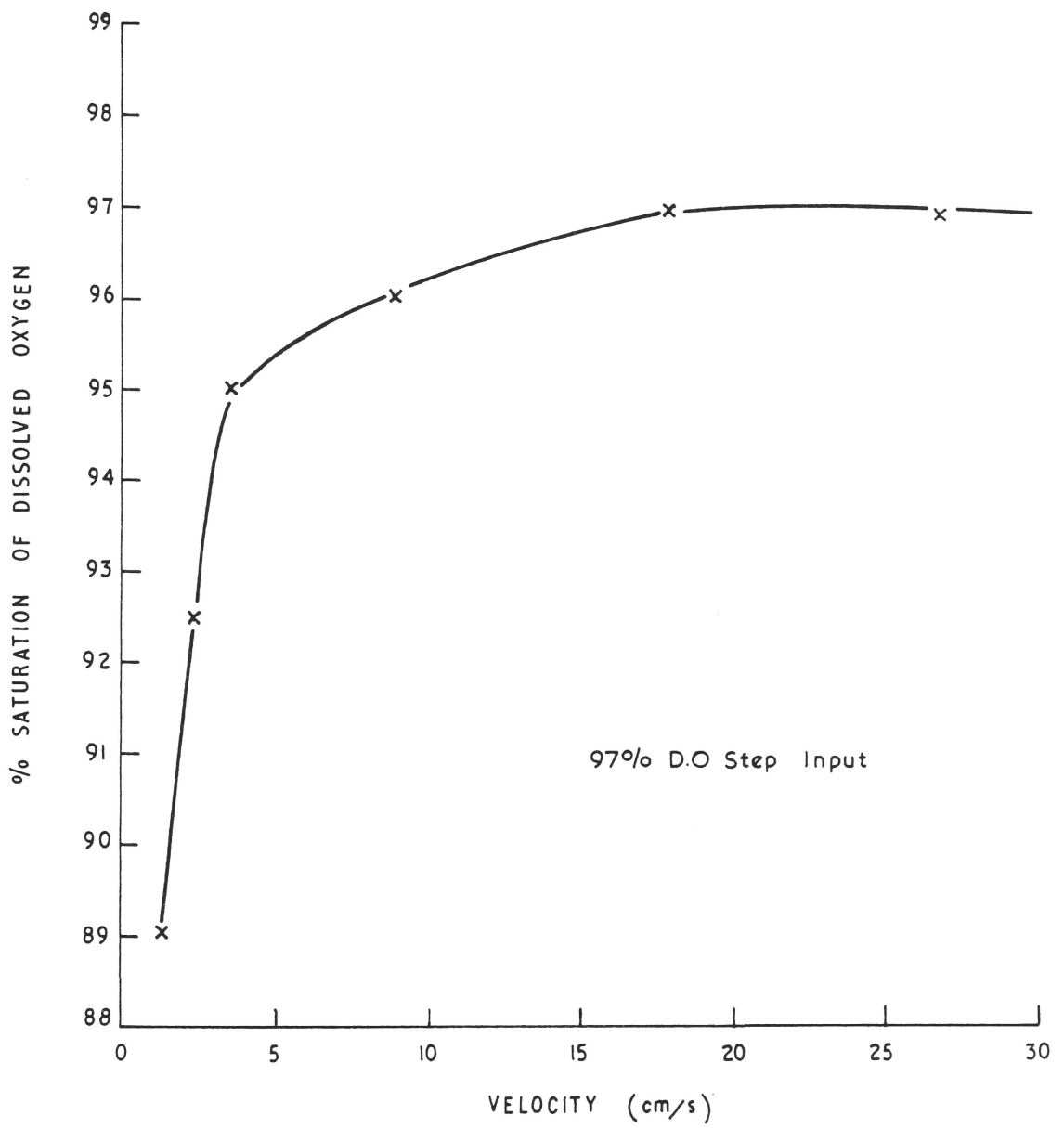
FIGURE B3: METER RESPONSE TIME

FIGURE B4: EFFECT OF STREAM VELOCITY
ON D.O READ-OUT.